

MARINE MICROBIAL PRODUCTS

APPLICATIONS AND OPPORTUNITIES

Edited by

Sesan Abiodun Aransiola, Mariam Iyabo Adeoba and Naga Raju Maddela



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Sesan Abiodun Aransiola

*Centre for Artificial Intelligence & Multidisciplinary Innovation Studies, College of
Accounting Sciences, University of South Africa, Pretoria, South Africa
Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria*

Mariam Iyabo Adeoba

*Biomechanics Research Group, Department of Mechanical,
Bioresources and Biomedical Engineering, College of Science,
Engineering and Technology (CSET), University of
South Africa (UNISA), Florida, South Africa*

Naga Raju Maddela

*Departamento de Ciencias Biológicas, Facultad la Ciencias
de la Salud, Universidad Técnica de Manabí, Portoviejo,
Manabí, Ecuador*



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List of contributors

Muhammed Abdulazeez

Department of Microbiology, Skyline University Nigeria, Kano State, Nigeria

Abdulhakeem Idris Abdulhakeem

Department of Biodiversity and Bioresources, Al-Farabi Kazakh National University, Almaty, Kazakhstan

Mustapha Abdulsalam

Department of Microbiology, Skyline University Nigeria, Kano State, Nigeria

Peter Olabisi Abioye

Department of Microbiology, Federal University of Technology Minna, Niger, Nigeria

Ngozi Kalu Achi

Department of Biochemistry, Micheal Okpara University of Agriculture, Umudike P.M.B, Umuahia, Abia, Nigeria

Aisha Eniola Adegbite

Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Habeebulahi Ajibola Adekilekun

Department of Pharmacology and Toxicology, Kampala International University, Bushenyi, Western Campus, Ishaka, Uganda; Department of Biochemistry, Micheal Okpara University of Agriculture, Umudike P.M.B, Umuahia, Abia, Nigeria

Mariam Iyabo Adeoba

Biomechanics Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, College of Science, Engineering and Technology (CSET), University of South Africa (UNISA), Florida, South Africa

Oluremi Racheal Adeyemo

Department of Automated Clinical Biochemistry, University Hospital Southampton, NHS Foundation Trust, Southampton, United Kingdom

Farida Mohammed Ado

Department Of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Mariam Ahmed

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Pilli Aishwarya

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Bolaji Oluwatosin Akanbi

Department Of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Joshua O. Akhigbe

Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Tobilola O. Akingbade

Department of Pharmaceutical Sciences, North Carolina Central University Sciences, Durham, NC, United States

Vivian Nonyelum Anakwenze

Department of Applied Microbiology and Brewing, Nnamdi Azikiwe University, Awka, Anambra, Nigeria

Adejoke Blessing Aransiola

Department of Surveying and Geoinformatics, Faculty of Environmental Science, University of Abuja, Abuja, Nigeria

Sesan Abiodun Aransiola

Centre for Artificial Intelligence & Multidisciplinary Innovation Studies, College of Accounting Sciences, University of South Africa, Pretoria, South Africa; Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Abraham Olufemi Asuku

Bioresources Development Centre, National Biotechnology Research and Development Agency, Ogbomoso, Oyo State, Nigeria; Department of Physiology, Faculty of Basic Medical Sciences, College of Health Sciences, University of Ilorin, Ilorin, Kwara State, Nigeria

Helen Shnada Auta

Department of Microbiology, Federal University of Technology Minna, Niger, Nigeria

Natalia Bailon-Moscoso

Universidad Técnica Particular de Loja, Loja, Ecuador

Abraham Bravo-Pinargote

Carrera de Bioquímica y Farmacia, Facultad de Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador

Jhon Cantos H.

Carrera de Bioquímica y Farmacia, Facultad de Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador

Rakesh Das

School of Pharmaceutical Technology, School of Health and Medical Sciences, Adamas University, Kolkata, West Bengal, India

Ranjit Das

Department of Microbiology, All India Institute of Medical Sciences (AIIMS), Kalyani, West Bengal, India

P. Deepalakshmi

Department of Chemistry, Nadar Saraswathi College of Arts and Science, Theni, Tamil Nadu, India

P. Gnana Deepu

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Arup Dey

Faculty of Pharmaceutical Science, Assam Down Town University, Guwahati, Assam, India

Rodrigo Duarte-Casar

Ingeniería en Alimentos, Pontificia Universidad Católica del Ecuador, Portoviejo, Manabí, Ecuador

Shehu-Alimi Elelu

Department of Chemistry, Howard University, Washington, DC, United States

Kingsley Erhons Enerijiofi

Department of Biological Sciences, College of Basic, Applied and Health Sciences, Glorious Vision University, Ogwa, Edo State, Nigeria

Prasad Ernala

Pilot Fermentation Operations and Bio-Manufacturing Process R&D, Verschuren Centre for Sustainability, Sydney, NS, Canada

Oyindamola Esan

Department of Microbiology, Faculty of Life Sciences, University of Benin, Benin, Edo, Nigeria

Daniel Uchechukwu Eze

Department of Pharmaceutical Sciences, North Carolina Central University Sciences, Durham, NC, United States; Department of Pharmaceutical Microbiology and Biotechnology, David Umahi Federal University of Health Sciences, Uburu, Ebonyi State, Nigeria

Kelechi Ezennubia

Department of Chemistry and Biochemistry, Baylor University, Waco, TX, United States

Abiodun Abidemi Folarin

Department of Chemistry and Biochemistry, North Carolina Central University, Durham, NC, United States

Manish Kumar Gautam

Faculty of Pharmaceutical Science, Assam Down Town University, Guwahati, Assam, India

Boje Gowd B.H

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Jogipeta Harihara

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Fahrul Hayup

Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, Johor, Malaysia

Gordon C. Ibeanu

Department of Pharmaceutical Sciences, North Carolina Central University Sciences, Durham, NC, United States

Roseline Rumi Ideh

Food and Industrial Biotechnology Department, National Biotechnology Research and Development Agency, Abuja, Nigeria

Uchechukwu Caroline Ilojinso

Department of Nursing, University of Derby, Derbyshire, United Kingdom

Jonathan Inetianbor

School of Health and Life Sciences, Coventry University Group, Coventry, United Kingdom

Amarachukwu Bernaldine Isiaka

Qatar Airways Medical Division, Qatar Airways, Doha, Qatar; School of Public Health, University of Port Harcourt, Rivers State, Nigeria

Dineshkumar Krishnamoorthy

Center for Genomics and Systems Biology, New York University Abu Dhabi, Saadiyat Campus, Abu Dhabi, United Arab Emirates

S. Chaitanya Kumari

Department of Microbiology, Bhavan's Vivekananda College of Science, Humanities and Commerce, Sainikpuri, Secunderabad, Telangana, India

Salami Olaitan Lateefat

Department of Chemistry and Molecular Biology, University of Gothenburg, Gothenburg, Sweden

Miracle Uwa Livinus

Department of Biochemistry, Skyline University Nigeria, Kano State, Nigeria

Salamatu S. Machunga-Mambula

Department Of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Naga Raju Maddela

Departamento de Ciencias Biológicas, Facultad la Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador

Daniel Makolo

Department of Microbiology, Baze University, Abuja, Nigeria

Ruben Babu Marabathula

Department of Genetics and Genomics, Yogi Vemana University, Kadapa, Andhra Pradesh, India

Tracy Masebe

Department of Life and Consumer Sciences, College of Agriculture and Environmental Sciences, University of South Africa (UNISA), Florida, Johannesburg, South Africa

Carola Millan

Universidad Adolfo Ibáñez, Campus Viña del Mar, Viña del Mar, Chile

Wael Mohamed

Basic Medical Science Department, Kulliyah of Medicine, International Islamic University Malaysia (IIUM), Kuantan, Pahang, Malaysia

Sandip Mondal

Amity Institute of Pharmacy, Amity University Kolkata, Newtown, Kolkata, West Bengal, India

Maria C.B.S.M Montenegro

LAQV@REQUIMTE, Department of Chemical Sciences, Faculty of Pharmacy, University of Porto, Porto, Portugal

Abdulkabir Danlami Muhammad

Department Of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Auwal Sagir Muhammad

School of Informatics, Xiamen University, Xiamen, P.R. China

Innocent Ojeba Musa

Department of Microbiology, Skyline University Nigeria, Kano State, Nigeria

Anjaneyulu Musini

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Venkateshwarlu Musini

Department of Civil Engineering, CMR College of Engineering and Technology, Hyderabad, Telangana, India

Rajesh Nambi

Department of Biotechnology and Bioinformatics, Yogi Vemana University, Kadapa, Andhra Pradesh, India

Himanshu Narayan Singh

Department of Systems Biology, Columbia University Irving Medical Centre, New York, NY, United States

Soumitra Nath

Department of Biotechnology, Gurucharan College, Silchar, Assam, India

Harry Ngwangwa

Unisa Biomedical Engineering Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, School of Engineering, College of Science Engineering and Technology, University of South Africa, Science Campus, Florida, South Africa

Sarah Chioma Nwakanma

Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Joy Chioma Okoli

Department of Pharmaceutical Sciences, North Carolina Central University Sciences, Durham, NC, United States

Adewale Odunayo Oladipo

Biomechanics Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, College of Science, Engineering and Technology (CSET), University of South Africa (UNISA), Florida, South Africa

Oluwatosin Olubunmi Oladipo

Department of Science Technology, Microbiology Unit, Federal Polytechnic, Ado Ekiti, Ekiti, Nigeria

Peace Ayo Olaoluwa

Department of Physiology, Faculty of Basic Medical Sciences, College of Health Sciences, University of Ilorin, Ilorin, Kwara State, Nigeria

Stephen Olori

Department of Microbiology, Faculty of Life Sciences, University of Benin, Benin, Edo, Nigeria

Olorunshola Dave Omodamiro

Department of Pharmacology and Toxicology, Kampala International University, Bushenyi, Western Campus, Ishaka, Uganda; Department of Biochemistry, Micheal Okpara University of Agriculture, Umudike P.M.B, Umuahia, Abia, Nigeria

Racheal M. Omodamiro

Department of Pharmaceutical Chemistry and Pharmacognosy, Kampala International University, Bushenyi, Western Campus, Ishaka, Uganda; National Root Crops Research Institute, Umudike, P.M.B, Umuahia, Abia, Nigeria

Magdalene Akhere Osaghae

Department of Microbiology, Faculty of Life Sciences, University of Benin, Benin, Edo, Nigeria; Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Aduba Osaretin

Department of Microbiology, Faculty of Life Sciences, University of Benin, Benin, Edo, Nigeria

Habeebat Adekilekun Oyewusi

Department of Science Technology, Biochemistry Unit, Federal Polytechnic, Ado Ekiti, Ekiti, Nigeria

Shiva Prasad Panajala

Department of Genetics and Biotechnology, University College of Sciences, Osmania University, Hyderabad, Telangana, India

Thanyani Pandelani

UNISA Biomedical Engineering Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, School of Engineering, College of Science Engineering and Technology, University of South Africa, Science Campus, Florida, South Africa

Gayathri Pandluru

Department of Biotechnology, University College of Sciences, Sri Krishnadevaraya University, Anantapuramu, Andhra Pradesh, India

Kameshpandian Paramasivam

DMI St. John The Baptist University, Lilongwe, Malawi

Osman Basha Pinjari

Department of Genetics and Genomics, Yogi Vemana University, Kadapa, Andhra Pradesh, India

Jogipeta Pruthvi Raj

Central Institute of Agricultural Engineering, Bhopal, Madhya pradesh, India

K. Deepak Raj

Department of Microbiology, Bhavan's Vivekananda College of Science, Humanities and Commerce, Sainikpuri, Secunderabad, Telangana, India

C.H. Rashmitha

Department of Microbiology, Bhavan's Vivekananda College of Science, Humanities and Commerce, Sainikpuri, Secunderabad, Telangana, India

Adriana Carolina Rincón Alarcón

Departamento de Ciencias Médicas, Facultad de Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador

Joan Manuel Rodríguez-Díaz

Departamento de Procesos Químicos, Biotecnología y Alimentos, Facultad de Ingenierías y Ciencias Aplicadas, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador; Laboratorio de Análisis Químicos y Biotecnológicos, Dirección de Investigación, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador

Marlene Rojas-Le-Fort

Ingeniería en Alimentos, Pontificia Universidad Católica del Ecuador, Portoviejo, Manabí, Ecuador

Juan Carlos Romero-Benavides

Universidad Técnica Particular de Loja, Loja, Ecuador

Adekunle Babajide Rowaiye

Department of Pharmaceutical Sciences, North Carolina Central University Sciences, Durham, NC, United States

Gedela Sandhya Rani

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Gandikota Sardhika

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

M. Srinivasulu

Department of Chemistry, Nadar Saraswathi College of Arts and Science, Theni, Tamil Nadu, India; Department of Biotechnology, Yogi Vemana University, Kadapa, Andhra Pradesh, India

Y. Srivalli

Department of Microbiology, Bhavan's Vivekananda College of Science, Humanities and Commerce, Sainikpuri, Secunderabad, Telangana, India

Prathipati Supriya

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University Hyderabad, Telangana, India

Vyshnava Satyanarayana Swamy

Department of Biotechnology, University College of Sciences, Sri Krishnadevaraya University, Anantapuramu, Andhra Pradesh, India

K. Swetha

Department of Biotechnology, University College of Sciences, Sri Krishnadevaraya University, Anantapuramu, Andhra Pradesh, India

Bashar Adekilekun Tijani

Obafemi Awolowo University Teaching Hospitals Complex, Ile-Ife, Osun, Nigeria

Tracy Uyigue

Department of Microbiology, Faculty of Life Sciences, University of Benin, Benin, Edo, Nigeria

Ugonna Henry Uzoka

Laboratory of Bacterial Disease (LDBAC), Department of Veterinary, Federal University of Viçosa, Minas Gerais, Brazil; Department of Veterinary Medicine, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria

Govindhasamay R. Varatharajan

Faculty of Biology, Shenzhen MSU-BIT University, Shenzhen, P.R. China

Kondakindi Venkateswar Reddy

Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

Amina Yahaya

Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

Fatima Adamu Yahaya

Department of Microbiology, Skyline University Nigeria, Kano State, Nigeria

Luis Angel Zambrano-Intriago

Departamento de Ciencias Biológicas, Facultad de Ciencias de La Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador

About the editors

Sesan Abiodun Aransiola is a notable PhD holder in environmental microbiology in the Department of Microbiology, Federal University of Technology, Minna, Nigeria. He obtained his first degree (B.Tech) and master's degree (M.Tech) from the same department in 2009 and 2014, respectively. He has demonstrated his research expertise in the production of vermicasts from vermicomposting (vermitechnology) of organic wastes to assist plants in the remediation of polluted soil with heavy metals. Currently, he is a lecturer at the Department of Microbiology, University of Abuja, Nigeria. His expertise spans environmental health, phytoremediation, vermicomposting, marine resources, and bioremediation of soil pollutants including plastics. Aransiola's research is deeply rooted in innovative solutions for soil and water remediation, with significant contributions to microbial biotechnology and waste management. He is an award-winning researcher and has over 100 publications including book chapters, research articles, and review articles of good international repute with high impact factor. He has coedited scientific books of global interest which include *Microbial Biotechnology for Bioenergy* (Elsevier), *Ecological Interplays in Microbial Enzymology*, *Prospects for Soil Regeneration and Its Impact on Environmental Protection*, *Soil Microbiome in Green Technology Sustainability*, *Marine Bioprospecting for Sustainable Blue-Bioeconomy* (Springer), *Microbial Biofilms – Applications and Control*, *Marine Greens: Environmental, Agricultural, Industrial and Biomedical Applications*, *Emerging Contaminants in Food and Food Products*, *Phytoremediation in Food Safety: Risks and Prospects*, *Biotoxins in Food: Threats and Detection* (CRC Press), with many more in the process. Also, he has worked to the rank of an assistant chief scientific officer at Bioresources Development Centre, National Biotechnology Research and Development Agency, Nigeria, where he was involved in the uses of vinasse (a by-product of ethanol) as biofertilizer to reclaim polluted soil for agricultural purposes. Dr. Aransiola's academic journey is complemented by a robust teaching career and active involvement in community services, where he leverages his knowledge to foster sustainability. His contributions continue to impact both academia and the broader environmental sciences community. Abiodun is a member of the Nigerian Society for Microbiology and American Society for Microbiology among others.



Naga Raju Maddela received his MSc (1996–98) and PhD (2012) in microbiology from Sri Krishnadevaraya University, Anantapuramu, India. During his doctoral program in the area of environmental microbiology, he investigated the effects of industrial effluents/insecticides on soil micro-organisms and their biological activities, and he is working as faculty in microbiology since 1998, teaching undergraduate and postgraduate students. He worked on Prometeo Investigator (fellowship received from SENESCYT) at Universidad Estatal Amazónica, Ecuador during 2013–15, and received "Postdoctoral Fellowship" (2016–18) from Sun Yat-sen University, China. He also received external funding from "China Postdoctoral Science Foundation" in 2017 and internal funding from "Universidad Técnica de Manabí" in 2020. He participated in national/international conferences



and presented research data in China, Cuba, Ecuador, India, and Singapore. Currently, he is working as a full professor at the Facultad de Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Ecuador. He has been actively publishing scientific articles, books (authored and edited), and chapters since 2007. As of now, he has published 110 articles, 25 books, and 50 book chapters.

Dr. Mariam Iyabo Adeoba is a highly accomplished researcher and educator with extensive experience in zoology, environmental management, and renewable energy, holding a PhD in zoology from the University of Johannesburg (UJ) and a master's degree in animal physiology from the University of Agriculture (UNAAB) in Nigeria. Dr. Adeoba has a solid academic background and a passion for addressing pressing environmental and sustainability challenges. Dr. Adeoba has demonstrated exceptional leadership, communication, and analytical skills. She has a proven track record of conducting impactful research and contributing to developing innovative solutions in areas such as renewable energy, water resources management, waste management, and nature conservation. As a postdoctoral research fellow at the University of South Africa (UNISA), Dr. Adeoba's research focuses on investigating the suitability and quality of fish waste for anaerobic digestion and evaluating the potential of wastewater sludge for renewable energy production. Her work in this area contributes to advancing sustainable bioenergy generation and environmental conservation. Dr. Adeoba has also played a significant role in USAID capacity-building and professional development initiatives and collaborated with the University of Johannesburg, particularly for women in the energy sector. As a Resource Person for the Women in the Just Energy Transition (JET Skills Program Phase II South Africa), she has designed and delivered training modules on renewable energy and project management to empower women and promote gender equality in the energy industry. In addition to her research and capacity-building efforts, Dr. Adeoba is actively involved in community engagement and environmental advocacy. As the cofounder of the Conserve Africa Initiative, a nonprofit organization focused on environmental preservation and community development, she leads initiatives to promote waste education, circular economy practices, and women's empowerment. Dr. Adeoba's commitment to excellence in research and education is reflected in her extensive publication record and involvement in academic activities. She has authored numerous research papers and book chapters covering various environmental science and biodiversity conservation methods.



Foreword



Marine microbial products (MMPs) with their unique bioactive compounds, antibiotic potential, anticancer properties, bioremediation potentials, enzymes, and probiotic productions are worthy to be discussed for brighter future for all in terms of provision of good health, friendly environment, sustainable agriculture, and industrial fruiting. By estimate, up to 75% of all marine species remain undiscovered, providing a vast, untapped source of new marine microbial products. MMPs, such as discodermolide and dolastatin, have shown anticancer properties and are being explored as potential cancer treatments. Marine microbial products provide a substantial reservoir of innovative antibiotics, antivirals, therapeutics, and immunosuppressive chemicals. These biologically active substances can effectively tackle emerging issues, such as antibiotic resistance and the demand for novel therapeutic agents. In industrial biotechnology, enzymes and bioactive chemicals derived from marine microbes find applications in bioremediation (removing environmental contaminants), food processing, and agriculture (as biofertilizers or biopesticides). Also, skincare and cosmetic formulations progressively incorporate marine microbial products, especially those possessing antioxidant and UV-protective characteristics. The food industry uses specific marine microorganisms as reservoirs of bioactive substances such as omega-3 fatty acids, pigments, and probiotics, which find utility in functional foods and dietary supplements. Marine microbial products provide ecologically sound alternatives to synthetic chemicals, especially in agriculture and waste management, as priorities shift towards sustainable practices.

While many books have described generally the products emanating from the marine environment, this book seeks to provide scientific information on the production and diverse applications of the marine microbial products, which has significant economic potential, with estimates suggesting that it could reach \$6.4 billion by 2025. This book, titled ***Marine Microbial Products: Applications and Opportunities***, delves into the oceans as a promising habitat for microorganisms for useful products.

This book explores the characterization and detection techniques of MMPs, marine microbial natural product prospects, marine greens and their double edge applications, development of marine microbial products as models for disease treatment, biomedical applications of MMPs, microbial degradation of microplastics through MMPs, marine microbial stimulants in agricultural sustainability, algae in renewable energy production for sustainable environment, and notable current innovations of the MMPs.

This book enables readers to explore the vast potential applications of MMPs organized into chapters for clarity and ease of understanding. This book is unique in its comprehensive coverage of diversity, applications, and current innovations of MMPs. This book is intended for students, researchers, and professionals interested in exploring and harnessing marine microbial resources. It will also benefit marine scientists and engineers.

Given all these benefits, having a book that expands the knowledge in applying these products would be great. Hence, the book would solve the associated problems surrounding the ongoing exploration and research into marine microbial products and present exciting opportunities for innovation and sustainable development across multiple sectors.

Prof. Salamatu S. Machunga-Mambula

Director

Central Laboratory Services Unit

University of Abuja, Abuja, Nigeria

May 8, 2025

Preface

Marine microorganisms, an extensive and varied assemblage of organisms residing in the oceans, contain many bioactive chemicals that have possible uses in several sectors. Often unique due to the extreme conditions in which they are synthesized, these chemicals provide a diverse array of advantages for human health, environmental sustainability, and technological progress.

This book, titled ***Marine Microbial Products: Applications and Opportunities***, consists of three sections. The first section presents the biodiversity of marine microorganisms capable of producing important marine products. Marine microbial products (MMPs) have a vast and growing scope due to the unique bioactive compounds they release which are often adapted to the extreme conditions of marine environments, making them particularly valuable for various applications. Concurrently, chapters in this section discuss the characterization and detection techniques of MMPs, the prospects of these products, and their development as model for disease treatment. In the second section titled Applications of Marine Microbial Productions, the authors discuss extensively on the MMPs' biomedical applications, bioremediation of pollutants, agricultural sustainability, renewable energy, and in the food industry. The third section deliberates on the current innovations in marine MMPs and various technology innovations in remediation, climate change mitigation, the role of machine learning in MMP prediction, and drug development. This section also discusses marine microbial prospecting of the blue bioeconomy and the future directions for research.

The entire book shows how microorganisms in the aquatic environment and their products could be used to add value to the environmental, agricultural, biomedical, and industrial sectors. The chapters were contributed by 105 academicians, scientists, and researchers from 20 different countries viz the United Kingdom, Nigeria, India, Kazakhstan, Ecuador, Canada, Qatar, United Arab Emirates, Sweden, Chile, Brazil, Uganda, Malawi, the United States, Portugal, South Africa, P.R. China, and Malaysia.

Sesan Abiodun Aransiola, PhD
Mariam Iyabo Adeoba, PhD
Naga Raju Maddela, Professor

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Sesan Abiodun Aransiola, PhD
Mariam Iyabo Adeoba, PhD
Naga Raju Maddela, Professor

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SECTION

Marine microbial
product diversity

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Marine microbial products: overview

K. Deepak Raj¹, Y. Srivalli¹, C.H. Rashmitha¹, Prasad Ernala² and S. Chaitanya Kumari¹

¹*Department of Microbiology, Bhavan's Vivekananda College of Science, Humanities and Commerce, Sainikpuri, Secunderabad, Telangana, India,*

²*Pilot Fermentation Operations and Bio-Manufacturing Process R&D, Verschuren Centre for Sustainability, Sydney, NS, Canada*

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1.1 Introduction

Marine microbial products (MMPs) have become a notable research focus because of their wide-ranging applications in cosmetics, pharmaceuticals, and environmental management. These products are extracted from marine microorganisms like bacteria, fungi, and algae, which live in various marine environments, including shallow waters, deep-sea hydrothermal vents, and coral reefs (Barzkar, et al., 2024).

Marine microorganisms play a crucial role in marine ecosystems, contributing to biochemical cycles, organic matter degradation, and oxygen production. They are responsible for more than 50% of the Earth’s oxygen production, primarily through phototrophic microorganisms like cyanobacteria and diatoms. Despite their importance, only a small fraction of marine microorganisms have been cultured and studied, with estimates suggesting that 90%–99% remain uncultured under standard laboratory conditions (Aransiola, Oyewole, et al., 2024; Glöckner et al., 2012).

The unique metabolic pathways and adaptation mechanisms of marine microorganisms result in natural products with unique structures and significant biological activities. These products include surfactants, glyco-peptides and lipo-peptides, exopolysaccharides, biocatalysts/enzymes, and bioactive compounds with antimicrobial, antitumor, and cytotoxic properties. For instance, peptides derived from microalgae like *Navicula salinicola* have been shown to inhibit gamma-glutamate transferase, reducing oxidative damage and delaying cell senescence. Similarly, peptides from *Chlorella* can reduce the expression of matrix metalloproteinase-1 (MMP-1), thereby delaying skin aging (Ding et al., 2022).

Marine microorganisms are also a valuable source of novel bioactive compounds for pharmaceutical applications. For example, marine bacteria have been found to produce antimalarial compounds, including polyketides and non-ribosomal peptides. Additionally, marine fungi have yielded antibacterial compounds, such as those isolated from *Streptomyces* species. The application of MMPs in cosmetics is gaining attention due to their safety and effectiveness. Metagenomics technology has become crucial in identifying and exploiting these products, as many marine microorganisms cannot be cultured using traditional methods. Overall, MMPs represent a promising frontier in biotechnology, offering opportunities for sustainable and environmentally friendly solutions across various industries (Aransiola, Bamisaye, et al., 2024; Karthikeyan et al., 2022).

1.2 Marine environment and microbial diversity

The marine environment, which covers over 70% of Earth, is an incredibly diverse ecosystem. Marine microbes, including viruses, bacteria, phytoplankton, and zooplankton, make up more than 95% of the

ocean's living matter. These organisms live in the water, sediments, and in close relationships with other organisms. The ocean presents a range of extreme natural conditions, such as those found in polar regions and hydrothermal vents and is constantly affected by human-caused stressors. As a result, marine ecosystems are home to organisms with remarkable adaptations that allow them to survive in extreme salinity, temperature, and pressure. This adaptability leads to significant genetic and functional diversity, which in turn enables the production of molecules with potential biotechnological applications. Marine microorganisms are of great interest for their potential to produce molecules that can be used in pharmaceuticals to treat diseases. Algae, for example, are a promising source of valuable lipids, pigments, and exopolysaccharides. Marine bacteria and fungi have also been shown to produce a wide range of novel compounds with antibiotic properties. Additionally, biomolecules produced by marine yeasts have shown potential for various applications, including the production of biosurfactants (Hosseini et al., 2022).

1.2.1 Marine bacterial diversity

Investigating the variety of marine bacteria is crucial for understanding how these communities are organized and spread throughout the ocean. Typically, bacteria are very small, usually under 1–2 micrometers. However, there are exceptions, such as *Epulopiscium fishelsoni*, a large Gram-positive bacterium found in the intestines of a Red Sea fish, which can reach sizes of 200–800 µm. In the ocean, the majority (90%) of bacteria are Gram-negative, exhibiting diverse traits. The structure of the Gram-negative cell wall appears to provide an advantage for survival in marine conditions (Das et al., 2006; Okewu et al., 2024).

1.2.1.1 Bacteria's role within the marine environment

High pressure, salinity, freezing temperatures, and darkness are some of the difficult circumstances found in the ocean. In this environment, marine heterotrophic bacteria have adapted to flourish. In order to retain cellular integrity in the salty environment, they need sodium ions for growth. They also exhibit oligotrophy, an adaptation to limited nutrient availability. These bacteria play a vital role in breaking down organic matter, contributing to decomposition and mineralization in sediments and the water column, releasing dissolved organic and inorganic substances. This process recycles nutrients from primary producers, making them available again (Das et al., 2006).

Heterotrophic microbes are key drivers of the ocean's organic composition. These bacteria form a significant portion of the microbial communities in the ocean's water column, driving the conversion of organic matter and the production of carbon dioxide. Their distribution is influenced by factors such as water temperature, salinity, and other physical and chemical properties. Additionally, they serve as a food source for various marine organisms. Therefore, bacteria are crucial for maintaining the health of the marine ecosystem and act as biological mediators in biogeochemical cycles (Das et al., 2006).

1.2.1.2 Marine microorganisms as sources of therapeutic enzymes and secondary metabolites

Salt-tolerant marine microorganisms are a valuable resource for therapeutic development. Their diverse enzymatic activities, particularly in halophilic organisms, enable them to catalyze unique

biochemical reactions under conditions that typically denature proteins. Seawater's similarity to human blood plasma suggests that marine-derived enzymes may offer safer therapeutic options with reduced toxicity (Das et al., 2006). Furthermore, marine bacteria produce unique secondary metabolites, including antibiotics, distinct from terrestrial counterparts. The antimicrobial properties of seawater, attributed to these bacterial products, have been recognized since the early work of Rosenfeld and Zobell. Current research focuses on exploring these antibiotic-producing marine bacteria to address the growing issue of multidrug-resistant human pathogens (Das et al., 2006).

1.2.2 Marine viruses: ecological importance

Viruses are the most numerous biological entities in aquatic environments, especially the ocean, but their diversity remains largely unknown. Traditionally, virus counts were done using transmission electron microscopy, a complex and imprecise method. Modern techniques like epifluorescence microscopy with DAPI or SYBR Green I staining have improved enumeration. Viral numbers in seawater often surpass bacterial counts by ten to a hundred times, though deep-sea sediments may show a reverse trend due to complex environmental interactions. Despite this variability, marine viruses are extremely abundant (10^9 to 10^{10} viruses per liter) and significantly impact marine ecosystems. They infect bacteria and phytoplankton, influencing their diversity and primary production. Viral lysis releases organic matter, diverting carbon from higher trophic levels back into dissolved organic carbon pools, affecting biogeochemical cycles (Das et al., 2006).

Additionally, viral activity contributes to the production of dimethyl sulfide (DMS), a key component of the global sulfur cycle. Viral lysis of phytoplankton releases dimethylsulfoniopropionate (DMSP), which is then converted to DMS. DMS can influence climate by forming sulfate aerosols in the atmosphere. Despite their ecological importance, viral biodiversity is poorly understood. Viruses likely play a critical role in global carbon budgets and, consequently, climate change (Das et al., 2006).

1.2.3 Marine actinomycetes—a boundary microorganism

Actinomycetes are a distinct group of Gram-positive bacteria, characterized by their filamentous, branching growth patterns. This unique morphology and growth behavior set them apart from typical bacteria. They are particularly valuable due to their ability to synthesize biologically active secondary metabolites and enzymes. Research has explored the diversity of actinomycetes across various marine habitats, including deep-sea regions, coastal waters, and mangrove ecosystems. Initially, it was believed that marine actinomycetes originated from terrestrial sources. However, both molecular and traditional methods have conclusively demonstrated their genuine presence and active role within marine environments (Das et al., 2006).

While terrestrial soils, particularly those that are warm and slightly acidic, are known to be rich in actinomycete diversity, marine sediments have also been extensively investigated for these bacteria. Consequently, numerous actinomycete genera have been identified in ocean-based studies. In spite of 32 genera classified based on chemical characteristics, the following genera have been specifically documented in marine environments: Actinomyces, Actinopolyspora, Micromonospora, Micropolyspora, Nocardia, Rhodococcus, Streptomyces, Streptosporangium, and Streptoverticillium (Das et al., 2006).

1.2.3.1 Actinomycetes from marine ecosystem as a reservoir of antibiotics

Marine actinomycetes are a significant and promising origin of new biologically active compounds. Due to the stark contrast between marine and terrestrial environments, these bacteria generate distinct types of antibiotics. Numerous researchers have successfully extracted various antibiotics from marine actinomycetes, which exhibit novel characteristics when compared to those originating from soil. Notably, a powerful and specific antifungal compound was discovered from actinomycetes found within marine sediment (Das et al., 2006).

1.2.4 Role of fungi in the marine ecosystem

Despite early recognition of fungi in marine environments, their substantial role in oceanic ecological processes was initially underestimated. Few researchers argued that a comprehensive definition of marine fungi necessitates a broader ecological perspective, rather than solely relying on physiological characteristics. They proposed a classification into obligate and facultative forms: Obligate marine fungi are those that exclusively grow and reproduce within marine habitats, while facultative marine fungi originate from freshwater or terrestrial environments but can also thrive and reproduce in the sea. As a vital source of organic carbon for animals at higher trophic levels, fungi support the energy flow and productivity of marine environments (Das et al., 2006).

Recent estimates suggest approximately 1500 marine fungal species, excluding those associated with lichens. Of these, about 800 are obligate marine species, encompassing groups such as Ascomycotina, Basidiomycotina, Deuteromycotina, lichen-forming fungi, and yeasts. The total number of filamentous higher marine fungi is estimated to be around 465 (Das et al., 2006).

1.2.4.1 Significance of marine fungi

Within marine ecosystems, endolithic fungi inhabiting calcareous animals are significant contributors to carbonate sediment formation in the deep ocean. Marine fungi hold a crucial position as widespread organisms, facilitating decomposition and nutrient cycling. Like other heterotrophic organisms active in soil litter, humus, and mineral layers, marine fungi utilize energy-rich compounds within decomposing organic matter, releasing essential nutrients trapped within these decaying materials. Additionally, by providing organic carbon, fungi support the basic nutritional requirements of animals at higher trophic levels and enhance the overall energy flow and productivity of marine environments (Das et al., 2006).

1.2.5 Microbial interactions

The vast diversity of marine microbes includes a wide range of taxonomic and functional groups. These microbes engage in intricate interactions that are essential for maintaining community stability and ecological function. However, determining the nature of these interactions is difficult. Marine microbial communities can be further categorized into distinct subgroups based on factors such as population size (common and uncommon organisms), metabolic roles (e.g., producers and consumers), and metabolic state (actively growing and inactive organisms). Increasing research indicates that these microbial subgroups exhibit variations in how they respond to environmental changes, how they interact with each other, and their spatial distribution (Liu et al., 2019).

Over the past few decades, extensive research has focused on understanding how microbes interact within their communities. These interactions, which can involve cooperation or competition for resources, as well as the exchange of signaling molecules and metabolites, are crucial for shaping the structure, function, and dynamic changes of microbial communities across diverse environments. These interactions, both within and between species, form the basis of what's often termed "microbial community intelligence," a concept with potential applications in various fields.

Interactions between microbes can have positive, negative, or neutral effects on the participating organisms. Based on these outcomes, interactions are categorized into distinct types. Examples include mutualism, where both species benefit; parasitism or predation, where one species benefits at the expense of the other; commensalism, where one species benefits and the other is unaffected; competition, where both species are negatively impacted; and amensalism, where one species is negatively impacted while the other is unaffected (Nawaz et al., 2022).

The deep ocean offers a diverse and extensive range of habitats for a wide array of microbial life, encompassing viruses, archaea, bacteria, fungi, and protists. Rather than existing in isolation, these deep-sea microbes typically engage in intricate ecological networks. They play a fundamental role in the biogeochemical cycling of crucial elements, including carbon, nitrogen, phosphorus, sulfur, and various trace metals (Nawaz et al., 2022).

A significant portion of microbial life resides within the energy-limited sediments of the deep ocean, which represent the planet's largest ecosystem. Furthermore, deep-sea hydrothermal vent chimneys, characterized by dramatic variations in physical and chemical conditions, host unique microbial communities. The abundance of chemolithoautotrophic bacteria and archaea in these communities is noteworthy. Anaerobic methane oxidation and sulfate reduction are connected processes that drive intricate microbial interactions in some of the ocean's most productive ecosystems, which are supported by deep-sea cold seeps. In order to address local nitrogen limitation, anaerobic methane-oxidizing archaea carry out nitrogen fixation, which is essential given the significant nitrogen requirements of cold seep chemosynthetic environments. The interrelated cycling of carbon, nitrogen, sulfur, and other vital elements is primarily driven by microbial interactions in both hydrothermal vent and methane seep environments (Nawaz et al., 2022).

The subseafloor deep biosphere represents another extreme oceanic habitat. The absence of sunlight and the extremely limited input of organic matter from the surface ocean constrain the growth and metabolic activities of deep biosphere microorganisms, which are severely restricted by the scarcity of energy and organic compounds. In these resource-poor settings, cooperative interactions between species, such as the exchange of metabolites and the sharing of biosynthetic pathways, likely become essential for local microbial communities to maximize the use of available energy and growth materials (Nawaz et al., 2022).

Redox reactions driven by biochemistry provide energy to microorganisms in the deep biosphere. Methane, hydrogen, reduced forms of iron and manganese, reduced sulfur compounds, and ammonia/ammonium are all useful electron donors in these processes. Oxygen, manganese, and iron oxides, oxidized nitrogen species like nitrate and nitrite, oxidized sulfur compounds like sulfate and sulfite, and oxidized carbon compounds like carbon dioxide are examples of electron acceptors. The variety, ecological roles, and geographic distribution of the resident microbial communities are significantly influenced by the availability of distinct electron donors and acceptors in deep biosphere environments (Nawaz et al., 2022).

1.2.6 Natural products from marine microorganisms

Oceans, which cover a significant portion of Earth, are home to a diverse array of organisms with substantial potential for generating natural compounds. In fact, marine life is recognized as a richer source of biologically active compounds compared to terrestrial organisms. Marine animals have undergone all phases of evolution because life first emerged in the water, which has allowed them to develop a vast array of chemicals with distinct structural and functional traits (Jiménez, 2018, Karthikeyan et al., 2022). Approximately 28,500 marine natural products (MNPs), including polysaccharides, peptides, polyketides, polyphenolic compounds, sterol-like compounds, and alkaloids, were known by the end of 2016 (Blunt et al., 2018). Numerous biological effects are demonstrated by these marine natural compounds, such as antiviral (Ji et al., 2018), antifungal (El-Hossary et al., 2017), antibacterial (Taher Mohie el-dien et al., 2023), and anticancer (Carroll et al., 2023). These secondary metabolites are positioned as interesting candidates for the development of novel drug models due to their wide spectrum of activity.

The ocean's largely unexplored regions, known for their rich biodiversity, represent a valuable source for identifying novel compounds with distinctive properties. The extended evolutionary history of marine life has yielded organisms possessing uncommon genetic material. The severe pressure (up to 1100 atmospheres), oxygen-deficient circumstances, sub-zero temperatures, strong acidity (pH 2.8), and extremely hot temperatures (over 100°C) found in hydrothermal vents are just a few of the harsh conditions that marine microorganisms have had to adapt to. Additionally, they have evolved defenses against radiation, fluctuating light levels, excessive salt concentrations, and restricted nutrition supply (Poli et al., 2017). Marine microorganisms have developed specialized survival strategies, including the synthesis of uncommon defensive chemicals, as a result of the substantial genetic and metabolic diversification facilitated by these severe environments. According to research, marine bacteria can produce a large range of distinct metabolites with a variety of biological activities that could find use in the pharmaceutical, cosmetic, and medical industries (Puttaswamygowda et al., 2019). Tables 1.1 and 1.2 enlists various biologically active metabolites produced, isolated, and purified that are reported to be produced by different species of bacteria, fungi, and microalgae (Ameen et al., 2021).

1.3 Marine natural product's and their unique properties

From marine organisms such as fungi, bacteria, algae, sponges, corals, mollusks, crustaceans, and tunicates, over 36,000 compounds have been identified. The diversity of these compounds is due to the unique environment in marine habitats. Marine organisms are exposed to unique and extreme environmental conditions leading to the development of special bioactive compounds absent in terrestrial organisms. Deep-sea organisms survive in high pressures and low temperatures, for which they synthesize structurally stable and potent metabolites for maintaining cellular function and defense. Living in saline environments requires marine species to develop osmo-regulatory compounds, so many of them show antimicrobial, antifungal, or cytotoxic properties (Barreca et al., 2020). Majority of the marine species rely on chemical warfare for producing toxins, deterrents to protect themselves from the predators, inhibit competitors, or attract symbiotic organisms. Many marine organisms, such as sponges and corals, act as host microbial symbionts. They help in the biosynthesis of the compounds with therapeutic potential, including antibiotics and anticancer agents.

Table 1.1 Biologically active metabolites produced by various marine microorganisms.		
Microorganism	Compound	Activity
Bacteria		
<i>Bacillus aerius</i> , <i>Bacillus oryzicola</i> , <i>Bacillus safensis</i> , <i>Bacillus boroniphilus</i> , <i>Bacillus altitudinis</i> and <i>Virgibacillus senegalensis</i>	Not identified	Antimicrobial
<i>Janibacter melonis</i> <i>Pseudomonas stutzeri</i>	Dentigerumycin	Antitumoral
<i>Streptomyces</i> sp and <i>Bacillus</i> sp	Not identified	Antioxidant
<i>Streptomyces</i> sp.52A	Pyrrolo[1-a]pyrazine-1,4-dione,hexahydro-3-(2-methylpropyl)	Antimicrobial, enzyme inhibitory, antioxidant and cytotoxic
<i>Aerococcus uriaeequi</i> HZ	Exopolysaccharides	Antioxidant
<i>Streptomyces</i> sp. 22745	Bagremycins	Antimicrobial
<i>Streptomyces</i> sp. Al Dhabi-90	3-methylpyridazine, n-hexadecanoic acid, indazol-4-one, octadecanoic acid and 3a-methyl-6-(4-methylphenyl) sul	Antibacterial
<i>Streptomyces chumphonensis</i>	Not identified	Antimicrobial
<i>Streptomyces</i> sp.	2-Alkyl-4-hydroxyquinolines	Antifungal
<i>Novosphingobium</i> sp. PP1Y	Not determined	Antioxidant
<i>Microbacterium aurantiacum</i> FSW-25	Exopolysaccharide	Antioxidant
<i>Penicillium</i> sp. 22380	Abyssomicin	Antiviral
Fungi		
<i>Simplicillium lamellicola</i> , <i>Leptosphaerulina</i> sp., <i>Penicillium citrinum</i> , <i>Penicillium chrysogenum</i> , <i>Aspergillus sydowii</i>	Not identified	Antibacterial
<i>Hansfordia sinuosae</i>	Polysaccharide	Antitumoral
<i>Penicillium</i> sp. ZZ901	(+)-Scleroderolide	Antiglioma and antibacterial
<i>Fusarium</i> sp. 152	Equisetin	Anti-MRSA
<i>Diaporthe</i> sp. SCSIO41011	Polyketides	Antiviral
<i>Trichoderma</i> sp. SCSIO41004	5-acetyl-2-methoxy-1,4,6-trihydroxy-anthraquinone	Antiviral
<i>Penicillium</i> sp. ZZ380	Pyrrospirone alkaloids	Antiglioma
<i>Aspergillus niger</i> AKV-MKBU	L-asparaginase	Anticancer
<i>Chaetomium</i> sp. NA-S01-R1	Chaephilone, chaetovirides	Antimicrobial, Antitumoral

<i>Aspergillus alabamensis</i> EN-547	4-epi-seco-shornephine A carboxylic	Antimicrobial
<i>Truncatella angustata</i>	Isoprenylated cyclohexanols	Antiviral
<i>Fusarium equiseti</i>	(115)-1,3,6-trihydroxi-7-(1-hydroxyethyl)-anthracene-9,10-dione	Cytotoxic
<i>Alternaria</i> sp.	7-acetyl-1,3,6-trihydroxyanthracene-9,10-dione	Antifungal
	Stemphyperlenol	Antibacterial
	Alterperyleneol	Cytotoxic
<i>Curvularia</i> sp. IFB-Z10	Spirocurvulaide	
<i>Penicillium chrysogenum</i>	Tyrosol	Anti-quorum sensing
<i>Penicillium</i> sp.	2-[(5-methyl-1,4-dioxan-2-yl)methoxy] ethanol	Antimicrobial
	2-[(2R-Hydroxypropanoyl)amino] benzamide, 4-hydroxybenzandehyde	Antimicrobial
	2',3'-Dihydrosorbicillin	
<i>Penicillium</i> sp. IMB17-046	Trypilepyrazinol	Anti-x-glucosidase/ Antiviral
	(+)-Neocitreoviridin	Antibacterial
	3B-Hydroxyergosta-8,14,24(28)-trien-7-one	Antiviral
<i>Penicillium sclerotiorin</i>	Azaphilone derivative	Anti-inflammatory
	Isochromophilone IX	
	Dicitrones	
<i>Penicillium citrinum</i> HDN-152-088	Sclerketide C	Antioxidant
<i>Aspergillus</i> sp.	Asperphenin A	Antitumoral
<i>Penicillium minioluteum</i> ZZ1657	N-acetyl-L-valine conjugated drimarane sesquiterpenoids	Antimicrobial
	Drimane sesquiterpenoids	Antiglioma, Antibacterial
<i>Aspergillus</i> sp. LS116	Aspergillsteroid A	Antibacterial
Microalgae		
<i>Prorocentrum hoffmannianum</i> , <i>Prorocentrum arenarium</i> , <i>Prorocentrum reticulatum</i> , <i>Alexandrium tamarensis</i> , <i>Gambierdiscus australes</i>	Not identified	Apoptotic
<i>Navicula</i> sp.	Sulfated polysaccharides	Antioxidant
<i>Skeletonema costatum</i> , <i>Chaetoceros pseudocurvisetus</i>	Not identified	Antibacterial
<i>Amphidinium carterae</i>	Amphidinol 22	Cytotoxicity, antimicrobial

Table 1.2 Enlists various bioactive secondary metabolites isolated from marine sources, and applications in different fields. Their applications include Anticancer, Antibacterial, Antibacterial and anticancer, Anti-inflammatory, Neurogenic activity, Antituberculosis, and Other Bioactive compounds (Karthikeyan et al., 2022).

Anticancer compounds		
Microorganism	Compound produced	Activity
<i>Streptomyces aureoverticillatus</i>	Aureoverticillactam	Cytotoxicity against tumor cell types
<i>Streptomyces sp.</i>	Caprolactones	Active against cancer cell lines
<i>Streptomyces sp.</i>	Chinikomycins	Antitumor action against human cancer cell lines
<i>Actinomadura sp.</i>	IB-00208	Cytotoxic on tumor cell lines, antibacterial
<i>Salinispora tropica</i>	Salinosporamide A	Cytotoxicity, proteasome inhibition, NF- κ B activation inhibition
<i>Streptomyces fradiae</i>	Urdamycin	Antibacterial and anticancer activity
<i>Aspergillus sp.</i>	Asperphenin A	Antitumoral
<i>Penicillium citrinum HDN-152-088</i>	Dicitrones	Antioxidant
<i>Streptomyces variabilis</i>	1-Hydroxy-1-Norresistomycin	Cytotoxic against gastric and hepatic carcinoma
<i>Streptomyces sp.</i>	Marmycin	Tumor cell cytotoxicity, apoptosis induction
<i>Streptomyces sp.</i>	Manumycin	Antitumor activity against human cancer cell lines
<i>Streptomyces sp.</i>	Daryamide D	Cytotoxic against colon carcinoma cell line
Antibacterial compounds		
<i>Micromonospora sp.</i>	Maklamicin	Antimicrobial against Gram-positive bacteria
<i>Streptomyces sp. SCSIO 01127</i>	Lobophorin F	Antibacterial against <i>Bacillus thuringiensis</i> , <i>Staphylococcus aureus</i>
<i>Streptomyces sp. strain C34</i>	Chaxamycins A–D	Antibacterial against <i>Staphylococcus aureus</i> , <i>Escherichia coli</i>
<i>Streptomyces asenjonii</i>	Asenjonamide C	Antibacterial against <i>Staphylococcus aureus</i> , <i>Enterococcus faecium</i>
<i>Streptomyces sp. QD01-2</i>	Gilvocarcin HE	Antimicrobial, Cytotoxic
<i>Streptomyces formicae KY5</i>	Formicamycins A–L	Antibacterial against MRSA, VRE
<i>Actinoallomurus sp.</i>	Allocyclinones	Antibacterial against <i>Staphylococcus aureus</i> , <i>Streptococcus pyogenes</i>
<i>Janibacter limosus</i>	Helquinoline	Antibacterial, Antifungal

<i>Streptomyces sp.</i> <i>Penicillium minioluteum</i> ZZ1657	Bonactin N-acetyl-L-valine conjugated drimarane sesquiterpenoids	Antibacterial, Antifungal Antimicrobial
<i>Streptomyces sp.</i> ZZ745 <i>Aspergillus sp.</i> LS116	Bagremycins Aspergillsteroid A	Antimicrobial Antibacterial
Antibacterial & anticancer		
<i>Streptomyces sp.</i> <i>Marinispora sp.</i> strain CNQ-140 <i>Streptomyces sp.</i>	Citreamicin A, B Marinomycin Nonactin	Antibacterial, Cytotoxic Antitumor Antibacterial, Antineoplastic
Antiinflammatory compounds		
<i>Hymeniadisines (Marine sponges)</i> <i>Penicillium sclerotiorin</i>	Hymeniadisines Azaphilone derivative	Suppresses IL-1, IL-2, IL-6, NO via NF- κ B inhibition Anti-inflammatory
Neurogenic activity		
<i>Streptomyces sp.</i> KS3	Komodoquinone A	Induces neuronal differentiation in Neuro 2A cells
Antituberculosis compounds		
<i>Streptomyces sp.</i>	Cyclomarins	Potential tuberculosis treatment candidate
Other bioactive compounds		
<i>Prorocentrum hoffmannianum</i> , <i>Prorocentrum arenarium</i> <i>Navicula sp.</i> <i>Aerococcus uriaeequi</i> HZ <i>Microbacterium aurantiacum</i> FSW-25 <i>Amphidinium carterae</i> <i>Vibrio neocaledonicus</i> <i>Streptomyces lateritius</i>	Not identified Sulfated polysaccharides Exopolysaccharides Exopolysaccharide Amphidinol 22 Marine extract Granaticin	Apoptotic Antioxidant Antioxidant Antioxidant Cytotoxicity, antimicrobial Acetylcholinesterase inhibition Antitumor against lymphocytic leukemia

Algae and corals are exposed to intense UV radiation leading to the production of UV-absorbing compounds like mycosporine-like amino acids (MAAs). They are of immense use in skincare and pharmaceuticals. MNPs are formed by specialized enzymatic pathways, creating unique three-dimensional structures that increase their specificity in biological activity. Marine natural compounds

have a higher proportion of sp^3 -hybridized carbons, multiple chiral centers, condensed aliphatic rings, and increased nitrogen content compared to the synthetic drugs. They also contain halogen atoms like chlorine and bromine, due to seawater composition and the role of marine enzymes ([Barreca et al., 2020](#)).

1.3.1 Impact on pharmacology

MNPs are special compounds found in the ocean which help in creating new medicines. For example, some MNPs have been discovered to effectively treat cancer with drugs like eribulin showing strong results against the tumors. MNPs also can fight bacteria, especially those that resist antibiotics. Some of these compounds can even reduce inflammation, which might help people with autoimmune diseases. Researchers are excited about MNPs because the variety of marine life can lead to discoveries in medicine. There are traditional uses for these sea products in different cultures, which can guide scientists in finding modern treatments.

1.3.2 Stress responses and environmental adaptations

Secondary metabolites in marine organisms are specialized compounds. They're not directly involved in the normal metabolic processes required for growth, development or reproduction. These metabolites are adaptive responses to various environmental stresses like fluctuations in light, temperature, and salinity. So, to survive and thrive in such environments, many marine organisms, like bacteria, algae, sponges, and corals produce secondary metabolites that help them cope with these stresses.

1.3.3 Cooperative interactions

Marine organisms, particularly those in biofilms, utilize quorum sensing and other microbial interactions (like crosstalk and electron transfer) to produce secondary metabolites. These interactions can be beneficial and aid in the identification of new bioactive substances ([Barreca et al., 2020](#)).

1.4 Marine natural product's derived compounds

1.4.1 Secondary metabolites

Marine microbial secondary metabolites hold significant pharmacological promise and contribute substantially to the development of new antimicrobial drugs ([Srinivasan et al., 2021](#)). Oceans serve as a rich reservoir of unique and bioactive compounds, making them a prime target for drug discovery ([Martins et al., 2014](#)). The increasing focus on MNPs has directly led to a rise in clinical trials evaluating marine metabolites against a variety of microbial pathogens. A key characteristic of these MNPs is their significantly different structural components compared to those found in terrestrial environments, often leading to novel mechanisms of action. Marine bacteria and fungi are particularly prolific producers of secondary metabolites with potent bioactivity, offering a natural arsenal against

other microorganisms. Marine bacteria, specifically, have been found to produce a range of valuable bioactive compounds, including antibacterial, antiviral, antifungal, and anticancer agents. The therapeutic potential of these bioactive compounds derived from marine microbes offers a powerful weapon in the ongoing battle against drug-resistant pathogens, potentially providing solutions for the next century. Several phyla of marine microbes, notably Actinobacteria, Bacteroidetes, Cyanobacteria, Firmicutes, Planctomycetes, and Proteobacteria, are frequently identified as sources of these therapeutic and bioactive compounds.

1.4.2 Bioactive compounds

1.4.2.1 Enzymes

Proteases are utilized in medicinal applications, the leather and detergent industries, as well as in anti-inflammatory and digestive medications. The many origins and traits of these biocatalysts in marine species have been uncovered by research on lipases and related enzymes. Studied cold-adapted lipases secreted by Antarctic *Moraxella* bacteria, finding optimal growth at 25°C but maximal lipase secretion at temperatures as low as 3°C. Screened 427 yeast strains, identifying nine lipase producers, including *Candida intermedia*, *Pichia guilliermondii*, *Candida parapsilosis*, *Lodderomyces elongisporus*, *Candida quercitrusa*, *Candida rugosa*, *Yarrowia lipolytica*, *Rhodotorula mucilaginosa*, and *Aureobasidium pullulans*. The capacity of some of these lipases to hydrolyze various oils suggests industrial potential. Purified a novel extracellular phospholipase C from a marine *Streptomyces* bacterium (selected from ~400 strains), demonstrating optimal activity at pH 8.0 and 45°C, with specificity for phosphatidylcholine hydrolysis (Maddela et al., 2022). Table 1.3 shows a list of scientists and their enzyme discovery.

Agar oligosaccharides are utilized in bread, beverages, and low-calorie items in the food sector. Particularly in Japan, they are also used as a hair conditioning additive and moisturizing cosmetic. Microorganisms produce the enzyme agarase, which is capable of degrading agar. Many bacterial genera, such as *Cytophaga*, *Bacillus*, *Vibrio*, *Alteromonas*, *Pseudoalteromonas*, and *Streptomyces*,

Table 1.3 List of proteases and lipases from different marine species.

Scientist	Year of discovery	Enzyme isolated	Enzyme discovered in
Dane	1950	Alkaline protease	<i>Bacillus licheniformis</i>
Nobou Kato	1972	New type of Alkaline protease	<i>Psychrobacter</i>
Chi et al.,	2007	Alkaline protease	Sea Saltern of China, Yellow Sea
Haddar et al.,	-	Alkaline protease	<i>Bacillus Mojavensis</i>
Krish	1935	Microbial lipase	<i>Penicillium oxalicum</i> and <i>Aspergillus flavus</i>

have been shown to produce agarase. Additionally, a marine *Vibrio* sp. (JT0107) was reported to be able to hydrolyze the α -1,3 glycosidic bond of agar via α -neogaro-oligosaccharides.

1.4.3 Anticancer

Life abounds in the maritime environment, which is home to a wide variety of organisms. These include invertebrates (like sponges, corals, worms, mollusks, and echinoderms), macroalgae (seaweeds), microorganisms (like bacteria, actinobacteria, cyanobacteria, autotrophic flagellates, diatoms, microalgae, and fungi), and even flowering plants (seagrasses, mangroves, and other halophytes). An estimated one to two million species make up this amazing biodiversity, of which about 250,000 have been described to date. Novel chemicals have been found to be abundant in this rich biodiversity. Every year since 2008, scientists have found more than 1000 novel chemicals with marine origins. Fungi, actinobacteria, and brown seaweed are among the organisms that have shown promise in the treatment of multiple myeloma, lymphomas, and solid tumors.

1.4.4 Alkaloids

Alkaloids are less prevalent in marine species than in terrestrial plants. One prominent exception is the tetrahydroisoquinoline alkaloid trametin. It was shown to be a byproduct of the bacterial symbiont *Candidatus Endoecteinascidia frumentensis* after being initially isolated from the Caribbean sea squirt *Ecteinascidia turbinata* during a National Cancer Institute (NCI) screening program. Two to three tetrahydroisoquinoline (THIQ) subunits and an active carbinolamine functional group are present in this strong ecteinascidin. Plinabulin (Fig. 1.1) is a synthetic dehydrodiketopiperazine that inhibits tubulin polymerization and is produced from the marine fungus metabolite halimide. By targeting the β -tubulin colchicine-binding site, it alters microtubule dynamics and prevents proliferative vascular endothelial cells from growing, which in turn alters the tumor vasculature. Clinical trials for it are presently underway.

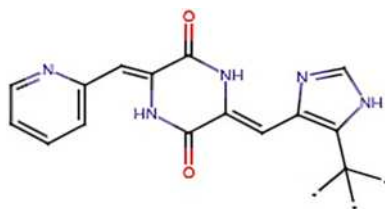


FIGURE 1.1

Depicting the molecular structure of plintabulin.

1.4.5 Beta lactones

While primarily produced by actinobacteria and fungi, β -lactones, highly reactive four-membered heterocyclic compounds, can also be found in higher plants and animals. Because they are vulnerable to nucleophilic attack by serine, threonine, or cysteine residues, they create stable covalent adducts that block enzymes that include these catalytic nucleophiles, especially lipases and proteases. This is the source of their reactivity. *Salinispora*, a genus of Actinobacteria that are obligate marine bacteria (requiring seawater for survival), is a valuable source of bioactive compounds. These marine Actinobacteria yielded the salinosporamides (Fig. 1.2A, B, C, D, E, F, G and H), a family of notable compounds initially isolated from *Salinispora tropica*.

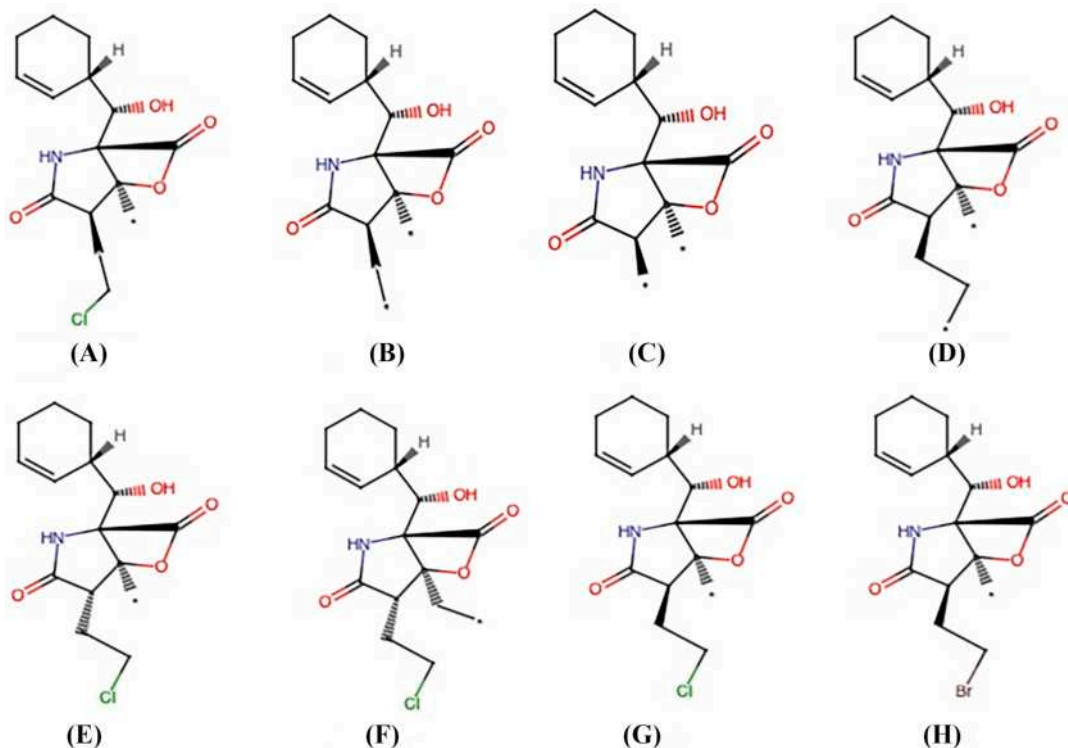


FIGURE 1.2

Shows the different molecular structures of salinosporamide. (A) Salinosporamide A; (b) Salinosporamide B; (C) Salinosporamide D; (D) Salinosporamide E; (E) Salinosporamide F; (F): Salinosporamide I; (G) Salinosporamide J; (H) Bromosalinosporamide.

1.4.6 Polysaccharides

Agar, alginate, and carrageenans are examples of seaweed-derived polysaccharides that are essential structural elements of intercellular matrix and cell walls. Agar is a complex mixture of two polysaccharides: charged, heterogeneous agarose and linear, neutral agarose, which make up over 70% of agar. Agar is mostly produced from red algae belonging to the *Gelidium* and *Gracilaria* genera. B-1, which was isolated from the culture of a marine *Pseudomonas* sp., is one of the sulfated polysaccharides that has demonstrated anti-tumor efficacy in preclinical tests of restricted scope.

1.4.7 Nucleoside derivatives

Bergmann et al. discovered spongothymidine (ara-T), an arabinonucleoside that was extracted from the Caribbean sponge *Tectitethya* crypta. Marked a sea change in drug discovery research using MNPs in the early 1950s. The structural inspiration for the synthesis of cytarabine (Fig. 1.3) (ara-C) and vidarabine (ara-A), the first two FDA-approved medications of marine origin, came from this chemical and other nucleosides produced from sponges. Notably, these medications were created in a lab prior to being isolated from natural sources, such as *Streptomyces antibioticus*, *Eunicella cavolini*, and *Streptomyces gryseus*.

1.4.8 Peptide derivatives

A wide variety of peptides with diverse biological activities, including anticancer properties, has been identified in numerous marine organisms, emphasizing the ocean's potential as a rich source of innovative therapeutic agents. One notable example of a marine-derived peptide with anticancer potential is plitidepsin (Fig. 1.4).

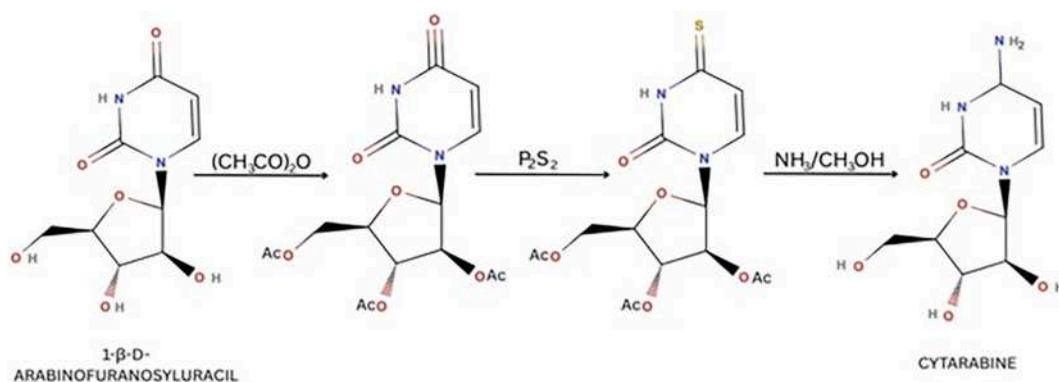
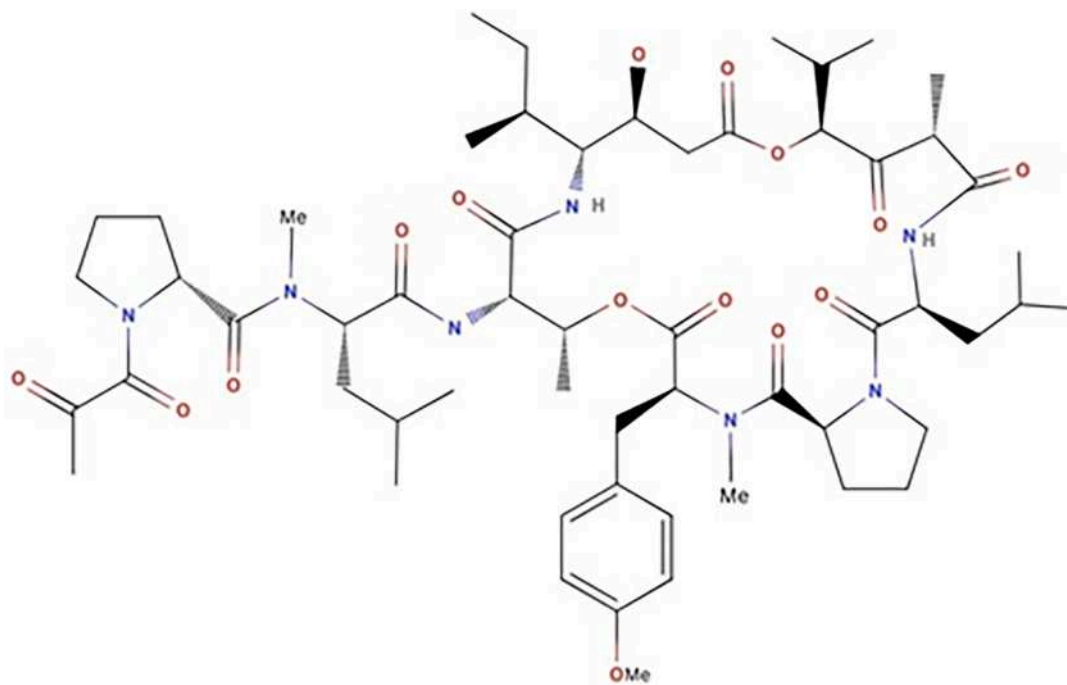


FIGURE 1.3

The synthesis of cytarabine.

**FIGURE 1.4**

Plitidepsin molecular structure, an anticancer peptide therapeutic.

1.5 Uses of marine natural product's

1.5.1 Therapeutic usage of drugs

1.5.1.1 Anticancer

Despite being relatively underexplored compared to terrestrial ecosystems, the marine environment holds immense potential due to its vast and unique biodiversity. In recent years, there has been a notable rise in the discovery and development of novel compounds from marine sources, particularly those showing promise in cancer treatment. This growing interest has resulted in an increasing number of marine-derived molecules being investigated in clinical trials for their anticancer properties. Remarkably, over ten drugs approved by the U.S. Food and Drug Administration (FDA) for the treatment of various cancers have originated from marine organisms, highlighting the ocean's value as a reservoir for innovative and effective therapeutic agents (Barreca et al., 2020). Some of these drugs include cytarabine, which is used for leukemia, nelarabine, a prodrug of ara-G that is often used in treating T-cell leukemia. Fludarabine phosphate, another important drug, is a prodrug of ara-A, which is commonly prescribed for chronic lymphocytic leukemia. The other key drugs are plitidepsin, which shows effectiveness in treating multiple types of cancers, midostaurin,

which is used for certain blood cancers like acute myeloid leukemia (AML). Eribulinmesylate has also gained approval for use in treating metastatic breast cancer. Brentuximabvedotin, polatuzumabvedotin, enfortumabvedotin, belantamabmafodotin, trabectedin, and lurbinectedin are therapies that work by attacking cancer cells in specific ways and minimizing harm to healthy cells (Barreca et al., 2020).

1.5.1.2 Antiviral

Viruses pose a significant threat to global health, being responsible for widespread diseases such as influenza, HIV, and COVID-19. Despite their impact, the development of effective antiviral therapies remains relatively slow. Traditionally, most antiviral drugs have been derived from terrestrial sources; however, recent research is increasingly turning toward marine environments in search of novel antiviral agents. Marine ecosystems, such as mangroves, are proving to be promising sources of bioactive compounds. For instance, Actinomycetes isolated from mangrove habitats have demonstrated strong antagonistic effects against pathogenic microorganisms, contributing to human health protection. For example the compound (Z)-1-((1-hydroxypenta-2,4-dien-1-yl)oxy)anthracene-9,10-dione, identified by Avilala et al. (2018) from *Nocardia alba* KC710971, which exhibited antiviral activity against two poultry viruses: Newcastle Disease Virus (NDV) and Infectious Bursal Disease Virus (IBDV). Additionally, a pregnane derivative (3 α -hydroxy-7-ene-6,20-dione), extracted from the marine fungus *Cladosporium* sp. collected from the South China Sea, showed antiviral potential against Respiratory Syncytial Virus (RSV). Another compound, Cladosporisteroid B, derived from the same fungus, showed weak activity against the H3N2 virus. Additionally, a new ergostane analog from the marine fungus *Penicillium* sp. exhibited broad-spectrum antiviral properties, including strong anti-HIV and anti-influenza activities, with effectiveness much greater than the standard antiviral drug ribavirin (Teng et al., 2020).

1.5.2 Environmental pollution

Biofloculants and Bioremediation plays a role in removal and detoxification of heavy metals such as mercury, lead, cadmium, and arsenic from contaminated water and soil. Marine plants and algae produce compounds that can bind to heavy metals, neutralizing their toxic effects. Marine-derived bacteria, also, degrade crude oil compounds, reducing their harmful impact on marine ecosystems. They can absorb or accumulate pollutants from their surrounding environment—a process known as bio absorption or bioaccumulation.

1.5.3 Cosmetics

1.5.3.1 Photo-protective compounds

Marine organisms are a rich source of photoprotective compounds, such as MAAs, scytonemin, and carotenoids, all of which are known for their ability to absorb ultraviolet (UV) radiation. These naturally occurring substances play a crucial role in shielding marine life from harmful UV exposure. MAAs, in particular, are a diverse group of small, water-soluble molecules (molecular weight < 400 Da) characterized by a cyclohexanone or cyclohexenimine ring structure linked to an amino acid or its imino alcohol (Rastogi et al., 2010). They absorb UV light in the 310–362 nm range

and possess high molar extinction coefficients, making them highly efficient UV filters. Beyond UV protection, MAAs have demonstrated antioxidant, anti-inflammatory, and anti-aging properties *in vitro* using human cell models. A prominent instance is palythine, a specific MAA derived from the red alga *Chondrusyendoi*. This compound has gained commercial interest and was incorporated into Aethic®'s skincare line, launched as Dermagie in 2021. These algae can be cultivated year-round and have shown remarkable efficacy in protecting human skin cells from both UVA and UVB radiation, even under artificial sunlight conditions comparable to peak summer intensity in Arizona. Such findings highlight the growing potential of marine-derived compounds in the development of next-generation sunscreens and skin care formulations.

1.5.3.2 Anti-aging products

Bioactive compounds obtained from marine sources—such as antioxidants, omega-3 fatty acids, vitamins, minerals, and polysaccharides—have shown significant potential in combating oxidative stress, inflammation, and metabolic disorders that are closely associated with the aging process (Harinisri Ram & Thamarai Selvi, 2024). When incorporated into functional foods, these marine-derived substances not only supply vital nutrients but also offer therapeutic benefits that support healthy aging and help prevent age-related diseases (Giuliani et al., 2024). Furthermore, current research explores how marine compounds interact with biological aging markers, their ability to slow down aging progression, and their role in managing age-related conditions. These compounds often exhibit unique mechanisms of action, making them particularly effective in addressing visible signs of aging and contributing to the maintenance of youthful skin (Han et al., 2024).

1.5.3.3 Skin-whitening products

Marine algae play a huge role in skincare, particularly in skin whitening and brightening products. Algae-derived compounds, such as fucoidan, carotenoids, and phlorotannins, are known for their ability to lighten pigmentation, provide antioxidant protection, and promote skin radiance. They are potential natural cosmetics. Marine organisms also have tiny compounds like trichodin. They prevent microbial contamination and moisturize the skin (Abouelkheir et al., 2024).

1.6 Advances in technology and research gaps

1.6.1 Discovery via conventional screenings

1.6.1.1 Marine organism collection

In the discovery of MNPS through conventional screenings, the collection of marine organisms from various environments, such as coral reefs, deep-sea, intertidal zones, and hydrothermal vents takes place. These organisms often produce unique compounds as a defense mechanism or for survival in extreme conditions. In this process, researchers focus on a wide variety of marine organisms like marine bacteria, fungi, algae, and sponges because of their ability to produce bioactive metabolites (Zhou et al., 2021).

1.6.1.2 Extraction of natural products

After collecting marine organisms, the bioactive compounds are extracted. Conventional methods of extraction generally include Solvent Extraction, solvents like methanol, ethanol, chloroform, or acetone are used to extract the compounds from the marine samples. The choice of solvent depends on the polarity of the target compounds. In Macroporous resin adsorption certain types of bioactive compounds, adsorption to resins is used, followed by elution with suitable solvents. Whereas Ultrasonic and Microwave-assisted extraction techniques use physical methods to enhance the extraction process, increasing yields and efficiency. Pressurized Liquid Extraction (PLE) is an efficient technique where solvents are applied at high pressures and temperatures to enhance extraction (Zhou et al., 2021).

1.6.1.3 Challenges in conventional screening

The development and application of MNPs involve multiple challenges, particularly in conventional screening methods. If a compound demonstrates effectiveness in treating diseases such as cancer, infections, or inflammation, it may advance to clinical trials. However, accessing marine organisms is often difficult due to logistical and financial constraints, especially when collecting specimens from deep-sea environments or remote locations. Many valuable marine organisms remain difficult to access because of environmental and geographical limitations (Zhou et al., 2021). Additionally, marine biodiversity is still largely unexplored, with numerous bioactive compounds yet to be identified. The complexity of these natural products poses further challenges, as their intricate structures often require sophisticated instrumentation and advanced techniques for synthesis, purification, and structural elucidation. Sustainability is another concern, as the extraction of marine organisms must be conducted responsibly to prevent over-exploitation and avoid negative impacts on marine ecosystems and biodiversity. Furthermore, the drug development process for marine-derived products is inherently slow. Despite being effective, conventional screening methods can take several years to progress from extraction to clinical application, delaying the availability of promising treatments (Zhou et al., 2021).

1.6.2 Marine microbial natural product discovery via metagenomics

MMNP discovery via metagenomics includes the collection of marine samples, which are collected from various environments, such as coral reefs, deep-sea ecosystems, hydrothermal vents, and tidal zones. These samples often contain diverse microbial communities, including bacteria, archaea, fungi, and algae, which are potential sources of natural products. DNA is extracted from the microbial communities present in the collected marine samples. Using advanced technologies such as high-throughput sequencing (NGS), we can sequence the entire microbial genome in a single run. This allows for a clear view of the microbial population and its genetic potential. After sequencing the DNA, the data are analyzed to predict the presence of genes that may encode biosynthetic pathways for secondary metabolites (natural products). Tools like gene annotation software help identify key biosynthetic gene clusters (BGCs) responsible for producing bioactive compounds. Key biosynthetic gene clusters often include those involved in the synthesis of polypeptides, non-ribosomal peptides, and terpenes, which are known to have therapeutic properties. Advanced bioinformatics tools are used to analyze the vast amount of sequencing data and identify potential gene clusters involved in the

production of novel compounds. This involves identifying the biosynthetic pathways of known and unknown metabolites, as well as predicting their molecular structure and bioactivity. Once potential BGCs are identified, these genes can be cloned into heterologous expression systems (e.g., model bacteria like *Escherichia coli* or *Streptomyces species*) to synthesize the compounds in the laboratory. The produced compounds can then be purified using chromatography methods like high-performance liquid chromatography (HPLC), and their structure is determined using techniques like NMR and mass spectrometry (Zhou et al., 2021).

1.6.2.1 Challenges of marine microbial natural product discovery via metagenomics

Metagenomic data analysis requires high computational power and expertise in bioinformatics. The sheer volume of sequencing data can be overwhelming, and interpreting the results to predict the biosynthetic pathways of novel compounds is complex. While metagenomics can predict the presence of biosynthetic gene clusters, the actual identification and validation of bioactive compounds still require experimental validation, which can be time-consuming and resource intensive. Even if a promising biosynthetic gene cluster is identified, expressing the corresponding compound in heterologous hosts can be challenging. Many marine microorganisms produce compounds that require specific environmental conditions for production, which may not be replicated in the lab. Once a compound is isolated, functional validation to confirm its biological activity is essential. This process can take considerable time and effort and often requires in vitro and in vivo testing (Zhou et al., 2021).

1.6.3 Exploring diverse biosynthetic pathways of marine microbial natural products through genomic approaches

Advancements in high sequencing technologies enable the comprehensive analysis of marine microbial genomes. Tools like antiSMASH facilitate the identification and annotation of BGCs within these genomes. By sequencing DNA extracted directly from environmental samples, researchers can access the genetic material of uncultured marine microbes (Mohamed et al., 2021). This approach uncovers BGCs from microorganisms that are difficult to cultivate in laboratory settings. Comparing genomes of different marine microorganisms helps identify conserved and unique BGCs, providing insights into the diversity of secondary metabolites they can produce. Techniques such as gene knockout and heterologous expression allow researchers to elucidate the functions of specific genes within BGCs, aiding in the characterization of the biosynthetic pathways of MMNPs.

1.6.4 Diversified marine microbial natural products via combinatorial biosynthesis

Combinatorial biosynthesis is being used to diversify the MMNP'S compounds. It focuses on how synthetic biology and genome mining are combined to enhance the diversity of MMNPs for pharmaceutical and biomedical applications. By combining combinatorial biosynthesis with genome mining and synthetic biology, researchers can generate a broader variety of MMNPs, rapidly identify promising drug candidates, and develop efficient production systems for scaling up their synthesis (Zhou et al., 2021).

1.6.5 Diversified marine microbial natural products via synthetic biology

Synthetic biology approaches to diversify MMNPs by analyzing the genomes of marine microorganisms, we can identify BGCs responsible for natural product synthesis. Synthetic biology enables the reconstruction and expression of these pathways in heterologous hosts, leading to the production of novel compounds (Tang, 2023).

1.6.6 Research gaps

One of the major challenges in MNPs research is the limited access to marine organisms, particularly those found in deep-sea or remote areas. The harsh and difficult-to-reach nature of these environments makes the collection of marine samples both expensive and time-consuming. There is a need of hour for more affordable and efficient technologies to facilitate marine sampling and access to these organisms for further research (Teng et al., 2020). Sustainability and conservation concerns also pose significant issues, as overharvesting marine organisms for natural product extraction can threaten biodiversity. Although sustainable practices are being developed, more efficient aquaculture systems and improved management strategies are necessary to ensure the long-term preservation of marine biodiversity. Many marine organisms produce bioactive compounds in small quantities, making large-scale production difficult without harming their populations. Additionally, marine ecosystems are highly complex, with intricate interactions among organisms contributing to the production of bioactive compounds. This complexity makes it challenging to isolate individual compounds and determine their precise mechanisms of action, highlighting the need for further research to understand the ecological roles of these compounds and how they can be replicated or enhanced for therapeutic use (Teng et al., 2020). Many marine-derived compounds have yet to receive clinical approval due to challenges in proving their safety and efficacy. More rigorous clinical trials, standardized production methods, and adherence to regulatory frameworks are required to bring these products to market. Although genomic and metagenomic approaches have accelerated the discovery of new bioactive compounds, there remains a lack of accurate bioinformatics tools to predict and analyze their biosynthetic pathways. The development of advanced computational models and AI-driven tools could greatly enhance the efficiency of MNPs discovery. Additionally, many marine-derived compounds are naturally produced in small quantities, making it difficult to scale up production for industrial or clinical applications. Further research on biotechnological methods, such as genetic engineering of marine microorganisms or the development of efficient culture systems, is needed to address these challenges and enable large-scale production (Teng et al., 2020).

1.7 Conclusion

MMPs represent a vast and largely untapped resource for biotechnology and pharmaceutical applications. The unique metabolic capabilities of marine microorganisms have led to the discovery of numerous bioactive compounds with potential uses in medicine, cosmetics, and environmental management. As research continues to uncover the diversity and complexity of marine microbial communities, it is likely that these organisms will yield many more valuable products. The integration of advanced technologies such as metagenomics will be crucial in fully exploiting this potential,

enabling the sustainable development of MMPs while preserving the delicate balance of marine ecosystems. Ultimately, the exploration of MMPs not only offers opportunities for innovation but also underscores the importance of conserving marine biodiversity for future generations.

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Characterization and detection techniques of marine microbial products

Innocent Ojeba Musa¹, Abdulhakeem Idris Abdulhakeem², Peter Olabisi Abioye³, Helen Shnada Auta³, Mustapha Abdulsalam¹, Miracle Uwa Livinus⁴, Muhammed Abdulazeez¹, Fatima Adamu Yahaya¹, Shehu-Alimi Elelu⁵, Salami Olaitan Lateefat⁶ and Auwal Sagir Muhammad⁷

¹Department of Microbiology, Skyline University Nigeria, Kano State, Nigeria,

²Department of Biodiversity and Bioresources, Al-Farabi Kazakh National University, Almaty, Kazakhstan,

³Department of Microbiology, Federal University of Technology Minna, Niger, Nigeria,

⁴Department of Biochemistry, Skyline University Nigeria, Kano State, Nigeria,

⁵Department of Chemistry, Howard University, Washington, DC, United States,

⁶Department of Chemistry and Molecular Biology, University of Gothenburg, Gothenburg, Sweden,

⁷School of Informatics, Xiamen University, Xiamen, P.R. China

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2.1 Introduction

Marine habitats extend over 71% of the total global area and can be considered an enormous asset of biological and chemical richness. These ecosystems are inhabited by an extraordinary diversity of microorganisms, bacteria, fungi, archaea, and microalgae that can withstand high pressure, high salinity, and changes in temperature. Such adaptations have seen marine microorganisms produce diverse bioactive compounds, which are generically referred to as marine microbial products. These products have attracted consideration in the past decades because of feature of new types of chemical structures, new classes of activity, and invulnerable prospects of use in pharmaceuticals, industry,

agriculture, and environmental protection (Aransiola, Oyewole, et al., 2024; Imhoff & Labes, 2020). Marine microbial products in many cases are secondary metabolites and are involved in ecological processes, for example, in defense, competition or signalization in their natural environment. For humans, it is a rich source of drugs and other useful materials or products that are obtainable from these compounds. Specific examples include salinosporamide A which is an anticancer compound from marine actinomycetes *Salinispora tropica* and marinopyrrole; an antibiotic with activity against multiple and drug resistant pathogens. In addition to medicine, marine enzymes such as proteases and lipases for instance have been used in the production of biofuels, in food processing and waste treatment (Aransiola, Bamisaye, et al., 2024; Maddela et al., 2022). Further, chemicals extracted from marine sources including astaxanthin are employed in cosmetic applications as well as functional foods because of their radicals scavenging activity. The discovery of products from marine microbes is today eased by developments made on biotechnology and chemical industry equipment's (Okewu et al., 2024). Molecular and culture-independent approaches like metagenomics, next-generation sequencing along with computational tools have let the researchers to design and detail the analysis of unculturable marine microorganisms accounts for more than 90% the marine microbial ecosystem. These tools enable the investigators to unlock the genetic potential of these organisms successfully identifying new biosynthetic gene clusters and divergent metabolic pathways (Zhang et al., 2023). Furthermore, improvements in chemical characterization methods, which include NMR and high-performance liquid chromatography (HPLC), have enlightened the processes of recognition and determination of structures of the compounds isolated from marine sources.

However, current research has not entirely solved all the problems faced in the utilization of the marine microbial products. Because the target habitats are large and remote, sample collection is challenging and resource-demanding. Moreover, some marine microorganisms are difficult to culture in isolators that restrain the discovery of their biosynthetic potencies. Some of the emerging technologies like co-cultivation techniques, designed marine environment, and synthetic biology methods have enriched literature with ways to overcome these barriers (Hamed et al., 2021).

This chapter will be concerned with general introduction of marine microbial products with special reference of techniques used in characterization and detection of the products. It starts with a taxonomy of the variety of marine microbial products and the source organism. Marine microbial products are not only indispensable to the development of medicine and biotechnology, but also are an important part of solving problems that affect the world in terms of antibiotic resistance, food shortage and environmental crises (Zhang et al., 2023).

New studies show that researchers have not yet described the previously unimagined capabilities and the importance of marine microorganisms for the needs of humanity. Thus, the process of opening these secrets starts with correct characterization and detection that are the basis of this chapter.

2.2 Classification of marine microbial products

There is also great variation in the gross form and function of the products because of the extensive variety of the marine microbes and conditions favoring their activities. All these products can be categorized generally in to a number of groups according to their chemical characteristics, biological activity, and the source species. It is only recommendable to study these classifications to consider

possible applications in the intended fields such as the pharmaceutical industry, biotechnology, or ecology (Zhang et al., 2023).

2.2.1 Bioactive compounds

Bioactive compounds are ancillary products formed in the marine microorganisms and in some cases, they may act as tools for survival in the competitive ocean environment. These compounds have diverse pharmacological activities such as antibacterial, antifungal, antiviral, anticancer, and antiinflammatory effects.

1. **Antibiotics:** Two classes of marine-derived antibiotics, the marinopyrroles and the abyssomicins, have recently been shown to be particularly effective against multidrug-resistant pathogens. These compounds have raised interest as possible remedies to the universal antimicrobial resistance problem (Huang et al., 2022).
2. **Anticancer agents:** Soptamide A isolated from marine sponge *Salinispora tropica* using proteasome inhibition has shown anticancer activity and is currently tested in clinical trials ().
3. **Antiviral agents:** Marine microbial products can resemble immunomodulating active components including alginate oligosaccharides and polysaccharide derived derivatives, which can effectively combat viruses including influenza and HIV (Kokoulin and Kiryanov, 2019).

2.2.2 Enzymes

Marine microorganisms produce diverse enzymes that have a high potential use in various industries and biotechnology. Further, these enzymes are generally more stable and reactive compared to enzymes found within terrestrial environments at extreme conditions.

1. **Hydrolytic enzymes:** Some of commonly used enzymes include amylases, proteases, cellulases used in food industry, bioenergy, and waste management sectors (Gomes et al., 2021).
2. **Oxidative enzymes:** Marine fungi have been used in bioremediation since laccases and peroxidases from these sources help to eliminate gases and compounds causing pollution in the environment (Xu et al., 2018).
3. **Lipases:** These enzymes are also vital in the making of biodiesel products as well as in production of some pharmaceutical products since they bring about esterification of fats in to fatty acids and glycerol (Xu et al., 2018).

2.2.3 Pigments and antioxidants

Marine microorganisms are potentials producers of pigments and antioxidants applicable in cosmetic, food, and nutritional supplements.

1. **Carotenoids:** Another carotenoid like astaxanthine and zeaxanthine has the ability to act as antioxidants and hence can be used in anti-ageing products (Ambati et al., 2019).

2. **Phycobiliproteins:** These pigments are sourced from cyanobacteria and microalgae and are used in natural food coloring as well as in fluorescent markers in biomedical applications (Patel et al., 2020).

2.2.4 Polysaccharides

Marine microbial polysaccharides are as diverse carbohydrate polymers that have versatile uses in biomedicine food and material science.

1. Exopolysaccharides: These molecules are manufactured by bacteria, including *Alteromonas* species and are found in the food industries where they act as emulsifiers, thickeners, and stabilizers (Torregrosa-Crespo et al., 2018).

2. Sulfated polysaccharides: Carrageenans and fucoidans also have anticoagulant, antiviral, and immunomodulatory properties (De Jesus Raposo et al., 2018).

2.2.5 Toxins

Many off marine microorganisms have attributes which are toxic to living organisms and has actively infra utilized in medicine.

1. Neurotoxins: Substances including marine bacteria-derived tetrodotoxin have been researched on their application in pain relief (Xu et al., 2018).

2. Cytotoxins: These are employed as leads in anticancer drug discovery because they are potent and can differentiate between sound and malignant cells (Skropeta et al., 2021).

2.2.6 Volatile organic compounds

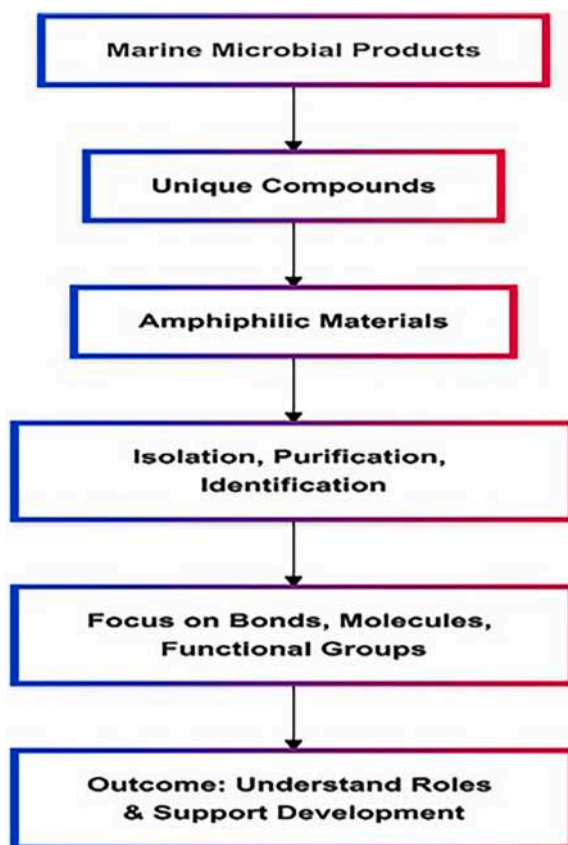
The measured constituents here are marine microbial VOCs, LMW, with action in QS and defense. They are increasingly considered for use as natural flavor enhancer and antimicrobial products (Patil et al., 2021).

2.2.7 Biosurfactants

Some biosurfactants are bioactive compounds synthesized by marine microbes. They have applications in enhanced oil recovery, bioremediation, and as emulsifying agents in foods and personal products. Examples of these include the Rhamnolipids and sophorolipids (Zhang et al., 2023).

2.3 Chemistry of marine microbial products

The chemical features of the amphiphilic materials are critical for the identification of the structure and role of marine microbial specimens. This includes separation, purification, and identification of compounds with respect of separating chemical bonds, types of molecules, and functional groups (Ganesan et al., 2021). Marine microorganisms are functionally and structurally different from other organisms, this leads in the production of unique compounds with unique structure chemistries thus the need for chemical characterization (Fig. 1).

**FIGURE 2.1**

Chemical characterization of marine microbial products.

2.3.1 Isolation and purification

The first process in chemical characterization is the extraction of marine microbial products from the microbial mass or culture broth. This process is very important in order to isolate target compounds from other cellular and extracellular debris.

- **Extraction techniques:** Among the methods of extraction include solvent extraction whereby solvents such as methanol, ethyl acetate, or end hexane dissolve compounds depending on polarity of compound. Liquid-liquid extraction and supercritical fluid extraction are better methods which has high efficiency and nontoxic characters ([Li et al., 2021](#)).
- **Chromatographic methods:** Coming out after purification can be done in a chromatography format including HPLC; GC or size exclusion chromatography. HPLC is especially useful for samples that are composed of several components because of high resolution and sensitivity ([Zhang et al., 2023](#)).

2.3.2 Structural elucidation

Once the marine microbial products are purified, their molecular conformation and absolute configuration are determined to decide intricacies of their chemical composition including functional groups. This process often employs advanced spectroscopic and spectrometric techniques:

1. Nuclear magnetic resonance spectroscopy: The method of NMR spectroscopy, or NMR for short, has been cited as one of the most important tools in elucidation of the structure of complicated organic compounds. The application of the molecular orbital theory is informative on connectivity of molecules, functional groups, and the positions of atoms. Some of such methods are 1D using NMR and other 2D methods, which include COSY, HSQC, and NOESY among others (Ganesan et al., 2019).

2. Mass spectrometry: The geometry of MS enables one to recognize the formulas of the molecules as well as the structural fragments of a compound given the molecular mass and recording of the way compound fragments. The primary purpose of using MS/MS is to obtain greater detail of the composition of large biomolecules. This method is usually applied combined with chromatographic methods like, HPLC-MS or GC-MS for increased measurand quantification (Nair et al., 2020).

3. Fourier-transform infrared spectroscopy: FTIR is used to determine functional groups using corresponding vibrational modes showing some characteristics of the frequencies. This technique is especially useful for identification of polysaccharides and lipids and proteins in marine microbial products (Al Ali et al., 2022).

2.3.3 Chemical fingerprinting

Chemical fingerprinting means the generation of a chemical identifier of a microbial product for its recognition and comparison with other chemical species.

1. High-resolution mass spectrometry: Compared to conventional MS, HRMS enables the identification of compounds with similar molecular weight (Wang et al., 2022).

2. Spectral libraries: Fingerprints can also be compared to databases such as MarinLit and AntiBase, which keeps records of marine natural products and their structures.

2.3.4 Limitations in the study of chemical composition

1. Complexity of marine samples: Products formed by marine microbes are generally present at very low levels and are accompanied by many other organic and inorganic matter, leading to the challenges observed in isolation and identification of the products.

2. Novel structures: In the case of marine microbial products, many of the products exhibit unique structural characteristics that the conventional characterization procedures cannot handle. This problem is being solved using more sophisticated computational methods and machine learning (Ahmed et al., 2023).

3. Instability of compounds: Although most of the compounds was extracted and analyzed, some of the marine compounds have chemical instabilities during experimentation.

2.3.5 Recent advancements

Recent developments in chemical identification technologies have highly improved the speed and precision of characterizing the marine microbial products.

1. Metabolomics: Metabolomics is the analytical process of profiling metabolome of microbial samples. Combined with MS and bioinformatics, this approach provides the opportunity to identify new compounds and construct a biosynthetic route (Li et al., 2021).

2. Cryo-electron microscopy (Cryo-EM): Cryo-electron microscopy has grown to become a popular technique that is used in visualizing large biomolecules like enzymes and protein complexes at near-atomic level (Huang et al., 2022).

2.4 Physical characterizations of marine microbial sourced product

Marine microbial products rely on physical characterization to determine the structure and performance attributes of processed materials. It offers information regarding morphology, particle size distribution, surface characteristics, and thermal stability as well as rheological properties, which determine the use and efficiency of these products in different sectors (Ganesan et al., 2021).

2.4.1 Morphological analysis

The structure of marine microbial products influences its responses to biological systems, the formation of stable formulations/formulations, and the efficiency in commercial applications such as drug delivery, catalytic processes, and biofilms.

2.4.1.1 Scanning electron microscopy

SEM provides high definition surface morphology that involves displaying of features such as roughness, porosity, and aggregation. SEM has found it useful in researching the surface morphology of the biofilms and polysaccharides produced by marine microbes (Patil et al., 2021).

- 1. Transmission electron microscopy:** TEM offers information on internal organization of nanoparticles or on biological material. For instance, by performing TEM analysis, it has been deciphered that nanoparticles synthesized from marine actinomycetes have core-shell structures (Kalimuthu et al., 2020).
- 2. Confocal laser scanning microscopy:** CLSM is utilized for data triangulation and to view the biofilms and microbial colonies in three dimensions. Especially useful in defining the position of cells and extracellular polymeric substances which have not attracted significant attention in previous studies (Wang et al., 2022).
- 3. Field emission scanning electron microscopy:** A newer version of SEM known as FESEM provides even better resolution making it ideal for use in nanostructured microbial products. FESEM has been used in studying the morphology of marine microbial pigments and biosurfactants (Ahmed et al., 2023).
- 4. Atomic force microscopy:** AFM determines roughness factors and mechanical parameters at nanometer scale. This technique has been applied to describe biofilms and supplied info

concerning the rigidity in addition to the adhesion forces of biofilm (Torregrosa-Crespo et al., 2018).

2.4.2 Particle size and zeta potential

The stability and interactions of marine microbial products significantly depend on particle size and zeta potential, especially in the functional systems like emulsions and nanoparticles.

1. **Dynamic light scattering:** This technique determines particle sizes in suspension by measuring its hydrodynamic diameter and quantify the particles size distribution. DLS is used very often while investigating biosurfactants and there is always a focus on the fact that those materials remained stable in a water content system (Kavitha and Ravikumar, 2021).
2. **Nanoparticle tracking analysis:** NTA incorporates light scattering along with simultaneous visualization of particle dynamics with size and concentration measurements of the particles. Recently, it has been useful for purpose of analyzing nanoparticles coming from marine fungi (Ahmed et al., 2023).
3. **Laser diffraction analysis:** Iron oxide particles range and aggregates of bigger size can be computed using this technique useful in analysis of biopolymers from marine microbes.
4. **Electrophoretic light scattering:** ELS analyzes zeta potential that is associated with the particle surface charge and its ability to remain in suspension. The zeta potential analysis is very important when it comes to shelf-life of bio-based emulsions (Ganesan et al., 2021).
5. **Field-flow fractionation:** FFF is a method that separates and characterizes the nanoparticles based on size and shape and is preferably applicable on complex microbial products mixtures (Sharma et al., 2020).

2.4.3 Thermal properties

Thermal analysis is an important tool in the determination of the stability of, the degradation processes occurring in, and processing conditions required for various marine microbial products.

1. **Differential scanning calorimetry:** DSC measures changes of state (e.g., the transition of solid to liquid called fusion or melting, as well as recrystallization). It is widely used to investigate the thermophysical characteristics of polysaccharides and lipid containing materials (Ganesan et al., 2021).
2. **Thermogravimetric analysis:** Weight changes as a function of temperature are indicated by TGA, which therefore gives details of heat break down. This technique has been employed to study the stability of bio based films from marine microbial products s (Sharma et al., 2020).
3. **Thermomechanical analysis:** TMA quantifies dimensions changes under heat or load, for polymer-based MMCs marine microbial products.
4. **Differential thermal analysis:** DTA is used to determine exothermic and endothermic reactions and understand decomposition or chemical changes in microbial compounds.
5. **Isothermal calorimetry:** This method determines heat flow at a constant temperature good in determining microbial activity in biofilms or enzymatic reactions.

2.4.4 Surface properties

The physicochemical nature of the surface of marine microbial products critically determines its behavior with other environments, materials, and other microorganisms (Musa et al., 2024). It defines the stickiness, wet ability, and compatibility, which defines products every engineered for uses such as bio-surfactants, coatings, and biofilm (Gómez-Sala et al., 2016).

Microbial contact angle measurement is a standard method for assessing the hydrogen bonding or lack of it on microbial cell surfaces. This method captures the angle created by a liquid droplet on a solid surface that helps to determine the wettability of the surface an important factor for more complex interactions such as biosurfactants and coatings (Wang et al., 2022). Likewise, inverse gas chromatography (IGC) technique can be used for the measurement of surface energy for which has a great importance in compatibility and adhesion characteristics (Liu et al., 2020).

Instrumental surface characterization techniques like XPS can further deconvolute the elements on the surface of the sample, atomic concentration, and different functional groups. This information is critical for altering surfaces to gain specific chemical characteristics (Chen et al., 2022). The second of these, surface plasmon resonance or SPR, is also helpful as it offers information in real-time on molecular involvement. It is employed to quantify biosurfactant activity and provide information regarding processes taking place on microbial surfaces (Patil et al., 2021). Further, quartz crystal microbalance, a precise mass measurement technique, is especially useful when studying biofilms, because of its ability to register changes in the mass and viscoelastic properties at surfaces (Huang et al., 2022).

2.4.5 Crystallinity and phase analysis

Marine microbial products are known to be highly crystalline and the behavior of their phases has strong influence on their mechanical, thermal, and chemical characteristics. Such characteristics are relevant to materializing target properties, the stability, and, optical trends of polymers, copolymers, and nanoparticles based on marine microorganisms (Chen et al., 2022).

Crystallographic analysis, particularly by means of X-ray diffraction (XRD) is an important tool for determining polymorphic forms and assessing the level of crystallinity in polymers and nanoparticles obtained from marine sources. This information is important for such request as it defines accurately the structural characteristics that are necessary for applications (Huang et al., 2022).

Furthermore, Fourier transform infrared spectroscopy (FTIR) must undergo Fourier transformation to analyze molecular vibrations in order to determine whether a material has a crystalline structure or is amorphous (Chen et al., 2022).

In PLM, the sample's refractive indices parallel and perpendicular to its reference axis are useful for supplementing the characterization of birefringent materials like crystalline polysaccharides by visually distinguishing the ordered arrangements of some samples using polarized light (Wang et al., 2022). XRD has a complementary technique known as Raman spectroscopy that gives vibrational information useful for description of substances in a crystalline form at a molecular level (Liu et al., 2020). Further, there are parameters like the small- angle X-ray scattering which provides detail structural information on the scale of nanometer and information about crystallinity of the marine microbial products for the application in nanotechnology.

2.4.6 Rheological properties

The rheological properties of marine microbial products are essential for defining their flow and deformation characteristics that are essential in application areas including pharmaceuticals, foods, and biomaterials. Some of these properties are particularly important for polysaccharides, biofilms, and gels.

As such, viscometry is an essential tool for both establishing viscosity and the flow properties of polysaccharides produced by microorganisms such as alginate and xanthan gum. These products affect their rheological performance for their usage as thickeners, stabilizers, or controlled release materials (Patil et al., 2021). Dynamic mechanical analysis (DMA) on the other hand provides a measure relating to viscoelastic behavior under a range of applied stresses. This is especially significant when assessing the mechanical properties of biofilms as well as hydrogels (Huang et al., 2022).

Storage and loss moduli are quantified using oscillatory rheometry, which underlines the solid/liquid nature of marine microbial materials. This technique is a critical one, especially when designing products with certain textural or elasticity characteristics (Chen et al., 2022). Furthermore, creep testing focuses on the deformation at constant stress, over a long period which is useful for understanding structural durability and performance (Wang et al., 2022). Capillary rheometry for the purpose of ascertaining the extrusion characteristics is important for bio-based films and polymers, enabling the optimization of materials for packaging and biomedical applications (Liu et al., 2020).

2.4.7 Optical properties

The photophysical properties of marine microbial products are pivotal in relation to the utilization of these products in imaging, sensing, and photo dynamic therapies. These properties are essential for compounds used in biosensors, pigments as well as nanomaterials.

UV-visible spectroscopy is used to quantify the absorbance of marine pigments and biosynthesized nanoparticles. This technique assists in the assessment of the photochemical activity and stability of bioactive compounds (Patil et al., 2021). Another tool is fluorescence spectroscopy, which is very important especially for determination of the fluorescent characteristics of compounds like phycobiliproteins are widely used in biotechnology and as diagnostic agents (Chen et al., 2022).

Marine microbial products' chiral optical properties can be examined through circular dichroism (CD) spectroscopy and provide useful information on the secondary structures of proteins as well as other biomolecules (Wang et al., 2022). Refractive index measurement relates light redirection through the solution; indeed, fundamental for emulsions and nanomaterials this quantitative data (Liu et al., 2020). Last, the photoluminescence spectroscopy examines the optical emission characteristics of marine microbial compounds and this is important to biosensors and optoelectronics applications (Huang et al., 2022).

2.5 Detection techniques for marine microbial products

Isolation and identification methods of marine microbial products are important for further characteristics and quantification of their active compounds (Ziko et al., 2019). These techniques usually employ high sensitivity and high specificity together with high precision to allow high accuracy. It is rather significant to point that the choice of the detection methods varies according to

the kind of microbial product to give detection, its application, and the matrix in which it will be detected (Chen et al., 2022).

2.5.1 Chromatographic techniques

Chromatographic procedures are widely used to separate and to identify the complex structures of the marine microbial metabolites. Hence, the gaseous sample introduction method most commonly used is the gas chromatography-mass spectrometry (GC-MS). This technique has been rewarding in the detection of the secondary metabolites as polyketides and terpenoids that could be synthesized by the marine actinomycetes (Rahman et al., 2022). Gas chromatography, for example, is standard practice in the separation and quantification of volatile compounds such as esters and alcohols. While HPLC is used alongside the separation and quantification of nonvolatile compound like peptides and alkaloids. It is more complex derivatives like reverse-phase HPLC are very useful for polar products like marine-derived antibiotics (Singh et al., 2023). However, for those that demand a much higher level of resolution and speed; the UHPLC can feature as a much better option that can give a much higher separation of the complex chemical-based marine microbial products. Thin layer chromatography (TLC) is still cheap, though it is used in first stages to test bioactive compounds in crude extracts before using more complex techniques.

2.5.2 Spectroscopic techniques

Optical methods are central to the determination of the structure and chemistry of microbial commodities based on their response to light. The application of Fourier Transform Infrared Spectroscopy (FTIR) for motif identification and characterization of chemicals including polysaccharides and lipids obtained from marine microorganisms has been widely employed (Huang et al., 2022). Nuclear magnetic resonance (NMR) spectroscopy is also another important technique which aids in explaining zones such as molecular structure, flexibility, and surrounding of bioactive compound, has become essential for characterizing new secondary metabolites (Xiao et al., 2023). UV-visible (UV-vis) spectroscopy is mainly used for identification of chromophore and biopigmented compounds such as carotenes and flavones present in marine microbial metabolites. MS and MS/MS in particular provides molecular mass and elemental composition data necessary for characterization of marine derived bioactive compounds. Furthermore, Raman spectroscopy that gives vibrational information can be used to differentiate between crystalline or amorphous structures in microbial products. In combination with other techniques, spectroscopy allows the investigation of the whole range of marine microbial metabolites and can help finding new bioactive compounds and their uses in biotechnological processes.

2.5.3 Genomic and proteomic approaches

Metagenomics, proteomics, transcriptomics, and metabolomics are modern omics technologies essential for detecting and understanding the genetic and protein profiles of marine microbes and their products. Metagenomic sequencing has helped in the description of the genomic profiles of

complex communities such as those of marine microbes, and the gene clusters that could be involved in production of metabolites including polyketides and nonribosomal peptides (Wang et al., 2022). Molecular methods such as LC-MS/MS allow for the identification and estimation of proteins and associating them with functional responsibilities in the synthesis of the bioactive compounds (Singh et al., 2023). Metabolic profiles and the expression of lipogenic genes were relatively consistent with data obtained through transcriptomics, such as RNA sequencing (RNA-Seq), which helps to determine gene expression profiles and the biosynthetic processes taking place under certain environmental conditions. The utilization of CRISPR has recently been employed for defining genes involved in bioactive compound biosynthesis pathways by marine microbes a phenomenon that has enriched our knowledge on microbial biosynthesis. The realization that metabolites as classified by metabolomics, the study of small molecule metabolites, are useful in identifying compounds such as biosurfactants and antimicrobials means that novel marine derived molecules with therapeutic properties will continue to be discovered (Singh et al., 2023).

2.5.4 Bioassays for activity detection

Bioassays are functional methods for determining the biological activity of marine microbial products for purposes such as arresting microbial, fungal, or cancerous growth. Thus, methods such as disk diffusion and MIC assays are mandatory for determining antibacterial or antifungal potential (Ahmed et al., 2023). Cytotoxicity assays such as MTT or XTT are useful in estimating the ability of microbial products to suppress growth of cancer cell lines and thereby provides a model to test for anticancer agents. Competitive inhibition enzyme assays like α -amylase, or protease inhibitory activities are important in detecting microbial natural products that target enzymes, products that find application in treatment of conditions like diabetes and infection. The one, two DPPH and ABTS assays determine the antioxidant property of marine microbial extracts that are finding application in the present world due to their health benefits. Microbial products' ability to inhibit biofilm formation is essential in medical and industrial products making use of microbial products, thus making biofilm inhibition assays particularly useful (Singh et al., 2023). These bioassays offer the opportunity to evaluate the probability of therapeutic application of marine microbial products, and further new drugs and bioactive products discovery.

2.5.5 Advanced imaging techniques

More specific imaging techniques play a crucial role in the determination of localization, morphology, and functional relationship of marine microbial products. Bioactive compounds can be tagged with fluorescent markers using fluorescence microscopy to observe the interfacing of these compounds with biological systems (Karthik et al., 2021). CLSM affords the 3D imaging which has benefit for the identification of biofilms and microbial colonies' location of the CFU, improving the overall knowledge of microbial behaviors in the multiphase systems. Transmission electron microscopy (TEM) provides the means for imaging microbes and microbial products at the atomic level, as well as providing any structural information related to biosynthesised nanoparticles. Atomic force microscopy (AFM) is another important technique for measuring surface morphology and forces

locally at the surface, most importantly for biofilms and microbial surfaces. The use of NanoSIMS supplements the investigation of isotopic ratios for imaging and therefore yields information on the metabolic function of marine microbes and on the distribution of distinctive molecules. These enhanced microscope capabilities are crucial in depicting and deciphering some of the intricate aspects and relationships of the marine microbial products hence enhancing the possibilities and application of these totipotent biomolecules (Karthik et al., 2021).

2.5.6 Biosensors and lab-on-a-chip technologies

Optical and instrumental techniques such as biosensors and lab-on-a-chip technologies have greatly advanced the detection and analysis of marine microbial products by providing quicker, more sensitive and cheaper techniques for diverse uses. For example, electrochemical biosensors, which employ the electrochemical signal of the metabolite, such as glucose, or of bioactive compounds to identify a microbe's metabolic presence offers a portable, real-time methodology. Technical breakthroughs such as SPR and fluorescence-based sensors have found applications in the real-time examination of marine-derived bioactive molecules; biosensors are highly sensitive and specific (Rahman et al., 2022). A microfluidic-based lab-on-a-chip that allows for the concerted analysis of diverse marine microbial extracts and their activities can be used to quickly identify new sources of bioactive compounds. Microbial sensors use the electrical impedance method to determine the microbial growth or product formation and is noninvasive and real-time. Advanced sensing, involving genetic characterization of marine microbes using DNA-based sensors determine species, their bioactive potential and the possibility of screening for bioactive compounds (Karthik et al., 2021). These technologies are critical in the progression of achieving higher throughput in marine microbial product detection so that the discovery of new bioactive molecules can be accelerated.

2.6 Applications of marine microbial products

The products derived from marine microorganisms have recently attracted much consideration owing to their multifunctionality in different sectors. Marine microorganisms grow in high pressure, saline, and low temperature conditions in their natural habitats, thus the bioactive compounds they constitute are structurally distinct from other compounds. These compounds as a source of new ideas in terms of activity in the pharmaceutical industry, agriculture, industrial applications, and environmental control (Chopra et al., 2014).

2.6.1 Pharmaceutical applications

Marine microbial products have been considered potential source for new drugs because of their rich and high activity. Some well-known secondary metabolites such as polyketides, nonribosomal peptides, and alkaloids have been converted into useful antibiotics. For instance, salinosporamide A, produced by *Salinispora tropica*, has been identified for its remarkable anticancer and antimicrobial aptitudes with the capacity to place it as a modern therapeutic compound (Kumar & Singh, 2021).

Moreover, marizomib, a proteasome inhibitor isolated from marine actinomycetes, is in trial for using in multiple Myeloma and Glioblastoma. This compound has been portrayed to be an effective cancer killing machine since it harnesses a different mechanism compared to using standard chemotherapy (Kim et al., 2022). Other example is cyanovirin –N which is marine microbial metabolite excavated from cyanobacteria; which has been effective against HIV and influenza viruses by interfering with viral entry mechanisms, providing a potential antiviral treatment (Mei et al., 2023). Also, other compounds isolated from marine sources which include lipoxazolidinones exhibit high potentiality of antiinflammatory and immunosuppressive agents for autoimmune diseases and other inflammations (Wang et al., 2022).

2.6.2 Agricultural applications

Marine microbial products are also key factors in evolving sustainable agriculture practices through improving cropping performance, and ability to withstand unfavorable environmental conditions. For example, lipopeptides and iturins as bioactive compounds derived from marine *Bacillus* species are active as biopesticides. The formulated compounds are toxic to the agricultural pests but have little or no impact on other useful insects making them environmentally friendly than conventional chemical pesticides (Sharma et al., 2020). As for the underwater environment, *Azotobacter* and *Rhizobium* species are valuable types of marine microbes as bio-fertilizers; they fix nitrogen from the air so as to enrich the ground. Additional extracellular polysaccharides released by these microbes improve the tendency for soil aggregation and water holding capacity, thus improving quality and stability of the structural elements in the soil. Furthermore, marine bacteria synthesizing plant growth regulators such as gibberellins and IAA enhances seed germination and root growth for enhanced crop production (Karthik et al., 2021). Other marine microbial products include siderophores, which are engaged in an effective biocontrol by restraining pathogenic microorganisms by sequestering iron and consequently, lowering plant diseases.

2.6.3 Industrial applications

Several marine microbial products are being sought after for several industrial uses due to their strong and multifunctional metabolic profiles. Examples of these marine enzyme are amylases, lipases, and proteases recovered from marine microorganisms, which play important roles in processed foods, detergents, textiles, and other related products. These enzymes are useful mainly due to the stability of their action in various unfavorable conditions, for example, in high salinity or high temperature which can be typical for industrial production (Huang et al., 2022). Furthermore, the marine microbes like *Thraustochytrium* also contain higher lipid content that can be further used in biodiesel application. In the same manner, marine algae used in bioethanol processing helps in improvement of renewable energy sources. Another remarkable example is the use for preparation of biodegradable plastics, where the primary components are exopolysaccharides originated from the marine bacteria of *Vibrio* spp. (Ahmed et al., 2023). Moreover, species-derived pigments including: carotenoids and violacein which are commonly used in cosmetics, textiles, and food industries since they act as natural colorant, and are environmentally friendly and nontoxic substances compared to synthetic dyes.

2.6.4 Environmental applications

Marine microbial products are of significant importance in solving some of the most urgent problems faced by the modern world, namely bioremediation and climate change. For instance, the marine bacteria *Alcanivorax borkumensis* has been shown as a unique characteristic of being highly specialized in breaking down hydrocarbons and has therefore been widely used to address oil pollution in marine ecosystems (Gimba et al., 2024; Xiao et al., 2023). In addition, oceanic microbes such as cyanobacteria that are capable of photosynthesis help in the global efforts of CAR aimed at reducing the impacts of climate change by incorporating atmospheric CO₂ into carbonious compounds. Similarly, marine microbial consortia have more recently been applied to the treatment of wastewater, notably by “harvesting” nutrients, organic compounds, and heavy metals in industrial effluent, and thus promoting cleaner water bodies (Kumar & Singh, 2021). Further, biosurfactants synthesized by marine microbes have been fruitful in increasing the solubility rate and removal efficiency of various hydrophobic compounds including oil and metal from the polluted sites for environmental cleanup.

2.6.5 Food and nutraceutical applications

Marine microbial products have been studied for their nutritional and functional values in the food and nutraceutical sector. For example omega-3 fatty acids, obtained from marine microbes such as *Schizochytrium*, are used in functional foods to improve cardiac health by decreasing cholesterol and preventing cardio vascular diseases. *Lactobacillus* spp. as marine-source probiotics are wholly applied to better the gut bacteria balance and immunity thereby being used in human and animal feed. In addition, peptides and polysaccharides derived from the marine environment have been identified to possess strong antioxidant, antidiabetic and cholesterol suppressant activities and these compounds are considered highly valuable in the formulation of dietary supplements (Mei et al., 2023). Marine microbial products also find their application in food preservation, especially the bacteriocin and other antimicrobial compounds derived from marine microbes having proved to be effective in preventing the spoilage of foods and thus enhancing the shelf life and food value of perishable food stuffs.

2.7 Challenges and limitations in the characterization and detection of marine microbial products

The identification of characterization of the marine microbial products also poses some difficulty because of the complicated matrix and the sophistication exhibited by the compounds. However, based on the current technology and methodological approaches, there are some constraints that have limited the optimal utilization of such resources (Gana et al., 2024).

2.7.1 Sampling challenges

Marine sampling inherits a high variability, and indeed, the main challenges arise when sampling from this environment. Temperature, salinity, and pressure changes are more often in the marine environment, and any change influences the metabolic rates of microbes and thus alters the type of

bioactive compounds they synthesize (Kim et al., 2022). Another encoder of variability is the locations where it occurs as well as the marine fabrications like coastal waters, deep-ocean hydrothermal vents thus the type of microbes differs depending on the type of ecosystem. These variations make it challenging to have standard and representative sampling across the various marine ecosystems. In addition, the research indicates that many potential microbial species are potential inhabitants of extreme and isolated World sites, for instance, polar region or deep sea hydrothermal environs. Physical accessibility to such regions and the overall costs affect the extent and how often sampling is conducted (Xiao et al., 2023). Furthermore, some microbial species which synthesize bioactive compounds are present in very low abundances in the diverse microbial population structure, and; the morphology of these species also poses a big challenge in their isolation and characterization. It also makes it even more difficult to obtain enough samples to analyze these target microbes to come up with new and more effective bioactive compounds.

2.7.2 Technical limitations

The complexity of the marine samples makes the process of discovering the bioactive compounds even more challenging. Marine samples can harbor a rich biosystem composed of microorganisms, organic and inorganic molecules, making sample preparation a complex process that masks the actual potential of marine bioactive compounds (Huang et al., 2022). Today we have better ways like HPLC and S which provide better sensitivity, still the challenge of looking for compounds that would be present in very small concentration is still difficult. This becomes tough when analyzing minor metabolites since they are often masked by other, more dominant species in the sample. Further, some marine microbial products are perishable when harvested and extracted from their original habitats, potentially degrading before the point they are discernable or can be characterized (Huang et al., 2022). Even relatively cheaper and more accessible instruments like gas chromatography, Fourier transform infrared spectroscopy, Raman spectroscopy, and fluorescence spectrophotometry are expensive and hard to come by, especially when standardized for advanced use with NMR, GC-MS, and cryo-electron microscopy (Mei et al., 2023).

2.7.3 Genomic and bioinformatics barriers

Notably, many marine microbial species' genomes are still either scantily genomic sequenced or inadequately represented, and this makes it difficult to identify biosynthetic gene clusters that could be gene responsible for the manufacture of bioactive compounds (Wang et al., 2022). The genome of marine microbes is highly diverse and most of the pathways involving synthesis of secondary metabolites are as yet unknown or only partially elucidated thus limiting the possibility of using such production at its potential. Further, despite advances in the generation of tremendous volumes of genetic data, existing methods of annotation pose a significant challenge of methods of annotation pose significant bottleneck. Due to the absence of comprehensive characterization of various biosynthetic genes, many of them remain poorly characterized and hence cannot be put to optimum use for bioactive compound production. Furthermore, the number of available public databases for marine microbial compounds is also rather limited and does not yet include sufficient coverage of newly identified compounds to known entities (Rahman et al., 2022). The lack of such bioinformatics resources hampers efficient search for the bioactivity of new bioactive products thereby affecting the progress in the field.

2.7.4 Ethical and legal considerations

Marine microbes offer important sources of food and energy, but these resources are regulated by significant ethical and legal measures, such as the Nagoya Protocol, which deals with access to genetic resources and sharing of benefits arising from their utilization. Although these regulations enhance the ethical standards within bioprospecting, they also impede or limit opportunities to acquire significant marine microbial species (Ahmed et al., 2023). In addition, IPR problems occur when many players address marine bioprospecting, questions of ownership and patenting, which slow down the process of putting marine-derived products on the market arise. Another issue of ethical concerns arises in respect of the effects of marine sampling on the environment. Coral reefs or deep-sea spaces, the subject of invasive collection techniques and extensive culture of marine microorganisms are delicate environments; thus, their exploitation inherently has unforeseen ecological impacts. Such issues raise the aspect of responsible and sustainable techniques in the marine biotechnology research.

2.7.5 Scale-up and commercialization challenges

There are many difficulties in transitions of laboratory-scale methodologies to large-scale industrial use. Perhaps the most outstanding challenge is fluctuations in yields since most of the ferm microbials generated through marine resources are produced in relatively small quantities, meaning that aspiring to scale up the production processes in order to supply the global market would be economically unsustainable (Mei et al., 2023). While techniques such as metabolic-engineering and fermentation optimization may also help in solving this problem, these techniques are as yet in the experimental-nascent stage. Furthermore, the ability to mimic the environmental conditions in which marine microorganisms can grow is not easy to do in bioreactors. Marine microbes tend to be very sensitive to temperature, pressure and salinity of the environment; replicating these ideal conditions on larger scale is a complex feat and expensive. In addition, the time required to introduce a new marine-derived product is relatively long and costly as all such products have to undergo some rigorous testing and approval, which can take up to several years. Last of all, the marine microbial products are also equally challenged by the synthetic counterparts and the terrestrial derived products which are already dominating in the respective markets, limiting their adoption in commercial applications (Mei et al., 2023).

2.7.6 Detection of novel compounds

This approach to discover new bioactive compounds originated from the marine microorganisms is however challenged by a number of factors such as these cryptic metabolites. In fact, most biosynthetic gene clusters are dormant under standard laboratory conditions, and, thus, the bioactive compounds which they potentially produce have not been identified and are not produced (Singh et al., 2023). Further, it has been difficult to separate structural isomers of marine microbial products because a given compound may have more than one isomer that is chemically similar. This is so because ordinary analytical techniques that would be used to distinguish between these isomers include NMR and MS/MS, and these tests need more advanced instruments and professionals. Furthermore, the matrix of the marine samples involves interferences such as salts and organic matter, which hampers the ability of spectroscopic and chromatographic methods to detect samples with high

sensitivity and accuracy. This interference can hide compounds that are rare to the system or completely new thus making it very difficult to discover new bioactive substances (Ziko et al., 2019).

2.7.6.1 Addressing challenges

In order to counter these issues, currently the marine biotechnology has considered several strategies. More effective and sustainable ways of collecting marine samples especially from isolated areas can be expected with newer sampling technologies including AUVs fitted with high end sensors. Emerging technologies, as TOF-MS and cryo-EM, will facilitate the further identification and characterization of new bioactive molecules. Besides, the use of synthetic biology approaches including crispr-cas9-based gene editing to awaken hidden biosynthetic machinery, enhance the synthesis of valuable secondary metabolites (Rahman et al., 2022). Data mining bioactive compounds can be more efficiently performed by using machine learning algorithms, which send the identification of potential candidates faster. These innovations are essential for solving the existing disadvantages in marine biotechnology as well as to use fully the potential of marine microbial products (Begrem et al., 2020).

2.8 Prospects for further development

The prospects for the development of marine microbial biotechnology will become one of the main ways to solve global problems associated with human health, agriculture, industrial and environmental safety. Nevertheless, the field has to address several problems of technical, environmental, and regulating character to make the best use of marine microorganisms for these purposes adequately. By overcoming these limitations, marine biotechnology can deliver revolutionary products that will be beneficial to almost every business field (Baranova et al., 2023; Musa et al., 2023).

2.8.1 Enhancing detection techniques

According to previous studies, one of the development trends of marine microbial biotechnology today is the combination of genomics, proteomics, metabolomics, and transcriptomics. These approaches provide a systematically detailed picture of microbial biosynthesis pathways for the identification of new bioactive molecules, and to help gain the insights into regulation of these biosynthesis routes (Mei et al., 2023). Altogether, these approaches, when applied in conjunction with advanced analytical techniques, can expose complex biochemical pathways that regulate synthesis of bioactive metabolites. Furthermore, instruments that are under development and employ the principles of TOF-MS and cryo-electron microscopy will also enhance the identification and structural characterization of marine microbial products with high sensitivity. And might it be, the continuous growth of AI and ML technology can also aid in fast-tracking identification of bioactive compounds. These tools can handle information from high throughput screenings making the discovery of more marine derived bioactive compounds faster and efficient. Furthermore, sampling using AUVs self-propelled, relatively independent submersibles equipped with sensors and automation means ems to be more remote and efficient in more remote aquatic environments. The combination of these advanced technologies will be used to support the discovery of new marine microbial products and the rapid development of these products as well (Rather et al., 2017).

2.8.2 Scaling-up production

A lot of work must be done to optimize the fermentation processes because a bio catalog of marine microorganisms enables the production of marine microbial products that can meet the required commercial scale. The current developed bioreactor systems require modification to attain these environmental conditions required for marine microbes and bioactive metabolites production. It suggested that strategies like adaptive laboratory evolution and metabolic engineering could mean a critical role in enhancing yields consistently producing a high quality, adequate volume of product (Ahmed et al., 2023). In addition, synthetic biology and genetic engineering technologies include CRISPR-Cas9 might be used to induce cryptic gene clusters, which remain inactive in the conventional laboratory conditions, thus having the potential to harbor unexplored biosynthetic activities. Besides these advancements, bioprocess integration could further integrate the steps to make upstream processes like in situ extraction to connect with downstream purification steps. This would lower the time and costs of performing the extraction and purification procedures using conventional techniques. Another possible method is consortium production in which different marine microorganisms with possible different metabolic pathways are grown in a single vessel. It had the potential to mirror natural microbial biofilms thus improving synthesis of the wanted bioactive molecules making the production methods more efficient and economic (Ahmed et al., 2023).

2.8.3 Expanding applications

The existing and potential markets for economic marine microbial products as highlighted include pharmaceuticals, agriculture, bioenergy, and lastly environmental applications. Marine-derived bioactive compounds should be routinely checked for emerging diseases such as antimicrobial resistance and new viruses as sea microorganisms are sources of new antimicrobial peptides (Kumar & Singh, 2021). Marine microbial products are important in sustainable agriculture since they offer natural substitutes such as microbial pesticides, microbial biofertilisers, and microbial growth promoters that will lower the harmful effects of farming techniques. In addition, marine microbes with capabilities of synthesizing biofuels or biopolymers mean that implementable and renewable energy sources besides fossil fuel and petrochemical products can be found. In environmental biotechnology applications, the possible uses of marine microbial enzymes, for instance, bioremediation, carbon capture, and waste management, makes it even more important to focus on this area. Such applications might solve some of the contemporary problems in the world, for example, climate change, and pollution, by using the inherent strengths of marine microorganisms in solving environmental issues (Musa et al., 2023).

2.8.4 Improving accessibility and collaboration

To accelerate the development and application of marine microbial biotechnology, efforts must be made to improve accessibility and foster greater collaboration within the scientific community. One of such strategies is the creation of public Web databases containing extensive data on the marine microbial genomics, metabolomics, and structural libraries. Such databases would allow people to compare newly found compounds with existing entities, increase the focus on sharing the findings, and step up interdisciplinary cooperation. Another area of collaboration is multifaceted where marine

biologists, chemists, engineers, and data scientists play important roles toward harnessing full potential of marine microbial products. It is also true that synergies can be achieved in shorter time through the use of expertise from different disciplines and through integration there is a faster identification and characterization of new active bio compounds for technological problems (Oladoja et al., 2019). Moreover, the local community around the marine habitats can be involved in bioprospecting in order to guarantee resource utilization from an ethics perspective with benefit sharing. It is also possible for communities to play a similar role in ensuring that there is sufficient protection for marine ecosystem for excessive exploitation (Musa et al., 2024).

2.8.5 Addressing ethical and legal challenges

The issues of ethical and legal concerns associated with access and use of marine microbial resources must therefore be considered so that bioprospecting can be done in a socially acceptable way. International conventions like the Nagoya Protocol tell the world that utilization of resources and marine species conservation can go hand in hand. Governing these common resources should guarantee the distribution of gains that accrue from the genetic resources for the use in marine systems to the countries or regions wherever the origins of the resources are derived from. However, management and ecological impacts concerning sustainable sampling techniques and cultivation practices should also be enhanced to reduce effects on other vulnerable natural resources in the marine system. This calls for improved less intrusive sampling that will not further disrupt the microenvironment occupied by the marine microorganisms. Moreover, training programmes and workshops may enhance awareness and technical constraint necessary for the researchers especially from the developing countries toward ethical and sustainable exploration and utilization of the marine microbial resources.

2.8.6 Conservation of marine microbial diversity

The problems of preservation of the diversity of marine microorganisms are of vital importance for the further future of the marine biotechnology. Measures to conserve vital biogeographical sites like coral reefs, deep sea hydrothermal vents, and mangrove forests depends with the microbial species that are found in these areas thus the need for policies. The creation of culture collections in specialized repositories also benefits from standardized collection of valuable marine microorganisms for future research and industry that remains significant. Therefore, ex situ conservation approaches including the development and maintenance of marine microbial culture banks may be useful toward providing for such valuable resources when the natural ecosystem. They are retrieved from becoming compromised. In addition, efforts to restore damaged marine habitats for rehabilitation work will also prove helpful for the recovery of native microbial-derived biological resources, improving the probability of identifying new bioactive structures. When marine microbial diversity is conserved by means of academic research, future generations are ensured of a valuable source of bioactive compounds (Gómez-Sala et al., 2016).

2.8.7 Recommendations

For the marine microbial products be in a position to achieve its average market price, the following strategy must be implemented. It is recommended that governments and funding bodies need to

identify and develop legitimate funding sources for MBT (marine biotechnology) because of its importance in addressing global challenges. In this sense, it is suggested that researchers embrace integrative perspectives and practices that encompass state-of-the-art tools, multi- and inter-professionalism as well as planetary health. Business ought to disclose commercialization processes that are environmentally friendly such as using environmentally sustainable production processes and proper waste disposal. Science educators should incorporate marine biotechnology as a discipline of study owing to growing prospects and challenges that the new generation scientists are more likely to encounter. When implemented, these strategies can transform the sector for marine microbial biotechnology to offer tremendous solutions in health, agriculture, industries, and most importantly environmental protection, for the present and the generations to come.

2.9 Conclusion

Marine microbial products industry is widely becoming a new source in biotechnology field due to huge chemical diversity and astonishing biological activities of those metabolites from marine microorganisms. These products have the capacity to change different aspects of our lives in practically every industry such as health, food production, and conservation, and the physical environment. Unfortunately, there are various difficulties such as technical issues, sampling issues and legal issues. Physical, chemical, and biological characterization approaches have enabled description of bioactive compounds and new detection methods such as microspectroscopy, HPLC, and Omics approaches have helped in the description of these bioactive compounds and new bioactivities. Nonetheless, to make the most out of them, it is crucial that we look at the issues involving scaling production, enhancing the detection rates, and making them sustainable. Future derivations have to proceed, thus, from the integration of AI and ML as well as synthetic biology with bio-screening and other more conventional forms of bioprospecting. Of particular importance will be sensitive nature of resource use and common governance on sustainable use of the seas' resources. Given current limitations and the use of new tools, marine microbial products will be inestimable assets in the fight against global problems, including drug-resistant bacteria and a search for novel sources of income based on the biophilia of our planet.

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Spatial and temporal variation of marine microbial populations

Manish Kumar Gautam¹, Arup Dey¹, Sandip Mondal², Rakesh Das³ and Ranjit Das⁴

¹*Faculty of Pharmaceutical Science, Assam Down Town University, Guwahati, Assam, India,*

²*Amity Institute of Pharmacy, Amity University Kolkata, Newtown, Kolkata, West Bengal, India,*

³*School of Pharmaceutical Technology, School of Health and Medical Sciences, Adamas University, Kolkata, West Bengal, India,*

⁴*Department of Microbiology, All India Institute of Medical Sciences (AIIMS), Kalyani, West Bengal, India*

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3.1 Introduction

Marine cage farming has become a very successful intensive aquaculture technique in recent years because of its low cost, flexibility, and high yield. Hanging cages in open ocean areas provide most of China's mariculture output (Wang et al., 2024). Changing hydrography and rising temperatures affect

regional biogeochemistry and make marine species more vulnerable in their native habitat by quickly melting ice sheets. Given the WAP region's ecological significance from its high primary production rates, productive food web, and notable CO₂ transfer between the air and sea, the effects of these climate change factors are considerable. Changes in sea ice cover, irradiance, and climatically controlled processes including the Southern Annular Mode, El Niño-Southern Oscillation, and the Amundsen Sea Low cause notable seasonal variation in the World Atmospheric Program (WAP) region. These characteristics and interannual fluctuations complicate predictions of how climate change will affect the WAP ecosystem (Smith & Stammerjohn, 2001). The microbial community—comprising viruses, bacteria, archaea, microbial eukaryotes (including fungi, heterotrophic protists, and phytoplankton)—controls the biogeochemical cycle and the productive WAP food web. Climate change makes the makeup of the WAP microbial community rather dynamic and influenced by physical and climatic variables changing with the seasons, years, and decades (Deppeler & Davidson, 2017).

Marine microbial communities are vital for the biogeochemistry of the ocean since they are important in the carbon, nitrogen, and sulfur cycles. Research on oceanographic time-series conducted at offshore locations shows that their composition is significantly influenced by seasons and annual recurring microbial turnover. Environmental gradients were found by these studies to be the cause of the observed variations (Aransiola et al., 2024; Fortunato et al., 2012). Spatial variation is especially evident when comparing nearshore and offshore microbial populations because of gradients such as dissolved organic matter, temperature, nutrient availability, and, especially in estuaries, the change in salinity from coastal to open ocean waters (Lucas et al., 2016).

3.2 Spatial variation in marine microbial communities

3.2.1 Horizontal distribution

Spatial variation greatly influences the distribution of bacterial and protist communities (Shurin et al., 2009). These communities' horizontal dispersion is influenced by ocean currents, up/down-welling mechanisms, and water masses (Sunagawa et al., 2015). These elements create a geographical impact as well as a distance-related pattern revealing how the composition of the community changes with the distance separating its members. Ocean currents could carry these microbes horizontally, possibly causing this (Wilkins et al., 2013). Horizontal currents can also mix the saltwater at a single depth. Saltwater thus has a distance-decay link that crosses the horizontal distance and the water column. Depth also relates to these geographic patterns as well (Milici et al., 2016). Comparing trends between prokaryotic and eukaryotic microbial community fractions is challenging because of their different body composition, trophic level, and dispersion capacities (Gong et al., 2023). Research is crucial to understanding the dispersion of microbial communities in the ocean since ocean fronts are tiny areas with notable horizontal gradients of water physicochemical properties, including temperature, salinity, and nutrients (Belkin et al., 2009). The migration patterns of many species include fronts, which serve crucial roles in marine ecosystems by increasing productivity, among other things (Belkin et al., 2009). Even though this front represents a relevant geographic area, comparatively little study has been done on its distribution and functionality, notwithstanding recent discoveries in the N cycling-mediated microbial communities (Semedo et al., 2021). A notable distance-decay association was

observed in several microorganisms on the horizontal scale. As demonstrated by this, microbial populations are shaped by environmental gradients and geographic distance (Wu et al., 2020). Similar distribution patterns and factors influencing alpha and beta diversities in bacterial and protist communities may be found in the subtropical North Pacific oligotrophic seas. The main factors influencing both communities are temperature, depth, and longitude. Except for Radiolaria, which is close to the surface, most microbial communities have not shown any discernible dispersion constraints up to 120 km. Nonetheless, a noteworthy distribution was seen for nine bacterial taxa essential to ecosystem activities. Utilizing high-throughput sequencing, the distribution of bacterial species across geographic and environmental gradients is being investigated. Bacterial colonies displayed remarkable vertical and horizontal dispersion under coastal gradients. The least discriminant analysis effect size determined the most significant taxa within each cluster, which also demonstrated a strong association with geographic and environmental parameters. Microbial biogeography, which examines how microorganisms react actively and passively to their ever-changing surroundings and geographic isolation, may be established using the effects of past and present ecological conditions. Microbial diversity is impacted by environmental factors and dispersion constraints concerning spatial size (Bi et al., 2022).

3.2.1.1 Coastal waters

Coastal regions are among the world's most productive, overfished, and threatened ecosystems (Nichols et al., 2010). The microbial component is crucial to the functioning and upkeep of these ecosystems, which offer a range of ecological and economic services and benefits (Falkowski et al., 2008). Communities of microorganisms can have a direct impact on the coastal environment through their taxonomic and functional makeup. While international expeditions have brought attention to global trends in the ocean microbiome, coastal microbial dynamics exhibit even more diversity in small geographic regions (Logares et al., 2020; Zinger et al., 2011). Variability in terrigenous inputs throughout the land-sea continuum is mostly caused by river runoff, which is the main source of nutrients, organic matter, and pollutants (Zoppini et al., 2019). Their quantity and quality are influenced by human activities, climatic circumstances (seasonality, severe events, etc.), and watershed features (size, soil type, relief, vegetation, etc.) (Milliman & Farnsworth, 2013). Throughout time and space, changes have a dynamic impact on the amount and structure of microbial communities in nutrients, phytoplankton, and other environmental elements (Arandia-Gorostidi et al., 2022). Given their critical involvement in food cycling, sulfate reduction, hydrocarbon degradation, and other ecological processes, it is imperative to comprehend the seasonal variation of microbial populations (Sachithanandam et al., 2020). The increased abundance can be a sign that surface waters have less fertilizer availability. Among the many marine species with functions in carbon cycling were *Gammaproteobacteria*, which were more abundant. With a few slight deviations, the classes of *Deltaproteobacteria*, *Epsilonproteobacteria*, and *Betaproteobacteria* showed comparatively lower abundances in every region. These classes may be the cause of the decreased abundance in all stations since they mostly consist of nitrifying and sulfate reducers as well as lower nutrient levels. Primary production-related cyanobacteria can bloom in the presence of nutrient enrichment, which can raise nitrogen and phosphorus loads from the use of nitrogen fertilizers, agriculture, groundwater discharge, human waste, and atmospheric deposition (Hafza et al., 2024).

3.2.1.2 Open ocean

These areas are crucial to global biogeochemical cycles, and microbial populations in oligotrophic zones are a key concept in global carbon budgets. Over 45% of the world's ocean surface is made up of subtropical oligotrophic gyres, one of the largest biomes on the planet. Although these nutrient-limited habitats are less productive than coastal regions, it is estimated that they provide more than 25% of the annual net marine primary production (Sarmiento et al., 2004). Given seasonal and geographical changes, it is essential to comprehend the variables impacting microbial populations in ocean habitats. Significant advancements have been achieved in this field within the last 30 years. The three phytoplankton types that predominate in the open ocean are *Prochlorococcus*, *Synechococcus*, and picophytoeukaryotes (PPE); these organisms are usually less than 2 μm . In the late 1980s, *Prochlorococcus* was the most common group (Chisholm et al., 1988). The prevalence of *Prochlorococcus* in nutrient-depleted locations and *Synechococcus* and PPE in nutrient-rich waters are clear examples of broad in situ trends, yet, geographical and temporal heterogeneity significantly hinders the worldwide generalization of these patterns (Fuhrman, 2009). The ranges of *Prochlorococcus* show a wide range of ecotypes that react differently to nutrients, light, and temperature. The vertical distributions and diversity of these organisms may be impacted by shifts in the quality and availability of nutrients in communities in the lower Oligotrophic zone (Bock et al., 2018).

3.2.1.3 Polar regions

Most lakes across the world are either continuously or seasonally covered in ice, yet little is known about the distribution of microorganisms and their impact. Microbial diversity and richness are lower in ice-covered tripolar lakes, where prokaryotes can tolerate severe environmental conditions better. Prokaryotes were primarily engaged in carbon/nitrogen metabolism in Arctic and Antarctic ice-covered lakes. In lakes covered in ice, the diversity and activity of microorganisms are impacted by extremely confined systems with low temperatures, light levels, and nutrient inputs. When there is ice, microbial biomass, and diversity are lower than when there is no ice (Cai et al., 2024). When algal-derived organic matter is first broken down, surface sediments at all stations dominate the bacterial families *Gammaproteobacteria*, *Alphaproteobacteria*, *Bacteroidota*, and NB1-j. Compared to heavy ice cover stations, low ice cover stations had higher concentrations of anaerobic bacterial communities of iron and sulfate reducers. In the ferruginous zone, the anaerobic microbial communities of *Desulfobacterota* were more abundant than below the oxic zone, suggesting low rates of organic matter burial in heavy ice cover sites (Baloza et al., 2023). Due to constitutive adaptations, certain microorganisms may flourish under particular conditions, such as high salt or low temperature. However, in settings that are subject to change, such as sea ice, acclimatization processes that enable a microbe to function in various circumstances could be more beneficial. These adaptations can change the environment of the organism and its neighbors and manifest as intracellular activity, membrane proteins, or the production of extracellular polymeric substances (EPS). Since the beginning of sea-ice microbiology, the protective role of EPS, which is gelatinous, has been recognized (Ewert & Deming, 2013). The acidic nature of membrane proteins is the same independent of the intracellular accumulation of organic solutes or K^+ ions in the cytoplasm because membrane proteins are made to function in a high-salinity environment (Saum et al., 2013). Although further research is required on in situ interactions with proteins in sea ice, the work demonstrates that

EPS improves the stability and half-life of a cold-active aminopeptidase from *C. psychrerythraea* in cold-adapted marine organisms (Bayer-Giraldi et al., 2011).

3.2.2 Vertical stratification

3.2.2.1 Epipelagic zone (0–200 m)

The richness of bacteria and archaea varies in deeper and higher levels, indicating a vertical stratification of microbial variety from the water's surface to 1500 m below it. There were no appreciable differences in the organization of the communities at the same depth. There is vertical stratification in microbial communities, with distinct communities in the deep ocean and similar populations at the topmost layer of saltwater. Plants, cyanobacteria, algae, and organisms that encode microbial rhodopsins all rely on the epipelagic zone—the uppermost layer of seawater that is exposed to sunlight—for primary production (Gómez-Consarnau et al., 2019). The number and variety of microorganisms determine seawater's vertical stratification. Higher temperature, dissolved oxygen, primary productivity, and mild salinity in the upper zone support various microbial developments. Conversely, the lower zone supports heterotrophic bacteria and those who can tolerate greater salt levels because of its higher salinity and lack of light (Qian et al., 2011). Upper-ocean stratification can directly affect the availability of light for photosynthesis and the movement of nutrients to deeper waters, both of which are vital for primary production (Yamaguchi & Suga, 2019). Through the food chain, primary productivity then influences marine species at higher trophic levels either directly or indirectly. Changes in important environmental factors in the water column, including light, food availability, temperature, and oxygen, also greatly affect plankton diversity and community structure (Wan et al., 2024). A unique diazotroph found in open waters, the heterocystous cyanobacteria coexist symbiotically with other phytoplankton members, primarily diatoms. Most diatoms in oligotrophic settings can fix nitrogen from the atmosphere because of these endosymbiotic interactions (Jabir et al., 2013). The study found that *protobacteria* were found in the bottom while cyanobacteria dominated the upper layer. Their predominance in the euphotic zone (20–50 m) results from their ability to perform photosynthesis and nitrogen-fixing under light and oxygen. Deeper waters' lower light intensity caused less Cyanobacteria (Qian et al., 2011). Endosymbiotic *cyanobacteria* are believed to be more common since they can fix atmospheric nitrogen in oligotrophic conditions. Since they symbiotically help them in fixing nitrogen for their metabolic activities, *noncyanophyceans* (diatoms) are essential for the nitrogen cycle of the region (Jabir et al., 2013).

3.2.2.2 Mesopelagic and bathypelagic zones

The mesopelagic zone is a crucial area of the ocean where carbon (C) is released into the water column and kept buried below. Because sinking particles are mesopelagic organisms' primary carbon and energy source, this mechanism is closely related with atmospheric CO₂ levels. Recent decades have seen measurements of the ratio of carbon exported to carbon absorbed by heterotrophic organisms (Baumas et al., 2023). Heterotrophic bacteria living in the dark ocean depend mostly on the settling organic detritus from the bright sea for their food. Other sources, such as chemoautotrophy, have been suggested since this sinking of organic molecules is inadequate to meet their energy needs. Marine prokaryotes, whether autotrophic or heterotrophic, may draw energy from reduced sulfur compounds including thiosulphate. Marine heterotrophic bacteria have demonstrated increased

organic carbon absorption, lower respiration, and thiosulphate oxidation (Srivastava et al., 2023). With photic, mesopelagic, and bathypelagic strains showing similar reactions to varied light, temperature, and pressure settings, the study found a strong vertical relationship among the heterotrophic culturable population. These bacteria's flexible metabolisms and nutrient availability could help to increase the ability to withstand long vertical and horizontal dispersion, therefore proving their high tolerance to different environments (Sanz-Sáez et al., 2020). The study looks at the species that can experience lower sulfur-based chemoautotrophy in the oxygenated bathypelagic zone and the potential function of thiosulphate as an energy source. Bathypelagic prokaryotic communities exhibited increased metabolic activity and gene activation when thiosulphate was included.

3.2.2.3 Deep-sea sediments

With their great water depths and unique physicochemical conditions, deep-sea environments host unique microbial communities essential for biogeochemical cycling. Seamount, trench, and cold seep habitats are examples of spatial arrangements where these communities differ in composition and function. Comprising 70–80% of the microbial populations, *Proteobacteria* is the main bacterial phylum in deep-sea sediments. *Bacteroidetes* and *Actinobacteria* dominate these sediments. Apart from obtaining a large number of uncultured genomes, the assembly and binning of in-depth metagenomes has deepened our understanding of biogeochemical cycling in deep-sea sediments and expanded the tree of life (Zhang et al., 2022). Deep-sea sediments cause more breakdown and transformation of these sinking particles, therefore enabling the sediment to retain carbon (Koeve, 2005).

3.2.3 Microenvironments and patchiness

Marine snow aggregates are heterogeneous clusters of both dead and living biological components. Their sinking rates and carbon transfer to the deep oceans are determined by their composition. Oligotrophic settings lack knowledge on total composition (Lundgreen et al., 2019). A study of the taxonomic diversity of Sargasso Sea aggregates found that, because of its higher nutrient content, marine snow and ambient water had different compositions (Steiner et al., 2020). Often, they are rather common in the upper 2000 m of the water column (Bochdansky et al., 2010). Marine snow settling at 3%–5% and 4%–22% per day is thought to remove particulate organic carbon and nitrogen from the surface waters (Shanks & Trent, 1980). The study finds that marine prokaryotes connected to snow have motility, winter cold adaptations, and somewhat anaerobic metabolism in summer. Free-living prokaryotes were more common in genes indicating participation in phosphorus restriction during the winter and those encouraging heterotrophic growth with CO-oxidation and proteorhodopsins during the summer. This taxonomic uniqueness resulted in various functional potentials (Lundgreen et al., 2019). Marine snow, a unique microhabitat with far higher concentrations of organic and inorganic nutrients than the surrounding water, is influenced by the northern Adriatic Sea's unique water mass circulation patterns, temperature changes, and nutrient content all (Cozzi et al., 2004). Microbial communities in sedimentary lakes are greatly impacted by cyanobacterial blooms, with the most up-regulated and least diversified activities occurring during bloom times. During interval periods, the archaeal community exhibits increased metabolic activity, including carbon-input-sensitive active methanogenesis. The ecological importance of methane cycling-related

microorganisms in lake sediments is demonstrated by the temporal dynamics of lacustrine microbial communities and microbial co-occurrence. It is uncertain, meanwhile, how sedimentary microbial populations relate to *cyanobacterial blooms*. Addressing the effects of *cyanobacterial blooms* on microbial communities requires an understanding of these processes (Yang et al., 2021). With the primary ecological effects being the assembly methods and interactions of prokaryotic and micro-eukaryotic communities (MECs), the diatom bloom substantially impacts the succession of microbial communities. Whereas *Alphaproteobacteria*, *Gammaproteobacteria*, *Cyanobacteria*, and *Flavobacteria* predominate in PCCs, MECs are composed of *Diatomea*, *Dinoflagellata*, and *Chlorophyta*. Environmental factors influencing PCCs and MECs include silicate and nitrate, which improve our comprehension of ecological processes and microbial interactions (Xie et al., 2021).

3.3 Temporal variation in marine microbial communities

Although marine microbial biogeography has been extensively researched, few studies have examined how communities vary over different time and space scales. The bacterioplankton population dynamics are within a 100 km radius, including free-living and particle-attached (Lucas et al., 2016). However, overriding this geographical variance is a significant temporal variation mainly driven by temperature over the whole transect. Temperature was the primary driver of change in the free-living community, while the particle-attached colony showed more pronounced patterns of spatial variation. Furthermore, the temporal fluctuation has been extensively studied in various aquatic environments. Warmth and levels of nutrient variations greatly influence seasonal fluctuations in the bacterial community's (BCC) composition (Andersson et al., 2010). Nonetheless, time factors appear to be significant in community formation and outweigh geographical variance. The primary driver of temporal change along the transect under study is temperature, which is also influenced by underlying short-term phenomena such as phytoplankton blooms.

3.3.1 Diel cycles

Marine organisms execute the sea of diel rhythmicity through the coordination of photoautotrophs and heterotrophic bacterioplankton, light, energy resources, and circadian rhythms. To anticipate daily light availability and adjust their metabolic processes, cyanobacteria employ an internal circadian clock. The circadian rhythm is essential for the oxidative pentose phosphate pathway to be inhibited in the morning. But while these organisms are frequently grown in lab environments with continuous light, little is known about their metabolic processes in a diurnal situation (Diamond et al., 2015). However, these photosynthetic organisms must be cultivated and maintained outside, where they will be exposed to light-dark (LD) cycles, in order to be used effectively on an industrial scale. It has been shown that the actual circadian clock of diverse cyanobacteria drives both metabolic rhythms and gene expression, synchronizing with external LD cycles (Dong et al., 2010). Compared to heterotrophic bacteria like *Escherichia coli*, phototrophic cyanobacteria pose an entirely new engineering problem since their metabolism is based on photosynthesis, which causes their cellular processes to react significantly to light (Wijffels et al., 2013). With the help of the histidine protein kinase CikA and KaiA, the clock synchronizes with the surroundings. Both proteins bind quinone

cofactors representing the cellular redox status, most likely plastoquinone found in the photosynthetic membrane (Wood et al., 2010). Changes in energy metabolism have, therefore, been shown to provide feedback in determining the time of clock oscillations (Pattanayak et al., 2014). Generally speaking, respiratory metabolism systems are engaged at night, whereas oxygenic photosynthesis systems are activated during the day. Furthermore, cyanobacteria employ the day and nighttime periods to separate incompatible metabolic activities (Stöckel et al., 2011). For example, *S. elongatus* starts light-independent protochlorophyllide reduction, an oxygen-sensitive activity, during the night when photosystem II is not generating oxygen (Reinbothe et al., 2010). The study shows a distinct viral effect through depth-independent and habitat-specific interactions on the diel cycle of the bacterial population. There is a positive correlation between diel change and community diversity in open oceans, since lytic viruses are more likely to lyse high viral lysis, which might diversify the bacterial community in the “Kill-the-Winner” manner (Winter et al., 2010). The study found that SAR11, a common bacterioplankton in the water, and virus abundances were strongly correlated. SAR11’s lowest abundances matched VA maximum values, indicating a predator-prey connection with viral lysis as a crucial regulator (Zhao et al., 2013). Through lineage-specific predation, viral predation is thought to increase species-level host diversity, resulting in a more diversified bacterial community, even on short periods like the diel cycle (Chen et al., 2019).

3.3.2 Seasonal dynamics

The diversity of the bacterial community fluctuated with the seasons; in all 5 years, it was highest around September and lowest around January. Seasonal groupings of the bay’s bacterial populations were established, and they were associated with environmental factors such as dissolved oxygen, salinity, and seawater temperature. Seasonality in marine microbes’ communities is another topic of study, in addition to the spatial differences revealed by such studies. This helps to understand the long-term responses of microbes to climate change by illuminating the mechanisms governing complex network interactions (Fuhrman et al., 2015). Galand et al. draw attention to the genetic potential of marine microbial communities by showcasing a variety of microbial metabolisms in the ocean as well as seasonal oscillations in populations (Galand et al., 2018). Over 5 years, the salinity at 1 m deep varied seasonally, decreasing from March to October or November. The low salinity was probably induced by rainfall. At 1 m deep, the seasonal pH change was larger than at 8 or 10 m. DO increase between February and April; it was favorably correlated with pH and negatively correlated with seawater temperature (Kobiyama et al., 2021).

Large phytoplankton blooms occur in mid- and high-latitude seas during the spring because of an extended photoperiod and modifications to physical, chemical, and biological ocean processes such as stratification, temperature, turbulence, and mixed layer depth (Behrenfeld & Boss, 2018). The timing and evolution of spring blooms determine which higher trophic-level organisms will benefit the most from the nutrient pool and eventually help export carbon to the deep ocean layers (Allen et al., 2005). In the context of human climate change, blooms may be occurring earlier due to increased spring temperatures or, as in the example above, earlier sea-ice loss (Leu et al., 2011). The potential effects of climate change on the timing and magnitude of phytoplankton blooms in an ocean are yet unclear, though.

The low total phytoplankton biomass discovered in our study is comparable to the phytoplankton biomass at a nearby location experiencing summer stratification (Pedrós-Alió et al., 1999). Under summer-stratified circumstances, picoeukaryotes are essential for the digestion of nitrogen sources and for the substantial downward export of biomass. Within the surface layer, bacterial phytoplankton are dependent on recycled nitrogen. The main source of carbon biomass throughout the summer stratification phase in the Mediterranean was picoeukaryotes. Their role in marine food webs and carbon fluxes will become clearer with more research on their main production contribution and transmission to higher trophic levels in the open Mediterranean Sea (Worden & Not, 2008).

As depth increased, the bacterial population changed, with the two main groupings being *Proteobacteria* and *Actinobacteria*. In contrast to stratification layers, winter mixing layers contained larger percentages of *actinobacteria*. Between the spring surface layer (16.6%) and the summer deep layer (0.24%), the proportion of *cyanobacteria* changed quickly. Bacteroidetes flourished in the summer surface layer but dwindled in conditions with little dissolved oxygen. Temperature, DO, and pH were examples of environmental variables that showed statistical significance. 81.7% of the variation in the microbial community was explained by six criteria. In contrast to summer and autumn groupings, winter and spring microbial communities differed (Yu et al., 2014).

3.3.3 Interannual and decadal trends

One important indication of interannual climate variability in the tropical Pacific air-sea system is the El Niño-Southern Oscillation (ENSO), which is characterized by warm and cold phases (Nagura & Konda, 2007). The ENSO impacts higher latitudes through several processes, including heat fluxes, changed transient eddy activity, anomalous atmospheric circulation, jet stream alterations, Walker circulation shifts, and Rossby waves (Yuan et al., 2018). The study in the Arctic Ocean (AO) examines how warm and cold ENSO and AO phases under both positive and negative phase conditions influence marine phytoplankton community structure. Its aim is to understand how changes in sea surface temperature and atmospheric oscillation influence Arctic ecosystems. The study does find, however, that the Chukchi Sea and the Bering Sea show contrary interannual fluctuations in phytoplankton group cell densities and biomarker concentrations (Liu et al., 2023). Decadal variations in atmospheric circulation and ENSO had a significant impact on the trend of the sedimentary record in the Bering Sea. One must take into account the decadal time frame relationship between ENSO and atmospheric circulation. Past research has revealed that the characteristics of the ENSO vary yearly. Especially, over the last 50 years, the amplitude and interannual oscillation frequency of the ENSO have changed dramatically (McGregor & Ebi, 2018). The structure of the microbial population in samples collected over several seasons and years was studied. It was found that the interannual variation and long-term stability data of the microbial population can reflect seasonal patterns and environmental factors changing from year to year, thus helping to preserve an average microbial community. Interdecadal processes like the El Niño-Southern Oscillation Index and the Pacific Decadal Oscillation Index could relate long-term dynamics at all depths. Seasonal variation is most clear around 5 and 890 m; environmental elements determine community variation at these heights (Cram et al., 2015).

Studies on *Prochlorococcus* and *Synechococcus* reveal seasonal and interannual variations in environmental patterns, with observed patterns significantly influenced by sampling months and

years. The traits of cyanobacteria will reveal how *bacterioplankton* respond to climatically caused environmental changes and diversity shifts. Over the annual cycle, temperature and nutrient levels have an anti-correlated relationship; winter and spring have the most nutrients while summer and autumn have the highest temperatures (Larkin et al., 2020).

3.4 Drivers of microbial variability

3.4.1 Temperature

The microbiome's capacity to respond to changes in the environment is influenced by ambient circumstances. Microbial communities are less susceptible to changes brought on by climate change in regions with more temperature variations. The physiological constraints of the organism, which are controlled by temperature and environmental diversity, have a major influence on its ability to adapt. As temperatures rise, ectotherms develop more slowly and achieve their thermal optimum. Tropical phytoplankton frequently stay around their ideal temperature, but microbial growth in temperate regions may be temperature-limited. The primary signal at this temperature, the composition of the microbial population, is comparatively constant (Wang et al., 2021). According to the study, phylotype abundance either continuously rose or fell throughout testing, indicating temperature specialization or temperature adaption. However, in a single experiment, the majority of temperature-responsive taxa saw significant changes, underscoring the significance of contextual context in microbial communities' reactions to climate-change variables (Yung et al., 2015).

3.4.2 Salinity

Their unique position makes coastal waters susceptible to saltwater incursion and terrestrial pollution. This work looked at the interactions of the nitrogen cycle and microbial community in a warm-season coastal eutrophic lake. Saltwater intrusion's increase in salinity affected surface water's bacterial diversity. Higher salinity upregulated genes connected to denitrification, dissimilatory nitrite reduction to ammonium, and ammonification; genes linked to nitrogen fixation and assimilatory nitrogen reduction were downregulated (Feng et al., 2023). Many environmental factors, including salinity, temperature, and light intensity, and nutrient levels, can influence the growth of algae in natural streams (Gao et al., 2018). Salinity and nutrients are believed to have a major impact on the growth of the microbial community in aquatic environments. Many saltwater environments have more microbial diversity, and many of these organisms have adjusted nicely to saline aquatic conditions. Conversely, high salinity stunted microbial growth and lowered their diversity and activity. Salinity therefore caused the microbial population in the aquatic habitat to differ significantly (Feng et al., 2023).

3.4.3 Nutrient availability

The survival, growth, and output of microorganisms depend heavily on the availability of nutrients in the world's seas. *Cyanobacteria* have an impact on the oligotrophic marine euphotic zone, which is

made up of the lower nutrient-replete layer (NRL) and upper nutrient-depleted layer (NDL). However, in ocean basins at low latitudes, substantial pycnocline stratification may result in nutrient deficiency. In the high waters, where nutrients are scarce, *Prochlorococcus* and *Synechococcus* are important marine primary producers and carbon fixers (Dupont et al., 2015). Certain eukaryotic phytoplankton types are more abundant in the north Pacific subtropical ocean's lower nutrient-enriched euphotic zone (Li et al., 2013). Low surface biomass, surface nutrient depletion, and constant stratification characterize the basin region, which is a typical oligotrophic marine ecosystem (Chen et al., 2021).

3.4.4 Ocean currents

The influence of ocean currents on the biogeography of marine microorganisms is being investigated internationally using thermophilic endospores as tracers. The study discovered that, at an estimated yearly rate of more than 108 spores per m², ocean currents and sedimentation play a role in the spread of Firmicutes spores to Arctic fjord deposits off the coast of Svalbard (Hubert et al., 2009). When spores in the rare biosphere and “microbial seed bank” are exposed to high temperatures during sediment incubation studies, they can germinate rapidly. The East Spitsbergen Current, which carries frigid water from the Arctic Ocean, and the West Spitsbergen Current, which flows towards the north from the Atlantic Ocean, are the two primary ocean currents that impact Svalbard's hydrography. Microbes' mobility is mostly dictated by their drift with ocean currents, which causes their surroundings to have wildly fluctuating temperatures (Gibbons et al., 2013). It is difficult to forecast the impacts of a projected 2–4°C increase in mean ocean temperature since there is no credible worldwide assessment of the thermal history of marine microorganisms, making it impossible to understand their thermal niche and performance under steady experimental settings (Raven & Doblin, 2014). In contrast, the average temperature exposure of microorganisms on the northern side of the Antarctic Circumpolar Current is as much as 6°C lower than the local in situ temperature. These variations can be explained by advection in the ocean currents (Doblin & Van Sebille, 2016).

3.4.5 Interactions with other organisms

Protists have a significant impact on nutrient cycling and ecosystem function as regulators of microbial populations and food webs. Intracellular parasites such as viruses and bacterial symbionts affect their activity. On the other hand, little is known about how they interact with viruses and bacteria. Common microbial eukaryotes that may be found in a variety of environments are called protists (Burki et al., 2021). The huge DNA viruses (nucleocytoplasmic large DNA viruses; Nucleocytoviricota) are a common yet mysterious class of viruses that infect protists (Abrahão et al., 2018). The functions and potential benefits of these internal bacteria are not well understood, despite the fact that protists are frequently associated with a range of bacterial endosymbionts (König et al., 2019). The study claims that while viral lysis pressure can lower network modularity, it can also enhance microbial linkages within network modules. Although viruses can help modules become more stable, they can also cause networks to be less stable. Viral lysis favors particular bacterial taxonomic groupings, such as Alphaproteobacteria and Betaproteobacteria, which limits their reaction to nutritional content. Moreover, the processing of resistance genes by viruses lessens the influence of environmental selection on host survival, therefore allowing hosts to endure environmental stresses

(Maurice et al., 2011). The metagenomic study reveals that more unusual mutualistic symbiosis between phages and bacteria correlates with higher levels of Cr-induced ecological stress. Lysogenic integration of lysogenic phages is the primary way phages help the microbiome adjust to difficult conditions. This lysogenic integration enhances the host's defenses against heavy metal toxicity by promoting the expression of resistance genes and the reproduction of related phages (Huang et al., 2021).

3.5 Tools and techniques for studying microbial variability

The tools and techniques employed for studying microbial variability are presented in Fig. 3.1.

3.5.1 Metagenomics and metatranscriptomics

Aquatic microbe research has been transformed by metagenomics, which has yielded hitherto unheard-of insights into their wide variety. The high cost of sequencing and the difficulties in analyzing data previously restricted research. But given metagenomics is a widely accessible technique. As previously mentioned, its main goal is to link biogeochemical phenomena with the

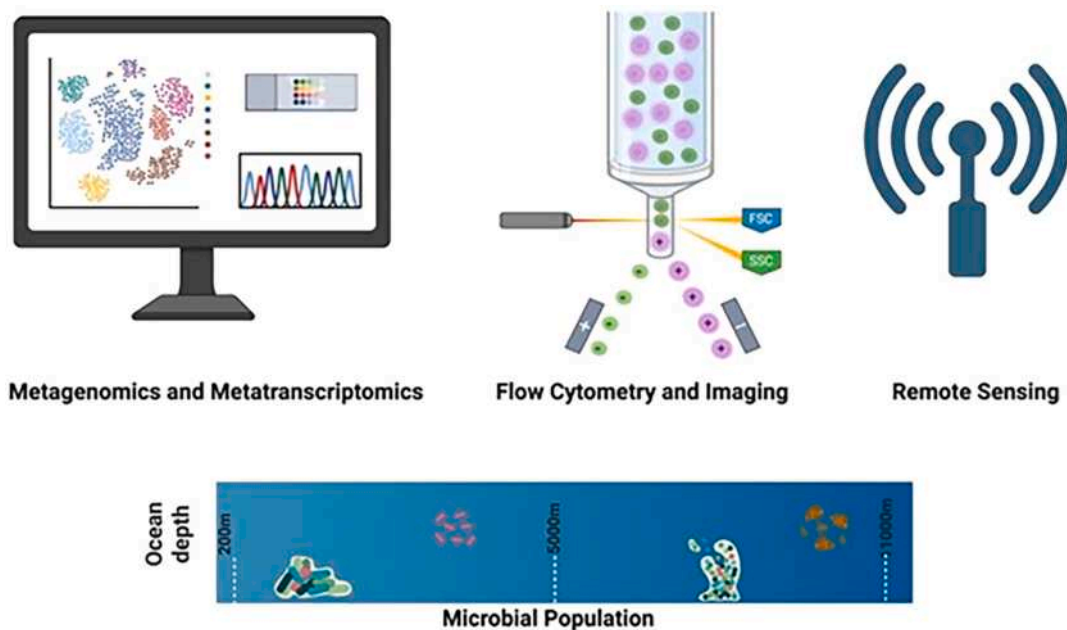


FIGURE 3.1

Tools and techniques used for studying microbial variability.

environmental and evolutionary changes occurring in microbial communities (Oremland et al., 2005). The quality and importance of insights are obviously dependent on the clarity of the problem stated, the formulation of testable hypotheses, the appropriate experimental design, the gathering of data, and the use of advanced statistical techniques. Focussing on the results presented in this special issue (Grossart et al., 2020), The study highlights the latest advancements in the study of microbial contributions to aquatic systems, made possible by metagenomics.

A useful method for researching mixed microbial assemblages is metatranscriptomics, often known as community gene expression profiling. It offers information on the transcript pool, which makes it possible to infer physiology specific to a certain taxon and comprehend the relationships between cell metabolism and ecosystem function. One important tool for marine metatranscriptomic research is the Marine Microbial Eukaryote Transcriptome Sequencing Project (MMETSP). Transcriptomes from more than 678 strains of Protistan are available in the MMETSP database. Older platforms like Illumina Miseq and Hiseq are still available, although they are being replaced by more recent ones like Nextseq and Novaseq. The predominant response of the community to its environment and a mixed community cellular state will be shown by the recorded gene expression patterns (Cohen et al., 2022).

3.5.2 Flow cytometry and imaging

Since the 1990s, flow cytometry has been employed to investigate marine microbial populations. Individual particle scatter and fluorescence characteristics are determined at extremely high rates (hundreds to thousands of particles per second) in flow cytometry. Even while the majority of researchers examine the produced “cytograms” by hand, automated techniques are now available for analyzing this type of microbial flow cytometry data. Using flow cytometry, artificial neural networks (ANNs) have been created to recognize up to 72 species of phytoplankton that are cultivated in the lab. Heterotrophic bacteria were later effectively identified using supervised single-cell classifiers, often by combining flow cytometry with a nucleic acid stain (Rubbens & Props, 2021). Tools for analyzing microbial variability have been depicted in Table 3.1.

3.6 Ecological and biogeochemical implications

Half of Earth’s biological carbon fixing occurs in marine habitats. For long-term carbon sequestration, photosynthetically fixed carbon must be transferred to deep ocean waters and sediments. Over geological periods, the biological carbon pump (BCP) modifies the climate by moving particulate organic carbon (POC) from the ocean’s surface to its core. Marine ecosystems and biogeochemical cycles are shaped by microorganisms, and the efficiency of carbon sequestration is regulated by microbial populations. Different techniques for carbon sequestration are made possible by two forms of organic carbon, POC, and DOC. This study investigates the biological and environmental factors controlling their dynamics and their quantitative role in modifying the climate (Dang, 2020).

Coastal areas are greatly affected by climate change, pollution, and human-caused eutrophication, which change ecosystem services like primary production and preservation of global temperatures. Many marine environments’ early environmental change is believed to be indicated by marine

Table 3.1 Tools for Analyzing Microbial Variation.				
Tool/Technique	Type	Measured Variables	Strengths	References
Metagenomics/ Metatranscriptomics	Molecular Biology	Taxonomic composition, gene expression	High-resolution, reveals uncultured diversity	Aplakidou et al. (2024)
Flow Cytometry	Cell-based	Cell size, abundance, pigment content	Rapid profiling, supports live-cell analysis	Vembadi et al. (2019)
Remote Sensing	Satellite Imaging	Chlorophyll, temperature, salinity	Broad spatial coverage, real-time observation	Kavanaugh et al. (2021)
Autonomous Ocean Sensors	In situ Technology	pH, oxygen, nutrients, turbidity	Long-term data from remote/hostile environments	Wang et al. (2019)
Oceanographic Databases	Computational Tool	Archived microbial and ocean parameter data	Integrative modeling and historical comparison	Sunagawa et al. (2015)

microbes. A unique index (microgAMBI) was created from relationships between marine bacterial populations and sediment contaminants to underline the importance of integrative evaluations of marine ecosystems. Disturbances and structural changes have impacted the functioning of certain benthic species, which could have a domino effect on the marine ecosystem. Integrative assessments combining de novo analysis and high-throughput sequencing are absolutely vital if one is to address these issues (Ramljak et al., 2024).

3.7 Conclusion

Comprehending the dynamics of maritime ecosystems and their adaptability to changing environmental conditions depends on knowledge of the geographical and temporal variation of marine microbial populations. Nitrogen fixation, sulfur metabolism, carbon cycling, and greenhouse gas control all depend on these microorganisms. An awareness of their spread across time and place helps one to predict ecological responses to global environmental change and control marine resources. High-throughput molecular techniques such as metagenomics and metatranscriptomics have improved our ability to study microbial communities in situ, enabling thorough characterization of diversity and function. The composition of the microbial population, which is shaped by seasonal cycles, sporadic events, and climate trends, offers early signs of ocean health and ecological disruptions. Microbial diversity, which makes them efficient early-warning signals, may influence fish population dynamics, zooplankton feeding patterns, and phytoplankton nutrient availability. Disruption of microbial-mediated carbon sequestration routes reduces the ocean's capacity to absorb atmospheric CO₂, therefore aggravating climate change feedback loops. Including microbiological information into fisheries management, marine spatial planning, and climate models will help to increase predictive accuracy and resilience strategies. For the purpose of guiding adaptive management strategies and guaranteeing early identification of ecosystem stress, conservation frameworks should also incorporate spatial and temporal microbiological data.

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Marine microbial biopolymers

Amarachukwu Bernaldine Isiaka^{1,2}, Ugonna Henry Uzoka^{3,4}, Uchechukwu Caroline Ilojinso⁵ and Vivian Nonyelum Anakwenze⁶

¹*Qatar Airways Medical Division, Qatar Airways, Doha, Qatar,*

²*School of Public Health, University of Port Harcourt, Rivers State, Nigeria,*

³*Laboratory of Bacterial Disease (LDBAC), Department of Veterinary, Federal University of Viçosa, Minas Gerais, Brazil,*

⁴*Department of Veterinary Medicine, Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria,*

⁵*Department of Nursing, University of Derby, Derbyshire, United Kingdom,*

⁶*Department of Applied Microbiology and Brewing, Nnamdi Azikiwe University, Awka, Anambra, Nigeria*

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4.1 Introduction

The marine ecosystem is one of the most biologically diverse environments on Earth, hosting an immense variety of microorganisms, including bacteria, archaea, fungi, microalgae, and actinomycetes. These organisms have evolved over millions of years, developing unique metabolic pathways to survive in diverse and often extreme conditions such as high pressure, varying temperatures, high salinity, and low nutrient availability (Isiaka et al., 2025; Aransiola, Oyewole, et al., 2024; Nambiar et al., 2024; Selvaraj & Singh, 2021). One of the most promising outcomes of these evolutionary adaptations is the microbial synthesis of biopolymers, macromolecular substances composed of

repeating monomeric units that exhibit eco-friendly, biodegradable, and biocompatible properties (Nambiar et al., 2024; Pandey & Kannaujiya, 2024). Marine microbial biopolymers encompass a wide range of structurally and functionally diverse compounds such as polyhydroxyalkanoates (PHAs), exopolysaccharides (EPS), polymeric proteins, glycoproteins, polyglutamic acid (PGA), chitin, chitosan, and others. These biopolymers are produced either as intracellular storage materials, extracellular matrix components, or protective layers that facilitate survival and adaptation under environmental stress (Kakkalameli et al., 2022; Moradali & Rehm, 2020a, 2020b). The interest in these natural polymers has grown exponentially over the past two decades due to increasing environmental concerns associated with synthetic plastics and the growing demand for sustainable and renewable alternatives (Matei et al., 2022; Ponnusamy & Mani, 2022).

One of the key advantages of marine microbial biopolymers over their synthetic counterparts is biodegradability. Unlike petroleum-based polymers that persist in the environment for centuries, biopolymers can be readily decomposed by microbial enzymatic systems under natural conditions, reducing their ecological footprint (Nambiar et al., 2024). Their biocompatibility and nontoxicity make them suitable for a wide array of applications in biomedicine, pharmaceuticals, tissue engineering, cosmetics, agriculture, packaging, wastewater treatment, and food industries (Isiaka et al., 2025; Ponnusamy and Mani, 2022). The biopolymer production potential of marine microorganisms is influenced by their ecological niche and physiological state. Gallo and Aulitto (2024) reported that extremophiles isolated from hydrothermal vents or hypersaline environments often produce exopolysaccharides with high thermal stability and metal-binding capacity, making them ideal for industrial use under harsh processing conditions. Marine-derived *Bacillus*, *Pseudomonas*, *Halomonas*, *Vibrio*, and *Alteromonas* species have been extensively studied for their ability to produce diverse polymers such as PHAs, EPS, and PGA (Nambiar et al., 2024; Selvaraj & Singh, 2021).

In terms of biosynthetic mechanisms, marine microbial biopolymers are synthesized through enzyme-catalyzed reactions that involve various metabolic intermediates and precursors. PHAs, for example, are synthesized via the fatty acid and acetyl-CoA pathway, while polysaccharides such as EPS are assembled through glycosyltransferase-mediated reactions (Yañez et al., 2020). With advancements in genomics, proteomics, and metabolomics, it has become possible to identify gene clusters responsible for polymer biosynthesis and to engineer microorganisms for enhanced yield, novel functionalities, and reduced production costs (Xu et al., 2023). Despite the promising features of marine microbial biopolymers, commercial-scale production still faces several challenges. These include low yield, high production cost, complex downstream processing, and the lack of optimized bioreactor systems for marine strains. However, innovations in fermentation technology, metabolic engineering, synthetic biology, and process integration are gradually overcoming these limitations, paving the way for large-scale exploitation of marine microbes as bio-factories (Ponnusamy & Mani, 2022; Xu et al., 2023).

The marine microbial world represents a vast, largely untapped resource for sustainable biopolymer production. Continued exploration, coupled with technological advancements, is expected to accelerate the development of marine biopolymers as viable alternatives to synthetic polymers, with far-reaching implications for environmental sustainability and industrial innovation (Aransiola, Bamisaye, et al., 2024). This chapter provides an in-depth analysis of the types, biosynthesis, extraction, and potential applications of marine microbial biopolymers, offering a comprehensive understanding of their role in the modern bioeconomy.

4.2 Sources and types of marine microbial biopolymers

4.2.1 Sources of marine microbial biopolymers

The marine environment covers over 70% of the Earth's surface and harbors a vast array of microbial life, ranging from bacteria, archaea, fungi, actinomycetes, to microalgae and cyanobacteria as shown in Fig. 4.1 (Pandey & Pande, 2023). These organisms thrive in unique ecological niches including extreme habitats such as hydrothermal vents, hypersaline lakes, deep-sea trenches, and polar regions. The stress conditions in these environments have driven evolutionary adaptations that enable marine microbes to produce structurally and functionally unique biopolymers with significant biotechnological applications (Gallo & Aulitto, 2024; Samalens et al., 2022). Marine microbial biopolymers such as polyhydroxyalkanoates (PHAs), polysaccharides, polyamides, polyesters, and proteinaceous compounds, are synthesized either as storage materials, structural components, or extracellular matrices. These polymers often display novel physicochemical properties such as high thermal stability, biodegradability, bioactivity, and emulsifying ability, distinguishing them from their terrestrial counterparts (Samalens et al., 2022).

4.2.2 Marine bacteria

Marine bacteria are among the most studied producers of microbial biopolymers. Their abundance, diversity, and capacity to adapt to a wide range of environmental conditions have made them key players in marine biopolymer biosynthesis. Notably, marine bacteria such as *Halomonas*, *Bacillus*, *Vibrio*, *Pseudoalteromonas*, *Alteromonas*, and *Alcanivorax* have been reported to produce various

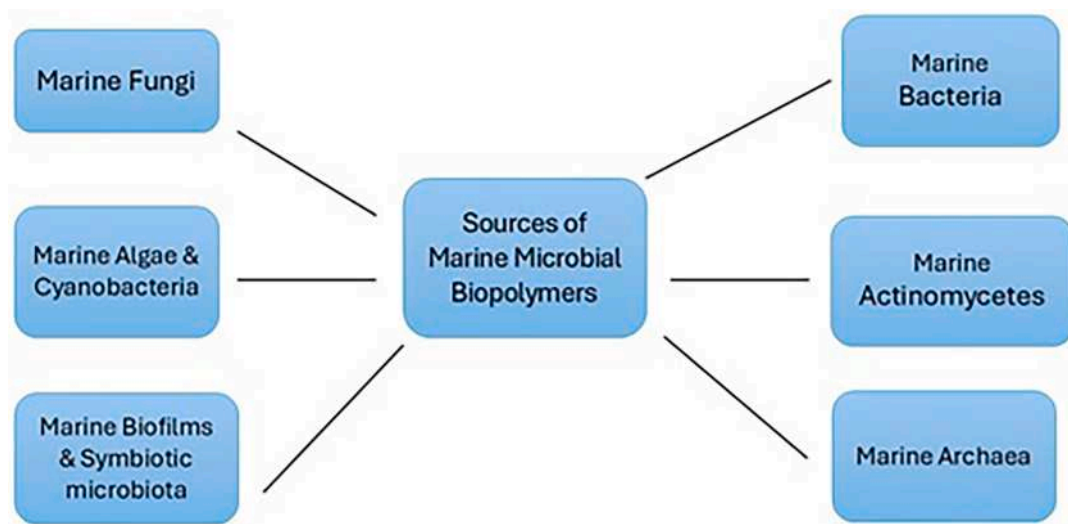


FIGURE 4.1

Sources of marine microbial biopolymers.

biopolymers. Stanley et al. (2021) reported that *Halomonas campisalis* and *Halomonas boliviensis* produce PHAs under high salinity and nutrient-limiting conditions. Their halotolerance allows open and continuous fermentation processes without strict aseptic conditions (Park, 2024). *Pseudoalteromonas antarctica*, isolated from Antarctic seawater, synthesizes cold-adapted EPS that remains viscous and bioactive at subzero temperatures, demonstrating potential applications in cryoprotection and cold-environment biotechnologies (Rizzo et al., 2021; Rizzo et al., 2022). Likewise, *Vibrio diabolicus*, isolated from hydrothermal vent ecosystems, produces an EPS that mimics glycosaminoglycans (GAGs) and is being explored in regenerative medicine due to its osteoinductive potential (Esposito et al., 2022). Moreover, deep-sea and sediment-associated bacteria such as *Shewanella*, *Marinobacter*, and *Idiomarina* also produce novel EPS with antioxidant, antimicrobial, and emulsifying properties (Vandecastelaere, 2008). These bacteria often form biofilms, wherein EPS contribute to surface adhesion, desiccation resistance, and nutrient acquisition.

4.2.3 Marine archaea

Marine archaea, particularly halophilic and thermophilic types, are increasingly recognized for their role in biopolymer production. *Haloferax mediterranei* is a prime example, capable of producing copolymers of PHA such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) using inexpensive carbon sources including agricultural waste (Longo et al., 2024). Unlike bacterial PHA producers, archaeal strains often function efficiently at high salinity (15%–30% NaCl) and temperature (> 45°C), making them ideal for industrial bioprocesses with lower contamination risk. Some archaea also synthesize sulfur-rich proteinaceous polymers and acidic EPS that confer extreme environmental resilience and bioactivity (Wang et al., 2025). However, due to their relatively recent exploration and the complexity of cultivating archaea under lab conditions, they remain underutilized despite their promising metabolic capacities.

4.2.4 Marine fungi

Marine fungi including yeasts, filamentous fungi, and dimorphic species, represent a significant but underexplored group of biopolymer producers. Isolated from substrates such as decaying marine vegetation, sea animals, coral reefs, and sediments, marine fungi exhibit metabolic plasticity and can thrive under saline and oxidative stress, triggering secondary metabolite production. Filamentous fungi like *Aspergillus niger*, *Trichoderma harzianum*, *Penicillium chrysogenum*, and *Fusarium solani* have been used to synthesize chitin, chitosan, and EPS (Debnath et al., 2021; Slavin & Bach, 2022). These polymers often display bioactive properties including antifungal, antioxidant, antiinflammatory, and wound-healing activities. Marine yeast species such as *Candida tropicalis* and *Rhodotorula mucilaginosa* have been reported to produce mannan- and glucan-rich EPS, which are known immunomodulators. Adaptations in these fungi to high pressure and salinity have led to the emergence of novel polymers with altered branching, sulfate content, and viscosity (Slavin & Bach, 2022).

4.2.5 Marine microalgae and cyanobacteria

Marine microalgae (e.g., *Chlorella vulgaris*, *Porphyridium cruentum*, *Dunaliella salina*) and cyanobacteria (e.g., *Arthrospira platensis* or *Spirulina*, *Nostoc commune*) produce large quantities

of extracellular polysaccharides, glycoproteins, and sulfated polysaccharides. These polymers are integral to cell wall structure and are often released as a protective response to environmental stresses such as UV radiation, desiccation, and nutrient depletion (Chandran et al., 2024). *Porphyridium* produces sulfated galactans with potent antiviral and anticoagulant properties, while *Arthrospira* secretes heteropolysaccharides that enhance immune response and act as prebiotics (Abd El Monsef et al., 2023). These polymers have applications in nutraceuticals, cosmetics, and pharmaceuticals, as well as in wastewater treatment due to their metal-binding properties. Microalgae-derived EPS are often enriched in uronic acids and sulfated sugars, which confer high water retention, gel-forming ability, and reactivity, making them attractive for drug delivery systems and tissue engineering scaffolds.

4.2.6 Marine actinomycetes

Marine actinomycetes, especially species from genera such as *Streptomyces*, *Micromonospora*, *Salinispora*, and *Nocardiosis*, are prolific producers of extracellular biopolymers with antimicrobial, anticancer, and immunomodulatory properties (Ruwandeeepika et al., 2022). These filamentous bacteria are commonly isolated from marine sediments, sponges, and mangrove roots. They produce unique EPS and glycoproteins with biofilm-inhibiting and surface-coating capabilities. Some actinomycetes also synthesize chitin-degrading enzymes and polymeric particles used in the formation of bioactive films and nanocomposites (Singh et al., 2021). Given their ability to tolerate high pressure, salt, and oxidative stress, marine actinomycetes are considered promising candidates for industrial-scale biosynthesis of value-added biopolymers.

4.2.7 Marine biofilms and symbiotic microbiota

Biofilms formed by marine microbial consortia on submerged surfaces or living hosts also represent significant sources of biopolymers (Maddela & Aransiola, 2022). These biofilms often consist of diverse bacteria, archaea, fungi, and microalgae embedded within a self-produced EPS matrix (Abioye et al., 2022). The EPS provides structural integrity, desiccation resistance, and defense against shear stress and antimicrobials (Balducci et al., 2023; Mouro et al., 2024). Symbiotic microbial communities in marine sponges, corals, mollusks, and echinoderms are also biopolymer producers. For instance, sponge-associated bacteria have been shown to produce sulfated polysaccharides, collagen-like proteins, and unusual peptide-polymers that contribute to host protection and skeletal formation (O'Brien et al., 2024).

4.2.8 Types of marine microbial biopolymers

Marine microbial biopolymers represent a diverse array of naturally synthesized macromolecules that serve structural, protective, and metabolic functions. These biopolymers are categorized based on their chemical structure and function into polysaccharides, polyhydroxyalkanoates (PHAs), proteinaceous polymers, polyamides, polyesters, glycolipids, and lipopeptides. Their adaptability to extreme marine conditions like high salinity, pressure, and low temperatures, endows them with

unique physicochemical and bioactive properties that are often superior to those of their terrestrial counterparts (Samalens et al., 2022).

4.2.9 Exopolysaccharides

Exopolysaccharides are among the most studied marine microbial biopolymers. They are high-molecular-weight, extracellularly secreted heteropolymers primarily composed of monosaccharide residues such as glucose, galactose, mannose, rhamnose, fucose, and uronic acids. Their physicochemical properties are modulated by noncarbohydrate substituents like acetyl, sulfate, or pyruvate groups (Moradali & Rehm, 2020a, 2020b; Tiwari et al., 2024). Marine bacteria such as *Alteromonas*, *Pseudoalteromonas*, *Vibrio*, and *Halomonas* spp. produce EPS with viscosifying, emulsifying, metal-chelating, and cryoprotective activities. Sulfated EPS from marine cyanobacteria like *Arthrospira platensis* and *Nostoc commune* exhibit potent immunomodulatory, antiviral (e.g., anti-HIV and anti-HSV), and anticancer properties (da Silva & Teixeira, 2024). EPS also play ecological roles, aiding in biofilm formation, surface attachment, protection against desiccation, and defense against host immune systems, especially in pathogenic marine strains (Das, 2022; Pugazhendhi et al., 2022). Their unique rheological properties also support their use in pharmaceuticals, wastewater treatment, and cosmetics (Jha et al., 2022).

4.2.10 Polyhydroxyalkanoates

PHAs are intracellular polyesters produced by various marine microorganisms under nutrient-limited conditions with excess carbon. These biopolymers act as carbon and energy storage compounds and include short-chain-length PHAs (e.g., PHB) and medium-chain-length PHAs (e.g., P(3HB-co-3HV)) (Longo et al., 2024). Marine genera such as *Halomonas*, *Alcanivorax*, *Thalassospira*, and *Vibrio* have been identified as efficient PHA producers. Stanley et al., (2021) reported that *Halomonas boliviensis* can accumulate up to 80% of its dry cell weight as PHB when cultured in saline media, reducing freshwater requirements and contamination risks. *Alcanivorax borkumensis*, a hydrocarbon-degrading marine bacterium, not only produces PHAs but also contributes to bioremediation in oil-polluted marine environments (Stanley et al., 2021). PHAs are biodegradable, thermoplastic, and biocompatible, making them suitable for use in bioplastics, surgical sutures, controlled drug delivery, and tissue engineering. Their degradation products (e.g., 3-hydroxybutyrate) are nontoxic and metabolizable in mammalian systems (Mierziak et al., 2021).

4.2.11 Polyamides and polyesters

Marine microbial polyamides and polyesters are lesser-known but increasingly significant classes of biopolymers. Polyamides are formed through the polymerization of amino acids, often via nonribosomal peptide synthetases (NRPSs), while polyesters may derive from hydroxy acid polymerization or biosynthetic modification of fatty acids (Rebuffat, 2022). Some sponge- and sediment-associated bacteria such as *Streptomyces* and *Salinispora* species produce peptide-based polyamides exhibiting antimicrobial and cytotoxic activities. These NRPS-derived polymers often feature unusual amino acids and heterocyclic rings, increasing their bioactivity (Zhang et al., 2025).

Polyester-producing marine microbes such as *Pseudomonas* spp. have been shown to generate medium-chain-length polyesters with elastomeric properties useful for packaging and biomedical devices. Their enzymatic synthesis routes can be tuned for specific monomer incorporation, yielding customizable material characteristics (Rebuffat, 2022).

4.2.12 Proteinaceous biopolymers

Marine microbes, particularly extremophilic archaea and bacteria, secrete structural proteins and proteinaceous polymers that are remarkably stable under harsh marine conditions. These include surface-layer (S-layer) proteins, collagen-like proteins, and hydrophobins. S-layer proteins from marine archaea such as *Halobacterium salinarum* form crystalline lattices on the cell surface and are highly resistant to enzymatic degradation, pH fluctuations, and ionic stress, offering potential in biosensing and nanofiltration (Atmakuri et al., 2024; Kalavalapalli et al., 2024). Marine-derived collagen-like proteins from bacteria associated with marine sponges and corals mimic mammalian extracellular matrix and promote cellular adhesion and tissue regeneration. Hydrophobin-like proteins from marine fungi such as *Aspergillus sydowii* exhibit amphipathic behavior, forming stable monolayers and enabling applications in drug encapsulation and surface functionalization (Kalavalapalli et al., 2024).

4.2.13 Glycolipids and lipopeptides

Marine microbial glycolipids and lipopeptides function primarily as biosurfactants and bioemulsifiers, reducing surface tension and enabling emulsification in marine and industrial settings. They also possess antimicrobial, antiadhesive, and antibiofilm properties. Marine *Bacillus* spp. produce lipopeptides such as surfactin, fengycin, and iturin with potent antifungal and antibacterial activities. *Pseudoalteromonas* spp. synthesize glycolipids with emulsifying and corrosion-inhibiting effects useful in bioremediation and marine coatings (Deryusheva et al., 2021; Sun et al., 2020). Due to their low toxicity and high biodegradability, these biopolymers are increasingly considered for environmental clean-up, agriculture (as biopesticides), personal care products, and even in oil recovery technologies.

4.3 Biosynthesis of marine biopolymers

Marine microbial biopolymers are structurally diverse and functionally versatile biomolecules synthesized by marine microorganisms, often as a survival strategy in response to environmental stressors. These biopolymers include polysaccharides, polyesters (e.g., PHAs), proteins, and glycoproteins (Table 4.1) and are distinguished by their biodegradability, biocompatibility, and environmental sustainability. The biosynthesis pathways of these compounds are tightly regulated through metabolic and genetic mechanisms that vary across microbial taxa and environmental conditions (Chevrette et al., 2020). The synthesis of marine microbial biopolymers is generally governed by enzymatic reactions involving substrate activation, polymerization, and exportation. Depending on the microbial species and the type of polymer, synthesis may occur intracellularly (e.g.,

Table 4.1 Biosynthetic pathways, key enzymes, precursors, and applications of marine microbial biopolymers.

Biopolymer	Key pathway	Key enzymes/processes	Main monomer/precursors	Applications
Polysaccharides (e.g., cellulose, glucans)	Glycolytic Pathway and Polysaccharide Biosynthesis	UDP-glucose pathway ADP-glucose pathway Wzx/Wzy-dependent pathway for extracellular polysaccharides	Glucose-6-phosphate, fructose-6-phosphate, UDP-glucose, ADP-glucose	Biofilms, food industry, medical (e.g., wound dressings) industrial
Polyhydroxyalkanoates (PHA)	Acetyl-CoA Pathway and PHA Synthase Pathway	Acetyl-CoA production via glycolysis PHA synthase (e.g., PhaC) for polymerization of 3-hydroxybutyryl-CoA intermediates	Acetyl-CoA, 3-hydroxybutyryl-CoA	Biodegradable plastics, medical applications
Polylactic Acid (PLA)	Lactic Acid Fermentation and Polymerization	Lactate dehydrogenase for lactic acid production Lactic acid polymerization by lactate polymerase	Glucose, pyruvate, lactic acid	Biodegradable plastics, medical applications
Chitosan and Chitin	Glucosamine Pathway and Chitin Synthase	Chitin synthase for chitin polymerization Chitin deacetylase for chitosan synthesis	N-acetylglucosamine (GlcNAc)	Biodegradable materials, agricultural applications
Polyglutamic Acid (PGA)	Glutamate Pathway and Polyglutamic Acid Synthase	Polyglutamic acid synthase (e.g., PgsBCA)	Glutamate	Food industry, medical applications, biotechnology
Exopolysaccharides (EPS)	Core Glycosylation and Export Pathways	Glycosyltransferases for polysaccharide synthesis Export systems (e.g., Wzx/Wzy, ABC transporters)	UDP-glucose, activated sugar precursors	Biofilms, medical (e.g., wound healing), industrial
Proteins (e.g., collagen, silk-like proteins)	Transcription and Translation	Ribosomal translation Post-translational modifications (e.g., hydroxylation, glycosylation)	Amino acids (glycine, alanine, serine)	Biodegradable materials, drug delivery, tissue engineering

PHA granules) or extracellularly (e.g., exopolysaccharides and biofilm matrix). Marine microorganisms utilize various carbon sources such as glucose, sucrose, glycerol, or even hydrocarbons, depending on their metabolic pathways and enzymatic inventory (Kashif et al., 2022). These processes are significantly influenced by environmental factors like temperature, salinity, pressure, pH, and nutrient availability. Marine extremophiles such as halophiles and psychrophiles, which thrive in saline and cold environments, respectively, often produce biopolymers with unique chemical properties that increase stability and functionality under harsh conditions (Mallik et al., 2024).

4.3.1 Polyhydroxyalkanoates biosynthesis

Polyhydroxyalkanoates (PHAs) are a diverse group of intracellular polyesters synthesized by various microorganisms as carbon and energy storage compounds. These biopolymers are synthesized primarily under nutrient-limiting conditions (e.g., nitrogen, phosphorus, or oxygen) in the presence of excess carbon sources (Saharan et al., 2024). Marine bacteria capable of producing PHAs offer immense promise due to their ability to survive in harsh environments and utilize diverse substrates, including marine organic matter and waste products. Owing to their biodegradability, biocompatibility, and thermoplastic properties, PHAs have gained significant interest as alternatives to petroleum-derived plastics (Kashif et al., 2022). PHAs are broadly classified into short-chain-length (scl-PHAs) which are composed of monomers with 3–5 carbon atoms (e.g., poly(3-hydroxybutyrate) [PHB]) and medium-chain-length (mcl-PHAs) which are composed of monomers with 6–14 carbon atoms, imparting elastomeric properties (Azizi et al., 2024). Structurally, PHAs consist of repeating units of R-hydroxyalkanoic acids, linked via ester bonds. The side chains (R groups) determine the physicochemical properties of the polymer, including crystallinity, melting point, and mechanical strength (Zhang et al., 2021).

Marine environments harbor a wide array of halophilic, psychrophilic, and moderately thermophilic bacteria capable of PHA synthesis. These include species from the genera *Halomonas*, *Marinobacter*, *Vibrio*, *Pseudoalteromonas*, and *Alcanivorax*. Halophilic bacteria such as *Halomonas boliviensis* and *Halomonas bluephagenesis* are particularly advantageous as they can be cultivated under unsterilized and high-salinity conditions, significantly reducing industrial production costs (Stanley et al., 2021). PHAs, particularly polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV), are intracellular polyesters synthesized by numerous marine bacteria, including *Halomonas*, *Pseudomonas*, *Marinobacter*, and *Vibrio* species. These biopolymers are typically produced under nutrient-limited (nitrogen, phosphorus, or oxygen) conditions when carbon is available in excess. Recent studies in *Halomonas bluephagenesis* show its ability to accumulate PHAs in saline media without sterilization, offering cost-effective industrial-scale production (Park, 2024). Moreover, metabolic engineering has been applied to introduce novel monomers (e.g., 4-hydroxybutyrate, medium-chain-length PHAs) to tailor polymer properties.

4.3.2 Biochemical pathways of polyhydroxyalkanoate biosynthesis

The biosynthesis of PHAs involves a well-characterized three-step enzymatic pathway, typically encoded by the *phaABC* operon:

- **Condensation of acetyl-CoA to acetoacetyl-CoA:** Catalyzed by β -ketothiolase (PhaA), this step condenses two molecules of acetyl-CoA into acetoacetyl-CoA. The activity of PhaA is sensitive to CoA/acetyl-CoA ratios and tightly regulated based on cellular metabolic status.
- **Reduction of acetoacetyl-CoA to 3-hydroxybutyryl-CoA:** The acetoacetyl-CoA reductase (PhaB) reduces acetoacetyl-CoA to (R)-3-hydroxybutyryl-CoA using NADPH as a reducing agent. The stereochemistry is crucial, as only the (R)-enantiomer serves as a substrate for PHA polymerization.
- **Polymerization of 3-hydroxybutyryl-CoA into PHAs:** The key enzyme PHA synthase (PhaC) catalyzes the polymerization of (R)-3-hydroxybutyryl-CoA into high molecular weight PHA granules within the cytoplasm. These granules are typically coated with granule-associated proteins such as phasins, which regulate their size and number (Yañez et al., 2020).

The synthesis pathway can be modified for different monomers, such as 3-hydroxyvalerate (3HV) or 3-hydroxyhexanoate (3HHx), depending on the carbon source and enzymatic specificity.

Wang et al. (2025) reported that environmental factors like salinity, temperature, nutrient limitation, pH and oxygen availability, profoundly influence PHA biosynthesis in marine microbes. High salinity favors halophilic producers like *Halomonas* spp., which accumulate PHAs efficiently in 5%–15% NaCl. While psychrophilic strains produce PHAs at low temperatures, allowing energy savings in bioprocesses, oxygen limitation can redirect metabolism toward PHA accumulation. Nitrogen, phosphorus, or magnesium depletion in the presence of carbon surplus stimulates PHA accumulation as a stress response (Romero-Frasca & Buitrón, 2024). Such adaptive mechanisms allow marine microbes to function as robust biopolymer producers under variable environmental conditions. Recent advances in synthetic biology and metabolic engineering have significantly enhanced PHA production in marine strains. Factors like overexpression of phaC and suppression of competing pathways improve carbon flux toward PHAs, while the introduction of genes for mcl-PHA synthesis allows the incorporation of novel monomers, broadening polymer functionality. Engineering of *Halomonas bluephagenesis* for open, nonsterile fermentation has led to low-cost, high-yield production systems (Park, 2024). Tools such as CRISPR/Cas9 and modular expression systems are now being applied to marine microbes to optimize yield, tailor polymer composition, and enable utilization of nonconventional feedstocks. PHAs from marine microorganisms have applications in biodegradable packaging materials, medical devices and drug delivery systems, 3D printing materials, agricultural films and mulch. Marine PHAs often possess unique material properties, such as salt resistance, flexibility, and hydrophobicity, enhancing their performance in specialized applications (Mitra et al., 2024).

4.3.3 Exopolysaccharides biosynthesis

Exopolysaccharides (EPSs) are high-molecular-weight polysaccharides secreted by a wide range of marine microorganisms, including bacteria, archaea, and some microalgae. These macromolecules serve multiple ecological and physiological functions such as biofilm formation, protection against desiccation and extreme environments, cell-cell communication, and nutrient acquisition. They are essential in marine microbial biofilm formation, surface colonization, metal chelation, desiccation resistance, and cryoprotection (Tiwari et al., 2024). EPS-producing marine microorganisms include species from the genera *Alteromonas*, *Pseudoalteromonas*, *Vibrio*, and *Salipiger*. Moreover, marine

microbial EPSs have gained increasing attention due to their novel structural diversity, unique physicochemical properties, and significant biotechnological potential.

4.3.4 Genetic and enzymatic pathways

The biosynthesis of marine microbial EPS involves a well-orchestrated sequence of enzymatic reactions, generally encoded by gene clusters responsible for sugar nucleotide synthesis, glycosyltransferase activity, polymerization, and secretion. Initially, simple sugar precursors such as glucose, fructose, or mannose are converted into activated sugar nucleotides like UDP-glucose, GDP-mannose, and dTDP-rhamnose. These precursors are the building blocks for polymer formation. Subsequently, glycosyltransferases catalyze the sequential addition of sugar units to a growing oligosaccharide chain. This step is crucial for determining the monosaccharide composition and linkage types that define the EPS's final structure (Moradali & Rehm, 2020a, 2020b). In many marine bacteria such as *Alteromonas macleodii* and *Pseudoalteromonas* spp., unique glycosyltransferase families have been identified, highlighting the structural diversity of marine EPSs (Tiwari et al., 2024). Polymerization of the sugar chains typically occurs via the Wzy-dependent pathway, ABC transporter-dependent pathway, or synthase-dependent pathway, depending on the microbial species. The Wzy-dependent pathway, common among Gram-negative marine bacteria, involves the flipping of lipid-linked oligosaccharide repeat units across the inner membrane followed by polymerization through Wzy polymerase activity (Knirel & Kenyon, 2021). The completed EPS is then secreted into the extracellular matrix through a complex secretion system involving proteins such as Wza, Wzc, and Wzb.

The regulation of EPS biosynthesis is tightly linked to environmental conditions and cellular physiological states. Factors such as nutrient availability, salinity, temperature, and the presence of metal ions can influence EPS yield and composition. Marine microbes often regulate EPS production as a survival strategy under stress conditions. For instance, *Halomonas* species increase EPS production under high salinity, which helps in osmoprotection and metal sequestration (Jha et al., 2022). On the molecular level, EPS gene expression is controlled by global regulators, quorum sensing systems, and two-component signal transduction pathways. In *Vibrio* spp., the quorum sensing regulator LuxR has been implicated in modulating EPS gene expression, linking community behavior with EPS-mediated biofilm formation (Chen et al., 2024). Moreover, cyclic di-GMP, a secondary messenger molecule, plays a critical role in EPS biosynthesis regulation by influencing the activity of glycosyltransferases and synthases.

The structural complexity of marine EPSs reflects the diversity of marine microbial life and their adaptation to extreme environments. These polymers may contain rare sugars like fucose, rhamnose, uronic acids, and sulfate groups, which confer unique rheological and biological properties. For example, the EPS produced by *Pseudoalteromonas antarctica* contains sulfate and carboxyl groups, making it effective as a cryoprotectant in cold marine environments (Sharma & Bhende, 2024). This structural variability is largely attributed to differences in gene clusters encoding for biosynthetic enzymes, as well as post-polymerization modifications such as sulfation, acetylation, and pyruvylation. These modifications can influence solubility, viscosity, and bioactivity of the EPS, making them valuable for applications in emulsification, heavy metal adsorption, and biomedical scaffolding.

Marine microbial EPSs have shown promise in various sectors including food, pharmaceuticals, wastewater treatment, and bioremediation. Their biodegradability, nontoxicity, and compatibility with living tissues make them ideal for drug delivery systems, wound healing dressings, and tissue engineering matrices (Das et al., 2023). In environmental applications, their ability to chelate heavy metals and form biofilms makes them useful in biofouling prevention and pollutant removal. Ongoing advances in synthetic biology and metabolic engineering are enabling the heterologous expression of marine EPS biosynthetic gene clusters in model organisms such as *Escherichia coli*, facilitating scalable and controllable production systems (Xu et al., 2022).

4.3.5 Polymeric proteins and glycoproteins

Polymeric proteins and glycoproteins are long-chain macromolecules composed of amino acids or amino acids conjugated with carbohydrate moieties. In marine microbes, these compounds serve various ecological roles, including biofilm formation, nutrient acquisition, cell adhesion, and protection against desiccation, osmotic stress, or enzymatic degradation (Kalavalapalli et al., 2024). Many marine bacteria, archaea, and some microalgae produce extracellular polymeric substances (EPSs) that include proteinaceous and glycoprotein components critical to the structural integrity and function of biofilms. One of the best-studied examples is the S-layer glycoproteins in halophilic archaea, which form crystalline surface arrays and are crucial for maintaining cell shape and osmotic balance (Atmakuri et al., 2024). Similarly, certain marine bacteria produce adhesive proteins and glycoproteins, such as *Pseudoalteromonas tunicata*, which secrete antifouling proteins to compete for surfaces in marine habitats (Kalavalapalli et al., 2024).

Marine microbial polymeric proteins and glycoproteins display remarkable diversity in their amino acid and sugar compositions. Structural features such as tandem repeats, crosslinking domains, and amphiphilic regions are common and often relate to their specific ecological functions. For instance, marine glycoproteins can function as biosurfactants, lowering surface tension and facilitating emulsification, as observed in glycoprotein emulsifiers from *Halomonas* and *Pseudoalteromonas* spp. (Deryusheva et al., 2021). Others exhibit antimicrobial, antiviral, or antitumor activities, attributed to their glycan moieties or charged amino acid residues. In deep-sea hydrothermal vent microbes, glycoproteins often feature sulfur-rich domains that bind to heavy metals or confer thermal stability, making them valuable in bioremediation or enzyme stabilization applications (Atmakuri et al., 2024).

4.3.6 Biosynthetic pathways

The biosynthesis of polymeric proteins and glycoproteins involves complex processes of transcription, translation, post-translational modification, and secretion. For polymeric proteins, gene clusters encoding structural proteins, regulatory elements, and secretion machinery are commonly found in marine microbial genomes. These proteins often undergo extensive folding and may include repetitive domains that facilitate polymerization and adherence to surfaces. Glycoprotein biosynthesis includes an additional layer of complexity due to glycosylation, the enzymatic process by which carbohydrate chains are covalently attached to proteins. This process can occur through either N-linked or O-linked glycosylation pathways, mediated by glycosyltransferases and oligosaccharyltransferases. In marine

microbes such as *Halobacterium salinarum* and *Marinomonas mediterranea*, both types of glycosylation have been reported, resulting in glycoproteins with enhanced stability and resistance to extreme environmental conditions (Sun et al., 2020). The glycosylation machinery in marine bacteria is highly versatile, often resulting in glycoproteins with uncommon sugar residues such as uronic acids, sulfated sugars, or methylated hexoses, features that may enhance bioactivity and binding specificity (Szymanski, 2022).

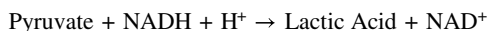
Marine glycoproteins show promise as bioadhesives, immunomodulators, and scaffolds for tissue engineering due to their biocompatibility and structural versatility (Krishnamurthi et al., 2024). Their resistance to proteolytic degradation and harsh conditions enhances their therapeutic utility, and their strong binding affinity to metals and organics allows their use in biosorption and bioremediation of polluted marine environments. Some glycoproteins possess emulsifying and stabilizing properties, applicable in food formulations and cosmetic products, especially those requiring functionality under extreme conditions like high salinity or variable pH. Emerging advances in protein engineering and synthetic biology are paving the way for the heterologous expression of these marine microbial genes in suitable hosts like *E. coli*, *Pichia pastoris*, or even plant systems, thereby enabling scalable and sustainable production (Szymanski, 2022).

4.3.7 Polylactic acid synthesis

Polylactic acid (PLA) is a biodegradable and bioactive thermoplastic polyester synthesized from lactic acid (LA), a monomer that can be microbially derived through fermentation processes. It is synthesized through the polymerization of lactic acid, which exists in two optically active isomers: L-(+)-lactic acid and D-(-)-lactic acid. Depending on the ratio of these isomers, it can exhibit different crystallinity and mechanical properties, making it a versatile material for varied applications (Balasubramanian et al., 2024). PLA is known for its biodegradability, biocompatibility, and thermal plasticity, and it is compostable under industrial conditions. PLA has garnered significant attention in recent years due to its promising role as a sustainable alternative to petroleum-based plastics, with applications ranging from biomedical devices to packaging materials. Although PLA is primarily produced industrially using terrestrial microbial strains, the exploration of marine microbial sources for lactic acid production is gaining momentum due to their robustness and unique metabolic capabilities in saline and extreme environments. The biopolymer is widely used in medical applications (e.g., sutures, stents, and drug delivery devices), food packaging, and textiles due to its mechanical strength and environmental friendliness (Biswas et al., 2022).

4.3.8 Microbial synthesis of lactic acid

Lactic acid production is typically achieved via microbial fermentation of carbohydrates by lactic acid bacteria (LAB), such as *Lactobacillus* species. However, marine microbes have been identified as novel producers of lactic acid, particularly under saline or nutrient-limited conditions. For instance, marine-derived strains like *Lactobacillus plantarum* isolated from seafood and *Halomonas* spp. from saline environments show efficient lactic acid production and tolerance to osmotic stress (Čanak et al., 2024). The general pathway for lactic acid production is glycolysis, where glucose is converted to pyruvate and subsequently to lactic acid by lactate dehydrogenase (LDH). The key reaction is:



Depending on the metabolic pathway utilized (homofermentative or heterofermentative), the end products may vary, but homofermentative strains predominantly yield lactic acid, which is preferable for PLA synthesis.

The conversion of lactic acid into PLA involves two main industrially relevant processes:

- **Direct polycondensation:** This process involves the direct condensation of lactic acid monomers with the elimination of water under high temperature and vacuum. However, this method typically yields PLA of low molecular weight due to the difficulty in removing water completely (Södergård et al., 2022).
- **Ring-opening polymerization (ROP):** The most effective method for high molecular weight PLA production involves the ring-opening polymerization of lactide (a cyclic dimer of lactic acid), catalyzed by metal-based catalysts like tin (II) octanoate. This method allows better control over polymer structure, molecular weight, and stereochemistry (Kricheldorf & Weidner, 2022).
- **Enzymatic polymerization:** Owing to the environmental concerns associated with chemical catalysts, enzyme-mediated PLA synthesis using lipases or proteases has been explored. Marine microbial enzymes show promising potential for this purpose due to their stability under extreme conditions, including high salinity and low temperatures (Södergård et al., 2022).

Marine microbes contribute to PLA synthesis in two main ways which are as producers of lactic acid under unique environmental conditions, and as sources of novel enzymes or biocatalysts that could be employed in the green synthesis of PLA. For example, some marine *Bacillus* species have been shown to produce both L- and D-lactic acid, depending on fermentation conditions, while extremophilic archaea offer thermostable enzymes suitable for polymer synthesis under harsh industrial conditions (Balasubramanian et al., 2024). The use of genetically engineered marine bacteria or cyanobacteria is also being investigated for the direct conversion of CO₂ and sunlight into lactic acid, a concept aligning with carbon-neutral goals (Zhuang et al., 2022). This synthetic biology-based approach can revolutionize PLA production by coupling it with marine microbial metabolism and phototrophy.

PLA has become an important component of circular economy strategies due to its ability to degrade into nontoxic by-products like CO₂ and water under composting conditions. As concerns about microplastic pollution in marine ecosystems grow, interest in marine-sourced PLA or biodegradable PLA alternatives that perform well in saline conditions is rising. The integration of marine microbial biotechnology into the PLA production pipeline could address sustainability challenges by reducing the dependence on freshwater and terrestrial biomass (Visco et al., 2022).

4.3.9 Polyglutamic acid synthesis

Polyglutamic acid (PGA) is a water-soluble, biodegradable, and nontoxic biopolymer composed of repeating units of glutamic acid. It exists in two primary forms based on the type of peptide bond linking the glutamate residues: α -PGA and γ -PGA and the γ -carboxy group of one glutamic acid molecule forms an amide bond with the α -amino group of the next. This γ -linkage confers distinct structural and functional attributes compared to α -peptides, including: excellent water solubility, biodegradability under environmental conditions, high viscosity and film-forming ability, and metal

ion binding and flocculation capacity (Elbanna et al., 2024). These properties make γ -PGA particularly valuable in medical fields (e.g., drug delivery, tissue engineering), as well as in food preservation and heavy metal chelation. While terrestrial strains such as *Bacillus subtilis* have been extensively utilized for γ -PGA production, increasing attention is now being directed toward marine microbial strains, which offer unique enzymatic systems, high salt tolerance, and the ability to thrive in nutrient-limited or extreme environments, making them ideal for sustainable industrial biopolymer production.

The most prominent microbial producers of γ -PGA include strains of the genus *Bacillus*, particularly *B. subtilis*, *B. licheniformis*, and *B. amyloliquefaciens*. Marine *Bacillus* strains have recently been isolated from seawater, marine sediments, and marine animals, exhibiting promising PGA-producing capabilities under saline and thermophilic conditions (Elbanna et al., 2024). For example, *B. subtilis* subsp. *natto*, isolated from fermented seafood, has shown enhanced γ -PGA synthesis in hyperosmotic conditions, with productivity influenced by carbon and nitrogen sources, temperature, pH, and ionic strength of the medium (Balogun-Agbaje et al., 2021).

4.3.10 Biosynthetic pathway of γ -PGA

The biosynthesis of γ -PGA in bacteria is a nonribosomal, enzyme-mediated process. It involves the following key components:

- **Glutamic acid precursor supply:** The biosynthesis begins with the intracellular availability of L-glutamic acid, which may be taken up from the environment or synthesized de novo via the tricarboxylic acid (TCA) cycle.
- **γ -PGA synthetase complex (PgsBCA):** This is a multi-enzyme complex composed of PgsB, an ATP-binding and polymerization unit, PgsC, a membrane-associated component, and PgsA, an anchoring protein facilitating transport and some strains also involve PgsE in regulating complex activity (Wu et al., 2025). The synthetase catalyzes the polymerization of glutamate monomers via γ -amide linkages using ATP as an energy source.

PGA production is tightly regulated by several genes, including *degQ*, *comP*, and *comA*, which influence the expression of the *pgs* operon in response to environmental signals and quorum sensing (Hu et al., 2022). PGA is secreted extracellularly, and the degree of polymerization is modulated by depolymerases and export mechanisms. Chain length is crucial as it affects viscosity, solubility, and bioactivity.

Marine-derived γ -PGA has demonstrated improved functional properties in terms of salt resistance and stability, expanding its applications in biomedical, as a drug carrier, wound dressing, and biodegradable sutures, in food industry, as a cryoprotectant and texture enhancer, in agriculture, as a biofertilizer carrier and plant growth promoter, and in environmental, for bioremediation and heavy metal removal due to its ion-chelating capacity (Wu et al., 2025). Marine microbial γ -PGA is especially promising for formulations requiring high salt tolerance, such as in aquaculture, marine cosmetics, and salt-affected agricultural soils.

4.3.11 Protein synthesis in marine microbial biopolymer production

Protein synthesis is the biological process through which cells generate new proteins. Proteins are essential macromolecules produced by all living organisms, including marine microbes. In marine microorganisms, as in all prokaryotes, this process is divided into three primary stages, transcription, the DNA sequence encoding a specific protein is transcribed into messenger RNA (mRNA) by RNA polymerase, translation, the mRNA is translated into a polypeptide chain using ribosomes, with the help of transfer RNA (tRNA) molecules that deliver specific amino acids, and post-translational modifications, proteins may undergo folding, glycosylation, or cleavage to become functionally active. The genetic code for protein synthesis is universal, but marine microbes possess unique adaptations such as codon usage bias and modified ribosomal structures to support life under high pressure, salinity, or temperature (Arella et al., 2021). In the realm of biopolymer research, marine microbial proteins and their derivatives play pivotal roles, not only as structural materials (e.g., structural proteins, glycoproteins) but also as functional agents (e.g., enzymes, transporters, signaling molecules) (Samalens et al., 2022). These proteins contribute directly or indirectly to the synthesis, secretion, and regulation of marine microbial biopolymers such as PHAs, EPSs, polyamino acids, and glycoproteins.

4.3.12 Protein synthesis in marine microbes

Marine environments present challenging conditions such as low temperatures, high salinity, and high hydrostatic pressure, necessitating adaptive mechanisms for protein synthesis. Cold-adapted enzymes (psychrophilic enzymes) exhibit high catalytic efficiency at low temperatures due to increased structural flexibility (Parvizpour et al., 2021). Salt-tolerant proteins have evolved higher acidic amino acid content, allowing them to remain functional in hypersaline environments (Singh et al., 2020). Pressure-resistant ribosomes and chaperones stabilize protein folding and translation under deep-sea pressures. These adaptations not only support survival but also enable marine microbes to efficiently synthesize biopolymer-associated proteins in extreme environments.

Protein synthesis is central to the production of biopolymers. Several proteins act as:

- Biosynthetic enzymes: Such as PHA synthases (PhaC), EPS glycosyltransferases, and PGA synthetases (PgsBCA complex).
- Regulatory proteins: That control gene expression for biopolymer synthesis under environmental cues (e.g., ComA, DegU in *Bacillus* species).
- Transport and secretion proteins: Responsible for exporting polymers such as EPS or γ -PGA across the cell membrane.
- Structural matrix proteins: That may co-polymerize with sugars or lipids to form glycoproteins and lipoproteins.

For example, in PHA production, PhaC (PHA synthase) is a protein that polymerizes hydroxyacyl-CoA monomers into PHA granules within the cytoplasm (Getahun et al., 2024).

4.3.13 Polysaccharide synthesis

Polysaccharides are vital biopolymers produced by a wide range of microorganisms, including marine bacteria, fungi, and algae. These polymers, which are long chains of monosaccharides, play critical roles in microbial physiology, including cell wall integrity, energy storage, and interactions with the environment. The biosynthesis of polysaccharides in marine microbes involves the enzymatic conversion of simple sugars (monosaccharides) into complex carbohydrate polymers ([Nasrollahzadeh et al., 2021](#)). The first step in polysaccharide biosynthesis is the formation of nucleotide-sugar precursors, which are activated forms of sugars (e.g., UDP-glucose, GDP-mannose). These precursors are generated via specific enzymes such as nucleotide-sugar pyrophosphorylases. The activated sugar precursors are then polymerized into oligosaccharides and polysaccharides by glycosyltransferases, enzymes that catalyze the transfer of sugar units to growing polysaccharide chains. In some cases, polysaccharides undergo elongation and branching. Branching is often catalyzed by branching enzymes, which introduce side chains into the main polysaccharide backbone. Once synthesized, polysaccharides are often secreted outside the cell through specialized transport systems. These systems may include ABC (ATP-binding cassette) transporters or type II secretion systems ([Kleczkowski & Igamberdiev, 2020](#)). Post-synthesis modifications, such as methylation, acetylation, or sulfation, may occur to fine-tune the properties of the polysaccharide. These modifications can influence the functional characteristics of the polysaccharide, such as its solubility or interaction with other molecules. Marine microbes synthesize a variety of polysaccharides as shown in [Fig. 4.2](#), which can be broadly classified into structural, energy storage, and extracellular polysaccharides ([Annava et al., 2020](#)).

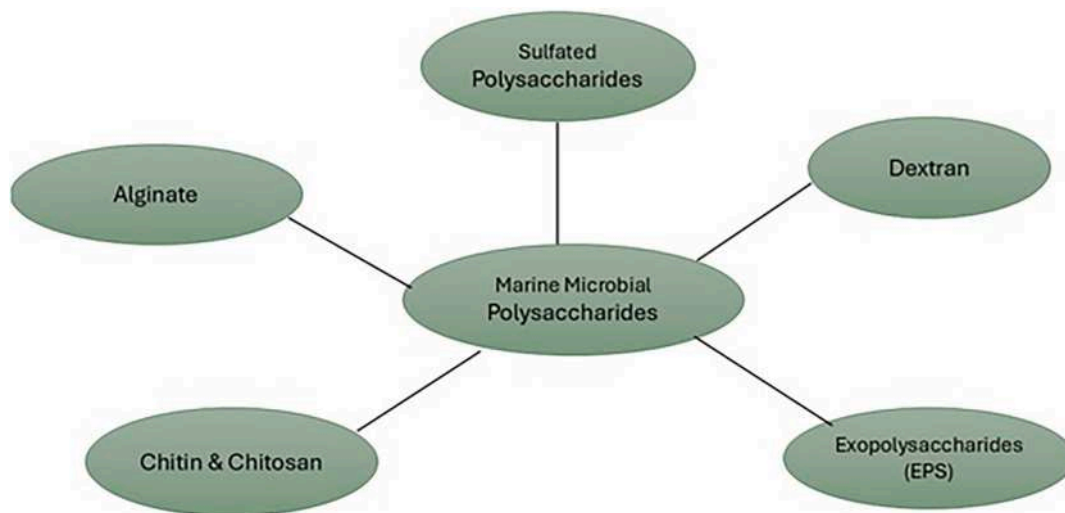


FIGURE 4.2

Marine microbial polysaccharides.

- **Exopolysaccharides (EPS):** Exopolysaccharides are secreted by microorganisms into the surrounding environment, often forming biofilms. These polysaccharides are typically composed of repeating units of sugar residues, sometimes modified with additional functional groups such as phosphate, acetate, or sulfate. EPS can serve as protective barriers, help in biofilm formation, and assist in the retention of water and nutrients. [Rana and Upadhyay \(2020\)](#) reported that *Pseudomonas* species, including marine strains, produce EPSs that are crucial for biofilm formation. These EPSs contribute to the microbe's ability to adhere to surfaces and resist harsh conditions such as desiccation and antimicrobial agents.
- **Alginate:** Alginate is a linear polysaccharide composed of repeating units of β -D-mannuronic acid (M) and α -L-guluronic acid (G). It is predominantly produced by marine bacteria like *Azotobacter vinelandii* and *Pseudomonas aeruginosa*. Alginate serves as a structural polysaccharide in biofilms and is widely used in the food, pharmaceutical, and biotechnology industries due to its gelling properties. In a study by [Das \(2022\)](#), *Pseudomonas* species, alginate production is regulated by the AlgC and AlgD operons, which encode enzymes responsible for the biosynthesis and polymerization of alginate.
- **Dextran:** Dextran is a branched polysaccharide made of α -D-glucose units linked by α -1,6 and α -1,3 glycosidic bonds. Marine microbes, particularly those in the genus *Leuconostoc*, are known to produce dextran, which has applications in the food industry, including as a stabilizing agent and a thickener.
- **Chitin and chitosan:** Chitin is a polymer of N-acetylglucosamine (GlcNAc), while chitosan is its deacetylated form. Both polysaccharides are important structural components of the cell walls of fungi and some marine invertebrates. Marine bacteria, such as *Vibrio* and *Aeromonas*, can synthesize chitin and chitosan, which are biopolymers of interest due to their biodegradable, nontoxic, and antimicrobial properties. Marine *Vibrio* species possess chitin synthase genes that enable them to produce chitin as a structural material ([Das et al., 2023](#)).
- **Sulfated polysaccharides:** Marine algae are well-known producers of sulfated polysaccharides such as carrageenan and agar. These polysaccharides have important functional properties, such as gelation and thickening, and are widely used in the food and pharmaceutical industries. Red algae like *Chondrus crispus* produce carrageenans, which are widely used as food additives and for biomedical applications ([Park et al., 2024](#)).

Several key enzymes are involved in the synthesis of marine microbial polysaccharides:

- **Glycosyltransferases:** These enzymes catalyze the transfer of sugar units to growing polysaccharide chains. They are responsible for polymer elongation and the formation of glycosidic linkages.
- **Polysaccharide synthases:** These enzymes are involved in the polymerization of monosaccharides into long polysaccharide chains. For example, alginate synthase in *Pseudomonas* catalyzes the polymerization of mannuronic and guluronic acids to form alginate.
- **Deacetylases:** These enzymes remove acetyl groups from polysaccharides, converting them into chitosan (from chitin) or other modified polysaccharides with distinct properties.
- **Sulfotransferases:** These enzymes catalyze the addition of sulfate groups to polysaccharides, as seen in the biosynthesis of sulfated polysaccharides like carrageenan.

Polysaccharides such as alginate and EPSs are used in environmental applications for oil spill cleanup and heavy metal removal. Their ability to encapsulate and sequester contaminants makes them valuable in bioremediation strategies (Kumawat et al., 2021). Polysaccharides like chitosan and alginate have antimicrobial, antiinflammatory, and wound-healing properties. They are used in drug delivery systems, wound dressings, and as scaffolds in tissue engineering (Kibungu et al., 2021). Marine polysaccharides such as agar and carrageenan are widely used as gelling agents, thickeners, and stabilizers in the food industry.

4.3.14 Chitosan and chitin biosynthesis

Chitosan and chitin are naturally occurring polysaccharides widely distributed in nature. Chitin is a biopolymer composed of N-acetylglucosamine (GlcNAc) units linked by β -1,4 glycosidic bonds, while chitosan is its deacetylated form. These biopolymers play essential roles in the structural integrity of many marine organisms, including fungi, arthropods, and mollusks, as well as in marine bacteria. Both chitosan and chitin have significant industrial relevance due to their biodegradability, nontoxic nature, and wide array of applications in sectors such as medicine, food, agriculture, and environmental management. In marine microbial systems, chitin and chitosan biosynthesis is regulated by various enzymes, and marine bacteria have been shown to produce these biopolymers as structural components or as part of their metabolic pathways. Understanding the biosynthesis of these polysaccharides can contribute to their large-scale production and the exploration of their potential applications (Ali et al., 2024).

The biosynthesis of chitosan and chitin is a multi-step process that involves the enzymatic conversion of simple sugars, such as glucose or glucosamine, into complex polymer structures. The biosynthesis is highly regulated, and several key enzymes are involved in the production of these biopolymers. The first step in chitin and chitosan biosynthesis is the synthesis of glucosamine (GlcN) from glucose. This process involves a series of enzymes, including glutamine: fructose-6-phosphate amidotransferase (GFAT), which catalyzes the conversion of fructose-6-phosphate to glucosamine-6-phosphate. Once glucosamine is synthesized, the next step is the N-acetylation of glucosamine to form N-acetylglucosamine (GlcNAc). This process is catalyzed by the enzyme N-acetyltransferase (GlmU), which transfers an acetyl group to the glucosamine molecule, forming GlcNAc. The next step involves the polymerization of GlcNAc to form chitin. This polymerization is catalyzed by chitin synthases, which facilitate the formation of the β -1,4 glycosidic bonds that link the individual GlcNAc units into long polysaccharide chains. Chitosan is produced by deacetylating chitin. The deacetylation process is carried out by chitin deacetylases (CDA), which remove the acetyl groups from GlcNAc units in the chitin chain, converting it to chitosan (Butnariu, 2023).

The key enzymes involved in the biosynthesis of chitosan and chitin are:

- **Glutamine fructose-6-phosphate amidotransferase (GFAT):** This enzyme is responsible for the conversion of fructose-6-phosphate to glucosamine-6-phosphate. It is a critical enzyme in the glucosamine biosynthesis pathway and is highly conserved in both prokaryotes and eukaryotes (Oliveira et al., 2023).
- **N-acetyltransferase (GlmU):** GlmU catalyzes the conversion of glucosamine-6-phosphate to N-acetylglucosamine, the building block for chitin biosynthesis. This enzyme is essential for chitin biosynthesis and is found in many microorganisms, including marine bacteria (Soni et al., 2023).

- **Chitin synthase (Chs):** Chitin synthases are responsible for the polymerization of GlcNAc to form chitin. These enzymes can form long chains of GlcNAc units by creating β -1,4 glycosidic bonds. Chitin synthase genes are found in marine bacteria such as *Vibrio*, *Aeromonas*, and *Pseudomonas*, as well as in fungi (Ali et al., 2024).
- **Chitin deacetylase (CDA):** Chitin deacetylases catalyze the removal of acetyl groups from N-acetylglucosamine units in chitin to form chitosan. This process can be carried out under certain conditions or in response to environmental stress. The CDA enzymes are responsible for the conversion of chitin into chitosan (Ali et al., 2024).

In marine environments, chitin and chitosan production occurs in a variety of microorganisms, including marine bacteria, fungi, and algae. These organisms have evolved the ability to synthesize these biopolymers as a structural component, often for protection or support. Marine bacteria such as *Vibrio* and *Aeromonas* species are capable of producing chitin and chitosan. These bacteria typically synthesize chitin as a structural material in their biofilms, which protects them from environmental stressors such as desiccation or antibiotic treatment. The chitosan produced by these bacteria is also of significant interest due to its biocompatibility and antimicrobial properties (Zhuang et al., 2022). Marine fungi, particularly those belonging to the genera *Penicillium* and *Aspergillus*, are known to produce both chitin and chitosan. These fungi synthesize chitin as part of their cell wall structure. Marine fungi are often studied for their potential in industrial applications, such as biodegradation and the production of chitosan for medical and agricultural purposes (Szymanski, 2022). While marine algae are not direct producers of chitin or chitosan, they can contribute to the production of other polysaccharides like agar and carrageenan, which are often compared with chitin in terms of their applications in the food and pharmaceutical industries (Stanley et al., 2021).

Chitosan is widely used in the production of biodegradable plastics due to its natural origin, nontoxicity, and biocompatibility. It is used in packaging materials, coatings, and medical products (Butnariu, 2023). It is used in agriculture as a natural pesticide, fungicide, and plant growth promoter. Its ability to stimulate plant defense mechanisms makes it a valuable tool in sustainable farming (Ali et al., 2024). Chitosan and chitin are used in water treatment processes, particularly in the removal of heavy metals and pollutants from wastewater. Their ability to absorb contaminants makes them effective in purifying water (Adelaja et al., 2024; Soni et al., 2023). Due to their biocompatibility and bioactivity, they are used as scaffolds in tissue regeneration and as antimicrobial agents (Oliveira et al., 2023).

4.3.15 Role of omics and synthetic biology in pathway elucidation

Advancements in genomics, transcriptomics, and proteomics have allowed the identification and characterization of biosynthetic gene clusters (BGCs) responsible for biopolymer production in marine microbes. Genome mining has revealed conserved motifs and operons related to EPS, PHA, and peptide biosynthesis (Vuong et al., 2021). Synthetic biology has enabled the cloning and expression of marine biosynthetic genes in fast-growing microbial hosts such as *E. coli* and *Corynebacterium glutamicum*. This approach has improved yield and facilitated the incorporation of unusual monomers, such as alginates and fucose-containing polysaccharides, for specialized biomedical applications (Chai et al., 2021).

4.4 Extraction and purification techniques for marine microbial biopolymers

The extraction and purification of marine microbial biopolymers (Table 4.2) are critical processes for isolating these biopolymers from microbial cultures or environmental samples. The method chosen depends on the type of biopolymer, its application, and the source.

4.4.1 Extraction techniques

4.4.1.1 Polyhydroxyalkanoates

To release PHAs from microbial cells, several cell disruption methods can be applied, such as mechanical disruption (e.g., sonication, high-pressure homogenization) or chemical treatments (e.g., using solvents like chloroform, or enzymes like lysozyme for cell wall degradation). Once the cells are disrupted, the biopolymer is extracted using organic solvents, primarily chloroform, which dissolves PHAs. The solvent is then evaporated, leaving the polymer behind. This method works well for PHAs with high molecular weight (e.g., polyhydroxybutyrate or PHB). For higher purity PHAs, ultrafiltration can be employed to remove small molecules and other contaminants from the polymer (Zhao et al., 2024).

4.4.1.2 Exopolysaccharides

EPSs are often extracted from culture media by boiling or autoclaving the microbial culture. The heat helps solubilize the polysaccharides. The supernatant is then separated by centrifugation. To purify EPS, alcohols such as ethanol or isopropanol are commonly used to precipitate the biopolymer from the supernatant. This technique helps concentrate and purify EPS by removing proteins, lipids, and small molecular contaminants. Dialysis using semipermeable membranes can also be employed to remove low-molecular-weight contaminants from EPS solutions (Shen et al., 2022).

4.4.1.3 Chitin and chitosan

Chitin extraction from marine sources: Chitin can be extracted from marine sources like shrimp shells or fungal cultures by removing proteins through alkaline treatments (e.g., using sodium hydroxide, NaOH). The shells are then treated with dilute acid to remove minerals. Calcium carbonate removal is also necessary to obtain pure chitin. This is accomplished by treating the material with diluted hydrochloric acid (HCl) (Islam et al., 2023).

Chitosan extraction from chitin: Chitosan is obtained by partial deacetylation of chitin. This is done by treating chitin with concentrated sodium hydroxide (NaOH) at high temperatures (e.g., 100°C–120°C). The process removes acetyl groups from the chitin molecule, yielding chitosan (Sixto-Berrocal et al., 2023).

4.4.1.4 Polysaccharides

Marine-derived polysaccharides such as alginate, carrageenan, and fucoidan are typically obtained through relatively simple yet effective techniques. Extraction techniques often begin with hot water extraction, followed by acid/base extraction to break down cell walls and release the polysaccharides.

Table 4.2 Extraction and purification methods of some marine biopolymers.

Biopolymer	Extraction techniques	Purification techniques
Polyhydroxyalkanoates (PHAs)	– Cell disruption (sonication, high-pressure homogenization) – Solvent extraction (e.g., chloroform) – Ultrafiltration	– Precipitation (using solvents like methanol or acetone) – Gel permeation chromatography (GPC)
Exopolysaccharides (EPS)	– Hot water extraction (boiling/autoclaving culture medium) – Alcohol precipitation (ethanol, isopropanol) – Dialysis	– Ion exchange chromatography – Size exclusion chromatography (SEC)
Chitin	– Deproteinization (alkaline treatment with NaOH) – Decalcification (acid treatment with HCl)	– Dialysis – Gel permeation chromatography (GPC)
Chitosan	– Deacetylation of chitin (using NaOH at high temperature)	– Dialysis – High-performance liquid chromatography (HPLC) – Gel permeation chromatography (GPC)
Polysaccharides	– Water extraction – Acid/base extraction – Alcohol precipitation – Centrifugation and filtration	– Dialysis – Column chromatography (gel filtration, ion-exchange) – Precipitation and recrystallization – Size exclusion chromatography
Polyglutamic Acid (PGA)	– Water extraction – Acid extraction – Ultrafiltration	– Precipitation (e.g., alcohol or acetone) – Dialysis – Gel filtration chromatography
Polylactic Acid (PLA)	– Fermentation (using <i>Lactobacillus</i>) – Solvent extraction (e.g., chloroform, dichloromethane) – Precipitation (alcohol or acetone)	– Solvent evaporation – Column chromatography (gel filtration, reverse-phase) – Drying under vacuum
Polymeric Proteins and Glycoproteins	– Centrifugation – Solvent extraction (aqueous buffers) – Chromatographic separation (e.g., affinity chromatography)	– Ultrafiltration – Ion exchange chromatography – Size exclusion chromatography (SEC)

(Continued)

Table 4.2 Extraction and purification methods of some marine biopolymers. *Continued*

Biopolymer	Extraction techniques	Purification techniques
Proteins (e.g., collagen, silk-like proteins)	– Cell lysis (e.g., sonication, freeze-thaw cycles) – Solvent extraction (urea or guanidine hydrochloride) – Ultrafiltration	– Affinity chromatography (e.g., His-tag, antibody-based) – Size exclusion chromatography – Ion exchange chromatography – Precipitation (e.g., ammonium sulfate)
Polyhydroxybutyrate (PHB) and other PHAs	– Acetone/chloroform extraction – Acidic/alkaline hydrolysis	– Precipitation (using methanol or acetone) – Gel permeation chromatography (GPC)
Advanced Techniques	– Supercritical fluid extraction (SFE) – Nanofiltration – Electrochemical extraction	– Nanofiltration – Ultrafiltration – Membrane filtration

Alcohols such as ethanol are used to precipitate the polysaccharide fractions, followed by centrifugation and filtration to remove insoluble matter (Dongre, 2021).

4.4.1.5 Polymeric proteins and glycoproteins

Proteins and glycoproteins are extracted from the cells or culture medium using centrifugation to separate the biomass from the supernatant. Proteins and glycoproteins can be solubilized using organic solvents, although caution must be exercised to prevent denaturation. Aqueous buffers are often preferred for protein extraction. After initial extraction, proteins and glycoproteins are purified using various chromatographic techniques, such as size exclusion chromatography (SEC), ion exchange chromatography (IEC), and affinity chromatography, depending on the target molecule's properties (Martins et al., 2024).

4.4.1.6 Polylactic acid

PLA is synthesized via microbial fermentation of lactic acid, primarily by *Lactobacillus* species. Extraction methods post-fermentation include solvent extraction using chloroform or dichloromethane, and precipitation with alcohol or acetone to isolate PLA from the fermentation broth (Dongre, 2021).

4.4.1.7 Polyglutamic acid

Extraction of PGA typically uses water or acid-based extraction, followed by ultrafiltration to concentrate PGA from the fermentation broth (Sixto-Berrocal et al., 2023). Purification involves

alcohol or acetone precipitation, dialysis, and gel filtration chromatography to eliminate contaminants and achieve high molecular weight purity.

4.4.1.8 Proteins (e.g., collagen, silk-like proteins)

Extraction methods vary by protein type. Cell lysis via sonication or freeze-thaw cycles is common. Proteins like collagen require solvent extraction with urea or guanidine hydrochloride for solubilization (Rajan, 2024). Recombinant silk-like proteins may be produced in microbial systems and extracted from inclusion bodies. Purification depends on the target protein's properties. Affinity chromatography (e.g., His-tag systems) allows specific binding and elution. Further polishing can be done using size-exclusion, ion exchange chromatography, and ammonium sulfate precipitation (Martins et al., 2024).

4.4.1.9 Polyhydroxybutyrate and other polyhydroxyalkanoates

One of the most common methods for PHB extraction is the use of acetone or chloroform. The cell mass is first dried and then treated with chloroform, which solubilizes the PHB. The organic solvent is then evaporated, leaving behind the PHB. Alkaline or acidic hydrolysis can also be employed for breaking down the cell walls and releasing the biopolymers (Mongili et al., 2021).

4.4.2 Purification techniques

4.4.2.1 Polyhydroxyalkanoates

After extraction, PHAs can be purified by precipitation using solvents like methanol or acetone, which precipitate PHAs from the solution. The purity is then improved by washing with additional solvent and drying. In some cases, especially for complex mixtures, chromatography (e.g., gel permeation chromatography) may be used for final purification of PHAs (Zhao et al., 2024).

4.4.2.2 Exopolysaccharides

EPSs often require purification by ion exchange chromatography, particularly when the EPS contains charged groups. This allows for the separation of EPS from other contaminants such as proteins and other biomolecules. Size exclusion chromatography (SEC) is used to separate EPS based on molecular size, providing an effective way to purify different molecular weight fractions of EPS (Shen et al., 2022).

4.4.2.3 Chitin and chitosan

After extraction, both chitin and chitosan can be purified using dialysis to remove any residual salts or small molecular impurities. To further purify chitosan, chromatography methods such as gel permeation chromatography (GPC) or high-performance liquid chromatography (HPLC) are used, based on the polymer's molecular weight and structure (Islam et al., 2023).

4.4.2.4 Polysaccharides

Purification of polysaccharides involves dialysis to remove low molecular weight impurities, and column chromatography techniques such as ion exchange and gel filtration, to isolate specific

molecular weight fractions. Size exclusion chromatography is particularly valuable for refining polysaccharide purity (Dongre, 2021).

4.4.2.5 *Polylactic acid*

Purification of PLA involves solvent evaporation, followed by drying under vacuum to eliminate residual solvents. Reverse-phase and gel filtration chromatography can be used for high-purity applications (Dongre, 2021).

4.4.2.6 *Polymeric proteins and glycoproteins*

Ultrafiltration membranes can concentrate polymeric proteins and glycoproteins, removing low-molecular-weight contaminants. This method purifies proteins based on their net charge, separating the target proteins from other impurities. SEC can also be used to separate proteins or glycoproteins based on size, providing a method to obtain purified proteins (Martins et al., 2024).

4.4.2.7 *New and advanced techniques*

Supercritical fluid extraction (SFE): Supercritical fluid extraction (SFE) using carbon dioxide (CO₂) is gaining attention as a green technology for extracting biopolymers like PHAs and EPS. CO₂, under high pressure and temperature, acts as a solvent to extract biopolymers, avoiding the use of harmful organic solvents (Nayir et al., 2023).

Nanofiltration: Nanofiltration, a membrane filtration technique, is increasingly used for purifying high-value biopolymers like chitosan and EPS. It provides a nonthermal separation method, maintaining the stability of the biopolymer (Alkhaldi et al., 2024).

Electrochemical extraction: Electrochemical methods have been investigated for extracting biopolymers from microbial biofilms or extracellular matrices. By applying electric fields, these methods can selectively break down the cell wall and release biopolymers (Alabi et al., 2024).

4.5 Properties and characteristics of marine microbial polymers

Marine microbial biopolymers are truly remarkable, showcasing unique physicochemical and biological traits that make them great sustainable alternatives to traditional materials. Among these, polyhydroxyalkanoates (PHAs) and exopolysaccharides (EPS) stand out as intriguing types of marine biopolymers produced by microorganisms. They are particularly noted for their biodegradability, biocompatibility, and impressive structural versatility.

4.5.1 Physicochemical properties

Marine microbial biopolymers exhibit a broad spectrum of molecular weights, exopolysaccharides (EPS) can range from 10⁵ to over 10⁷ Da, influencing viscosity, gelling behavior, and functional roles in biofilm formation (Cázares-Vásquez et al., 2021). Polyhydroxyalkanoates (PHAs), synthesized as intracellular granules, also show significant molecular diversity, dictated by the carbon source and fermentation parameters (Liang et al., 2024). They boast mechanical and thermal properties that can

rival conventional plastics such as polypropylene (PP) and low-density polyethylene (LDPE) (Kourmentza and Kornaros, 2016; Naser et al., 2021; Volova et al., 2013). For instance, poly(3-hydroxybutyrate) (PHB), a type of short-chain-length PHA (scl-PHA), is known for its stiffness and brittleness due to its crystalline structure. It can withstand thermal conditions up to 160°C–180°C, which is comparable to polypropylene, although its lower melting point (~170°C) can limit its use in high-temperature applications (Volova et al., 2013). When 3-hydroxyvalerate (HV) is added to PHB, it forms PHBV, a copolymer that offers improved flexibility and ease of processing (López et al., 2015). This incorporation of HV units into PHB results in poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), which is tougher, more flexible, and easier to work with thermally (López et al., 2015). The solubility of marine microbial biopolymers is largely governed by their functional groups, hydroxyl, carboxyl, amino, and sulfate, which confer hydrophilicity or hydrophobicity. Polysaccharides such as alginate, produced by marine Pseudomonads, are highly water-soluble and display high hydration capacities, making them excellent emulsifiers and thickening agents (Abka-Khajouei et al., 2022). In contrast, PHAs are water-insoluble, lending themselves to use in bioplastics and medical implants. Marine microbial biopolymers often exhibit exceptional stability under extreme conditions. EPS derived from extremophilic marine bacteria such as *Thermococcus* and *Halomonas* can tolerate high salinity, temperature, and pH fluctuations, which is crucial for industrial bioprocesses (Gan et al., 2024). PHAs are thermoplastic, with melting points ranging between 160°C–180°C, allowing them to be processed using conventional plastic-manufacturing techniques (Enfrin & Giustozzi, 2022).

Exopolysaccharides (EPS) also have a variety of physicochemical properties that boost their functionality. Their thermal stability can differ based on their composition and structure, often enabling them to resist degradation at higher temperatures. Additionally, their solubility in water is a key characteristic, influencing how EPS interacts with biological molecules and their suitability for various applications. Many marine exopolysaccharides (EPS) show impressive solubility, making them great candidates for drug delivery and various biomedical uses (Andrew and Jayaraman, 2022; Liu et al., 2024). These EPS play vital ecological roles, such as forming biofilms and providing structural support to microbial communities (Liu et al., 2024). In-depth analytical studies using Nuclear Magnetic Resonance (NMR) spectroscopy and mass spectrometry (MS) have revealed the monosaccharide compositions of different marine bacterial EPS. For instance, EPS from marine bacteria like *Pseudoalteromonas* spp. exhibit varying thermal stability and solubility, with glucose and galactose being the most prevalent in their monosaccharide profiles (Chakraborty et al., 2024). Mechanical strength is another key factor, as it affects the structural integrity of EPS scaffolds used in biomedical applications. EPS from *Virgibacillus dokdonensis* and *Alteromonas macleodii* can form hydrogels with adjustable mechanical strength, making them suitable for scaffolds and drug delivery systems (Andrew & Jayaraman, 2022; Concórdio-Reis et al., 2024).

4.5.2 Mechanical and rheological properties

PHAs exhibit mechanical properties similar to petrochemical-derived plastics such as polypropylene and polyethylene. Their tensile strength and elasticity can be tailored by modifying monomer composition (Lalonde et al., 2025). EPS and polysaccharides from marine bacteria, though less robust, show excellent flexibility and viscoelastic behavior, useful in coatings and biomedical gels. The rheological behavior of marine microbial polysaccharides is particularly valuable. EPS from

Pseudoalteromonas antarctica and *Vibrio diabolicus* demonstrate high viscosity at low concentrations, shear-thinning behavior, and stability over a wide pH range, making them ideal for use in cosmetics, food, and pharmaceuticals (Concórdio-Reis et al., 2021).

4.5.3 Biodegradability and biocompatibility properties

A hallmark feature of marine microbial biopolymers is their biodegradability in natural environments, mediated by microbial enzymes and abiotic factors. Meereboer et al. (2020) reported that polyhydroxyalkanoates (PHAs) break down into water, carbon dioxide, and biomass through microbial action, positioning them as eco-friendly alternatives to traditional plastics that linger in the environment. This biodegradability helps combat plastic pollution and its negative environmental effects (Meereboer et al., 2020). PHAs can fully degrade in marine settings within 6 to 24 months thanks to microbial enzymes, which is a stark contrast to the long-lasting synthetic plastics like polyethylene (Meereboer et al., 2020). Similarly, EPS from *Sphingomonas* spp. break down quickly in marine sediments and human tissues, reducing their ecological footprint (Liu et al., 2024; Omura et al., 2023) while chitin and chitosan degrade through enzymatic cleavage by chitinases and lysozymes, respectively (Ali et al., 2024).

Biocompatibility is a key feature of these polymers especially for medical and pharmaceutical applications. Chitosan, alginate, and certain PHAs have been extensively studied for their nontoxicity, lack of immunogenicity, and ability to support cell adhesion and growth, making them suitable for tissue engineering, drug delivery, and wound-healing applications (Dhanial et al., 2022; Khan & Alamry, 2021). PHAs are nontoxic, FDA-approved, and can be safely used in medical settings without triggering any adverse reactions. They're perfect for a range of applications, including surgical sutures, implants, bone tissue regeneration, and biodegradable drug delivery systems (Chen, 2009; Li et al., 2021; Reddy et al., 2003; Ren et al., 2023). Interestingly, PHAs also show promise in cancer detection; for instance, PHB can specifically attach to target proteins in breast cancer cells, helping to differentiate them from normal cells (O'Connor et al., 2013; Sabarinathan et al., 2018). These polymers are naturally produced by bacteria as intracellular granules, acting as reserves for carbon and energy. This sets them apart from marine microbial polymers like polylactic acid (PLA) and polybutylene succinate (PBS), which are chemically made from lactic and succinic acids, respectively (Kourmentza et al., 2017).

While PLA and PBS are also biodegradable and biocompatible like PHAs, the microbial production of PHAs using renewable feedstocks and waste materials presents a more sustainable and cost-effective option. The use of mixed microbial consortia and waste streams as substrates further boosts the sustainability of PHA production (Zhou et al., 2023). Numerous in vitro studies show that EPS have minimal cytotoxic effects on human cells, with viability rates over 90% even at high concentrations, making them ideal for applications like wound dressings, cartilage repair, and immunomodulatory therapies (Liu et al., 2024; Patel et al., 2025; Yano et al., 2023). When we compare synthetic polymers, such as polyethylene and nylon, they may be versatile and strong, but they fall short in terms of eco-friendliness. On the other hand, marine microbial polymers come with several benefits; they are biodegradable, biocompatible, and derived from natural sources, which helps reduce their carbon footprint and enhances their sustainability (Naser et al., 2021; Sagpariya et al., 2024).

4.5.4 Antioxidant, antimicrobial, and antiinflammatory properties

Marine microbial biopolymers are not merely structural; many possess bioactive properties. Sulfated polysaccharides, like those produced by *Pseudoalteromonas* and *Vibrio* spp., have demonstrated antioxidant and antimicrobial activities. These attributes are thought to derive from their ability to scavenge free radicals and disrupt microbial membranes (Khan & Alamry, 2021). Chitosan, derived from chitin, has broad-spectrum antimicrobial properties effective against bacteria, fungi, and viruses, attributed to its polycationic nature that disrupts negatively charged microbial cell walls (Dhanial et al., 2022). Some glycoproteins exhibit antiinflammatory properties, potentially useful for treating chronic wounds and inflammatory diseases.

4.5.5 Ecological and environmental resilience

In marine environments, microbial biopolymers contribute significantly to ecological functions. They facilitate biofilm formation, nutrient capture, and protection against desiccation, salinity, and UV radiation (Mouro et al., 2024). Their role in the formation of marine snow and carbon sequestration further highlights their environmental importance.

4.6 Applications of marine microbial biopolymers

Marine microbial biopolymers have emerged as sustainable and versatile alternatives to synthetic materials, owing to their unique structural diversity, functional versatility, environmental compatibility, and bioactivity. These polymers such as polyhydroxyalkanoates (PHAs), exopolysaccharides (EPS), polyglutamic acid (PGA), polylactic acid (PLA), chitin, chitosan, and various glycoproteins, are produced by marine bacteria, archaea, and fungi under various environmental conditions. As shown in Table 4.3, they have diverse applications across different sectors including biomedical, pharmaceutical, environmental, agricultural, cosmetic, and food industries (Mouro et al., 2024; Shah, 2022).

4.6.1 Biomedical and pharmaceutical applications

Marine microbial biopolymers play a crucial role in the biomedical and pharmaceutical industries due to their biocompatibility, nontoxicity, and potential for functionalization across various therapeutic applications. One of the major uses of these biopolymers is in drug delivery systems. Polymers such as polyhydroxyalkanoates (PHAs), chitosan, and polylactic acid (PLA) are employed to create nano- and micro-particles that encapsulate drugs for targeted delivery (Vlachopoulos et al., 2022). These polymer-based systems ensure controlled drug release, which minimizes side effects and enhances bioavailability. Paul et al. (2024) reported that PHAs and PLA are particularly effective in delivering chemotherapy and hormonal therapy, while chitosan and exopolysaccharide (EPS)-based nanoparticles help improve the absorption of drugs with low solubility. In wound healing, chitosan and EPS such as alginates, stand out for their antibacterial properties. These materials are commonly used in wound dressings to prevent infections, reduce inflammation, and accelerate tissue regeneration.

Table 4.3 Applications of marine microbial biopolymers in various sectors.

Application area	Biopolymers involved	Key uses/benefits
Biomedical and Pharmaceutical	PHAs, Chitosan, EPS, PLA, PGA	Drug delivery systems, wound healing, tissue engineering, antimicrobial agents, antioxidant agents
Environmental and Industrial	PHAs, PLA, Chitosan, EPS	Bioplastics, bioremediation, corrosion inhibition, biofilm control, wastewater treatment
Food and Nutraceutical	Chitosan, EPS (e.g., alginate, carrageenan), PLA	Food packaging, thickening and gelling agents, dietary supplements, functional foods
Agricultural	Chitosan, EPS, PGA	Biopesticides, fertilizer carriers, soil conditioners, plant growth promoters
Cosmetic and Personal Care	Chitosan, EPS, PLA	Skin hydration, antiaging, moisturizing agents, hair care, personal care products
Marine Biotechnology and Nanotechnology	PHAs, Chitosan, EPS, PLA	Nanocarriers, biosensors, enzyme immobilization, biotechnological tools
Marine Biopolymer-Based Hybrid Materials	PHAs, Chitosan, EPS, PLA	Biodegradable films, soil erosion control, water retention enhancers, soil-binding composites

Chitosan, in particular, forms a gel matrix that helps keep the wound moist, creating an optimal environment for healing (Khan & Alamry, 2021). Marine biopolymers also find significant application in tissue engineering. Materials like PHAs and PLA are used to create biodegradable scaffolds that mimic the structure of natural tissues (Dhanial et al., 2022). These scaffolds support the growth of skin, bone, and cartilage cells, making them valuable in regenerative medicine. Their application has paved the way for advancements in artificial organ development and bone grafting (Dhanial et al., 2022; Reddy et al., 2021). Additionally, antimicrobial and antioxidant agents derived from marine sources, especially EPS from marine bacteria and chitosan, have shown considerable potential. These biopolymers possess strong antimicrobial and antioxidant activities, making them suitable for use in wound healing formulations, preventing microbial infections, and mitigating oxidative stress in various medical treatments (Vlachopoulos et al., 2022).

4.6.2 Environmental and industrial applications

Marine microbial biopolymers are gaining significant attention in environmental and industrial sectors due to their biodegradability, eco-friendliness, and potential to support sustainability initiatives across various domains. One of the most prominent applications is in the production of bioplastics. Biopolymers such as PHAs and PLA are central to the development of biodegradable plastic materials (Shah et al., 2025). Unlike conventional plastics derived from petrochemicals, these bioplastics can decompose naturally, significantly reducing environmental pollution. PHAs, which are produced by marine bacteria, are completely biodegradable and are especially suited for use in packaging,

including single-use products. These materials are increasingly being adopted as sustainable alternatives to traditional plastics like polyethylene and polypropylene, commonly used in food and medical product packaging (Dhanial et al., 2022). Another critical application is in bioremediation. Both chitosan and EPS possess the ability to bind heavy metals and organic pollutants, making them highly effective in cleaning up contaminated environments. Ali et al. (2024) reported that chitosan-based materials are used to extract harmful substances such as lead, mercury, and pesticides from polluted water. Additionally, EPS contribute to detoxifying ecosystems by breaking down complex organic pollutants into harmless compounds, playing a vital role in the remediation of oil spills and heavy-metal-contaminated sites (Ghosh et al., 2024). Marine biopolymers also offer solutions for corrosion inhibition in industrial settings. Chitosan and EPS are used to develop coatings that protect metal surfaces from microbial-induced corrosion (MIC), particularly in harsh marine and industrial environments (Ali et al., 2024; Ghosh et al., 2024). These coatings inhibit the growth of corrosion-causing microorganisms and are especially valuable in sectors such as oil and gas, as well as for marine infrastructure including pipelines, tanks, and ship hulls (Kalajahi et al., 2024). In addition, marine EPS are playing an important role in biofilm control. Biopolymers produced by bacteria like *Pseudomonas* and *Alteromonas*, are utilized in creating antibiofilm agents that prevent the formation of microbial films on various surfaces (Zayed et al., 2022). Biofilms are notoriously difficult to remove and pose risks to both health and equipment functionality. EPS-based solutions are being applied to protect pipelines, industrial machinery, and medical devices from biofilm-related complications (Vlachopoulos et al., 2022).

4.6.3 Food and nutraceutical applications

Marine microbial biopolymers are increasingly valued in the food and nutraceutical industries for their functional versatility. Their natural gelling, thickening, and preservative properties make them ideal as food additives, packaging materials, and components of health-promoting products. In food packaging, biopolymers such as PLA and PHAs are emerging as sustainable alternatives to conventional plastic materials. These biodegradable polymers are used to create films and containers that are not only compostable but also effective at extending the shelf life of food products. By acting as barriers against moisture, oxygen, and other environmental factors, PLA and PHAs help preserve food freshness while reducing plastic waste and environmental impact (Naser et al., 2021). Marine-derived exopolysaccharides (EPS) including alginate, agar, and carrageenan, play a key role as texturizing and gelling agents in the food industry (Amer et al., 2025; Gan et al., 2024). These biopolymers are widely used in products such as jams, candies, dairy goods, and processed meats to improve viscosity, texture, and stability. Their ability to enhance the physical properties of food without affecting taste makes them valuable ingredients in many formulations (Amer et al., 2025). In the realm of dietary supplements, chitosan extracted from marine crustaceans, is popular for its fat-binding capabilities, which support weight management by reducing fat absorption in the digestive tract (Ali et al., 2024). Furthermore, EPS from marine microbes offer prebiotic benefits, fostering the growth of beneficial gut bacteria and contributing to improved digestive health (Gan et al., 2024). Marine microbial biopolymers also contribute to the development of functional foods that offer health benefits beyond basic nutrition. Abedi et al. (2023) reported that seaweed-derived EPS are incorporated into food products for their immune-boosting, antioxidant, and antiinflammatory

properties. Ingredients like alginate and carrageenan not only enhance digestion and nutrient absorption but also promote overall wellness, making them a staple in health-oriented food innovations (Abedi et al., 2023).

4.6.4 Agricultural applications

Marine microbial biopolymers are becoming vital tools in agriculture, supporting sustainable farming practices, improving crop productivity, and increasing plant resilience against environmental stress. One important application is in the development of biopesticides. Chitosan, derived from marine sources, has been shown to boost plant defenses against fungal and bacterial pathogens (Riseh et al., 2022). It works by activating natural immune responses within plants, enabling them to fend off microbial attacks more effectively. Similarly, exopolysaccharides (EPS) produced by marine bacteria possess antimicrobial properties that can be harnessed in eco-friendly crop protection products (Ghosh et al., 2024). Marine biopolymers also serve as effective fertilizer carriers. EPS and polyglutamic acid (PGA) are used to formulate slow-release fertilizers that release nutrients gradually, matching plant uptake needs (Eddarai et al., 2024). This controlled nutrient delivery improves absorption efficiency and minimizes runoff, helping farmers reduce environmental impact while maintaining healthy crop growth (Riseh et al., 2022). In addition, marine EPS and PGA function as soil conditioners, improving soil quality in several ways. They enhance water retention, promote aeration, and boost beneficial microbial activity in the soil. These improvements not only support healthy root development but also reduce erosion particularly in dry or degraded regions, ensuring better nutrient availability and stronger, more resilient plants (Puglia et al., 2021).

4.6.5 Cosmetic and personal care applications

Marine microbial biopolymers are making a significant impact in the cosmetic and personal care industry thanks to their natural moisturizing, antiaging, and antioxidant properties. These compounds are increasingly incorporated into skincare and haircare formulations aimed at improving both aesthetics and health. In skin care, biopolymers such as chitosan and exopolysaccharides (EPS) are commonly used in moisturizers, creams, and lotions (Baptista & Freitas, 2021; Benhadda et al., 2023; Gupta et al., 2022). Their ability to form a lightweight, breathable film on the skin helps lock in moisture and enhance skin hydration. These ingredients are particularly beneficial for products targeting dry or sensitive skin, offering soothing effects and protection against environmental aggressors (Gupta et al., 2022). For antiaging purposes, marine-derived polysaccharides including sulfated EPS, are prized for their potent antioxidant and antiinflammatory activities. These compounds combat oxidative stress, which is a major contributor to skin aging. By protecting skin cells from damage caused by free radicals and UV exposure, they help reduce the appearance of fine lines and wrinkles, making them valuable components in antiaging serums and creams (Benhadda et al., 2023). In hair care, chitosan is frequently added to shampoos and conditioners to improve hair texture, strength, and shine (Coutinho, 2023). It forms a protective film over hair strands, helping retain moisture and smooth the hair surface, leading to more manageable and healthier-looking hair. Moreover, its antimicrobial properties help maintain scalp health by preventing dandruff and reducing the risk of scalp infections (Coutinho, 2023; Morganti et al., 2021).

4.6.6 Biocompatible materials in nanotechnology

Marine microbial biopolymers are increasingly being recognized as promising materials in nanotechnology due to their natural biodegradability, biocompatibility, and structural adaptability. These properties make them ideal candidates for a wide range of applications, particularly where safety and environmental sustainability are critical. In the development of nanoparticles and nanospheres, biopolymers such as PHAs, PLA, and chitosan are used to engineer nanoscale carriers for drug delivery, gene therapy, and biosensing (Dhanial et al., 2022; Enfrin & Giustozzi, 2022). These nanoparticles can be tailored to deliver specific therapeutic agents or genetic materials with high precision. Their biodegradable nature allows them to safely degrade within the body, significantly reducing the risk of long-term toxicity and side effects (Liu et al., 2024). Marine biopolymers are also instrumental in forming nanocomposites, where they are combined with nanofillers like carbon nanotubes, graphene, or silica nanoparticles (Paul et al., 2024). These hybrid materials exhibit superior mechanical strength, enhanced thermal stability, and improved electrical conductivity. As a result, they are being explored for use in cutting-edge fields such as flexible electronics, high-performance batteries, and environmental sensing technologies (Shah et al., 2025). In the realm of biosensors and diagnostic devices, chitosan and various EPS are utilized to create sensitive detection systems capable of identifying specific biological molecules or pathogens (Amer et al., 2025). These biopolymer-based biosensors are able to detect even trace amounts of target analytes, making them highly effective for use in medical diagnostics, environmental monitoring, and food safety assurance (Naser et al., 2021; Vlachopoulos et al., 2022).

4.6.7 Marine biopolymer-based hybrid materials

Beyond their standalone applications, marine microbial biopolymers are increasingly being incorporated into hybrid materials, combining the advantages of natural biopolymers with other synthetic or natural compounds. These hybrid systems enhance the functional properties of materials, opening up new possibilities across various industries. In the development of polymer blends and coatings, marine biopolymers such as PHAs and chitosan are often combined with synthetic polymers to create improved biodegradable films REF. These blends can be engineered to enhance key attributes like mechanical strength, flexibility, and water resistance, while still maintaining biodegradability and environmental friendliness (Khan & Alamry, 2021; Meereboer et al., 2020). Such materials are especially valuable in applications like sustainable packaging, biomedical coatings, and agricultural films (Khan & Alamry, 2021). In agriculture, hybrid biopolymer systems are used to improve soil and crop management. For example, marine biopolymers like EPS and PLA can be blended with natural fibers such as hemp or cotton to form composite materials with superior water retention and soil-binding capabilities (Macheca et al., 2024). These materials are ideal for producing eco-friendly mulch films, which help conserve soil moisture, suppress weed growth, and reduce erosion. This integration supports more sustainable farming practices and enhances crop resilience, particularly in water-scarce or erosion-prone areas (Ansabayeva et al., 2025).

4.7 Sustainability and environmental impact

A major environmental concern that harms marine habitats is plastic pollution. The pursuit of sustainable alternatives has been driven by the environmental persistence of conventional plastics and their contribution to microplastic pollution. Marine biopolymers, which are made from marine creatures including algae, crab shells, and microorganisms, have drawn interest as potential eco-friendly alternatives to synthetic plastics (Tennakoon et al., 2023).

4.7.1 Marine biopolymers as eco-friendly substitutes for polymers

Marine biopolymers are naturally occurring macromolecules produced by marine organisms and they often exhibit biodegradability and biocompatibility. Common marine-derived biopolymers include chitosan, alginate, carrageenan, and polyhydroxyalkanoates (PHAs). Unlike petroleum-based plastics, these biopolymers degrade more rapidly in natural environments, thereby reducing the accumulation of persistent plastic waste (Samalens et al., 2022). Chitosan, which is a biodegradable substance with antibacterial qualities is derived from chitin, which is present in crab shells. It provides a sustainable substitute for synthetic plastics when used in biodegradable packaging materials (Sofyan, 2024). Alginate, on the other hand is derived from brown seaweed and is useful in food packaging and biomedical domains because of its nontoxic properties and gel-forming capacity (Ye et al., 2024). Carrageenan, is polysaccharide derived from red algae and it is widely used in the food industry and bioplastics sector for its film-forming and stabilizing properties (Krishnan et al., 2024). PHAs are a class of biopolymers that is produced by marine bacteria. They have thermoplastic properties that are similar to conventional plastics but has superior biodegradability (Alsaadi et al., 2022).

4.7.2 Mechanisms of plastic pollution reduction

Marine biopolymers play a significant role in reducing plastic pollution through various mechanisms. One of their key advantages is their biodegradability in marine environments; unlike synthetic plastics that can persist for centuries, marine biopolymers naturally degrade, minimizing the risk of long-term environmental contamination (Pinaeva & Noskov, 2024). They also serve as sustainable alternatives to petroleum-based plastics, particularly in the context of single-use products, thereby helping to alleviate the growing burden of plastic waste (Wani et al., 2021). Moreover, some marine biopolymers break down into nontoxic by-products, which prevents the formation of harmful microplastics that pose a serious threat to marine biodiversity (Kumar et al., 2023). In addition to these benefits, certain marine biopolymers like chitosan possess adsorptive properties that enable them to encapsulate and remove pollutants, such as heavy metals and microplastics, from aquatic ecosystems (Doyo et al., 2023).

4.7.3 Life cycle assessment and eco-friendliness

A life cycle assessment (LCA) of marine biopolymers offers a comprehensive view of their environmental impact, encompassing every stage from raw material extraction to final disposal. This evaluation takes into account factors such as energy consumption, emissions, biodegradability, and

end-of-life options. Generally, marine biopolymers exhibit a lower carbon footprint than petroleum-based plastics, positioning them as a more environmentally sustainable alternative (Fatima, 2024). During the production phase, marine biopolymers often require less energy and produce fewer greenhouse gas emissions than synthetic plastics, although challenges related to resource availability and processing efficiency remain. In the use phase, they are nontoxic and safe for applications in food packaging, medicine, and agriculture, thereby reducing the chemical pollution typically associated with the degradation of synthetic plastics. At the end-of-life stage, their natural biodegradability allows for composting, microbial breakdown in marine environments, or eco-friendly processing in waste management systems, significantly reducing waste accumulation. When compared to biodegradable plastics made from terrestrial plants, marine biopolymers offer benefits such as faster degradation in aquatic ecosystems and reduced pressure on food crop resources. Nevertheless, the need for chemical modifications to enhance their mechanical properties may lead to environmental trade-offs, highlighting the importance of balanced innovation (Samalens et al., 2022).

4.7.4 Challenges in scaling up production for industrial use

While marine biopolymers offer a promising solution to plastic pollution, several challenges hinder their large-scale industrial adoption. One major barrier is the high production cost; the extraction and processing of marine biopolymers often demand specialized techniques and equipment, making them more expensive than conventional plastics (Coppola et al., 2020). Additionally, raw material availability poses a significant constraint, as large-scale production relies on a consistent supply of marine biomass, which can be disrupted by factors such as seasonal fluctuations, climate change, and over-harvesting (Alias et al., 2022). Processing and manufacturing also present hurdles due to the unique physicochemical properties of marine biopolymers. Enhancing their durability, flexibility, and thermal stability often requires modifications that complicate production (Akinsemolu et al., 2024). Regulatory and standardization issues further complicate commercialization, as compliance with varying environmental and safety regulations across regions demands the establishment of universal standards for biopolymer quality and biodegradability (Possidónio et al., 2025). Moreover, consumer acceptance and market competitiveness remain challenges, as marine biopolymers must contend with the low cost and well-established infrastructure of traditional plastics despite increasing interest in sustainable alternatives (Alias et al., 2022). Scaling up biotechnological processes, such as microbial-derived polyhydroxyalkanoates (PHAs), also requires advanced fermentation technologies and significant investment in research and development. Finally, although marine biopolymers are biodegradable, current infrastructure for their disposal and recycling remains underdeveloped, necessitating improvements to ensure their environmental benefits are fully realized (Coppola et al., 2020).

4.8 Challenges and future perspectives on marine microbial products

The development and commercialization of marine microbial products hold immense potential but are currently limited by a range of technical, economic, and regulatory challenges. Cultivating marine microbes under controlled laboratory conditions is often difficult due to their complex and specific

environmental requirements, and scaling up production necessitates sophisticated biotechnological solutions (Wang et al., 2021). Economically, the high costs associated with marine microbial research, bioprocessing, and extraction pose significant barriers to widespread adoption. Therefore, there is a pressing need for sustainable and cost-efficient production methods (Vaou et al., 2021). Regulatory frameworks also present hurdles; the stringent regulations surrounding marine resource utilization, safety assessments, and product approvals often delay commercialization efforts. Establishing standardized international guidelines for marine biotechnology is essential to streamline these processes (Vaou et al., 2021). Addressing these challenges requires a multidisciplinary research approach. According to Dittami et al. (2021), progress in this field depends on collaboration across various scientific domains. Biotechnology and microbiology are crucial for understanding microbial genetics and metabolic pathways, which are key to optimizing production. Materials science and engineering contribute innovations in biopolymer formulation and processing, enhancing product scalability and performance. Environmental science ensures the ecological sustainability of marine microbial applications, while insights from policy and economics help navigate market forces and regulatory landscapes to support successful commercialization.

Looking forward, future research should prioritize the discovery of novel marine-derived biopolymers with improved biodegradability and more cost-effective production processes. Cutting-edge advancements in synthetic biology and nanotechnology are expected to significantly broaden the application of these materials, particularly in areas such as sustainable packaging, biomedical devices, and environmental remediation.

4.9 Conclusion

Marine microbial biopolymers represent a promising class of sustainable materials that are gaining increasing attention due to their remarkable properties, such as biodegradability, biocompatibility, and structural versatility. These biopolymers, including polyhydroxyalkanoates (PHAs), exopolysaccharides (EPS), chitosan, and other polymeric compounds, are produced by marine microorganisms through well-characterized biosynthetic pathways. Their unique attributes make them ideal candidates for various industrial applications, ranging from biodegradable plastics and drug delivery systems to bioactive materials in cosmetics, agriculture, and environmental protection. The ongoing advancements in the extraction and purification techniques of these biopolymers have enhanced the efficiency of their industrial-scale production, further driving their potential for large-scale applications. As the demand for sustainable alternatives to conventional petroleum-based products continues to rise, marine microbial biopolymers stand out as a key solution to address environmental and health concerns. The continued exploration of marine microorganisms for the production of biopolymers opens new avenues for green technologies and circular economies, facilitating the development of materials that are not only eco-friendly but also contribute to a more sustainable and biodegradable future. As research advances, the full potential of these marine-derived biopolymers will likely revolutionize industries and pave the way for innovative applications that promote both sustainability and environmental stewardship.

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Impact of marine pollution on marine microbial products

5

**Habeebulahi Ajibola Adekilekun^{1,2}, Olorunshola Dave Omodamiro^{1,2}, Ngozi Kalu Achi²,
Habeebat Adekilekun Oyewusi³, Racheal M. Omodamiro^{4,5}, Bashar Adekilekun Tijani⁶,
Oluwatosin Olubunmi Oladipo⁷ and Fahrul Hayup⁸**

¹*Department of Pharmacology and Toxicology, Kampala International University, Bushenyi, Western Campus, Ishaka, Uganda,*

²*Department of Biochemistry, Micheal Okpara University of Agriculture, Umudike P.M.B, Umuahia, Abia, Nigeria,*

³*Department of Science Technology, Biochemistry Unit, Federal Polytechnic, Ado Ekiti, Ekiti, Nigeria,*

⁴*Department of Pharmaceutical Chemistry and Pharmacognosy, Kampala International University, Bushenyi, Western Campus, Ishaka, Uganda,*

⁵*National Root Crops Research Institute, Umudike, P.M.B, Umuahia, Abia, Nigeria,*

⁶*Obafemi Awolowo University Teaching Hospitals Complex, Ile-Ife, Osun, Nigeria,*

⁷*Department of Science Technology, Microbiology Unit, Federal Polytechnic, Ado Ekiti, Ekiti, Nigeria,*

⁸*Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, Johor, Malaysia*

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5.1 Introduction

5.1.1 Types and effects of marine pollution on marine microorganisms

Marine pollution is an occurrence of harmful effects in the ocean through the access of chemicals, waste (agricultural and residential), or invasive organisms, though, majority of marine pollution originates from land (Oyewusi, Wahab, et al., 2020; Verma et al., 2020). Marine microbial products are compounds created by many microorganisms like fungi, bacteria, archaea, microalgae, and algae found in marine environments. Marine microorganisms are found in the oceans and other saline environments, they have

also been seen as a rich source of valuable natural products with a varied range of potential uses. They have the capacity to produce a vast number of secondary metabolites which also exhibit effective biological activities and possess significant commercial value (Oyewusi, Adedamola Akinyede, et al., 2024; Oyewusi, Oladipo, et al., 2024; Weis, 2024; Yu & Singh, 2023). Marine environments are household to a vast and various array of microorganisms, collectively known as marine microbiomes, which play an important role in the overall health and functioning of the world's oceans. Unfortunately, these delicate ecosystems are gradually under menace from numerous forms of marine pollution, including the proliferation of microplastics and other contaminants (Yang et al., 2021; Yu & Singh, 2023).

Microplastics' presence in marine environment becomes growing concern, as these tiny particles can thus act as a direction for harmful pollutants disrupting the natural methods of marine ecosystems (Upendra & Kaur, 2023; Yang et al., 2021; Yu & Singh, 2023). Microplastics have been found to accumulate within tissues of the marine organisms, involving those occupying the bottom of the food-chain, such as zooplankton and filter-feeding organisms (Yu & Singh, 2023). This can have far-reaching consequences, as these microplastics and their associated pollutants may eventually may be ingested into the human via foods, therefore, posing prospective health risks (Upendra & Kaur, 2023).

Marine pollution, a pervasive and escalating threat to the health of the oceans, encompasses the addition of harmful materials or energy into the oceanic environs, resulting to negative effects on living resources, marine ecosystems and also human health. The origin of marine pollution are diverse and could be from either or both land-based and maritime events (Oyewusi, et al., 2022; Ulfah & Roesa, 2020). Land-based origin, include manufacturing discharge, agricultural runoff, and untreated sewage contribute considerably to the inflow of pollutants into coastal waters (Kruse et al., 2023). Microplastic pollution also reported to have a detrimental effect on the marine microbiome, disrupting the complex web of interactions that support the production of valuable microbial products including pharmaceutical compounds, enzymes, and biofuels. They are important sources of economic and ecological significance, and their disorder could have significant values for human and marine ecosystems well being (Ulfah & Roesa, 2020).

World population and products consumption growth have increased the accumulations of pollutants in the marine environs (Oyewusi, Adedamola Akinyede, et al., 2024; Oyewusi, Wahab, et al., 2024). Due to high demand for plastic globally, its production continuously increasing, this effectually cause rising oceanic plastic deposit (Wilcox et al., 2020). The pharmaceutical pollution is also projected to increase in proportional to population growing, causing a greater chemicals deposition that enter the ocean, such as contraceptive drugs, having possibility of inducing reproductive catastrophe and sex alterations in different fish species. Additionally, with further research and development, new chemical products are produced mostly in large volume and their impacts on the marine environment are unnoticed and untested. With this, it shows that marine pollution could be harmful to the organisms via the food-web in various ways. Persistent organic pollutants (POPs) and heavy metals accumulated even at trace amount in organisms can cause physiological impairment and behavioral distortion. Artificial lights at night along ocean coasts can also disrupt organism predation, navigation, and vertical movement. Some pollutants also have high capacity to bioaccumulation, making them more concentrated in some marine species. Economically, marine pollution also poses a huge risk because a typical consequence from pollution disproportionately impact many countries with less funds to intervene and remediate the impacts. Another angle to the negative impact of marine pollution is underdevelopment effects on coastal tourism, shipping, and fisheries. This can also be a source of contamination to seafood, which is risky to human health, and

also cause significant financial loss for investors and host communities. Current remediation approaches, policies, and regulations for most marine pollutants and ecosystems are costly and time consuming (Willis et al., 2022).

5.1.2 The significance of marine microbial products

These products have various applications in medicine, agriculture, and industry, including antibiotics, enzymes, and biofuels (Fig. 5.1). Marine microorganisms (e.g. bacteria, archaea, and unicellular eukaryotes) play a vital role in preserving the delicate marine ecosystems and therefore, have the potential to produce a different array of compounds with various applications. Different marine bacteria have been used to produce an amazing diversity of marine microbial natural products that are indicated for many biological actions, including antimicrobial, anticardiovascular agents, and antitumor. The distinctive metabolic pathways with their secondary metabolites of marine microbes in relation to their dynamic and challenging environments have therefore contributed to the development of many natural products (Mohamed et al., 2021).

The marine microbial products are important in many ways, as they have contributed immensely in the fields of biotechnology, pharmaceuticals, and industrial uses. Several marine-derived compounds have shown promising medicinal properties which are in different developmental stages including clinical trials (Okeke et al., 2024). Furthermore, marine bacteria also produce a variety of

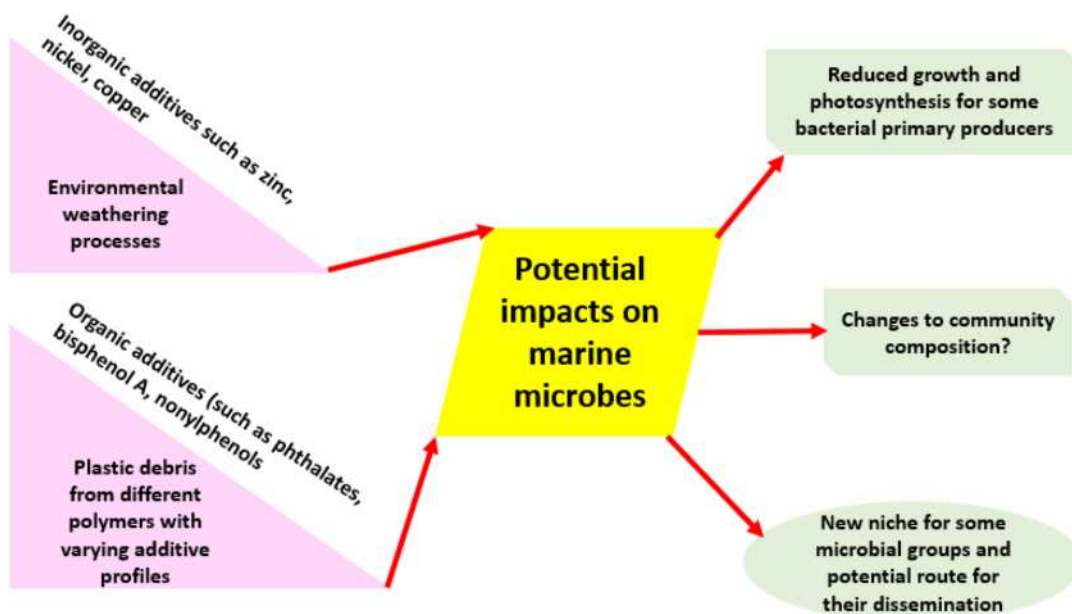


FIGURE 5.1

Marine microbial products significance areas.

pigments, which are used in different industries, including cosmetics, food production, and textiles (Nawaz, 2020). Marine pollution thus has significant effect on marine microbial products, influencing their diversity, production, and likely applications, Fig. 5.1.

5.2 Causes and effects of marine pollution

Marine pollution is a daunting environmental problem that entails the release of various contaminants, including chemicals, plastics, and biological compounds, into marine and coastal ecosystems. The contaminants (Fig. 5.2) have major effects on aquatic ecosystems, wildlife, and human health. Vessel activities are among the key sources of marine pollution, including oil discharge, sewage, and waste from the vessels (Ulfah & Roesa, 2020). These activities as shown in Fig. 5.2 definitely result in the release of harmful substances and garbage into the ocean, which in turn causes damage to marine organisms and disruption to maritime activities (Ulfah & Roesa, 2020).

Another significant source of marine pollution is land-based activity, with plastic litter and other contaminants being washed into the ocean through water courses and storm run-off. Plastic pollutants remain in the environment for long periods, building up within marine environments and posing risks to marine animals that ingest or become entangled in litter (Alam, 2023).

Marine pollution has overpowering and consequential impacts. The plastic pollution, for instance, can have harmful impacts on the marine ecosystem by causing entanglement, ingestion, and the disruption of ecosystem processes. Further, the emission of chemicals and other pollutants into the marine ecosystem can have a cascading effect, polluting food webs and thereby posing threats to human health through the consumption of the contaminated seafood (Alam, 2023).

Marine pollution is defined as the pollution of seas and oceans due to activities conducted by humans that negatively impact marine life, ecosystems, and human health. Marine pollution is an ancient threat to ocean health and therefore requires global intervention to reverse its impacts



FIGURE 5.2

Sources of marine pollution.

Table 5.1; Fig. 5.3. Effective waste management, stronger legislations, and public awareness are essential in stemming pollution and preserving marine diversity (Reichelt-Brushett, 2023; Verma et al., 2020; Weis, 2024). Marine microbes, including bacteria, phytoplankton, and zooplankton, play an important function in oceanic ecosystems, stabilizing the food web and controlling biogeochemical cycles. Marine pollution has profound effects on microorganisms, with cascading consequences for marine ecosystems and global environmental balance. Addressing pollution through sustainable practices, regulatory measures, and scientific research is essential to preserving marine microbial diversity and function. However, marine pollution significantly affects these microorganisms in the following ways **Table 5.1** (Chen et al., 2020; Oliveira et al., 2020; Reichelt-Brushett, 2023; Verma et al., 2020; Weis, 2024). The human race creates a substantial amount of solid waste everyday such as plastic objects which are considered single use, disposable, and convenient. Macroplastic/primary microplastics (< 5 mm in diameter) can enter the environment from many sources and eventually enter the ocean. Microplastics/secondary microplastics occur from the disintegration of other plastic items/pieces generated during product use, for example, tire wear or fibers from clothing. This implies that even if discharges of larger items of plastic were controlled or stop from entering the marine environment, good quantity of microplastic as a consequence of the fragmentation of larger items that are already in the environment will continue. Nanoplastics are less than 1000 nm in size and can be from primary or secondary sources. Like microplastics, nanoplastics have been ignored part of plastic pollution because they seemed to be the last stage before complete degradation and mineralization. Therefore, the presence of nanoplastics in the marine environment is likely to be of increasing significantly with time (Kruse et al., 2023; Napper & Thompson, 2020).

Thermal pollution can be defined as the warming of the ecosystem due to which the desirable living conditions of organisms are adversely impacted. Studies reveal even a minor change in ambient temperature and oxygen levels can have a profound effect on ecosystems. When an industry/organization consumes water from a natural source, it discharges the water back into natural resources upon heating it up or cooling it down, which subsequently changes the oxygen levels; eventually, it has devastative effects on local ecosystems and populations (Kumar et al., 2020).

5.2.1 Impact of marine pollution on marine microbial products

Marine microorganisms producing various bioactive compounds that are engaged in medicine, biotechnology, and industry (Beaumont et al., 2019; Todd et al., 2010). However, pollution in marine environments significantly impacts microbial productivity and the availability of these valuable products. Marine pollution threatens the natural productivity and biotechnological potential of marine microorganisms. Protecting marine ecosystems through pollution control and conservation efforts is essential to sustaining the discovery and production of valuable microbial products (Strain et al., 2022; Weis, 2024). Among these effects of pollution on the marine microbial product are listed below and specifically discussed based on the two major pollutions (oil spillage and plastics) (Fig. 5.4):

1. Reduced microbial biodiversity
2. Disruption of metabolic pathways
3. Bioaccumulation of toxic substances
4. Decline in biotechnological potential
5. Impact on carbon and nitrogen cycling

Table 5.1 Various types of marine pollution with their effects.

Types	Causative items	Description/effect	References
Plastic pollution	Plastic bags, bottles, fishing nets, and microplastics	Most prevalent pollutants in marine environments; degrade marine ecosystems and pose threats to marine organisms through ingestion and entanglement. Microplastics act as carriers of toxic chemicals and can be ingested by microorganisms leading to bioaccumulation of harmful substances, affecting microbial functions and impacting larger organisms in the food chain	Bottari et al., 2024 ; Kruse et al., 2023 ; Obebe & Adamu, 2020 ; Thushari & Senevirathna, 2020 ; Williams & Rangel-Buitrago, 2022
Chemical pollution	Toxic chemicals from industrial waste, agricultural runoff, and household products, Heavy metals (e.g., mercury, lead), pesticides, and pharmaceuticals	Disrupt marine biodiversity and accumulate in the food chain, affecting human health. These substances interfere with microbial metabolism, reduce growth rates, and can lead to mutations or cell death	Reckendorf et al., 2023 ; Schaap et al., 2023 ; Todd et al., 2010 ; Verma et al., 2020
Oil pollution	Oil spills from tankers, offshore drilling, and pipeline leaks	Release hydrocarbons into the ocean, coating marine life and habitats. Oil pollution leads to the destruction of coral reefs, fish populations, and seabirds.	Zadjelovic et al., 2020 ; (Jha & Dahiya, 2022); Shah & Soni, 2024
Nutrient pollution (Eutrophication)	Excessive nutrients, primarily from agricultural fertilizers and sewage	Enter the ocean and cause algal blooms. These blooms deplete oxygen altitudes, leading to hypoxic situations or “dead zones,” where marine life is inhibited.	Aniebone et al., 2024 , Mullungal et al., 2024

Radioactive pollution	Radioactive substances from nuclear power plants, weapon testing, and accidents (e.g., Fukushima disaster)	Introduces harmful radiation into marine environments, affecting marine organisms and human health through seafood consumption.	Reichelt-Brushett & Oakes, 2023 ; (Rathnayake & Rajapaksha, 2025) ; Uchechukwu et al., 2025
Noise pollution	Shipping, underwater construction, and military sonar disturb marine life, especially marine mammals like whales and dolphins	These disturbances interfere with communication, navigation, and reproduction. While noise pollution mainly affects larger marine species, studies suggest that increased underwater noise may disrupt microbial interactions and growth patterns in sediments and water columns	Parul et al., 2025 ; Slabbekoorn, 2019 ; Veldeki, 2023 ; Weilgart, 2023
Thermal pollution	Power plants and industrial facilities discharge warm water into oceans, altering temperature balances and affecting marine species that are sensitive to temperature changes	Thermal pollution can lead to coral bleaching and ecosystem disruption.	Devi & Dhanalakshimi, 2020 ; Jawad, 2021 ; Parul et al., 2025
Marine debris	Besides plastics, other debris such as glass, rubber, metal, and discarded fishing gear	These materials can injure or kill marine species and disrupt ecosystems.	Kruse et al., 2023 ; Napper & Thompson, 2020

6. Threats to marine-derived pharmaceuticals

7. Altered genetic potential of microbes

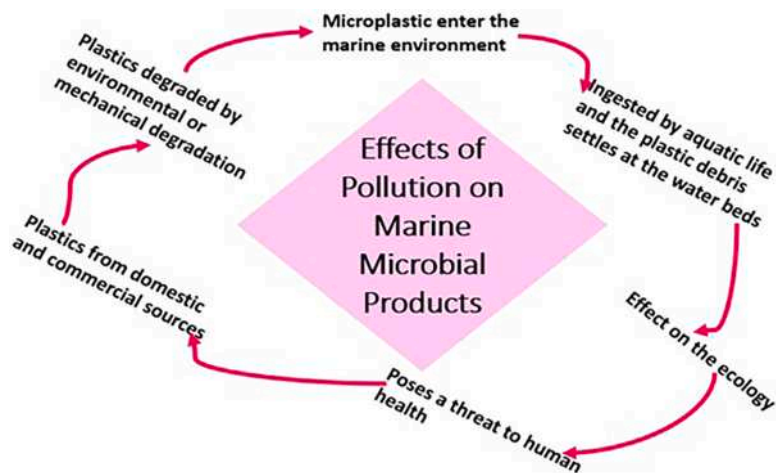
5.2.2 Major forms of marine pollution

5.2.2.1 Impact of oil spills on marine microbial communities

Accidental oil spills especially during oil drilling activities cause catastrophic ecological offenses and therefore require immediate intervention to alleviate the likely impacts to marine ecosystems ([Teichtmann et al., 2023](#)). Oil spills remain the most severe methods of marine pollution, causing significant disruptions to marine microbial communities [Fig. 5.5](#). Microorganisms play a crucial role in marine ecosystems, particularly in nutrient cycling and biodegradation. However, oil spills

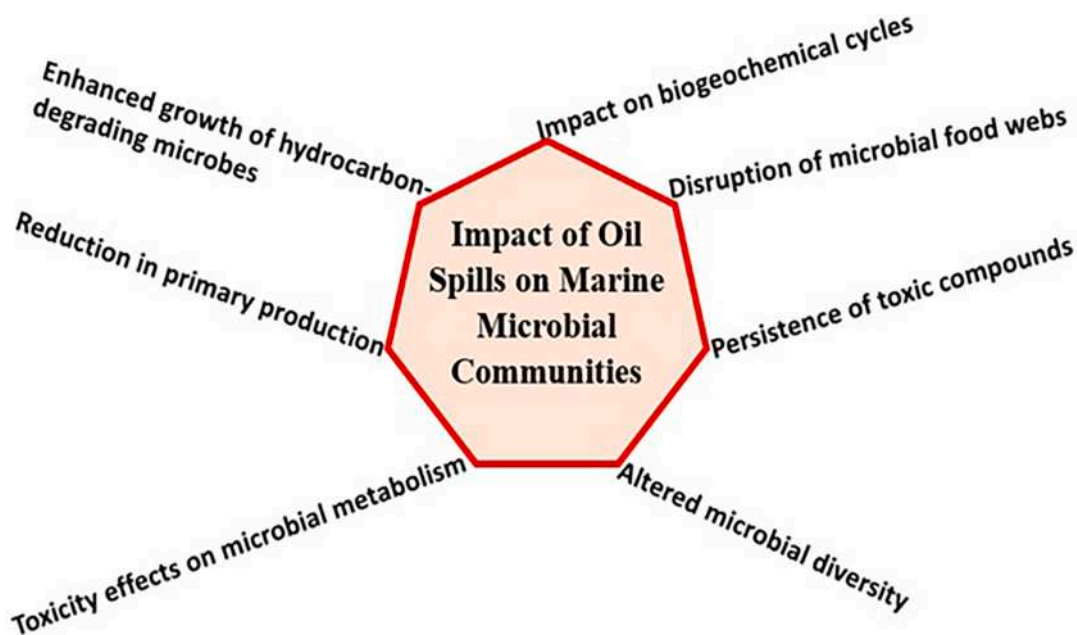
**FIGURE 5.3**

Types of marine pollution.

**FIGURE 5.4**

Effects of pollution on marine microbial products.

introduce hydrocarbon pollutants that can alter microbial diversity, functionality, and ecosystem balance. Oil spills significantly impact marine microbial communities, altering biodiversity, metabolism, and ecological functions. While some microbes contribute to oil degradation, the long-term effects of oil pollution can disrupt marine ecosystems. Effective response strategies, including bioremediation and pollution control, are crucial to mitigating these effects and restoring microbial balance in affected marine environments. Oil spills radically modify marine microbial habitat conformation, resulting to a decline in species productivity and diversity, this in collaboration with selected oil-degrading microbes. Evidently, obligate hydrocarbonoclastic bacteria (OHCB) degrade hydrocarbons present in crude oil and its byproducts, using hydrocarbons as their only source

**FIGURE 5.5**

Basic impacts of oil spills on marine microbial communities.

for carbon and energy. Though OHCB have been described to degrade some other compounds in pure cultures, there is limited evidence that they compete for nonhydrocarbon substrates within their environment (Zadjelovic et al., 2020). The fact is that OHCB are normally existing in exceedingly low amounts in uncontaminated milieus but rapidly become abundant following oil-spillages (Thomas et al., 2020). Oil spills at the coastal water line can therefore have disturbing effects on native ecosystems, ranging from microscopic level through the seabirds to advanced mammals (Cobanli et al., 2022).

5.3 Effects of plastic pollution on marine microbial products

Obviously recognized globally that the marine plastic pollution (MPP) threatens fish, and mammal species. Images showing that some animals entangled in plastic debris even sometimes their stomachs are filled with plastic fragments, these critical situations have incited scientific and public concern for globally interventions. Nevertheless, relatively studies have reflected how marine plastic pollution could affect a tiniest life among the marine microorganisms. Whereas, such tiny microorganisms are also needed in many ways including the photosynthetic production, biogeochemical recycling, and generally marine food web (Tetu et al., 2020). Plastic pollution is one growing environmental menace, affecting marine ecosystems and microbial communities. The marine microorganisms play crucial

part in producing bioactive compounds with pharmaceutical, industrial, and ecological significance. However, plastic waste and microplastics introduce pollutants that impact microbial diversity and their ability to produce essential bioactive compounds. MPP poses a grave threat to marine microbial communities and their ability to produce valuable bioactive compounds. Protecting marine ecosystems from plastic contamination is essential for preserving microbial diversity and ensuring the continued discovery of marine-derived pharmaceuticals and industrial products (Techtmann et al., 2023). The key effects of MPP could be discussed in many ways (Fig. 5.6). MPP causes **disruption of microbial diversity** by altering microbial community composition through specific plastic-degrading bacteria while reducing the diversity of other beneficial microbial species that should have been involved in bioactive compound production. Another effect could be through **adsorption and transport of toxic chemicals** by microplastics including heavy metals, and even persistent organic pollutants (POPs). These toxic materials definitely affect microbial metabolism that eventually hinders marine-derived products. **Bioaccumulation of microplastics in microbes** can cause internalization of microplastics, leading to cellular damage and stress responses that may also hinder their ability to produce bioactive compounds. The **impact MPP on marine biogeochemical cycles** can disrupt microbial roles in carbon, nitrogen, and sulfur cycling. These alterations can indirectly affect microbial productivity and the availability of key compounds essential for marine biotechnology. Pollution-induced stress can lead to genetic mutations or functional losses, reducing their effectiveness in biotechnological applications. Toxicological effect of plastic can cause the **emergence of harmful pathogenic microbes** including antibiotic-resistant pathogens, whereas

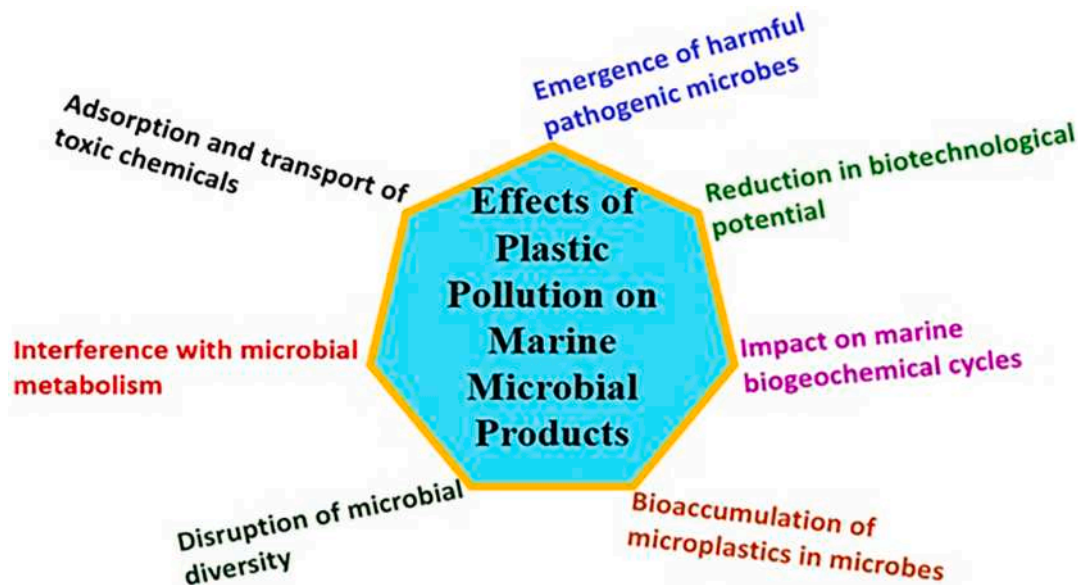


FIGURE 5.6

The basic effects of plastic pollution on marine microbial products.

antimicrobial resistance has been a serious problem globally. This move can moderate the control of beneficial microbes that also contribute to the production of MMP (Akan et al., 2021; Anjana et al., 2020; Cobanli et al., 2022; Mishra et al., 2024; Techtmann et al., 2023; Tetu et al., 2020; Vaksmaa et al., 2021).

5.4 Effects of marine pollution on marine microbial products

Sea is one of the world's top manufacturers of bioactive marine chemicals from the marine environment. Different species of marine bacteria have been found to possess the capacity for generating vast numbers of MMPs with antimicrobial, antitumor, antiinflammatory, and anticardiovascular activities (Mohamed et al., 2021; Weis et al., 2024). Utilization of marine organisms to synthesize greener, eco-friendly products through biotransformation is a novel alternative for cosmetic, and pharmaceutical industries (Ding et al., 2022).

With uncontrolled expansion of industry and farming over a time period resulting in continuous release of environmental contaminants to Earth's aquatic habitats hence influencing biodiversity on a worldwide scale. Natural and human-induced processes have the potential to cause widespread dispersal of pollutants into freshwater and marine ecosystems either intentionally or unintentionally, often causing acute and chronic changes in the ecophysiology of aquatic organisms (Diner et al., 2024; Weis et al., 2024). Substances derived from the sea have the potential to be used for different purposes (i.e., food additives, medicines, and cosmetics). For the case of drugs and food supplements, products are somehow controlled by their application. Therefore, the output are negatively affected by marines pollutions (Diner et al., 2024; Fonseca et al., 2023; Stien, 2020; Weis et al., 2024; Yang et al., 2021). Environmental pollution is still a serious global issue, and it is causing significant threats to the health of ecosystems and human health. Urbanization, industrialization, and all other economic processes that are caused by human action are significant in the overall environmental pollution of the present times. In recent years, much has been done toward the understanding of the complexities of pollution as well as toward the development of newer techniques of practical control and amelioration. The employment of cleaner technology, advanced treatment technologies, and advanced monitoring approaches holds great potential to safeguard the environment and ecosystems and ultimately the well being of all human beings on our planet (Diner et al., 2024; Khanam et al., 2023; Weis et al., 2024).

5.5 Conclusion

In conclusion, creeping ocean pollution is a momentous threat to the intricate realm of water microbial products, chemical products of profound ecological and biotechnological value. Increasing deposition of polluting compounds, such as heavy metals, industrial pollutants, plastics, and crop residues, into ocean systems disrupts the delicate balance of microbial communities, thus affecting their production, quality, and utility of resulting products (Curren et al., 2020). Marine microbes, including bacteria, fungi, algae, and archaea, are prolific producers of a wide variety of bioactive compounds, enzymes, polysaccharides, pigments, and other valuable products with uses that span from pharmaceuticals,

nutraceuticals, cosmetics, to bioremediation (Napper & Thompson, 2020). However, the constant influx of pollutants into marine ecosystems initiates a cascade of adverse effects on these microbial populations and their metabolic activities. However, the constant flow of pollutants into oceanic habitats sets off a chain of adverse effects on such microbial populations and their metabolic activities. Toxicity from exposure to heavy metals, such as lead, mercury, and cadmium, can have detrimental effects on marine microbes by inhibiting their growth, hampering their enzymatic activity, and interfering with their cellular processes (Ahamad et al., 2024). Marine pollution has deep impacts on marine microbial products, such as diversity, production, and potential applications. There are solutions to addressing marine pollution that exist and will require collaborative effort globally and in various sectors/stakeholders.

This involves policy reform which is at the core of formulating the important legislative agenda to trigger mitigation initiatives that are key in curbing through managing wastes and disposals. Sensitization and education regarding the problems caused by wastes are of essence in changing behavior patterns of individuals in terms of consumption and disposals. Quantification of environmental emissions captures the magnitude of the problem. It is also evident that once in the environment, plastics are highly resistant and hard to remove. There is an urgency for action, and the size of the problem is such that one single measure will not suffice. We have to at the same time apply a number of measures like, reduction, reuse, and recyclability with urgency (Kruse et al., 2023; Napper & Thompson, 2020). Therefore, development and effective implementation of regulatory policies on marine pollution with the promotion of bioremediation activities can always be the mitigating way-forward to marine pollution in order to maintain the marine ecosystem clean and support biotechnology research and development for global benefit (Diner et al., 2024; Khanam et al., 2023).

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Applications of marine microbial productions

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Biomedical applications of marine microbial products

6

Mariam Iyabo Adeoba¹, Thanyani Pandelani², Harry Ngwangwa², Tracy Masebe³ and Adewale Odunayo Oladipo¹

¹*Biomechanics Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, College of Science, Engineering and Technology (CSET), University of South Africa (UNISA), Florida, South Africa,*

²*Unisa Biomedical Engineering Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, School of Engineering, College of Science Engineering and Technology, University of South Africa, Science Campus, Florida, South Africa,*

³*Department of Life and Consumer Sciences, College of Agriculture and Environmental Sciences, University of South Africa (UNISA), Florida, Johannesburg, South Africa*

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6.1 Introduction

According to [Rigogliuso et al. \(2023\)](#), marine microbial products (MMPs) are a rich and mainly unexplored source of bioactive chemicals with substantial potential in biomedicine. Bacteria, fungus, and algae are examples of marine microbes that create secondary metabolites that have evolved to fulfill various ecological roles, including communication, competition, and defense. Since these substances have demonstrated exceptional pharmacological qualities, MMPs are important in creating novel therapeutic agents, especially in regenerative medicine and drug discovery. The unrealized potential of MMPs as a source of novel medications has been brought to light by the growing investigation of marine ecosystems and the advancements in microbiological research. These therapies could address unmet medical needs, especially for disorders resistant to conventional treatments.

When scientists discovered the distinct chemical makeup of marine animals in the early 20th century, interest in materials produced from marine sources began. Exploration of marine flora and fauna led to the discovery of MMPs. However, attention to marine microorganisms, especially those found in oceanic ecosystems, did not grow until the 1950s and 1960s. Several interesting chemicals with medicinal potential were identified due to early research on marine microorganisms, including fungus and bacteria. New classes of bioactive compounds have been discovered thanks to the abundance of understudied microbial biodiversity found in the marine environment, which is home to a vast diversity of microorganisms in different ecological niches (Shu & Huang, 2022). A landmark moment in the history of MMP discovery came in the 1970s with the identification of the first marine-derived antibiotic, *Erythromycin*, produced by the bacterium *Saccharopolyspora erythraea*. This compound, used as an antibiotic, marked the beginning of systematic efforts to explore marine microorganisms for novel drug leads. Since then, marine-derived bioactive compounds have contributed to developing critical pharmaceuticals, particularly in the fight against bacterial infections, cancer, and chronic diseases. The rich chemical diversity found in marine microorganisms continues to fuel intense research into new classes of compounds that are bioactive and effective in various therapeutic applications.

The significance of MMPs in contemporary medication development has increased dramatically in recent years. With their capacity to generate distinct bioactive molecules that are very different from those derived from terrestrial sources, marine microorganisms provide a clear advantage in the search for novel therapeutic agents that can overcome the drawbacks of currently available medications. MMPs have demonstrated encouraging activity in several therapeutic domains, including cardiovascular illness, neurological diseases, oncology, and antibiotic resistance, a growing global health concern. While some compounds derived from marine sources have demonstrated strong anti-cancer effects by focusing on pathways involved in tumor growth and metastasis, others have demonstrated efficacy in treating drug-resistant infections from pathogens like *Mycobacterium tuberculosis* and *Staphylococcus aureus*. The significance of MMPs extends beyond infectious diseases and cancer treatment; they also hold substantial promise in regenerative medicine (Main et al., 2023). Several marine microbial compounds exhibit remarkable anti-inflammatory, wound healing, and tissue regeneration properties. Marine-derived biomaterials, including those sourced from microorganisms, are increasingly being investigated for wound healing, bone regeneration, and even stem cell therapies. The discovery of bioactive peptides and proteins from marine microbes has expanded the horizon of regenerative medicine, offering potential treatments for various chronic conditions that require tissue regeneration, including spinal cord injuries, osteoarthritis, and burns. Moreover, MMPs are at the forefront of addressing challenges posed by the rising tide of antimicrobial resistance (AMR). The increasing prevalence of antibiotic-resistant infections underscores the urgent need for new, effective antimicrobial agents. Marine-derived products, which often have distinct mechanisms of action, provide an exciting avenue for developing next-generation antibiotics and antifungal agents. By focusing on the unique secondary metabolites produced by marine microbes, researchers are uncovering new ways to combat resistant pathogens, providing hope for more effective treatments in the future.

MMPs are an understudied but fascinating resource in biomedicine because they provide a wide range of bioactive compounds with different pharmacological properties (Ahmed et al., 2022). The historical discovery of MMPs and advancements in marine microbiology have led to an expanding field of research focused on harnessing the therapeutic potential of these compounds. In modern drug

research and regenerative medicine, these items provide a helpful alternative to traditional pharmaceuticals, particularly in tissue regeneration, AMR, and cancer treatment. Unlocking the full potential of MMPs and developing innovative treatment approaches to address some of the most urgent global health issues depend on the ongoing study of marine microorganisms.

6.2 Biotechnological potential of marine microbial products

The enormous biotechnological potential of MMPs has attracted much interest, especially in antibacterial, antiviral, and anticancer treatments. Marine microorganisms have evolved special bioactive chemicals with strong biological activity because of the harsh conditions in the marine environment, including high pressure, salt, and low light (Ghosh et al., 2022). These substances, which are frequently created as secondary metabolites, provide marine life with chemical defenses but have also shown great promise in biotechnological and pharmacological uses. This examines MMPs antibacterial, antiviral, and anticancer qualities, emphasizing their important significance in contemporary therapeutic research and drug discovery.

The discovery of marine-derived antibiotics and antifungals has revolutionized the field of antimicrobial drug development. Marine microorganisms, including bacteria, fungi, and actinomycetes, produce a range of bioactive compounds that exhibit strong antimicrobial properties. These natural products can inhibit the growth of pathogenic microorganisms, including bacteria, fungi, and other microbes, making them vital sources of novel therapeutic agents, particularly in the face of growing concerns over AMR. Erythromycin, which was isolated from the marine bacteria *Saccharopolyspora erythraea* in the 1950s, is among the most well-known instances of antibiotics produced from marine sources. In treating bacterial infections, particularly those brought on by Gram-positive bacteria, erythromycin has emerged as a key component. A viable remedy for the growing issue of antibiotic resistance is offered by other marine-derived antibiotics, such as Lobophorin from marine actinomycetes and Bromosporine from marine sponges, which have demonstrated efficacy against bacterial strains resistant to multiple drugs. Similarly, marine fungi like *Aspergillus* and *Penicillium* generate a range of antifungal substances, including *Pyranonigrin A*, that have demonstrated efficacy against fungal infections in humans. Marine microbes have created special chemicals that target bacteria resistant to antibiotics and conventional antibacterial agents. The ongoing discovery of such novel antimicrobial agents from marine sources offers hope for combating the rising tide of AMR and expanding the arsenal of drugs available to treat infectious diseases.

In addition to their antibacterial properties, marine microbes provide a rich source of antiviral medications, which are increasingly important in the fight against viral illnesses (Cedeño Muñoz et al., 2024; Geahchan et al., 2021). These marine-derived antiviral compounds can target a range of viral infections, including those that cause diseases like HIV, influenza, and emerging viruses like SARS-CoV-2. Marine microorganisms create various bioactive compounds with antiviral effects, from direct virus inhibition to immune regulation. Olivomycin is one such substance made by the marine actinomycete *Streptomyces albus*. Olivomycin has shown significant antiviral activity against the herpes simplex virus and other DNA viruses, inhibiting viral replication by interfering with viral DNA synthesis. Other marine-derived antiviral compounds, such as *Palytoxin* from marine corals, have exhibited activity against retroviruses, including HIV. These compounds are of particular

interest because of their ability to target specific steps in the viral replication cycle, providing a unique mechanism of action compared to conventional antiviral drugs. Another promising marine antiviral agent is *Marinomycin*, derived from marine actinomycetes, which has demonstrated activity against various RNA viruses, including the hepatitis C virus. The increasing incidence of viral infections and the rise of drug-resistant viral strains highlight the urgent need for new antiviral agents. MMPs represent a largely untapped source of novel antiviral compounds with unique structures and mechanisms of action, providing a promising avenue for developing antiviral drugs.

With several of its chemicals demonstrating cytotoxic activity against cancer cells, MMPs also hold great promise for cancer therapy. Sea microorganisms have produced a multitude of complex secondary metabolites with anticancer capabilities due to the harsh conditions of the sea environment (Geahchan et al., 2021). These substances can target cancer cells in several ways, including suppressing metastasis, inducing apoptosis, and inhibiting cell proliferation. The chemical Bryostatin-1, which was isolated from the marine bryozoan *Bugula neritina*, is among the most well-known instances of anticancer medicines obtained from marine sources. By activating protein kinase C, a crucial enzyme involved in cell signaling and tumor progression, bryostatin-1 has shown intense action against various cancer types, including lymphoma, breast cancer, and prostate cancer. Clinical trials of bryostatin-1 are presently being conducted as a component of combination medicines to increase the efficacy of chemotherapy and enhance patient outcomes. Other marine microbial compounds, including bryostatins, have demonstrated potential in the treatment of cancer. Similarly, compounds like *Marine Microbe Derived Cytotoxic Peptides* and *Lobophorin A* have demonstrated the ability to inhibit cancer cell growth and proliferation through various molecular mechanisms, making them potential candidates for the development of targeted cancer therapies. Moreover, some marine microbes produce compounds with anti-metastatic properties, which can prevent the spread of cancer cells to other parts of the body. *Salinosporamide A*, previously mentioned for its antimicrobial properties, has also shown significant anti-cancer activity by inducing cell cycle arrest and apoptosis in cancer cells. Its ability to target proteasomal degradation pathways in cancer cells highlights its potential as a novel treatment for resistant cancers.

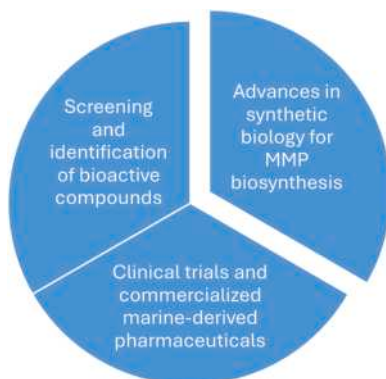
Products from marine microbes have a wealth of biotechnological promises, especially for antibacterial, antiviral, and anticancer treatments. Thanks to the special bioactive chemicals obtained from marine microorganisms, drugs that treat serious health issues, including cancer, viral infections, and antibiotic resistance, have already been developed. New, highly effective medicinal compounds will undoubtedly be discovered because of ongoing research into marine ecosystems and the expanding knowledge of marine microbial biodiversity (Sigwart et al., 2021). The biotechnological uses of MMPs constitute a promising area in contemporary medicine, potentially transforming therapeutic approaches and enhancing global health outcomes as we deal with a growing burden of infectious diseases and cancer (Table 6.1).

6.3 Marine microbial products in drug discovery and development

As illustrated in Fig. 6.1, MMPs have become a major source of bioactive chemicals, providing new avenues for medication, discovery and development. Numerous natural compounds with strong pharmacological qualities are produced by marine microorganisms, such as bacteria, fungus, and actinomycetes. The medicinal potential of these substances, which are developed to aid species in

Table 6.1 Summary of major marine-derived bioactive compounds.

Compound	Source organism	Function	Target disease/condition	Development status
Trabectedin (ET-743)	Ecteinascidia turbinata (sea squirt)	DNA-binding, antitumor agent	Soft tissue sarcoma, ovarian cancer	Approved (clinical)
Brentuximab vedotin (SGN-35)	Marine-derived peptide conjugate	Antibody-drug conjugate targeting CD30	Hodgkin lymphoma, systemic anaplastic large-cell lymphoma	Approved (clinical)
Ziconotide (Prialt®)	Conus magus (marine cone snail)	Calcium channel blocker (analgesic)	Chronic severe pain (neuropathic)	Approved (Clinical)
Salinosporamide A (Marizomib)	Salinispora tropica (marine actinomycete)	Proteasome inhibitor	Multiple myeloma, glioblastoma	Clinical (Phase III)
Didemnin B	Trididemnum solidum (tunicate)	Antiviral and antitumor peptide	Viral infections, cancer	Preclinical (discontinued)
Halichondrin B / Eribulin	Halichondria okadai (marine sponge)	Microtubule dynamics inhibitor	Metastatic breast cancer	Approved (clinical)
Bryostatin-1	Bugula neritina (marine bryozoan)	Protein kinase C modulator	Alzheimer's disease, cancer	Clinical (Phase II)
Plitidepsin (Aplidin®)	Aplidium albicans (tunicate)	Antiviral, antitumor	Multiple myeloma, COVID-19 (investigated)	Approved in some countries (clinical)
Soblidotin (TZT-1027)	Marine sponge-derived	Microtubule-targeting agent	Solid tumors	Clinical (Phase II)
Hemiasterlin	Hemiasterella minor (marine sponge)	Microtubule depolymerizer	Prostate and colon cancers	Preclinical

**FIGURE 6.1**

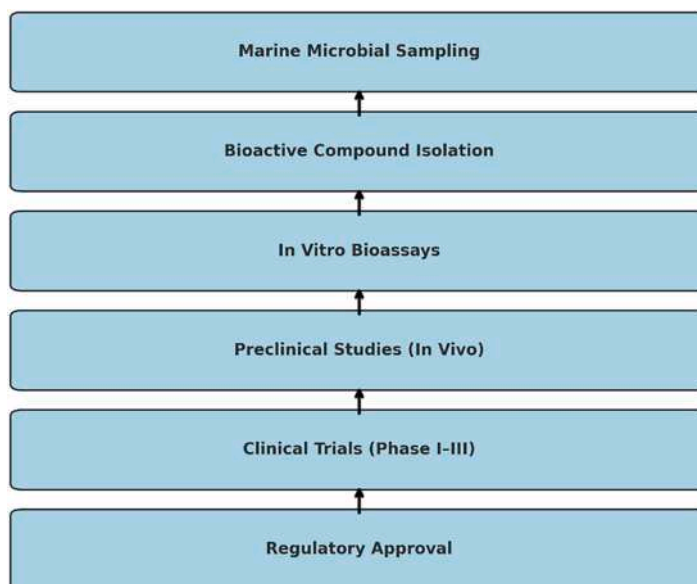
Marine microbial products in drug discovery and development.

surviving in hostile marine settings, is being investigated increasingly ([Aransiola et al., 2024](#)). Clinical trials and the commercialization of medications produced from marine sources are covered, along with the procedures for screening and finding bioactive chemicals and the developments in synthetic biology to manufacture MMPs.

The discovery of novel bioactive compounds from marine microorganisms begins with effective screening methods. Marine environments, such as deep-sea ecosystems, coral reefs, and tidal pools, host vast unexplored microbial diversity ([Shredah et al., 2023](#)). To access this biodiversity, researchers often collect marine samples, such as water, sediment, or marine organisms, and isolate the microorganisms residing within them. These microorganisms are then cultured and screened to produce bioactive compounds with pharmacological properties.

The primary goal of the screening process is to identify compounds that exhibit activity against specific biological targets, such as cancer cells, bacterial or fungal pathogens, or viral infections. The screening process typically involves using bioassays to test the extracted compounds' antimicrobial, antiviral, anticancer, or anti-inflammatory properties. In recent years, high-throughput screening (HTS) technologies have accelerated the identification of promising bioactive compounds from marine microorganisms. These technologies allow researchers to screen thousands of microbial extracts in a short period, vastly expanding the potential to discover novel compounds. Additionally, advances in genomics and metagenomics have enabled researchers to gain deeper insight into the genetic makeup of marine microorganisms, further aiding the identification of bioactive compounds ([Huang et al., 2023](#)). By analyzing microbial genomes, scientists can predict the production of specific secondary metabolites, guiding the isolation of promising drug leads ([Fig. 6.2](#)).

Even with MMPs' encouraging promise, producing enough marine-derived chemicals for therapeutic use is still challenging. The microbial producers of many marine natural products only create trace amounts, which makes large-scale manufacturing challenging and expensive. However, new approaches to this problem are being offered by developments in metabolic engineering and synthetic biology. Researchers can alter the biosynthesis pathways of marine microbes or even transfer genes from marine organisms into more easily grown microorganisms through synthetic

**FIGURE 6.2**

Flow diagram illustrating the drug development stages from marine microbial product isolation to clinical trials.

biology (Bourgade & Stensjö, 2022). Scientists can maximize the synthesis of desirable bioactive chemicals by using genetic engineering approaches. This process is known as heterologous expression, allowing for the large-scale production of marine bioactive compounds. Moreover, advances in gene editing tools, such as CRISPR-Cas9, have made it possible to fine-tune the biosynthetic pathways of marine microorganisms, enhancing the yield and efficiency of compound production. This reduces the cost of drug development and ensures a more sustainable supply of bioactive marine compounds for clinical applications. By combining synthetic biology with traditional fermentation techniques, researchers can create a platform for the large-scale production of marine-derived drugs, facilitating the transition from laboratory discovery to commercial production.

Promising MMPs must pass stringent testing in preclinical and clinical studies to evaluate their safety, efficacy, and therapeutic potential when found and generated in adequate amounts. There are various steps involved in turning a natural product into an authorized medication, such as in vitro testing, animal research, and human clinical trials. Numerous medications with marine origins have already progressed to clinical trials and found success on the market. Cytarabine, an anticancer medication made from the marine sponge *Tethya crypta*, is among the most well-known examples. Since its approval in the 1960s, cytarabine has been used extensively to treat lymphoma and leukemia. Another successful marine-derived drug is *Erythromycin*, an antibiotic isolated from the marine bacterium *Saccharopolyspora erythraea*. Erythromycin has been used for decades to treat various bacterial infections and remains an important part of the antibiotic armamentarium. More recently, *Bromosporine*, a compound derived from marine bacteria, has shown promising results in preclinical studies for its antimicrobial activity against resistant bacterial strains. In addition to antimicrobial and

anticancer drugs, marine-derived products are being tested for their potential in treating neurodegenerative diseases, such as Alzheimer's and Parkinson's diseases, and viral infections like HIV. For example, *Bromophene*, isolated from marine fungi, has shown antiviral properties and is currently undergoing trials for its potential to treat viral infections. The commercialization of marine-derived pharmaceuticals has spurred the development of biotechnological platforms to produce these compounds. Biotech companies have increasingly focused on marine drug discovery, recognizing the potential for new marketable drugs that address the growing global health challenges of AMR, cancer, and viral diseases (Gomes et al., 2021).

Novel bioactive chemicals with various pharmacological characteristics can be found in MMPs, which opens exciting new possibilities for medication development and discovery. Advances in metagenomics, genomics, and HTS have entirely changed the process of finding and screening marine microbes for medicinal chemicals. Furthermore, these chemicals are now more readily available for clinical trials and commercial applications due to the large-scale synthesis made possible by synthetic biology and metabolic engineering. Numerous medications derived from marine sources, such as erythromycin and cytarabine, have already shown notable clinical effectiveness, and research is still being conducted to find novel therapeutic compounds from the marine environment. As the global demand for new drugs to combat AMR, cancer, and viral infections grows, MMPs are poised to play a critical role in shaping the future of biomedicine.

6.4 Role of marine microbial products in regenerative medicine

The developing area of regenerative medicine aims to replace or repair damaged tissues and organs by utilizing the body's inherent healing mechanisms, as illustrated in Fig. 6.3. Marine microbes are

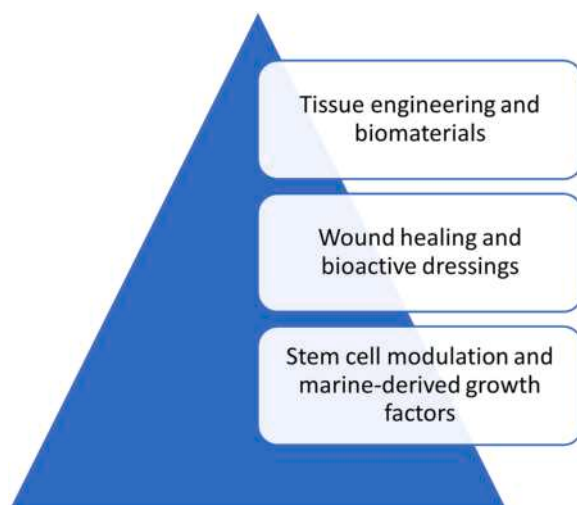


FIGURE 6.3

Role of marine microbial products in regenerative medicine.

becoming more well-known as new sources of therapeutic agents because of their special bioactive substances that can aid in stem cell regulation, wound healing, and tissue engineering. Numerous organisms in the oceans, including bacteria, fungi, and algae, are the source of MMPs. These organisms have evolved to create a wide range of bioactive compounds. These products have enormous potential in regenerative medicine because of their unique qualities, including biocompatibility, bioactivity, and the capacity to stimulate tissue regeneration.

Tissue engineering is a cornerstone of regenerative medicine, where scaffolds, cells, and bioactive molecules are combined to create functional tissues for therapeutic purposes. Marine-derived compounds have been increasingly integrated into developing biomaterials used in tissue engineering (Fernandes et al., 2022). Chitosan, a biopolymer derived from marine crustaceans, is a prime example. It is widely used as a scaffold material due to its biocompatibility, biodegradability, and antimicrobial properties. Chitosan's ability to support cell growth, facilitate tissue attachment, and promote angiogenesis (forming new blood vessels) makes it an ideal candidate for various tissue engineering applications, including skin, bone, and cartilage regeneration. Marine sponges, corals, and algae also produce collagen-like proteins and polysaccharides that can be used to create scaffolds for tissue regeneration. These materials mimic the extracellular matrix (ECM), which provides structural and biochemical support to cells, and thus facilitate tissue formation and repair. Marine-derived ECM components in tissue engineering have shown promise in enhancing cellular differentiation and promoting the regeneration of tissues such as cartilage, bone, and skin.

The ability of marine microbial compounds to hasten wound healing is among their most important uses in regenerative medicine. Effective therapies are necessary to improve tissue healing and lower problems like infection in chronic wounds, such as diabetic ulcers, burns, and pressure sores (Eriksson et al., 2022). Bioactive substances from marine sources, including proteins, polysaccharides, and peptides, have demonstrated outstanding potential. Marine-derived bioactive dressings have improved wound healing by promoting tissue regeneration and reducing infection. Alginate dressings can absorb wound exudate, maintain a moist wound environment, and promote cell migration, thereby speeding up the healing process. Furthermore, marine-derived antimicrobial peptides (AMPs) have been identified in marine organisms like fish and mollusks. These peptides have broad-spectrum antimicrobial activity and can be incorporated into wound dressings to prevent infection and promote healing.

Additionally, marine microbes produce enzymes, such as collagenases, which aid in breaking down damaged ECM components during the healing process. These enzymes promote the turnover of dead tissue and facilitate the migration of healing cells to the wound site. The use of MMPs in bioactive dressings accelerates healing, reduces scarring, and improves tissue regeneration. Stem cell therapy holds great promise for regenerative medicine, as stem cells can differentiate into various cell types and regenerate damaged tissues. The effectiveness of stem cell therapy depends, in part, on the molecular signals that guide stem cell differentiation and tissue formation. Marine-derived growth factors and signaling molecules have shown potential in modulating stem cell behavior, enhancing their regenerative potential.

Marine organisms produce various growth factors, cytokines, and other bioactive molecules that can influence stem cell proliferation, differentiation, and migration (Nathan & Ramachandran, 2022). When derived from marine sources, these growth factors are particularly effective in stimulating stem cell activity and tissue regeneration. Marine microorganisms also produce novel molecules interacting with stem cells to promote their survival and differentiation. Marine-derived polysaccharides like

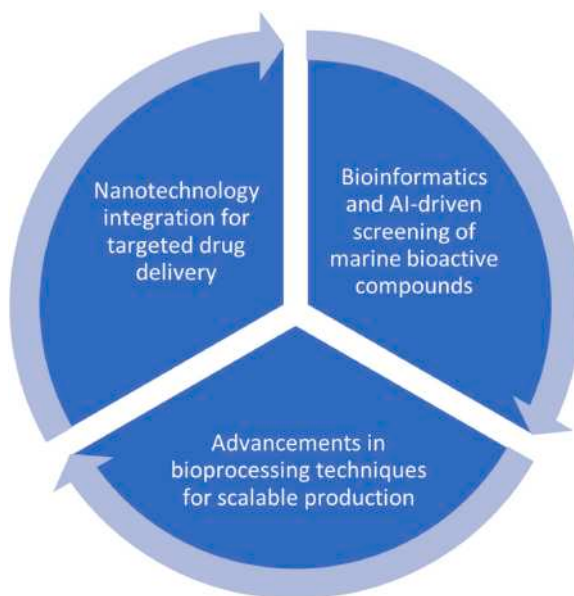
fucoidan, found in brown algae, have enhanced the proliferation and differentiation of mesenchymal stem cells, a type of stem cell commonly used in regenerative therapies. These molecules can activate specific cell surface receptors, triggering intracellular signaling pathways that promote stem cell differentiation into desired cell types, such as cartilage, bone, or nerve cells. Furthermore, three-dimensional scaffolds that offer a microenvironment favorable to stem cell growth and differentiation can be made using ECM components derived from marine sources, such as marine sponges. The effectiveness and results of regeneration treatments may be enhanced by adding MMPs to stem cell-based therapies. Products made from marine microbes have special and exciting prospects for the development of regenerative medicine. Scientists and medical professionals can create novel biomaterials for tissue engineering, hasten wound healing, and enhance stem cell-based treatments by utilizing the bioactive chemicals found in marine species. The continued exploration of marine microbes for their regenerative properties can revolutionize the treatment of injuries, degenerative diseases, and chronic conditions, ultimately improving patient outcomes and quality of life (Carvalho et al., 2021). As research in this field progresses, integrating marine-derived compounds into clinical practice will likely expand, offering novel solutions to some of the most challenging medical conditions in regenerative medicine.

6.5 Technological advancements in marine microbial product utilization

More than 70% of the Earth's surface comprises seas home to various marine life. Many of these organisms have special qualities that might be used in various fields, including business, agriculture, and medicine. The capacity of marine microbes to generate bioactive chemicals with unique structures and biological activities has drawn more attention than ever before (Aransiola et al., 2021; Srinivasan et al., 2021). Significant technological developments in recent years have made exploring and using MMPs easier, especially in industrial processes, bioengineering, and medication research (Fig. 6.4). These technological innovations, including integrating nanotechnology, bioinformatics, artificial intelligence (AI)-driven screening, and advanced bioprocessing techniques, enhance the discovery, production, and application of marine bioactive compounds.

The utilization of MMPs for medication research and discovery is among their most intriguing uses. Numerous bioactive substances with potential medical uses, such as antibacterial, anticancer, and anti-inflammatory qualities, are produced by marine species. The difficulty, though, frequently resides in efficiently delivering these substances to the intended locations within the body. A potent method for overcoming this obstacle is nanotechnology, particularly when paired with MMPs. Nanoparticles, which can be designed to encapsulate bioactive chemicals taken from marine sources, are made possible by nanotechnology. By targeting cells or tissues, these nanoparticles can improve the effectiveness of medications and reduce their adverse side effects. Similarly, nanoparticles can deliver anticancer compounds from marine microbes directly to tumor sites, minimizing damage to healthy cells and improving the therapeutic outcome. The integration of nanotechnology with MMPs is poised to revolutionize drug delivery systems, making treatments more precise, effective, and safe (Mohanta et al., 2023).

Identifying and discovering bioactive compounds from marine microbes has traditionally been a slow and labor-intensive. However, recent advancements in bioinformatics and AI-driven

**FIGURE 6.4**

Technological advancements in marine microbial product utilization.

technologies are dramatically speeding up this process. Bioinformatics allows scientists to analyze the genetic sequences of marine microbes, identifying genes that are likely to encode for bioactive compounds. This approach, known as genomic mining, can provide insights into the molecular pathways and structures of novel bioactive molecules before they are produced. AI, on the other hand, is transforming the way we screen for potential bioactive compounds. Machine learning algorithms can analyze vast datasets of marine microbial genomes, metabolites, and experimental results, predicting which compounds may possess desirable biological activities. By automating the screening process, AI can prioritize the most promising candidates for further research, increasing the likelihood of discovering effective drugs. AI is also being used to optimize the production of bioactive compounds by predicting how certain strains of marine microbes will behave under different growth conditions, leading to more efficient and cost-effective production strategies. For instance, AI models have lately been included in early drug discovery pipelines, target prediction, and bioprocess control. Among the noteworthy AI tools and platforms used in these fields are AI compound prediction tools such as DeepChem. Deepchem is an open-source deep learning toolkit meant for bioactivity and molecular property prediction. It supports activities including virtual screening and graph convolutional network toxicity estimate (Wu et al., 2018). MoleculeNet is a benchmark suite merged with DeepChem designed to validate molecular machine learning models. DeepMind developed AlphaFold, a deep learning model that highly accurately forecasts protein 3D structures, so enabling studies on marine compound-target interactions (Jumper et al., 2021). A graph neural network-based tool for QSAR modeling and natural product efficacy prediction, Chemprop (Yang et al., 2019). AI tools are

currently being exploited for fermentation optimization. Minimally experimental runs of Bayesian Optimization (e.g., Spearmint) are used to optimize culture conditions. Widely used for bioprocess modeling and increasing metabolite yields from marine microbial fermentation, artificial neural networks and genetic algorithms (Damian et al., 2024). IBM RXN is also used to simulate biosynthesis routes and support reaction condition design on a cloud-based AI platform in data mining and process design to extract and combine biological relationships for enhanced compound yield.

Finding new marine bioactive chemicals is crucial, but scaling up production to satisfy industrial demands is the next big obstacle. Conventional fermentation methods can be ineffective and challenging to scale when used to produce bioactive chemicals from marine microorganisms. However, the scalability and cost-effectiveness of producing MMPs have been greatly enhanced by recent developments in bioprocessing techniques. The creation of microbial strains that have been developed and optimized for large-scale fermentation is one example of this progress. Researchers can alter marine microorganisms' metabolic pathways to increase their yields of bioactive chemicals more effectively by using synthetic biology techniques. Additionally, advances in bioreactor design, including continuous-flow systems, have made it possible to maintain optimal growth conditions for marine microbes over extended periods, further improving the scalability of production processes.

Additionally, biocatalysis is being investigated as a potential substitute technique to produce bioactive chemicals originating from marine sources. Using marine microorganisms' enzymes to catalyze the creation of complex compounds is known as biocatalysis. This method is a desirable substitute for conventional chemical synthesis techniques since it has several benefits, such as good selectivity, benign reaction conditions, and fewer byproducts. It is feasible to create more economical and environmentally friendly production processes for marine bioactive chemicals by fusing biocatalysis with sophisticated fermentation techniques. Many industries could be revolutionized using MMPs, including those in biotechnology, agriculture, and medicine (Olaniyan & Adetunji, 2021). The integration of nanotechnology for targeted drug delivery, bioinformatics and AI-driven screening for compound discovery, and advancements in bioprocessing techniques for scalable production are accelerating the development and commercialization of marine bioactive compounds. These technological advancements are not only enabling the identification of new therapeutic agents but are also enhancing the efficiency, safety, and sustainability of their production. As research in marine microbiology continues to evolve, it is likely that these technologies will play an even more prominent role in harnessing the vast potential of the ocean's microbial inhabitants for a wide range of applications.

6.6 Challenges and barriers to biomedical applications

Significant progress has been made in the realm of biomedical applications, particularly with the discovery of new chemicals and materials obtained from natural resources. Among the most promising sources are marine creatures, which have exhibited exceptional bioactivity and therapeutic potential (Macedo et al., 2021). However, several obstacles and difficulties prevent the broad use of marine-derived products in biomedical applications, even despite the growing interest in these goods. These obstacles include issues with commercialization and large-scale production, ethical and legal

issues with marine bioprospecting, and environmental issues with the use of marine resources, as seen in Fig. 6.5. Addressing these obstacles is crucial for ensuring the sustainable and effective use of marine-based biomedical innovations.

The challenge of producing marine-derived products on a large scale is one of the main obstacles to their broad use in biomedical applications. Low levels of some bioactive substances, including peptides, enzymes, and polysaccharides, that have been extracted from marine species can be found in their native environments. Large amounts of marine organisms are frequently needed to harvest these chemicals from wild populations, which can be expensive and time-consuming. Furthermore, it is frequently difficult and ineffective to extract, purify, and formulate these chemicals into useful biomedical products. It can be difficult to guarantee consistent quality and performance for therapeutic applications due to batch-to-batch variability in marine-derived chemicals, in addition to the low yields from natural sources. The production of these compounds through traditional harvesting methods is not only limited by the availability of marine organisms but also by the ecological impacts of overharvesting. As a result, the economic feasibility of scaling up the production of marine-derived biomaterials and drugs becomes increasingly difficult. To overcome these challenges, researchers are exploring alternative approaches such as recombinant DNA technology, microbial fermentation, and cell culture systems to produce marine-derived compounds in larger quantities. However, these technologies still face significant hurdles in terms of optimizing yield, cost-effectiveness, and ensuring the biological activity of the compounds. Until these production methods are optimized for scale, the commercialization of marine-derived biomedical products will remain limited.

There are serious ethical and regulatory issues with marine bioprospecting, which is the study of aquatic species for possible biomedical uses. The harvest of marine species for commercial reasons

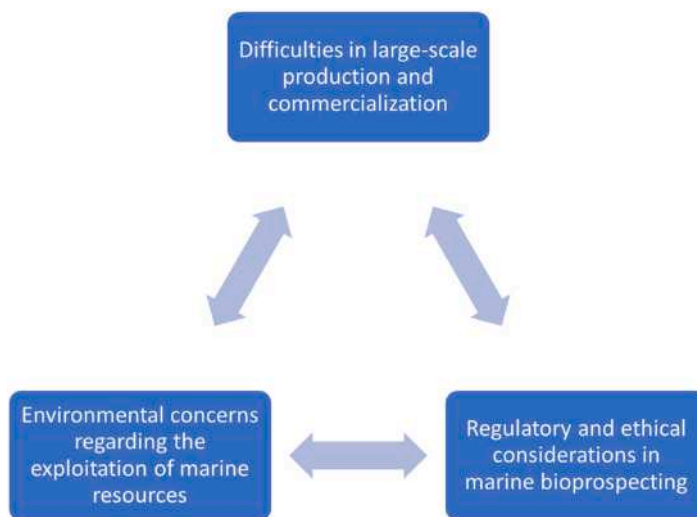


FIGURE 6.5

Challenges and barriers to biomedical applications.

must be done in a way that is both ethical and legal because marine biodiversity is a precious and irreplaceable resource. Conflicts over intellectual property rights and the fair sharing of profits might result from the absence of international regulations controlling the harvesting and marketing of marine species. The CBD, an international treaty aimed at conserving biodiversity and ensuring the fair sharing of benefits arising from the use of genetic resources, provides a framework for bioprospecting. However, the implementation of the CBD has been slow, and there remains a lack of uniformity in regulations across countries and regions (Sandström et al., 2023). This regulatory uncertainty creates challenges for companies and researchers involved in marine bioprospecting, as they must navigate a complex legal landscape to ensure that they are complying with local, national, and international laws. Ethical considerations also play a crucial role in marine bioprospecting. Many marine species are threatened by overexploitation, habitat destruction, and climate change. The collection of marine organisms for bioprospecting must be conducted sustainably to avoid further depletion of these species. Furthermore, there is growing concern about the exploitation of traditional knowledge held by indigenous communities, who may have valuable insights into the medicinal uses of marine organisms. Ensuring that these communities are fairly compensated for their contributions is an ethical consideration that must be addressed to avoid exploitation and ensure that the benefits of marine bioprospecting are shared equitably.

The exploitation of marine resources for biomedical applications also raises significant environmental concerns. Overharvesting marine organisms to extract bioactive compounds can lead to population decline, disruption of marine ecosystems, and loss of biodiversity. In particular, the collection of specific marine species, such as sponges, corals, and marine invertebrates, can cause irreversible damage to fragile marine ecosystems, including coral reefs and deep-sea habitats. In addition to direct harvesting, marine bioprospecting can involve destructive practices, such as dredging, trawling, and other forms of habitat destruction. These methods damage marine organisms' habitats and disturb the delicate balance of marine ecosystems, which can have far-reaching consequences for global biodiversity and climate regulation. As the demand for marine-derived biomedical products increases, the pressure on marine ecosystems to supply these resources will intensify, exacerbating these environmental issues. Sustainable harvesting methods and attempts to raise marine species in regulated settings—like marine aquaculture—should be investigated to allay these worries. By creating synthetic or semi-synthetic substitutes for naturally derived chemicals, marine biotechnology can also potentially lessen the need for wild harvesting. Furthermore, because marine microorganisms like bacteria and algae can be cultivated in labs and do not need to be extracted in huge quantities from wild populations, using them to produce bioactive substances offers a more sustainable method. Marine-derived products have much potential for biomedical applications, but several major obstacles to their development and commercialization exist. Difficulties in large-scale production, regulatory and ethical considerations, and environmental concerns related to resource exploitation must be carefully addressed to ensure the sustainable and equitable use of marine resources in the biomedical field. Advances in biotechnological methods for producing marine-derived compounds and stronger regulatory frameworks and sustainable practices will be essential for overcoming these barriers. Only through a concerted effort to address these challenges can the full potential of marine bioprospecting be realized, leading to novel and effective biomedical solutions that benefit human health and the environment.

6.7 Future directions and research opportunities

Marine creatures produce a wide variety of bioactive chemicals, making the oceans an extraordinarily enormous and mostly unexplored source of biodiversity (Porzani & Nowruzi, 2023). These substances, referred to as MMPs, have enormous potential for the creation of innovative medications, biomaterials, and therapeutic agents for use in biomedical settings. To reach its full potential, the science of marine bioprospecting must overcome several obstacles in the search for and use of these bioactive molecules. For marine bioprospecting to be viable and sustainable in the future, it will be essential to grow marine bioprospecting projects, create creative strategies for sustainable MMP use, and put strong ethical and legal frameworks in place.

The practice of searching for aquatic species for possible beneficial substances, or marine bioprospecting, has grown significantly in the last several years. But a large portion of the ocean's biodiversity is still unknown. Extending efforts to investigate under-explored areas and marine ecosystems, such as deep-sea habitats, hydrothermal vents, and polar regions, is crucial for the future of marine bioprospecting. Because of the special species that have adapted to these harsh settings, new bioactive chemicals with potentially ground-breaking biomedical applications are produced. To accelerate marine bioprospecting activities, technological innovations like next-generation sequencing, HTS tools, and enhanced ocean exploration techniques will be crucial. These technologies, along with metagenomics (the study of genetic material recovered directly from environmental samples), will allow for the identification of novel bioactive compounds at an unprecedented scale. Additionally, interdisciplinary collaboration between marine biologists, chemists, pharmacologists, and biotechnologists will be essential to accelerate the discovery and development of marine-derived therapeutic agents. Collaborative networks and consortia could help to pool resources and expertise, enabling the efficient exploration of marine ecosystems and the identification of compounds with biomedical potential.

Even though marine bioprospecting has a lot of potential, using MMPs sustainably is still a major worry. Due to their slow rate of reproduction, many marine creatures are susceptible to overfishing and population decline. This raises questions regarding the environmental effects of exploiting marine resources and poses a hurdle to the large-scale commercial production of products obtained from marine sources. Innovative strategies are desperately needed to guarantee that marine bioprospecting is ecologically conscious and sustainable as the demand for MMPs rises. The creation of marine aquaculture systems, which entail the sustainable regulated production of marine creatures like algae, corals, or sponges, is one viable strategy. Aquaculture allows for the harvesting of bioactive compounds without depleting wild populations, thus reducing the environmental impact of marine bioprospecting. By cultivating algae in controlled environments, researchers can ensure a consistent supply of bioactive compounds without compromising the integrity of marine ecosystems. Another innovative strategy involves marine biotechnology, particularly the use of microorganisms such as bacteria, fungi, and marine-derived yeasts. These microorganisms can be cultured in laboratories to produce bioactive compounds on a large scale. Researchers may be able to create recombinant production systems that produce greater amounts of bioactive compounds without the need for wild harvesting by separating and identifying the genetic pathways in these organisms that produce bioactive molecules (D'Amelia et al., 2021). With synthetic biology, in which microbes are modified to make molecules that do not exist naturally, this method also presents the prospect of creating novel compounds. Furthermore, increasing the sustainability of MMP consumption would need increasing

the effectiveness of the extraction and purification procedures for compounds originating from marine sources. Green chemistry developments and eco-friendly extraction technologies, including solvent-free or supercritical CO₂ extraction, can reduce the environmental impact of these processes without sacrificing the potency of the bioactive molecules.

The rapid expansion of marine bioprospecting brings with it the need for robust ethical and legal frameworks to ensure the fair and sustainable use of marine resources. As marine organisms are often considered part of the public domain, the lack of clear ownership or intellectual property rights presents challenges for both researchers and companies engaged in marine bioprospecting. Without clear regulations, there is the potential for biopiracy where marine genetic resources are exploited without providing fair compensation to the countries or communities that may have contributed knowledge or access to these resources. To address these challenges, international policies and conventions should be developed to establish clear guidelines for marine bioprospecting. The Convention on Biological Diversity (CBD) and its Nagoya Protocol already provide a framework for the fair and equitable sharing of benefits arising from the use of genetic resources, but these regulations are still not universally adopted. Strengthening the implementation of the CBD and ensuring that countries adhere to these principles is critical for protecting the rights of nations and indigenous communities involved in marine bioprospecting. In addition, national and international regulations should require that marine bioprospecting initiatives adhere to principles of sustainability and conservation. This includes ensuring that the extraction of marine organisms for bioprospecting does not lead to the overharvesting of endangered species or the degradation of marine ecosystems. Policymakers should also promote the establishment of marine protected areas to safeguard marine biodiversity and provide a haven for vulnerable species. Furthermore, there is a growing need for ethical guidelines that protect the traditional knowledge of indigenous communities who have long understood the medicinal properties of marine organisms. These communities should be included in the decision-making process regarding marine genetic resources, ensuring that they are compensated adequately for their contributions and that their knowledge is respected and protected.

Despite the promising future of marine bioprospecting and its biological uses, numerous challenges must be addressed to ensure its sustainability and ethical behavior. Expanding bioprospecting activities will be necessary to find new bioactive compounds, particularly in unexplored maritime settings. In the meantime, innovative techniques like biotechnology and marine aquaculture will ensure that marine resources are exploited responsibly, reducing the ecological impact of harvesting (Glencross et al., 2023). Finally, the interests of the natural world and the communities who rely on maritime resources shall be safeguarded by the establishment of just and transparent ethical and legal frameworks. By addressing these challenges, the biomedical field can unlock the full potential of marine-derived products, ultimately improving human health and fostering a more sustainable relationship with the oceans.

6.8 Conclusion

MMPs offer significant biomedical potential, with an expanding body of research demonstrating their diverse therapeutic applications. Marine organisms, including bacteria, fungi, and algae, produce unique bioactive compounds that can serve as novel antibiotics, anticancer agents, wound healing

materials, and biomaterials for tissue engineering. These compounds are particularly valuable due to their distinct molecular structures and bioactivity, which are often not in terrestrial organisms. With its complex and extreme conditions, the marine environment has led to the evolution of compounds with remarkable pharmacological properties, presenting an untapped resource for drug discovery and therapeutic development.

Important discoveries highlight how MMPs might help with some of the most urgent medical issues, such as tissue regeneration, persistent wounds, and antibiotic resistance. Clinical studies have shown the effectiveness of MMPs in terms of growth factors, polysaccharides, and AMPs, indicating their wide range of uses in the pharmaceutical and healthcare sectors. These products are being investigated more and more as supplements or substitutes for established medications, providing fresh approaches to treatment, especially for ailments for which there are currently few options. There are great opportunities for the future of MMP integration in cutting-edge medical applications. Current issues with large-scale manufacturing are anticipated to be resolved by biotechnology innovations including recombinant production and sustainable marine cultivation. Additionally, creating ethical and regulatory frameworks will guarantee the continued responsibility and equity of marine bioprospecting. MMPs have the potential to transform drug discovery, regenerative therapies, and personalized medicine, making them a vital component of next-generation healthcare solutions.

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Antiaging products from marine sponges and their symbiotic microbes

Adekunle Babajide Rowaiye¹, Daniel Uchechukwu Eze^{1,2}, Joy Chioma Okoli¹,
Tobilola O. Akingbade¹, Abiodun Abidemi Folarin³, Kelechi Ezennubia⁴ and Gordon C. Ibeanu¹

¹Department of Pharmaceutical Sciences, North Carolina Central University Sciences, Durham, NC, United States,

²Department of Pharmaceutical Microbiology and Biotechnology, David Umahi Federal University of Health Sciences, Uburu, Ebonyi State, Nigeria,

³Department of Chemistry and Biochemistry, North Carolina Central University, Durham, NC, United States,

⁴Department of Chemistry and Biochemistry, Baylor University, Waco, TX, United States

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7.1 Introduction

The global demand for antiaging solutions has surged due to growing consumer awareness, biotechnological advancements, and an aging population. The antiaging skincare industry was projected to surpass \$71.6 billion by 2023, driven by increasing interest in effective and natural products (Adhikari et al., 2025). Consumers, particularly in Asia and North America, are shifting toward preventive skincare, contributing to market expansion (Rodriguez et al., 2024).

A major industry trend is the preference for natural and bioactive ingredients, as concerns over synthetic chemicals drive demand for plant-based and marine-derived compounds. Marine sponges, known for their antioxidant and collagen-boosting properties, are becoming key elements in next-generation antiaging formulations (Esposito et al., 2021). At the same time, biotechnological

innovations such as exosome-based treatments, peptide formulations, and microbiome-enhancing skincare have reshaped the industry. Notably, cell culture-conditioned media offer enhanced rejuvenation and skin repair, bridging dermatology and biotechnology (Rodriguez et al., 2024). Additionally, sustainability and ethical concerns are influencing consumer choices, fueling demand for biomass-based cosmetics, biodegradable packaging, and cruelty-free solutions (Arung et al., 2024).

Another breakthrough is synbiotic skincare, which combines prebiotics and probiotics to optimize skin microbiome health. Research on marine microorganisms, particularly sponges, highlights their antioxidant activity and collagen production, making them essential for advanced antiaging solutions (Rahman et al., 2024).

Marine ecosystems, covering over 70% of the earth's surface, are a vast source of bioactive compounds with pharmaceutical, cosmetic, and nutraceutical applications (Gozai-Alghamdi et al., 2025; Kumarasinghe et al., 2025). Extreme marine conditions drive the evolution of unique biochemical pathways, making these organisms valuable for novel metabolites (Rampelotto, 2024).

Recent studies identified antiviral piperazine derivatives from *Haloplegma duperreyi* (Boopathi et al., 2025) and antitumor bioactive molecules from *Callinectes sapidus* (Longo et al., 2025). Antiaging molecules that show antioxidant and collagen-boosting effects (El-Seedi et al., 2025). As bioprospecting advances, sustainable harvesting and synthesis methods are being explored to minimize environmental impact while maximizing medicinal and industrial potential (Sahebkar & Eid, 2025).

Marine sponges (*Porifera*), among the oldest metazoans, maintain intricate symbiotic relationships with bacteria, archaea, cyanobacteria, microalgae, and fungi, which aid in physiology, defense, and bioactive metabolite production. Microbiome profiling has identified *Actinomyces* in tropical sponges, producing antibacterial, antiviral, and antiinflammatory compounds (Weeraphan et al., 2025). Antarctic sponges support microbial eukaryotes that influence nutrient cycling and host defense (López-Rodríguez et al., 2024). Symbionts can constitute up to 40% of sponge biomass, providing nutritional and defensive benefits. *Halichondria* species harbor *Candidatus Entotheonella*, a key producer of bioactive metabolites (Kim et al., 2025). Recent metagenomic studies also uncovered many bioactive molecules with antiaging applications. Research continues to explore microbial diversity in sponges for pharmaceutical and cosmetic applications (Ding et al., 2022).

This study explores antiaging products derived from marine sponges and their symbiotic microbes, focusing on their bioactive molecules and mechanisms of action. It investigates how these marine-derived molecules contribute to skin regeneration, collagen synthesis, antioxidant, and other antiaging activities. The findings highlight the potential of sponge-associated microbes in developing innovative and sustainable antiaging formulations.

7.2 Aging and its molecular mechanisms

7.2.1 Oxidative stress and aging

Aging is a complex biological process shaped by genetic, environmental, and biochemical influences. The oxidative stress theory, one of the most accepted explanations of aging, proposes that an imbalance between reactive oxygen species (ROS) production and antioxidant defenses leads to

cumulative cellular and molecular damage (Hajam et al., 2022). Excessive ROS contributes to DNA damage, lipid peroxidation, and protein oxidation, resulting in cellular decline (Jomova et al., 2023). Mitochondria, the main source of ROS, become less efficient with age, leading to dysfunction linked to neurodegenerative disorders, cardiovascular diseases, and metabolic conditions (Ionescu-Tucker & Cotman, 2021; Vatner et al., 2020).

Oxidative stress also accelerates skin aging through collagen degradation (Papaccio et al., 2022) and impacts ovarian function, thereby affecting female fertility (Yang et al., 2021). To combat ROS, cells use antioxidant systems, notably the Keap1-Nrf2 pathway, which regulates protective responses; its dysfunction is associated with accelerated aging. Enhancing Nrf2 activity may delay age-related decline (Yu & Xiao, 2021). Autophagy is another protective mechanism that clears damaged cellular components; impaired autophagy increases oxidative stress and aging (Peters et al., 2020).

Several interventions aim to reduce oxidative stress and promote longevity. Dietary antioxidants, such as polyphenols, flavonoids, and vitamins C and E, help neutralize free radicals and improve health span by boosting cellular defenses and reducing inflammation (Akbari et al., 2022). These are found in fruits, vegetables, and beverages like green tea and are linked to improved cognition and reduced chronic disease risk (Kandlur et al., 2020).

Physical activity enhances mitochondrial efficiency, reduces ROS, and upregulates endogenous antioxidant enzymes like superoxide dismutase (SOD) and glutathione peroxidase (Powers et al., 2022). Exercise also improves insulin sensitivity and autophagy, supporting longevity (Zhou et al., 2025). Caloric restriction, without malnutrition, is another effective strategy. It lowers ROS production, improves mitochondrial function, and activates longevity pathways such as sirtuins (SIRT) and AMP-activated protein kinase (AMPK), promoting metabolic efficiency and DNA repair (Luo et al., 2020; Rakshe et al., 2024; Tomtheelnganbee et al., 2022).

Pharmacological agents are emerging as potential antiaging therapies. Resveratrol activates the SIRT1 pathway, mimicking caloric restriction and enhancing mitochondrial function (Venkat et al., 2023). Metformin exhibits antioxidant effects and may extend lifespan by reducing oxidative damage and inflammation (Feng et al., 2022). Rapamycin, an mTOR inhibitor, delays aging by reducing cellular senescence and enhancing autophagy (Zhang et al., 2021).

Oxidative stress is a major driver of aging and associated diseases, but interventions like dietary antioxidants, physical activity, caloric restriction, and pharmacological agents offer promising strategies to enhance cellular resilience and promote healthy aging.

7.2.2 Chronic inflammation and cellular senescence

Chronic inflammation and cellular senescence are closely linked biological processes that play critical roles in aging and the development of age-related diseases. Inflammation, while vital for immune defense, becomes harmful when chronic, leading to tissue damage and dysfunction. Cellular senescence, a state of irreversible cell cycle arrest, contributes to tissue aging when senescent cells accumulate and secrete pro-inflammatory factors collectively known as the senescence-associated secretory phenotype (SASP), which fuels further inflammation and senescence (Livshits & Kalinkovich, 2023; Thapa et al., 2025).

Aging is marked by mitochondrial dysfunction, immune dysregulation, and altered nutrient-sensing, all of which contribute to chronic inflammation and cellular aging. Mitochondrial damage in

senescent cells elevates ROS levels, impairing energy metabolism and triggering inflammatory pathways like NF- κ B and the NLRP3 inflammasome. These changes disrupt homeostasis and promote fibrosis, immune exhaustion, and tissue degeneration (Li, Li, et al., 2023; Li, Lu, et al., 2023; Wu et al., 2025).

Immune decline during aging reduces clearance of senescent cells, intensifying SASP-driven inflammation and contributing to vascular aging, cognitive decline, and metabolic dysfunction (Wang et al., 2025). Aging also affects nutrient-sensing pathways, mTOR becomes hyperactivated while AMPK activity declines, disrupting autophagy, lipid metabolism, and mitochondrial biogenesis. This imbalance accelerates cellular aging and contributes to diseases like diabetes, obesity, and neurodegeneration (Chrienova et al., 2021; Karagounis & Kassis, 2025).

Chronic inflammation, or “inflammaging,” is a major factor in age-related conditions, impacting the brain, heart, and musculoskeletal system. In the brain, sustained neuroinflammation involving microglia and cytokines leads to synaptic damage and cognitive decline, contributing to Alzheimer’s and Parkinson’s diseases (Balestri et al., 2024). In the cardiovascular system, inflammation promotes endothelial dysfunction, arterial stiffness, and atherosclerosis, increasing the risk of hypertension and stroke (Pacinella et al., 2022). In the musculoskeletal system, senescent cells in joints accelerate cartilage breakdown and bone loss, contributing to osteoarthritis, osteoporosis, pain, and reduced mobility (Favino et al., 2024).

To counter these effects, several therapeutic strategies have emerged. Senolytics selectively eliminate senescent cells, reducing SASP and reversing age-related damage (Lagoumtzi & Chondrogianni, 2021). Antiinflammatory phytochemicals like curcumin, resveratrol, and polyphenols modulate inflammatory pathways and oxidative stress, improving tissue health and promoting longevity (Rudrapal et al., 2022). Microbiome-targeted therapies, including probiotics and synbiotics, restore gut microbial balance, reduce systemic inflammation, and enhance immune regulation (Jadhav et al., 2023).

Recent studies also explore mechanisms contributing to inflammation and senescence. Hypoxia and hypoxia-inducible factors (HIFs) promote inflammation and lung aging (Thapa et al., 2025). Mitochondrial dysfunction drives ROS accumulation and tissue degeneration (Wu et al., 2025). Circadian rhythm disruption exacerbates inflammation and senescence (Wang et al., 2025), while nutrient-sensing imbalances accelerate aging via mTOR and AMPK dysregulation (Karagounis & Kassis, 2025). Neuroinflammation is linked to vascular aging and T-cell senescence, affecting brain health (Zhang et al., 2025); and ferroptosis contributes to vascular inflammation and cardiovascular aging (Sun et al., 2024). Inflammation in joints and bones accelerates skeletal degeneration (Hu et al., 2025), and gut microbiome modulation shows potential in reducing inflammation and promoting healthy aging (Donati Zeppa et al., 2022).

7.2.3 Decline in tissue regeneration and repair mechanisms

Aging is characterized by a progressive decline in tissue regeneration and repair, resulting in impaired wound healing, muscle atrophy, and slower recovery from injuries (Guo et al., 2022). This deterioration is driven by stem cell exhaustion, chronic inflammation, mitochondrial dysfunction, and extracellular matrix (ECM) degradation (Leyane et al., 2022). Mesenchymal stem cells (MSCs)

and muscle satellite cells exhibit reduced proliferative and differentiation capacity with age, impairing skeletal muscle and bone regeneration (Dai et al., 2022).

Mitochondrial dysfunction and oxidative stress further compromise tissue repair by increasing ROS production, promoting senescence-associated secretory phenotype (SASP), and impairing regenerative pathways, especially in neural and musculoskeletal tissues (Wan et al., 2021). Aging also leads to ECM degradation and decreased collagen synthesis, reducing tissue strength and disrupting cellular signaling. Inflammaging and SASP-related fibrosis exacerbate these effects, further hindering tissue regeneration (Guvatova et al., 2022; Mebratu et al., 2023).

7.3 Marine sponges: a rich source of bioactive metabolites

7.3.1 Diversity and ecological significance of marine sponges

Marine sponges (phylum *Porifera*) are among the oldest multicellular organisms, exhibiting remarkable diversity with nearly 9000 known species. They play crucial ecological roles in marine ecosystems, including nutrient cycling, water filtration, and providing habitat for numerous marine species (Bechtel & Bich, 2024; Stratmann et al., 2025).

Sponges thrive in diverse habitats, from shallow coral reefs to deep-sea environments. They exhibit complex symbiotic relationships with microbes, which contribute to their metabolic versatility and ability to produce bioactive compounds (Suruthi et al., 2025). Studies have shown that sponge-associated microbiomes play a pivotal role in carbon and nitrogen cycling, helping to maintain the ecological balance of marine ecosystems (Hanz et al., 2022). Marine sponges play a crucial role in maintaining ecological balance by performing essential functions in marine ecosystems. One of their primary contributions is water filtration, as they filter vast amounts of seawater, effectively removing particulate organic matter and regulating microbial populations (Ribes et al., 2023). This process helps maintain water clarity and nutrient cycling, benefiting marine life.

Additionally, sponges contribute to habitat formation, providing shelter and sustenance for various marine organisms. Their complex structures foster biodiversity, particularly in reef ecosystems, where they serve as habitats for small invertebrates and fish species (Morais et al., 2024). Beyond their structural role, marine sponges and their symbiotic microbes produce a wide array of bioactive compounds, including secondary metabolites with antimicrobial, antiviral, and even antiaging properties. These bioactive substances have significant implications for medicine and biotechnology (Mehbub et al., 2024).

Sponges demonstrate remarkable resilience to climate change, exhibiting adaptability to changing oceanic conditions. Their responses to environmental stressors make them valuable indicators for monitoring ecological shifts, providing insight into the health of marine ecosystems (Bosch-Belmar et al., 2023).

Through these vital ecological functions, sponges not only support marine biodiversity but also offer potential solutions for biomedical advancements and environmental monitoring. Recent research highlights the potential of sponges as biotechnological resources for drug discovery and environmental conservation. Given their role in maintaining marine ecosystem stability, protecting sponge biodiversity is crucial for the health of global oceans.

7.3.2 The symbiotic relationship between marine sponges and microbes

Marine sponges (*Porifera*) indeed form complex symbiotic relationships with diverse microbial communities, which contribute significantly to their ecological success and biochemical diversity (Williams et al., 2024; Yu et al., 2020). These ancient metazoans host a wide array of microorganisms, including bacteria, archaea, fungi, and viruses, which play crucial roles in various aspects of sponge biology (Williams et al., 2024).

The symbiotic relationships between sponges and their microbial partners are defined by a complex interplay of biological features that support both partners and enhance sponge survival across diverse marine environments. One of the most striking characteristics of these associations is the sheer abundance of microbial populations within sponge tissues, which can be several orders of magnitude higher than those found in the surrounding seawater. This high microbial density forms the basis for a rich and diverse microbial community (Williams et al., 2024).

Sponge microbiomes are typically dominated by members of the phylum *Pseudomonadota* and several other core phyla, but they may also encompass up to 30 additional variable phyla, reflecting a broad taxonomic diversity. Despite this diversity, microbial communities within individual sponge species tend to be relatively stable, while considerable variation is observed between species. This pattern points to a high degree of host specificity, where each sponge species maintains a unique and consistent microbial consortium (Williams et al., 2024).

Functionally, these microbial symbionts play critical roles in sponge physiology. They contribute to the host's nutrition through processes such as carbon fixation, B vitamin synthesis, sulfite oxidation, and various forms of nitrogen metabolism (Williams et al., 2024). Beyond nutritional support, microbial partners also enhance the sponge's defense mechanisms. Many of the bioactive compounds produced by sponges are either synthesized directly by microbial symbionts or facilitated by their metabolic pathways. These compounds help protect the sponge against predators, pathogens, and competing organisms (Mehbub et al., 2024). Additionally, the presence of symbiotic microbes allows sponges to thrive in a range of marine environments, including extreme habitats like the deep sea. By aiding chemical adaptation and environmental resilience, microbial partnerships are essential to sponge survival and ecological success (Garritano et al., 2023).

Sponge-associated microbes indeed play crucial roles in maintaining the health and functionality of their host through various mechanisms, including nutrient cycling, chemical defense, and detoxification.

Sponge-associated microorganisms play a vital role in nutrient cycling within both the sponge host and the surrounding marine environment. These symbionts contribute to nitrogen fixation by converting atmospheric nitrogen into bioavailable forms, thus supplying an essential nutrient to the host (Cristi et al., 2022). They are also deeply involved in carbon processing, as sponges and their microbial partners metabolize a significant portion of reef primary production, promoting rapid carbon turnover in reef ecosystems (Colman, 2015). Additionally, sponge endosymbionts have been shown to play a crucial role in marine phosphorus cycling through the production and accumulation of polyphosphate (Colman, 2015). In terms of sulfur metabolism, some sponge-associated bacteria carry out sulfate reduction, further supporting elemental cycling within the sponge holobiont (Abbas & Mahmoud, 2022).

The production of secondary metabolites by sponge-associated microbes plays a vital role in chemical defense, contributing significantly to the sponge's survival in competitive marine

environments. Many of these microbes produce antimicrobial substances that help regulate the sponge's internal microbial community and protect against external microbial threats (Abbas & Mahmoud, 2022). Remarkably, over 5000 bioactive compounds have been isolated from approximately 500 sponge species, with a significant proportion believed to originate from their microbial symbionts (Abbas & Mahmoud, 2022). These metabolites exhibit diverse biological activities, including antifouling properties. For instance, compounds produced by the fungus *Eurotium chevalieri*, found in association with sponges, effectively inhibit the adhesion and growth of marine bacteria and microalgae (Li, Li, et al., 2023; Li, Lu, et al., 2023).

Sponge-associated microbes play a crucial role in enhancing the host's ability to adapt to various environmental stressors. In naturally acidified marine environments, certain sponge species exhibit microbiomes with increased potential for energy-efficient carbon fixation and nitrogen metabolism, aiding in adaptation to ocean acidification (Botté et al., 2019). These symbiotic relationships also demonstrate resilience to nutrient fluctuations; some sponge species maintain stable microbial communities even under eutrophic conditions with elevated nutrient levels (Aransiola et al., 2024; Simister et al., 2012). Additionally, while not directly linked to microbial symbionts, some sponges show high tolerance to short-term acute salinity changes, with microbial communities remaining stable despite the stress (Glasl et al., 2018).

Marine sponges are classified into high-microbial-abundance (HMA) and low-microbial-abundance (LMA) species, with HMA sponges hosting significantly denser and more diverse microbial communities compared to their LMA counterparts (Gan et al., 2024; Moitinho-Silva et al., 2017). HMA sponges harbor 2–4 orders of magnitude greater densities of microbes than LMA sponges, with microbial communities in HMA sponges being dominated by phyla such as *Proteobacteria*, *Chloroflexi*, and *Acidobacteria*, while LMA sponges are primarily dominated by *Proteobacteria* or *Cyanobacteria* (Gan et al., 2024; Moitinho-Silva et al., 2017). The HMA-LMA dichotomy reflects distinct life-history strategies, with LMA sponges exhibiting higher pumping rates and relying more on particulate organic matter, while HMA sponges have a denser mesohyl, lower pumping rates, and depend more on dissolved organic matter (Gan et al., 2024; Lesser, 2023).

Marine sponges host diverse microbial communities that play critical roles in their survival, resilience, and bioactive compound production, with many of these metabolites originating from symbiotic microbes rather than the sponge itself (Mehbub et al., 2024; Varijakzhan et al., 2021). These microbial partners enhance sponge adaptation to extreme environments, as observed in Antarctic species where symbionts provide cold resistance and metabolic flexibility (González-Aravena et al., 2019; Moreno-Pino et al., 2024). Symbiotic microbes contribute to sponge health by offering protection against environmental stressors, aiding adaptation to climate change and pollution (Cárdenas et al., 2019; Díez-Vives et al., 2022). Metagenomic studies reveal that these microbes possess unique genetic adaptations that enhance symbiotic stability, reinforcing the crucial role of microbial diversity in sponge ecology (Engelberts et al., 2020; Storey et al., 2020).

Microbial-derived bioactive compounds support antiaging by targeting key pathways such as mitochondrial bioenergetics and autophagy. Probiotics like *Lactobacillus paracasei* HII01 enhance lifespan and promote healthy aging by activating the DAF-16 signaling pathway, inducing antioxidant responses, and improving mitochondrial function (Kumaree et al., 2023). Certain lactic acid bacteria strains have been shown to increase longevity and improve various aspects of healthy aging, including delayed age-related physical decline, enhanced gut integrity, and improved cognitive functions (Kumar et al., 2022). Additionally, bioactive factors from natural sources, including microbial

metabolites, have demonstrated promising antiaging effects by modulating biological pathways associated with skin integrity and youthfulness, such as promoting collagen synthesis and enhancing skin barrier function (He et al., 2024).

7.3.3 Classes of bioactive molecules from sponges and symbiont microbes

Marine sponge-derived molecules exhibit potent antiaging effects through multiple mechanisms, including antioxidant, antiinflammatory, and tissue-regenerative activities (Fig. 7.1). The classes of bioactive molecules include alkaloids, terpenoids, polyketides, and peptides (Table 7.1).

7.3.3.1 Alkaloids

Alkaloids are nitrogen-containing secondary metabolites known for their diverse and potent bioactive properties. Marine sponges have been identified as a rich source of alkaloids with potential antiaging effects. Bromopyrrole alkaloids, such as Agelastine D from *Agelas* sp. sponges, have been shown to

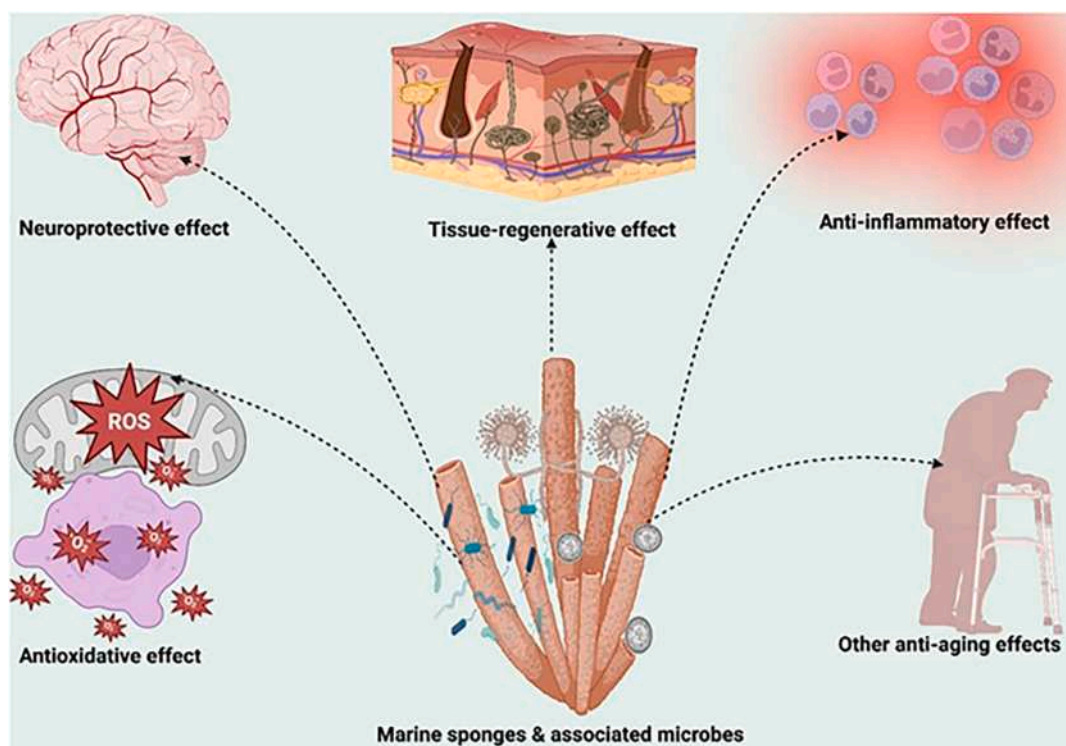


FIGURE 7.1

The Antiaging effects of marine sponges and associated microbes.

[Created in BioRender.com].

Tables 7.1 Some biomolecules produced by Marine sponges and symbiont microbes, and their antiaging activities.

Molecule/Class	Source	Antiaging effect (References).
Agelastine D (Alkaloid)	<i>Agelas sp</i>	Antiinflammatory (Kang et al., 2014).
Hymenialdisine (Alkaloid)	<i>Hymeniacidon sp</i>	Antiinflammatory (Nguyen & Tepe, 2009)
Fistularins (Alkaloid)	<i>Ecionemia acervus</i>	Antiinflammatory (Ji et al., 2021).
(+)-Aeropylsinin-1 (Alkaloid)	<i>Aplysina aerophoba</i> ,	Antiinflammatory (García-Vilas et al., 2015).
Discorhabdins (Alkaloid)	<i>Latrunculia biformis</i> ,	Antioxidative (Li et al., 2019).
Hyrtilusulawesine (Alkaloid)	<i>Hyrtilus erectus</i>	Antiinflammatory (Sauleau et al., 2006).
Topsentin (Alkaloid)	<i>Spongisorites genitrix</i>	Antiinflammatory (Hwang et al., 2020).
Fascaplysin (Alkaloid)	<i>Fascaplysinopsis</i>	Neuroprotective (Mittapalli & Kumari, 2024).
Manzamine A (Alkaloid)	<i>Amphimedon</i>	Antiinflammatory (Klosowska et al., 2012).
Monanchomycin B (Alkaloid)	<i>Monanchora pulchra</i>	Antiinflammatory (Korolkova et al., 2017).
Dysiarenone (Terpenoids)	<i>Dysidea arenaria</i>	Antiinflammatory (Jiao et al., 2018)
9,11-Dihydrogracilin (Terpenoids)	<i>Dendrilla membranosa</i>	Antiinflammatory (Ciaglia et al., 2017).
Carotenoids (Terpenoids)	<i>Sinularia sp.</i>	Antioxidative (Kusmita et al., 2023)
Fucoxanthin (Terpenoids)	<i>Halichondria panicea</i>	Antiinflammatory (Kang et al., 2023) & Antioxidative (Din et al., 2022).
Dysiherbols D and E (Terpenoids)	<i>Dysidea avara</i>	Antiinflammatory (Hong-Yan et al., 2022)
Manoalide (Terpenoids)	<i>Luffariella variabilis</i>	Antiinflammatory (Fenical, 1996).
Septosone A (Terpenoids)	<i>Dysidea septosa</i>	Antiinflammatory (Li, Ma, et al., 2021; Li, Wang, et al., 2021)
Arenarialins A–F (Terpenoids)	<i>Dysidea arenaria</i>	Antiinflammatory (Li et al., 2024)
Dactylospongins A, B, and D (Terpenoids)	<i>Dactylospongia sp.</i>	Antiinflammatory (Fuloria et al., 2022)
Epimuquibilin A (Terpenoids)	<i>Latrunculia</i>	Antiinflammatory (Cheenpracha et al., 2010).
Eurobenzophenone B (Polyketide)	<i>Suberea mollis</i>	Antiinflammatory (Li, Ma, et al., 2021).
Euroxanthone A (Polyketide)	<i>Suberea mollis</i>	Antiinflammatory (Li, Ma, et al., 2021).
(+)-Discodermolide (Polyketide)	<i>Discodermia dissolute</i>	Neuroprotective (Forman et al., 2004).

(Continued)

Tables 7.1 Some biomolecules produced by Marine sponges and symbiont microbes, and their antiaging activities. Continued

Molecule/Class	Source	Antiaging effect (References).
Phakellistatins (Peptides)	<i>Stylissa carteri</i>	Antiinflammatory (Kita et al., 2013).
Solomonamide A (Peptides)	<i>Theonella swinhoei</i>	Antiinflammatory (Festa, De Marino, Sepe, D'Auria, Bifulco, Débitus, et al., 2011).
Perthamides (Peptides)	<i>Theonella swinhoei</i> .	Antiinflammatory (Festa, De Marino, Sepe, D'Auria, Bifulco, Andrés, et al., 2011)

inhibit NF- κ B activity in specific contexts like RANKL-induced osteoclastogenesis, demonstrating their ability to modulate inflammatory signaling pathways (Kang et al., 2014). Additionally, those derived from *Aaptos aaptos* and *Hyrtios* sponges possess strong antioxidant properties, effectively scavenging free radicals. This activity helps to reduce oxidative stress and protect cells from related damage (Utkina, 2009).

Exposure of human rheumatoid synovial fibroblasts (RSF) to IL-1 β upregulates phospholipase A2 (PLA2) and cyclooxygenase-2 (COX-2), leading to increased prostaglandin E2 (PGE2) production, a process regulated by the pro-inflammatory transcription factor NF κ B. Hymenialdisine, is a bioactive pyrrole alkaloid isolated from marine sponges, primarily from the genera *Axinella*, *Stylissa*, *Hymeniacidon*, *Acanthella*, and *Pseudaxinyssa*, was found to inhibit IL-1 β -induced NF κ B activation, significantly reducing NF κ B DNA binding, p65 nuclear translocation, and the transcription of COX-2 and PLA2, thereby suppressing PGE2 production in a concentration-dependent manner (IC₅₀ ~1 μ M). This inhibition was specific to NF κ B-regulated genes, as hymenialdisine suppressed IL-8 production but did not affect vascular endothelial growth factor (VEGF), highlighting its potential as a novel antiinflammatory agent targeting NF κ B in inflammatory diseases (Nguyen & Tepe, 2009; Roshak et al., 1997).

Fistularins, bromotyrosine-derived alkaloids isolated from the marine sponge *Ecionemia acervus* exhibit notable antiinflammatory properties. These compounds inhibit the production of inflammatory mediators such as NO, PGE2, TNF- α , IL-1 β , and IL-6 induced by lipopolysaccharide and interferon- γ . Their antiinflammatory activity is associated with the downregulation of inducible nitric oxide synthase (iNOS), cyclooxygenase-2 (COX-2), and MAPK phosphorylation, primarily through the inhibition of NF- κ B nuclear translocation (Ji et al., 2021). (+)-Aeropylsinin-1, another bromotyrosine-derived alkaloid derived from the marine sponge *Aplysina aerophoba*, has demonstrated significant antiinflammatory, antiangiogenic, and antitumor activities in preclinical studies. Its broad range of biological effects highlights its potential pharmaceutical value for the treatment of various diseases (García-Vilas et al., 2015).

Discorhabdins are a unique class of marine alkaloids characterized by a pyrroloiminoquinone core structure. They are predominantly isolated from Antarctic deep-sea sponges, especially *Latrunculia bififormis*, which thrive in extreme marine environments. These compounds have attracted scientific interest due to their potent biological activities, particularly their antioxidant properties.

Discorhabdins have been shown to inhibit oxidative DNA damage by scavenging ROS and stabilizing redox balance within cells. By modulating key redox signaling pathways, they contribute to the protection of cellular components from oxidative stress. Consequently, discorhabdins help prevent DNA mutations and cellular degeneration, making them promising candidates for therapeutic development in age-related and oxidative stress-associated diseases (Li et al., 2019).

Indole alkaloids derived from marine sponges have demonstrated cytoprotective ability modulating oxidative stress, and inflammation. Two novel aplysinopsin-type indole alkaloids, along with three previously known indole alkaloids, were isolated from the marine sponge *Hyrtios erecta*. These compounds demonstrated selective inhibitory activity against the neuronal isoform of nitric oxide synthase (nNOS) (Aoki et al., 2001). Hyrtiosulawesine, isolated from the methanolic crude extract of the Red Sea marine sponge *Hyrtios erectus*, exhibited significant antiphospholipase A2 activity, demonstrating an IC₅₀ value of 14 μ M in a fluorometric assay using *Crotalus adamanteus* venom phospholipase A2 (Sauleau et al., 2006).

Topsentin, a bis(indolyl)imidazole alkaloid from the marine sponge *Spongosorites genitrix*, was found to have photoprotective effects against UVB-induced skin inflammation in HaCaT keratinocyte cells by suppressing COX-2 expression, inhibiting AP-1 and MAPK pathways, and downregulating miR-4485 and its target TNF- α IP2. These effects were further validated in a reconstructed human skin model. The results suggest Topsentin's potential as an active ingredient in cosmetic formulations for treating skin inflammation (Hwang et al., 2020).

Fascaplysin is another marine-derived indole alkaloid, specifically belonging to the subclass of β -carboline alkaloids. It is isolated from the marine sponges of the *Fascaplysinopsis* and *Hyrtios* genera (Mittapalli & Kumari, 2024). Fascaplysin has been found to inhibit β -amyloid (A β) fibrillization in vitro. Similarly, 9-Methylfascaplysin, a derivative of the marine natural product Fascaplysin, has shown promising potential for the treatment of Alzheimer's disease due to its neuroprotective effects against β -amyloid (A β)-induced toxicity. To enhance its therapeutic efficacy, 9-methylfascaplysin was designed and synthesized from 5-methyltryptamine as a novel analog of Fascaplysin. Notably, it exhibited significantly greater potency in inhibiting A β fibril formation compared to its parent compound. When incubated with A β , 9-methylfascaplysin markedly reduced A β oligomer formation, suggesting a strong inhibitory effect on A β aggregation. These findings position 9-methylfascaplysin as one of the most potent marine-derived compounds with anti-A β neuroprotective properties. However, despite its therapeutic potential, the pharmacokinetic profile of 9-methylfascaplysin, which is essential for preclinical development, remains insufficiently characterized (Sun et al., 2019; Zhang et al., 2025).

Manzamine A (MZA), another β -carboline-containing alkaloid, can be obtained from the Okinawan sponges of the genus *Amphimedon* (Hu et al., 2003). MZA, a newly synthesized complex alkaloid with antiinflammatory properties, was evaluated for its ability to modulate cytokine production in osteoarthritis (OA) fibroblasts, which are known to release pro-inflammatory cytokines. At nontoxic concentrations up to 2.5 μ M, MZA significantly reduced MCP-1 production in OA fibroblasts, as confirmed by antibody microarrays and ELISA, while its effect on IL-6 production varied by concentration. These findings suggest that MZA can alter cytokine secretion in OA fibroblasts, highlighting its potential as a therapeutic agent for inflammation-related conditions (Klosowska et al., 2012).

Monanchomycalin B, a Guanidine alkaloid from the sponge *Monanchora pulchra* has been identified as a selective inhibitor of TRPV1, TRPV2, and TRPV3 ion channels with no activity

against TRPA1. The TRPV subfamily of ion channels, including TRPV1, TRPV2, and TRPV3, plays a crucial role in regulating inflammation and pain by mediating cytokine release, immune cell activation, and sensory responses. By selectively inhibiting TRPV1–3 channels, Monanchomycin B exhibit promising antiinflammatory and analgesic potential (Korolkova et al., 2017).

7.3.3.2 Terpenoids

Terpenoids are a major class of bioactive compounds found in marine sponges, with antiinflammatory and antioxidative properties. Dysiarenone, a dimeric C21 meroterpenoid, isolated from the marine sponge *Dysidea arenaria*, exhibits inhibitory activities against COX-2 expression and PGE2 production in LPS-stimulated macrophages. This compound showed an IC50 value of 6.4 μ M for inhibiting COX-2 expression and PGE2 production in LPS-stimulated RAW264.7 macrophages (Jiao et al., 2018). Additionally, Dysiarenone demonstrates antiinflammatory and antioxidant properties by inhibiting the 5-LOX/NF- κ B/MAPK pathway and upregulating the Nrf2/HO-1 signaling pathway (Hu et al., 2021).

A Norditerpene (C19 terpenoid) 9,11-Dihydrogracilin A (DHG), isolated from the Antarctic marine sponge *Dendrilla membranosa*, exhibits notable **immunomodulatory and antiinflammatory properties**. In both **in vitro** (using human PBMCs and HaCaT keratinocytes) and **in vivo** (murine ear edema model) studies, DHG was shown to reduce immune cell proliferation, induce apoptosis, and downregulate key inflammatory signaling pathways including **NF- κ B**, **STAT**, and **ERK** phosphorylation. It also suppressed **IL-6** production, slightly decreased **IL-10**, but did not affect **TNF- α** levels. In keratinocytes, DHG reduced cell viability, growth, and migration, suggesting potential in managing skin inflammation. In the croton oil-induced mouse ear inflammation model, **the topical application of DHG significantly reduced edema**, supporting its promise as a therapeutic candidate for **inflammatory skin disorders** (Ciaglia et al., 2017).

Carotenoids, a subclass of isoprenoids, are naturally produced by various microorganisms, including symbiotic bacteria. In a recent study, we isolated and characterized carotenoids from a bacterial symbiont associated with *Sinularia* sp., a soft coral collected from Panjang Island in the North Java Sea. The symbiont, identified as *Virgibacillus* sp. (strain 19.PP.Sc.13), produced carotenoids that demonstrated notable antioxidant activity and UVA-protective properties, qualifying them as effective natural sunblock agents. These findings highlight the potential of *Virgibacillus* sp.-derived carotenoids for use in antioxidants, sun protection, and antibacterial applications, supporting their value in marine-derived cosmeceuticals and therapeutics (Kusmita et al., 2023).

Fucoanthin (FX), an oxygenated carotenoid, is not inherently synthesized by marine sponges but is primarily produced by brown algae *Phaeophyceae* (Bai et al., 2022). However, it may be found in association with marine sponges such as *Halichondria* species (e.g., *Halichondria panicea*), which commonly host or coexist with fucoxanthin-rich brown algae on their surfaces (Rosenfeld & Paine, 2002). A study by Kang et al (2023) demonstrated that FX markedly suppressed ionizing radiation (IR)-induced upregulation of pro-inflammatory genes, including *Il1b*, *Tnf*, and *Ccl2*, and inhibited the polarization of macrophages toward the pro-inflammatory M1 phenotype. Furthermore, FX modulated IR-responsive metabolic gene expression involved in glycolysis and mitochondrial biogenesis. The antiinflammatory and metabolic regulatory effects of FX in irradiated macrophages were attributed to its ability to enhance the expression and activity of the antiaging molecule SIRT1 and estrogen receptor alpha (ER α). FX also exhibits potent antioxidant activity, primarily attributed to

its unique chemical structure, which includes an allenic bond, hydroxyl groups on aromatic rings, and an epoxide moiety. These electron-rich features enhance FX's capacity to neutralize a wide range of free radicals by effectively donating electrons and stabilizing reactive species (Din et al., 2022).

Hong-Yan et al. (2022) reported the isolation and structural elucidation of four new sesquiterpene quinone meroterpenoids, including Dysiherbols D and E, from the marine sponge *Dysidea avara* collected from the South China Sea. These compounds represent a unique subclass of marine-derived meroterpenoids known for their pharmacological potential. Biological evaluation revealed that Dysiherbols D and E exhibited moderate inhibitory activity against TNF- α -induced NF- κ B activation in human HEK-293T cells, with IC₅₀ values of 10.2 μ M and 8.6 μ M, respectively. This inhibition suggests their potential as antiinflammatory agents by targeting a key signaling pathway involved in immune and inflammatory responses.

Manoalide, a sesterterpenoid, isolated in Hawaii and California from the marine sponge *Luffariella variabilis*, is recognized for its potent antiinflammatory and analgesic properties, with promising potential in antiaging skincare applications. Manoalide exerts its effects by inhibiting phospholipase A2 (PLA2), a critical enzyme that initiates the inflammatory cascade. By doing so, it effectively blocks the synthesis of downstream inflammatory mediators, including products of the cyclooxygenase and lipoxygenase pathways, which are involved in pain, swelling, and tissue damage (Fenical, 1996). Manoalide has demonstrated potential antipsoriatic activity, having advanced to Phase II clinical trials as a topical treatment for psoriasis. Furthermore, by reducing inflammation-induced cellular damage, it may help delay skin aging, supporting its role as a multifunctional agent in dermatological and cosmeceutical formulations (National Center for Advancing Translational Sciences, n.d.).

Septosone A, a meroterpenoid isolated from the marine sponge *Dysidea septosa*, demonstrates in vivo antiinflammatory activity by alleviating macrophage migration and inhibiting TNF- α -induced NF- κ B activation. This compound inhibits NF- κ B activation induced by TNF- α with an IC₅₀ value of 6.8 μ M in human HEK-293T cells (Fuloria et al., 2022; Li, Ma, et al., 2021). At concentrations of 2.5–10 μ M, Septosone A exhibits antiinflammatory activity comparable to that of Indomethacin (Tian et al., 2023). Additionally, Septosone A has been shown to inactivate the NF- κ B signaling pathway in CuSO₄-induced transgenic fluorescent zebrafish, further demonstrating its potential for mitigating inflammation (Dimitrova et al., 2025).

In a recent study, researchers reported the discovery of six new sesquiterpene quinone/hydroquinone meroterpenoids, named Arenarialins A–F, from the marine sponge *Dysidea arenaria* collected in the South China Sea. These compounds were found to significantly inhibit the production of pro-inflammatory cytokines TNF- α and IL-6 in LPS-induced RAW264.7 macrophages, indicating their potential as antiinflammatory agents. Among them, Arenarialin D demonstrated a noteworthy ability to regulate the NF- κ B/MAPK signaling pathway, a central mechanism in inflammation modulation. The chemical structures of the isolated compounds were elucidated using a combination of high-resolution mass spectrometry (HRMS), nuclear magnetic resonance (NMR), DP4+ statistical analysis, and electronic circular dichroism (ECD) calculations. These findings highlight the antiaging properties of these compounds (Li et al., 2024). Sesquiterpene-quinones from *Dysidea* have also been shown to inhibit human neutrophil free radical release, which could be related to antiinflammatory effects (Mayer et al., 2009).

Yuan et al. (2025) reported eleven new nitrogenous meroterpenoids (55–65) isolated from the marine sponge *Dysidea cinerea* collected in the South China Sea. Compounds 55–57 and 60 showed

moderate inhibitory activities against PTP1B, ATP-citrate lyase, and SH2 domain-containing phosphatase-1 with IC₅₀ values ranging from 2.8 to 27 μ M. Also, Fuloria et al. (2022) reported the isolation of Dactylospongins A, B, and D, along with other sesquiterpene hydroquinone meroterpenoids, from the marine sponge *Dactylospongia* sp. These compounds exhibited inhibitory activity on the production of PGE₂, IL-6, IL-1 β , and IL-8 in LPS-stimulated cells, with IC₅₀ values ranging from 5.1 to 9.2 μ M.

Epimuqubilin A, a norsesterterpene peroxide isolated from a marine sponge of the genus *Latrunculia*, exhibited potent inhibitory activity against nitric oxide (NO) production in LPS-activated murine macrophage RAW264.7 cells, with an IC₅₀ value of 7.4 μ M, approximately three times more effective than the positive control, L-NG-monomethyl arginine citrate. Other norsesterterpene cyclic peroxides from the same sponge species also exhibited NO inhibitory activity, with Sigmosceptrellin A showing an IC₅₀ value of 9.9 μ M (Cheenpracha et al., 2010).

7.3.3.3 Polyketides

Marine sponges, along with their symbiotic microorganisms, are prolific producers of structurally diverse polyketides known for their potent antiaging, antioxidant, and antiinflammatory properties. These secondary metabolite compounds are synthesized by polyketide synthases (PKS), which are complex enzymatic systems found in marine sponges and their associated microbiomes. Marine sponges, particularly those of the order *Haplosclerida*, are rich in polyketides and their production is influenced by various factors such as environmental conditions, symbiotic relationships with microorganisms, and the sponge's own defense mechanisms (Mehbub et al., 2024).

Eurobenzophenone B and Euroxanthone A, two notable polyketides isolated from the marine sponge like *Suberea mollis* associated fungus *Aspergillus europaeus*, have demonstrated significant antiinflammatory activity. These compounds exert their effects through multiple mechanisms, including the inhibition of nitric oxide (NO) and prostaglandin E₂ (PGE₂) overproduction in (LPS)-stimulated macrophages and microglia. Additionally, they suppress the expression of key pro-inflammatory enzymes, inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2), while also reducing the levels of pro-inflammatory cytokines such as TNF- α , IL-1 β , IL-6, and IL-12 (Li, Ma, et al., 2021). These effects are mediated in part by the negative regulation of the NF- κ B signaling pathway, highlighting the therapeutic potential of sponge-derived polyketides in aging and inflammation-related disorders. (+)-Discodermolide is a highly potent polyketide natural product originally isolated from the marine sponge *Discodermia dissolute* (Gunasekera et al., 1990). (+)-Discodermolide has demonstrated neuroprotective effects in recent Alzheimer's research. Its microtubule-stabilizing properties help counteract amyloid-induced disruption of neuronal function. In a transgenic mouse model of human tauopathy, it restored fast axonal transport and reversed motor impairments by stabilizing microtubules and mitigating tau protein aggregation (Forman et al., 2004).

7.3.3.4 Peptides and proteins

Marine sponges are widely recognized as prolific sources of bioactive peptides, encompassing a broad range of structural types, including linear peptides, cyclic peptides, peptide lactones, and depsipeptides. Many of these molecules undergo extensive post-translational modifications, such as the incorporation of nonproteinogenic amino acids or hydroxy acid residues, while others resemble classical ribosomally synthesized peptides with only subtle alterations (Matsunaga & Fusetani, 2003).

Traditionally, the study of sponge-derived peptides has been hindered by their low abundance and high sequence diversity, particularly those produced by symbiotic bacteria. These factors have made peptide isolation and structural elucidation highly challenging. However, recent advancements in mass spectrometry-based techniques have revealed a much broader diversity of these peptides than previously recognized (Lin et al., 2024).

It is well established that symbiotic bacteria contribute significantly to the chemical diversity of marine sponges by producing bioactive peptides, both through ribosomal (RiPPs) and nonribosomal biosynthetic pathways. More recently, it has become clear that the sponges themselves also synthesize a distinct repertoire of bioactive macrocyclic peptides. These include phakellistatins and other proline-rich macrocyclic peptides (PRMPs), which are typically fewer than 15 amino acids in length and contain multiple proline residues (Lin et al., 2024).

Leveraging transcriptomic data from the *Stylissa carteri* sponge, researchers have developed methods to systematically identify sponge-encoded RiPPs (Lin et al., 2024). This led to the discovery of 46 distinct RiPP-type core peptide sequences, ten of which matched previously characterized PRMPs, further emphasizing the biosynthetic capabilities of the sponge host itself (Lin et al., 2024). A novel cyclic heptapeptide, Stylissatin A, was isolated from the marine sponge *Stylissa massa* collected in Papua New Guinea. Its structure, determined using NMR spectroscopy, Marfey's method, and MS/MS analysis, was identified as cyclo-[Tyr¹-Ile²-Phe³-Pro⁴-Ile⁵-Pro⁶-Phe⁷]. Stylissatin A demonstrated antiinflammatory potential by inhibiting nitric oxide production in LPS-stimulated RAW264.7 murine macrophage cells, with an IC₅₀ value of 87 μM (Kita et al., 2013).

Solomonamide A, a peptide isolated from the marine sponge *Theonella swinhoei*, was structurally characterized using NMR spectroscopy and high-resolution mass spectrometry, revealing it to be 4-amino(2'-amino-4'-hydroxyphenyl)-3,5-dihydroxy-2-methyl-6-oxohexanoic acid (ADMOA). In pharmacological testing, Solomonamide A exhibited dose-dependent antiinflammatory activity, producing approximately a 60% reduction in edema in mice at an intraperitoneal dose of 100 μg/kg (Festa, De Marino, Sepe, D'Auria, Bifulco, Débitus, et al., 2011).

Peptides derived from marine sponges such as *Axinella carteri* have demonstrated notable antiinflammatory activity in biological models. In a specific study, gel preparations containing marine sponge extract at concentrations of 0.02% to 0.04% exhibited a measurable healing effect on inflammation. Notably, the 0.04% sponge extract gel achieved an **88.73% inhibition rate**, showing comparable efficacy to the standard 1% diclofenac sodium (Natrium diclofenac) gel. The application of the *Axinella carteri* extract gel significantly reduced leg edema in mice, further supporting its antiinflammatory potential. Based on the calculated inhibition percentages, the 0.04% concentration was deemed most effective, demonstrating similar performance to the positive control. These findings suggest that *Axinella carteri* extract could serve as a promising natural alternative in antiinflammatory therapy (Mayefis et al., 2021).

Also, novel cyclopeptides, perthamides were isolated from the polar extracts of the marine sponge *Theonella swinhoei*. Their structures, which include a unique β-amino acid unit known as AHMOA, were elucidated using NMR and mass spectrometry data. These peptides demonstrated the ability to inhibit the release of pro-inflammatory cytokines TNF-α and IL-8 in primary human keratinocyte (PHK) cells in a dose-dependent manner (Festa, De Marino, Sepe, D'Auria, Bifulco, Andrés, et al., 2011).

Nonribosomal peptides (NRPs) produced by marine sponges and their symbiotic microbes exhibit a broad spectrum of biological activities, including promising antiaging effects. Synthesized by

nonribosomal peptide synthetases (NRPSs), these compounds have garnered attention for their pharmaceutical potential, as recent studies highlight their abundance and functional diversity in marine sponge-microbe systems (Woodhouse et al., 2013). The diversity of NRPs in marine sponges is significant, with deep sequencing studies identifying hundreds of novel ketosynthase and condensation domain sequences within the microbiomes of Australian marine sponges (Woodhouse et al., 2013).

Peptides can also be obtained from protein hydrolysates. *Chondrosia reniformis*, a marine demosponge, is a valuable source of glycosaminoglycan-like polysaccharides and collagen-based biomaterials with therapeutic potential in skin regeneration, wound healing, and inflammation control. Its extracts promote skin regeneration by enhancing extracellular matrix (ECM) synthesis, supporting fibroblast proliferation, and increasing fibronectin production (Tassara et al., 2023). In wound healing, 2D collagen membranes derived from the sponge accelerate keratinocyte and fibroblast migration, aiding wound closure and preventing bacterial infiltration. The sponge's collagen is highly stable, resistant to heat and enzymatic degradation, making it suitable for long-term regenerative applications. Additionally, *C. reniformis* exhibits strong antiinflammatory activity by modulating cytokine pathways like TGF- β and TNF, reducing IL-1, and promoting tissue repair. In diabetic patients, marine collagen peptides (MCPs) from this sponge lower inflammatory markers (hs-CRP, NO) and increase antiinflammatory agents (PGI₂, adiponectin). It also offers antioxidant protection by scavenging free radicals, reducing lipid peroxidation, and boosting antioxidant enzymes like superoxide dismutase, helping to counter age-related oxidative decline and extend lifespan in animal models (Pozzolini et al., 2018; Tassara et al., 2023).

7.3.3.5 Others

Mycosporines and mycosporine-like amino acids (MAAs) function as natural UV-absorbing compounds, offering photoprotection, antiinflammatory, and antiaging benefits. These water-soluble molecules, commonly found in marine organisms such as algae, cyanobacteria, and sponges, protect against UV-induced oxidative stress, making them ideal for incorporation into sunscreens and skin-rejuvenating formulations (Esposito et al., 2021).

Many other bioactive molecules can be produced for extracellular vesicles (EVs) produced by symbiont bacteria. EVs are a heterogeneous group of membrane-bound structures, typically spheroid or cup-shaped, released by living cells into their surrounding environment. Found across a wide range of prokaryotes and eukaryotes, EVs serve as crucial mediators of intercellular communication (Fang et al., 2022). In marine microbes, EVs have garnered attention for their role in modulating cellular signaling and facilitating tissue repair, particularly in aging systems (Biller et al., 2023). These vesicles carry a diverse cargo of bioactive molecules, including lipids, proteins, nucleic acids, small metabolites, enzymes, sterols, polysaccharides, pigments, and toxins, that can influence the physiology of target cells and regulate key biological pathways (Fang et al., 2022). In oceanic ecosystems, EVs are found throughout various depths of the water column, and their functional impact is shaped by both biotic factors and abiotic conditions.

Quantitative studies of marine microbial cultures have shown that EV production rates vary significantly among microbial taxa, sometimes by an order of magnitude, and respond dynamically to environmental changes (Biller et al., 2023).

In a study by Li, Wang, et al. (2021), it demonstrated that *Bacteroidetes* commonly associated with marine sponges played a role in their host's development. In this study, 13 bacterial species representing 12 genera were isolated from the sponge *Tedania* sp., all of which significantly enhanced larval settlement, achieving rates 30.00%–53.33% higher than control groups. Notably, six of these species produced EVs that further boosted settlement rates, up to 86.67% ($p < 0.05$). Fluorescent tracking revealed that these EVs migrated into sponge larvae, actively participating from the planktonic stage through metamorphosis.

These findings indicate that marine sponges may selectively enrich *Bacteroidetes* due to their essential role in host development, reinforcing the concept of reciprocal adaptive co-evolution between sponges and their microbial symbionts. Moreover, the insights gained into extracellular vesicle production contribute to a deeper understanding of microbe-host interactions and open new avenues for investigating their ecological functions and biomedical applications, particularly in the context of marine ecosystems and aging-related processes.

7.4 Implications, advances, challenges and future perspectives

Marine sponges and their symbiotic microbes represent a vast and underexplored reservoir of bioactive compounds with significant potential for antiaging applications, offering natural products such as peptides, alkaloids, polyketides, and collagen derivatives that exhibit potent antioxidant, antiinflammatory, and regenerative properties (Alves et al., 2020). These molecules provide promising therapeutic avenues in dermatology, neurodegeneration, and age-related metabolic disorders, thereby reinforcing the ecological and biomedical value of marine sponge holobionts. Compounds like collagen peptides, carotenoids, and mycosporine-like amino acids (MAAs) derived from marine sponges have already been incorporated into skincare products for their moisturizing, UV-protective, and antiwrinkle effects (Esposito et al., 2021), while alkaloids, polyketides, and enzyme inhibitors sourced from sponge-associated microbes show therapeutic promise for managing chronic inflammation and neurodegenerative diseases (Dou & Dong, 2019).

These discoveries highlight the importance of conserving marine habitats, especially as biodiversity loss from overharvesting and habitat degradation threatens the natural sources of these bioactives. Recent progress in this field has been largely driven by the integration of omics technologies and synthetic biology; multi-omics platforms, spanning genomics, transcriptomics, proteomics, and metabolomics, have improved our capacity to identify and characterize novel compounds from sponge-associated microbes (Gavrilidou et al., 2021). Additionally, metagenomic mining and high-throughput sequencing have uncovered hidden biosynthetic gene clusters (BGCs) responsible for structurally unique and pharmacologically potent secondary metabolites (Dinglasan et al., 2025).

Technological advancements have also addressed the challenge of microbial unculturability through innovations such as co-culture techniques, high-throughput culturing, and AI-assisted metagenomic screening, allowing researchers to access and study previously elusive microbial symbionts (Lagier et al., 2018). Furthermore, bioprospecting in extreme environments, including

deep-sea and polar ecosystems, has led to the discovery of rare antiaging compounds with novel mechanisms of action (Kannabiran, 2024). Synthetic biology and metabolic engineering now facilitate the transfer of sponge-derived biosynthetic pathways into heterologous microbial hosts, enabling sustainable and scalable production of these valuable compounds (Indraningrat et al., 2016), while nanobiotechnology enhances therapeutic delivery and precision through targeted systems that improve bioavailability at the cellular level (Cai et al., 2025).

Despite these advancements, challenges persist. The inherently slow growth and low biomass of marine sponges limit direct compound extraction at commercial scales, and environmental variability can alter metabolite profiles, complicating standardization and reproducibility (Prajaputra et al., 2024). Although in vitro cultivation of sponge-associated microbes and heterologous expression systems provide alternatives, issues surrounding scalability, compound integrity, and production costs remain unresolved (Almeida et al., 2022). Regulatory barriers also present significant hurdles, particularly for marine-derived pharmaceuticals, due to complex extraction processes, ecological concerns, and high clinical development costs. Furthermore, the low bioavailability of certain compounds necessitates advanced formulation strategies to improve their stability, absorption, and therapeutic efficacy (Martins et al., 2014).

Looking ahead, the future of antiaging compound discovery from marine sponges will rely on the integration of conservation strategies, biotechnology, and digital innovation. The establishment of marine protected areas (MPAs) and sustainable aquaculture practices can safeguard sponge biodiversity while supporting nonextractive bioprospecting (Sotelo et al., 2021). Emerging technologies such as microbial fermentation, CRISPR-Cas genome editing, and AI-assisted metabolic pathway optimization offer scalable and renewable alternatives to wild harvesting (Sadanov et al., 2025). Machine learning and AI-driven drug discovery are expected to accelerate the identification and preclinical assessment of sponge-derived compounds by predicting pharmacokinetic profiles, molecular targets, and toxicity (Santana et al., 2021). Combined with advances in bioprinting, synthetic biology, and smart delivery platforms, the path forward lies in merging ecological responsibility with high-tech innovation to bring marine-derived antiaging therapies from seabed to clinic (Ragozzino et al., 2025).

7.5 Conclusion

Recent research highlights marine sponges and their symbiotic microbes as promising sources of antiaging molecules, such as terpenes, alkaloids, polyketides, and peptides, which help combat oxidative stress, inflammation, collagen breakdown, and cellular aging. Sponge-associated bacteria are key producers of these bioactives, often offering greater stability and effectiveness than synthetic options. Advancing this field requires an interdisciplinary approach, while addressing challenges in sustainable harvesting and scalable production through tools like synthetic biology, metagenomics, nanotechnology, and AI-driven drug discovery. Future efforts need to focus on clinical validation and formulation for cosmeceutical, nutraceutical, and pharmaceutical use.

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Applications of machine learning, genomics and synthetic biology in marine microbial products

Ruben Babu Marabathula¹, Rajesh Nambi², M. Srinivasulu³ and Osman Basha Pinjari¹

¹*Department of Genetics and Genomics, Yogi Vemana University, Kadapa, Andhra Pradesh, India,*

²*Department of Biotechnology and Bioinformatics, Yogi Vemana University, Kadapa, Andhra Pradesh, India,*

³*Department of Biotechnology, Yogi Vemana University, Kadapa, Andhra Pradesh, India*

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8.1 Introduction

8.1.1 Importance of marine microbial products

Marine microorganisms represent a vast, largely untapped reservoir of bioactive compounds with immense potential across diverse fields, including pharmaceuticals, agriculture, energy, and environmental management (Ambrosino et al., 2019). The extreme conditions of marine ecosystems characterized by high pressures, variable temperatures, salinity, and limited nutrients have driven the evolution of unique metabolic pathways in these microorganisms, resulting in the synthesis of structurally novel compounds (Kilinç, 2024). Many of these compounds exhibit remarkable biological activities, making marine microbes promising candidates for developing new antibiotics, anticancer agents, enzymes, and biofuels (Kilinç, 2024).

8.1.2 Challenges in prediction and monitoring

Despite the promising potential of marine microbial products, their discovery and monitoring present considerable challenges. Traditional approaches rely heavily on culture-based techniques, which are inherently labor-intensive and inefficient, capturing only a small fraction of marine microbial diversity. It is estimated that over 99% of marine microorganisms remain unculturable under standard laboratory conditions, creating a significant knowledge gap in marine microbial ecology and limiting access to their metabolic potential (Khan et al., 2018).

Furthermore, microbial activity in marine environments is highly dynamic, influenced by environmental factors such as temperature, salinity, and nutrient fluxes, complicating efforts to monitor product synthesis in natural settings (Ambrosino et al., 2019). The emergence of high-throughput sequencing and omics technologies has revolutionized marine microbiology, providing unprecedented access to microbial genomes, transcriptomes, and metabolomes (D'Elia et al., 2024). These advances have led to the discovery of numerous biosynthetic gene clusters (BGCs) responsible

for bioactive compound production, offering exciting prospects for marine biotechnology (Goshisht, 2024). However, the sheer volume of genomic data generated by these methods poses a new challenge—the need for robust computational strategies capable of analyzing complex microbial communities and extracting meaningful insights from vast datasets (Srivastava & Brylinski, 2025).

8.1.3 Role of machine learning in marine biotechnology

Machine Learning (ML) has emerged as a transformative tool for addressing these challenges by offering sophisticated algorithms capable of handling large datasets, identifying patterns, and making accurate predictions regarding microbial behavior and product synthesis (D'Elia et al., 2024). In marine biotechnology, ML techniques are increasingly being employed to streamline microbial product discovery, accelerating the identification of promising microbial strains and optimizing culture conditions (Kilinc, 2024).

Various ML approaches have been applied to marine microbial research. Supervised learning techniques have proven effective in microbial species classification, while unsupervised learning has been used for microbial community clustering. Additionally, reinforcement learning (RL) has shown promise in dynamically optimizing bioprocesses (Kilinc, 2024). These models offer the ability to analyze genomic and metagenomic data, identify novel biosynthetic pathways, and predict bioactivity, thereby enhancing the efficiency of marine microbial product discovery (Srivastava & Brylinski, 2025). Moreover, ML has enabled real-time monitoring of microbial ecosystems, providing deeper insights into marine microbial biodiversity and advancing the sustainable management of marine resources.

This chapter explores the diverse applications of ML in marine microbial product prediction and monitoring, with a focus on genomic and metagenomic data analysis, predictive modeling, and real-time bioprocess optimization. Furthermore, key case studies, integration with synthetic biology and remote sensing technologies, as well as future challenges and research directions, are discussed to provide a comprehensive understanding of the role of ML in unlocking marine microbial biodiversity.

8.2 Machine learning: an overview

8.2.1 Basics of machine learning

ML is a subfield of artificial intelligence that focuses on developing algorithms capable of learning patterns from data to make predictions or decisions without being explicitly programmed. In the context of microbial marine product prediction, ML offers robust methodologies for processing complex biological datasets and uncovering relationships between microbial genomes, environmental factors, and bioactive compound production (Ambrosino et al., 2019). The successful application of ML in marine biotechnology is underpinned by three core components: data, algorithms, and models.

Data serves as the foundation of any ML system, providing the raw material from which models extract patterns and insights. In marine microbiology, data is derived from diverse sources, including genomic and metagenomic sequencing, transcriptomic profiles, and environmental parameters such as temperature, salinity, and nutrient levels (Ambrosino et al., 2019). These datasets may be structured, such as tabular datasets with labeled microbial species, or unstructured, encompassing raw genomic

sequences and ecological metadata (Goshisht, 2024). The volume and diversity of data collected directly influence the complexity and performance of ML models.

ML algorithms represent the computational methods that process input data to identify patterns and make predictions. In marine microbial product prediction, various algorithms are employed, each offering unique strengths. For example, regression algorithms are commonly used to predict microbial product yields, while classification algorithms such as random forest (RF) and support vector machines (SVMs) are applied to identify microbial species with bioactive potential (Ambrosino et al., 2019). Additionally, clustering techniques like k-means clustering help group microbial communities based on genetic or metabolic characteristics, thereby enabling the discovery of novel microbial strains with industrial applications (Goshisht, 2024). More advanced approaches, such as deep learning (DL) models and convolutional neural networks (CNNs), are increasingly used to process complex genomic data and enhance predictive accuracy (Goshisht, 2024).

A ML model is the product of training an algorithm on a given dataset. Once trained, these models generalize from the input data to make predictions on unseen data. In marine biotechnology, trained ML models are employed to predict microbial product yields, identify promising microbial strains, and optimize bioprocessing conditions (Ambrosino et al., 2019). Notably, RL has been applied to dynamically adjust bioreactor conditions in real time, enhancing product yields and resource efficiency (Goshisht, 2024).

8.2.2 Types of machine learning

ML techniques are broadly categorized into supervised learning, unsupervised learning, and RL. Each method offers unique advantages in microbial marine product prediction, depending on the nature of the data and the desired outcome (D'Elia et al., 2024). (Table 8.1, Table 8.2)

8.2.2.1 Supervised learning

Supervised learning has been effectively applied to microbial species classification and metabolite prediction, enhancing the understanding of microbial interactions and identifying potential bioactive compounds (Srivastava & Brylinski, 2025).

In marine microbial studies, techniques such as RF and SVMs have been applied to predict the presence of antimicrobial peptides from metagenomic datasets. For instance, RF models effectively classify microbial species based on genetic markers, while SVMs excel in identifying marine microbes with high biopolymer production potential (D'Elia et al., 2024).

8.2.2.2 Unsupervised learning

Unsupervised learning is used when datasets lack labeled outcomes. Algorithms uncover hidden patterns, cluster similar data points, and detect anomalies without human supervision. In marine biotechnology, k-means clustering and Principal Component Analysis are commonly used to group microbial species with similar metabolic profiles and reduce high-dimensional genomic data (Kilinc, 2024). Unsupervised learning has been applied to identify microbial consortia involved in polyhydroxyalkanoate synthesis—a biodegradable plastic precursor by clustering microbial communities based on metabolic traits. These insights facilitate the discovery of novel microbial strains with enhanced product yields (Kilinc, 2024).

Table 8.1 Applications of machine learning in microbial marine product discovery.

Application	Methods	References
Predicting <i>Vibrio</i> concentrations	Random Forest, Support Vector Machine, Elastic Net	Karanth et al. (2024)
Distinguishing MNPs and TNPs	Random Forest, SVM, Multilayer Perceptron	Pereira (2021)
Discovering AMPs from marine biofilms	Ribosome profiling, Deep Learning	Fan et al. (2024)
Predicting AMPs from Cnidarians	In silico proteolysis, Shallow- and Deep-Learning models	Barroso et al. (2025)
Identifying AMPs in macroalgae	Random Forest, Artificial Neural Networks	Caprani et al. (2021)
Predicting <i>Karenia brevis</i> blooms	SVM, Relevance Vector Machine, Naive Bayes classifier, ANN	Li et al. (2021)
Predicting bacterial growth	Ultraviolet spectroscopy with 1DCNN-PLSR Parallel 1DCNN-SVR Adaptation	Ma et al. (2024)
Screening antiviral compounds	Message-passing neural networks	Zhang et al. (2024)
Predicting therapeutic targets	Machine learning models with biochemical descriptors	Soares et al. (2024)
Optimizing fucoxanthin production	Random Forest, Statistical analysis	Manochkumar et al. (2023) , Reynolds-Brandão et al. (2024)
Discovering natural products	Genome mining, Dereplication, Biological target prediction	Arnold et al. (2023) , Nagar et al. (2023) , Yuan et al. (2023)

8.2.2.3 Reinforcement learning

RL has been increasingly applied to microbial environments to optimize growth conditions and enhance product yields ([Goshisht, 2024](#)). In marine bioprocessing, RL-driven systems have been employed to optimize bioreactor conditions for marine algae, significantly improving lipid production for biofuels. The model continuously refines its strategy based on feedback, enhancing production efficiency while minimizing resource consumption ([D'Elia et al., 2024](#)).

8.3 Prediction of microbial marine products using machine learning

ML has transformed microbial marine product discovery by enabling the rapid analysis of complex datasets, enhancing predictions of bioactive compounds, biosynthetic pathways, and microbial interactions with unprecedented accuracy. Traditional discovery methods relied on labor-intensive

Table 8.2 Machine learning techniques for microbial product prediction.				
ML Technique	Application	Advantages	Limitations	References
Random Forest (RF)	BGC identification, microbial community prediction	Handles high-dimensional data, robust to overfitting	Requires large datasets for accurate performance	Arnold et al. (2023) , Prihoda et al. (2020)
Support Vector Machines (SVMs)	BGC classification, infection prediction	Effective in high-dimensional spaces	Computationally expensive for large datasets	
Convolutional Neural Networks (CNNs)	Metabolite structure prediction, bioactivity classification	Excellent at feature extraction from complex data	Requires large labeled datasets for training	Ma et al. (2024) , Prihoda et al. (2020)
Recurrent Neural Networks	Predicting biosynthetic pathways, sequence data analysis	Captures sequential dependencies in genomic data	Prone to vanishing gradient problem with long sequences	Arnold et al. (2023)
Graph Neural Networks	Compound structure modeling, bioactivity prediction	Models complex molecular structures effectively	Requires graph-based data representation	Arnold et al. (2023)
K-Means Clustering	Microbial community analysis, gene co-occurrence patterns	Simple and fast, identifies natural groupings in data	Sensitive to initialization and number of clusters	Prihoda et al. (2020)
Gradient Boosting Models	Bioactivity prediction, prioritizing novel compounds	Improves accuracy with ensemble learning	Prone to overfitting if not properly tuned	Prihoda et al. (2020)
BGC, <i>biosynthetic gene cluster</i> .				

culture-based techniques and biochemical assays, limiting the speed and scale of exploration (Arnold et al., 2023). With the increasing availability of high-throughput sequencing and multi-omics data, ML now offers more efficient pathways to uncover microbial products by revealing hidden patterns in genetic and environmental data (Jiang, Luo, et al., 2022).

8.3.1 Genome mining and biosynthetic gene cluster prediction

A key focus of ML in microbial marine product prediction is genome mining the process of identifying BGCs responsible for producing bioactive compounds. Supervised learning models like RF and SVMs have been particularly effective in distinguishing BGCs from non-BGC regions by training on labeled datasets of known gene clusters (Arnold et al., 2023).

RF models applied to genomic datasets have successfully predicted novel BGCs in marine actinomycetes, leading to the discovery of antimicrobial compounds (Arnold et al., 2023). Additionally, unsupervised learning techniques, such as k-means clustering, have been employed to group gene clusters with similar biosynthetic pathways, providing deeper insights into microbial ecology (Prihoda et al., 2020). DL models like CNNs and Recurrent Neural Networks are increasingly used to predict biosynthetic pathways, leveraging vast sequencing data to detect novel microbial products (Chen et al., 2024; Ma et al., 2024).

8.3.2 Metagenomics and microbial community analysis

Marine environments host complex microbial communities, often dominated by unculturable microbes. Metagenomics the direct sequencing of environmental DNA (eDNA) has emerged as a powerful tool to study these communities and identify novel BGCs (Sabaria, 2024). ML algorithms applied to metagenomic datasets have facilitated the prediction of microbial behavior and community dynamics, uncovering microbial contributions to nutrient cycling and biogeochemical processes (Ghannam & Techtmann, 2021).

In a recent study, eDNA analysis combined with RF models enabled researchers to predict microbial population shifts and detect new microbial strains, significantly advancing the understanding of microbial ecology and the discovery of marine natural products (Sabaria, 2024). Moreover, unsupervised clustering techniques have been applied to identify co-occurring genes indicative of BGCs, broadening the scope for bioprospecting (Sabaria, 2024).

8.3.3 Bioactivity predicting and compound structure

Another critical application of ML lies in predicting the bioactivity of microbial products once BGCs are identified. Supervised ML techniques, such as decision trees and GBMs, have been trained on large datasets of known bioactive compounds to predict the likelihood of antimicrobial, anticancer, or antiviral properties in newly discovered compounds (Prihoda et al., 2020).

For example, CNNs have been used to predict compound structures and their corresponding biological activities by analyzing molecular fingerprints and chemical descriptors (Prihoda et al., 2020). Furthermore, graph neural networks and autoencoders have shown remarkable success in

learning structural relationships between microbial metabolites, providing insights into novel drug candidates (Arnold et al., 2023).

8.4 Monitoring microbial marine products using machine learning

Monitoring microbial marine products (MMPs) is essential for understanding microbial diversity, ecosystem health, and the sustainable management of marine resources. Traditionally, microbial monitoring relied on labor-intensive sampling and culture-based techniques, which often overlooked vast populations of unculturable microbes. The advent of ML has transformed microbial monitoring by enabling real-time analysis of large datasets, improving the detection of environmental changes, microbial interactions, and bioactive compound production (Ghannam & Techtmann, 2021). ML applications in this field span across areas such as eDNA analysis, harmful algal bloom (HAB) prediction, tracking microbial community dynamics, and pollution monitoring each contributing to more effective marine ecosystem management (Fig. 8.1).

8.4.1 Environmental DNA analysis for microbial monitoring

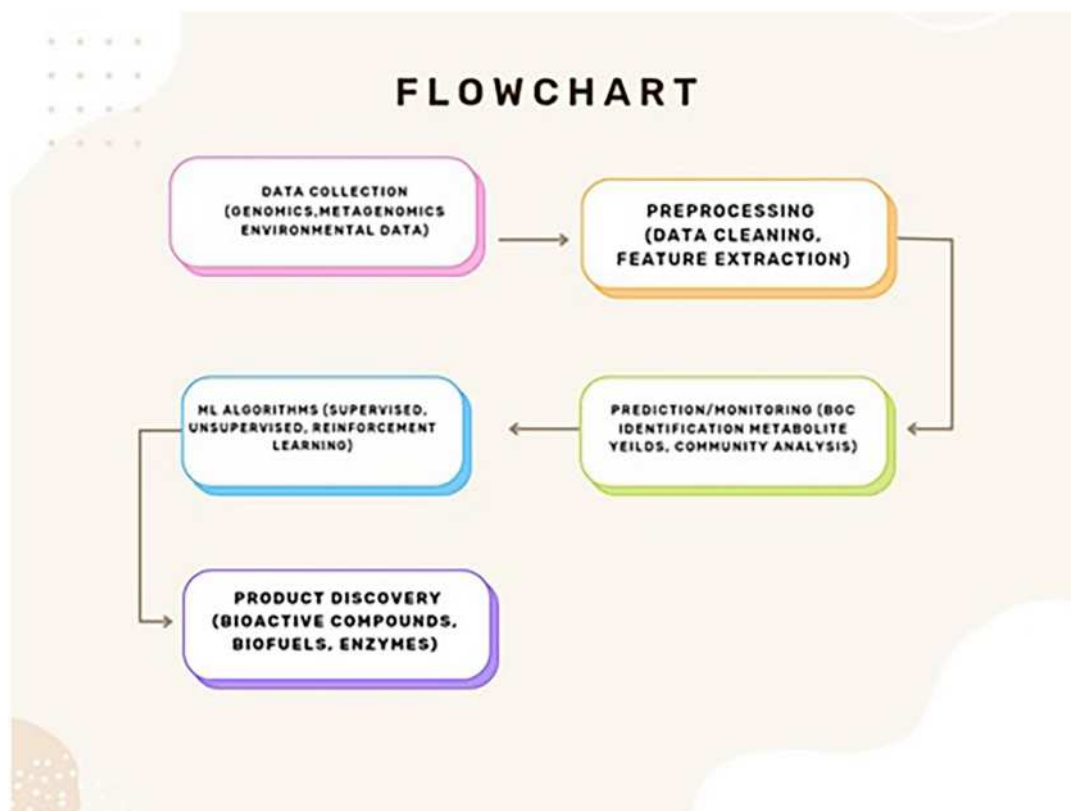
eDNA analysis has become a cornerstone in microbial monitoring, offering a non-invasive method to study microbial biodiversity. eDNA refers to genetic material shed by organisms into their surroundings, which can be collected from seawater and analyzed to infer microbial community composition. ML techniques applied to eDNA datasets have enhanced researchers' ability to track microbial populations, identify emerging species, and monitor ecological changes in near real-time (Ghannam & Techtmann, 2021).

In particular, RF and SVMs have been employed to classify microbial populations based on eDNA sequences, revealing microbial responses to changing environmental conditions (Sabaria, 2024). These techniques have also improved the detection of microbial signatures associated with specific biosynthetic pathways, enhancing the tracking of natural product biosynthesis in marine environments.

8.4.2 Prediction of harmful algal blooms

HABs sudden proliferations of algae that produce toxins harmful to marine life and humans pose significant ecological and economic risks. Predicting these events is crucial for mitigating their impact. ML has become an indispensable tool in HAB prediction by integrating environmental parameters such as sea surface temperature, chlorophyll *a* concentration, and nutrient levels into predictive models.

For instance, ML classification algorithms have been successfully applied to forecast *Karenia brevis* blooms on the West Florida Shelf. By analyzing historical datasets, RF and artificial neural networks (ANNs) achieved high accuracy in predicting bloom occurrences, enabling the creation of early warning systems to mitigate ecological and economic impacts (Li et al., 2021). Such predictive models not only support public health interventions but also help minimize economic losses from fisheries closures and tourism disruptions.

**FIGURE 8.1**

Machine learning pipeline for microbial marine product discovery, illustrating key steps from data collection and preprocessing to prediction, monitoring, and product discovery.

8.4.3 Microbial community dynamics and biogeochemical cycles

Marine microbial communities play pivotal roles in biogeochemical processes such as carbon sequestration, nitrogen fixation, and phosphorus cycling. Monitoring these communities is essential for understanding ecosystem functions and assessing the impacts of environmental stressors and climate change.

ML techniques have been integrated with metagenomics and metabolomics to model microbial contributions to these cycles. In particular, Gradient Boosting Models (GBMs) have been used to predict microbial responses to environmental stressors, shedding light on the microbial processes underlying carbon cycling and nutrient transformations (Prihoda et al., 2020). Furthermore, unsupervised clustering techniques have improved our understanding of microbial diversity and ecosystem resilience by grouping microbial taxa based on ecological niches (Ghannam & Techtmann, 2021).

These insights are critical for identifying microbial indicators of ecosystem health, enabling the development of early warning systems for detecting environmental degradation and informing marine conservation policies.

8.4.4 Monitoring microplastic transport and pollution

The rising levels of marine plastic pollution have profoundly impacted microbial communities, with microplastics creating “plastispheres” unique ecosystems on plastic surfaces that harbor microbial colonizers, including pathogens (Aransiola et al., 2025). Understanding the transport and ecological impact of microplastics has become a pressing research priority, and ML has been instrumental in advancing this field.

In a recent study, CNNs were used to analyze satellite imagery, accurately predicting microplastic accumulation zones in marine environments (Phan & Luscombe, 2023). Additionally, Decision Tree Classifiers have been integrated with oceanographic data to predict microplastic dispersal patterns, contributing to long-term pollution monitoring and guiding targeted cleanup efforts. These models offer new avenues for tracking pollution hotspots and understanding the broader impacts of plastic pollution on marine microbial ecosystems.

8.4.5 Autonomous monitoring with unmanned systems

The deployment of autonomous underwater vehicles (AUVs) and unmanned surface vehicles equipped with ML-driven sensors has opened new frontiers in microbial monitoring. These unmanned systems are capable of collecting environmental data across vast oceanic regions, enabling near real-time insights into microbial dynamics and ecosystem changes (Almeida, 2022).

8.4.6 Monitoring microbial marine products

ML techniques offer robust solutions for monitoring microbial activities and environmental changes in marine ecosystems. One crucial application is environmental monitoring and prediction, where ML models have been instrumental in forecasting microbial behavior and addressing ecological challenges. For instance, models such as SVM and ANN have been employed to predict HABs, identifying key environmental factors like wind patterns and nutrient availability that influence bloom formation (Li et al., 2021). Similarly, ultraviolet spectroscopy combined with ML models facilitates the real-time monitoring of marine pathogenic bacteria, enabling early detection of ecological threats (Chen et al., 2024; Ma et al., 2024).

Another significant area is the prediction of pathogenic microorganisms on microplastics. Deep neural networks and RF models have been utilized to predict the abundance of pathogenic *Vibrio* spp. on microplastics, offering insights into the impact of environmental factors like salinity and temperature on microbial presence (Jiang et al., 2022). Moreover, ML techniques, including image segmentation and DL, have improved the accuracy of antimicrobial resistance (AMR) prediction in marine environments. This early detection capability is crucial for managing AMR, which poses a significant threat to public health and marine ecosystems (Fough et al., 2024).

In addition, ML algorithms have been applied to classify microalgae species, monitor their growth, and explore their applications in bioenergy and environmental purification (Ning et al., 2022; Syed et

al., 2024). Water quality prediction has also benefited from ML applications, with ANN and SVM models effectively predicting water quality and HABs in coastal areas, thus aiding in water quality management and the prevention of related damages (Deng et al., 2021).

ML techniques further extend to corrosion monitoring in marine environments, where algorithms like ANNs and RF are used to predict and detect corrosion, ensuring the structural integrity of marine infrastructure, especially in offshore and oil and gas industries (Imran et al., 2024). Additionally, ML has been employed to study emerging contaminants such as microplastics and antibiotic resistance genes. These models effectively predict the occurrence, distribution, and bioeffects of contaminants, enhancing environmental monitoring and management efforts (Lei et al., 2023). Lastly, ML models are increasingly used to predict marine hypoxia by simulating complex marine biogeochemical processes, aiding aquaculture and fisheries management by improving predictions of oxygen levels and informing observation measurement arrays (Skákala et al., 2023).

8.5 Integration with remote sensing and metagenomics

8.5.1 Remote sensing

The integration of ML with remote sensing offers powerful tools for analyzing complex environmental datasets, enabling more accurate predictions and enhancing resource management (Sabaria et al., 2024; Ma et al., 2024). ML techniques improve the utilization of remote sensing data for applications such as environmental monitoring, geological analysis, and biodiversity assessment (El-Omairi & Garouani, 2023; Han et al., 2023).

DL models, particularly CNNs, have significantly enhanced the performance of remote sensing technologies, achieving unprecedented improvements in land cover mapping, vegetation monitoring, soil property estimation, and natural disaster management (Chen et al., 2023; Ghanbari et al., 2021). Integrating ML with remote sensing provides an efficient means of deciphering Earth's geological features, enabling multi-source data fusion, up-to-date environmental insights, and vast data management capabilities (El-Omairi et al., 2023).

8.5.2 Metagenomics

ML has transformed the study of microbial communities by enhancing the analysis of large-scale metagenomic datasets. These advancements have improved taxonomic classification, functional annotation, and the prediction of microbial interactions, offering valuable insights into microbial ecology and metabolic potential (Sabaria et al., 2024).

Integrating ML with metagenomics has led to breakthroughs in microbial diversity exploration, antibiotic resistance detection, bioremediation, and the discovery of novel bioproducts (Sabaria et al., 2024). The capacity of ML to process massive datasets and uncover intricate patterns has made it indispensable in microbiome research, addressing challenges such as data standardization, interpretability, and interdisciplinary collaboration (D'Elia et al., 2024).

The synergy between ML, remote sensing, and metagenomics has reshaped microbial marine product monitoring and prediction. DL models have proven highly effective in remote sensing

applications, handling complex environmental data with remarkable accuracy (Chen et al., 2023). Transfer learning (TL) has further enhanced these applications by addressing domain shift challenges and reducing the dependency on labeled data (Ma et al., 2024).

Additionally, SVMs have emerged as reliable tools for lithological mapping and other environmental studies (Mohamed Ali El-Omairi et al., 2023). Integrating expert knowledge with ML methodologies, alongside Geographic Information Systems (GIS) and high-performance computing, significantly boosts model efficiency and generalizability in marine monitoring contexts. Such interdisciplinary approaches offer deeper insights into microbial marine ecosystems and facilitate more precise environmental change monitoring (Han et al., 2023).

8.6 Key Applications and case studies

8.6.1 Pharmaceutical compound discovery

Marine microorganisms offer immense potential for the discovery of novel pharmaceutical compounds, such as antibiotics and anticancer agents. ML techniques like RF and SVMs have been used to identify BGCs responsible for producing bioactive metabolites, streamlining natural product discovery (Goshisht, 2024).

8.6.2 Biofuel production from marine microbes

Microalgae play a crucial role in marine ecosystems and hold significant promise for biofuel production. ML algorithms have been successfully applied to monitor microalgae growth, classify species, and optimize conditions for biofuel production (Ning et al., 2022; Syed et al., 2024).

8.6.3 Harmful algal bloom prediction

ML models, such as SVMs and ANNs, have been employed to predict HABs caused by toxic dinoflagellates like *Karenia brevis*. These models identify key environmental factors—such as wind patterns and nutrient availability—that influence bloom formation, providing early warnings and aiding coastal management (Deng et al., 2021; Li et al., 2021).

8.6.4 Pathogenic bacteria growth prediction

Ultraviolet spectroscopy combined with ML models has enabled the prediction of marine pathogenic bacteria growth, allowing real-time monitoring and early detection of potential ecological threats (Chen et al., 2024; Ma et al., 2024).

8.6.5 Predicting pathogenic microorganisms on microplastics

Deep neural networks and RF models have been used to predict the abundance of pathogenic *Vibrio* spp. on microplastics. These models reveal the impact of environmental factors like salinity and

temperature on microbial abundance, aiding dynamic monitoring systems for potential health risks (Jiang et al., 2022).

8.6.6 Antimicrobial resistance detection

ML techniques, including image segmentation and DL, have enhanced the accuracy of predicting AMR in marine environments. Early detection of AMR is critical for mitigating public health risks and preserving marine ecosystem balance (Fough et al., 2023). The use of ML to analyze high-dimensional microbiome data has been pivotal in uncovering resistance genes and tracking their spread across marine ecosystems (D'Elia et al., 2024).

8.6.7 Water quality prediction and harmful algal blooms

ANNs and SVMs have been applied to predict water quality and HABs in coastal areas. These models provide accurate forecasts, helping manage water quality and prevent ecological damage (Deng et al., 2021).

8.6.8 Corrosion monitoring in marine environments

In marine, offshore, and oil and gas industries, ML algorithms—such as ANNs and RF—have been deployed to predict and detect corrosion, ensuring the structural integrity of marine infrastructure (Imran et al., 2024).

8.6.9 Emerging contaminants and environmental monitoring

ML has been applied to track emerging contaminants, such as microplastics and antibiotic resistance genes, in marine environments. These models effectively predict the occurrence, distribution, and ecological impacts of contaminants, supporting environmental monitoring and management (Lei et al., 2023).

8.6.10 Predicting marine hypoxia

ML models are being developed to emulate complex marine biogeochemical processes, enhancing the prediction of hypoxia in marine environments. These tools support the development of digital twins for aquaculture and fisheries, providing valuable insights into oxygen level fluctuations and ecosystem health (Skákala et al., 2023).

8.6.11 Environmental monitoring and prediction

ML techniques have been instrumental in monitoring microbial behavior in marine environments, addressing ecological challenges. For example, RF models have been applied to forecast *Vibrio vulnificus* infections by incorporating environmental factors like temperature, salinity, and

chlorophyll *a* concentration (Campbell et al., 2025). Similarly, SVMs and neural networks have been used to predict *Vibrio parahaemolyticus* concentrations in seawater and oysters, identifying turbidity as a key driver of microbial growth (Karanth et al., 2024).

8.6.12 Soil organic carbon estimation

Integrating remote sensing, ML, and proximal sensing spectroscopy has improved the precision of Soil Organic Carbon estimation. This supports local economies by enhancing farmers' ability to monitor soil health, promoting sustainable agricultural practices (Li et al., 2023).

8.7 Challenges and future directions

8.7.1 Data scarcity and quality

One of the most pressing challenges in ML-driven microbial monitoring is data scarcity. Marine environments are vast and under-sampled, resulting in datasets that lack the diversity necessary to train robust ML models (Arnold et al., 2023). The limited availability of labeled data for marine microbes can hinder model performance, as many species remain uncultured and unexplored (Sabaria, 2024). Furthermore, the complexity of marine ecosystems demands datasets that capture dynamic environmental variables, which are often incomplete or inconsistent (Li et al., 2021). Integrating diverse data sources—such as satellite imagery, geological surveys, and environmental monitoring systems—could help address this limitation by providing richer datasets for training more accurate models (Han et al., 2023).

8.7.2 Model interpretability and trust

Another significant hurdle is the interpretability of ML models. DL techniques often operate as “black boxes,” making it challenging to trace the decision-making processes behind predictions (Ghannam & Techtmann, 2021). This lack of transparency raises concerns regarding the biological relevance of the outputs and limits trust in ML predictions among marine scientists and policymakers. XAI techniques are emerging as promising solutions to enhance model transparency and extract meaningful biological insights from complex datasets (Arnold et al., 2023). Additionally, developing models capable of handling the complexity and variability of metagenomic data while remaining interpretable is an ongoing challenge (Sabaria et al., 2024).

8.7.3 Interdisciplinary collaboration

The successful application of ML in marine microbial research requires interdisciplinary collaboration between marine scientists, bioinformaticians, data scientists, and engineers. Combining domain expertise with ML methodologies is essential to ensure that models are not only accurate but also biologically meaningful. Integrating knowledge from fields such as genomics, metabolomics, and metagenomics can provide a more comprehensive view of microbial processes, further improving

predictive accuracy (Nagar et al., 2023). Moreover, the deployment of AUVs equipped with real-time sensors could revolutionize marine microbial monitoring by expanding data collection efforts and enabling real-time insights into ecosystem health (Almeida, 2022).

8.7.4 Complexity of marine ecosystems

Marine environments are highly dynamic, and predicting microbial behavior in such systems requires models that can handle complex, high-dimensional data (Chen et al., 2024; Li et al., 2021; Ma et al., 2024). Developing models that can handle the complexity and variability of metagenomic data is an ongoing challenge. (Sabaria et al., 2024).

8.7.5 Integration of knowledge and techniques

Expert knowledge, GIS, and high-performance computing techniques will be helpful to improve the efficiency and generalizability of ML and DL methods for processing the multi-platform RS data (Han et al., 2023). Despite the advancements in ML for microbial marine product prediction, several challenges remain.

Future research should focus on developing larger, well-curated datasets, and improving model interpretability to address these challenges.

8.8 Conclusion

ML has emerged as a transformative tool in the prediction and monitoring of MMPs, offering novel approaches to harness the immense biodiversity of marine microbes. As explored throughout this chapter, ML algorithms have demonstrated remarkable potential in uncovering BGCs, predicting metabolite yields, optimizing bioprocess conditions, and enhancing real-time monitoring of microbial ecosystems (D'Elia et al., 2024). From supervised learning techniques that classify microbial species and identify promising bioactive compounds to unsupervised learning approaches that reveal hidden microbial community structures, ML has provided insights that traditional methods could not achieve (Goshisht, 2024). RL has further expanded these capabilities by dynamically optimizing environmental conditions to maximize microbial productivity (Kiling, 2024).

The integration of ML with high-throughput sequencing technologies, remote sensing, and synthetic biology has paved the way for accelerated discoveries and improved process efficiencies in marine biotechnology. Notably, the applications of ML extend beyond microbial product discovery into fields such as pharmaceutical compound development, biofuel production, and environmental management (Ambrosino et al., 2019). As case studies have illustrated, these ML-driven innovations hold significant promise for addressing global challenges, including the need for sustainable energy sources and effective environmental remediation (Srivastava & Brylinski, 2025).

However, several challenges remain. Data scarcity, model interpretability, and the need for experimental validation present ongoing hurdles to the widespread adoption of ML in marine microbial research. Additionally, ethical and environmental considerations regarding the deployment

of autonomous monitoring systems and engineered microbes require careful navigation (Ambrosino et al., 2019). Future research must focus on enhancing data-sharing practices, improving model transparency, and strengthening interdisciplinary collaborations to ensure the responsible application of ML technologies (D’Elia et al., 2024).

The future of ML in marine biotechnology is exceptionally promising. Emerging technologies such as TL, few-shot learning, and explainable AI (XAI) are poised to further enhance the accuracy and interpretability of predictive models (Goshisht, 2024). Moreover, the integration of ML with synthetic biology will unlock new pathways for engineering microbial cell factories, while advancements in real-time environmental monitoring will improve our understanding of microbial dynamics in complex marine ecosystems (Kilinç, 2024).

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Utilization of marine microbial products for the creation of biosensors

Vyshnava Satyanarayana Swamy¹, K. Swetha¹, Gayathri Pandluru¹, Shiva Prasad Panajala², Kameshpandian Paramasivam³, Dineshkumar Krishnamoorthy⁴ and M. Srinivasulu⁵

¹*Department of Biotechnology, University College of Sciences, Sri Krishnadevaraya University, Anantapuramu, Andhra Pradesh, India,*

²*Department of Genetics and Biotechnology, University College of Sciences, Osmania University, Hyderabad, Telangana, India,*

³*DMI St. John The Baptist University, Lilongwe, Malawi,*

⁴*Center for Genomics and Systems Biology, New York University Abu Dhabi, Saadiyat Campus, Abu Dhabi, United Arab Emirates,*

⁵*Department of Biotechnology, Yogi Vemana University, Kadapa, Andhra Pradesh, India*

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9.1 Introduction

Below the Earth's oceanic surface exists a substantial, mainly unexploited pool of microbial life possessing remarkable metabolic capabilities. Marine microorganisms that have adapted to extreme environmental circumstances, including high pressure, salt, and low temperatures, have developed distinctive metabolic pathways, resulting in the synthesis of structurally varied and frequently bioactive metabolites (Giordano, 2020). These bacteria constitute a vital asset for numerous biotechnological applications, especially in the advancement of biosensors. Although terrestrial bacteria have historically prevailed in microbial biotechnology, marine microbes are becoming recognized as preferable possibilities in several contexts owing to their remarkable resilience and metabolic uniqueness (Robaina-Estévez & Gutiérrez, 2024).

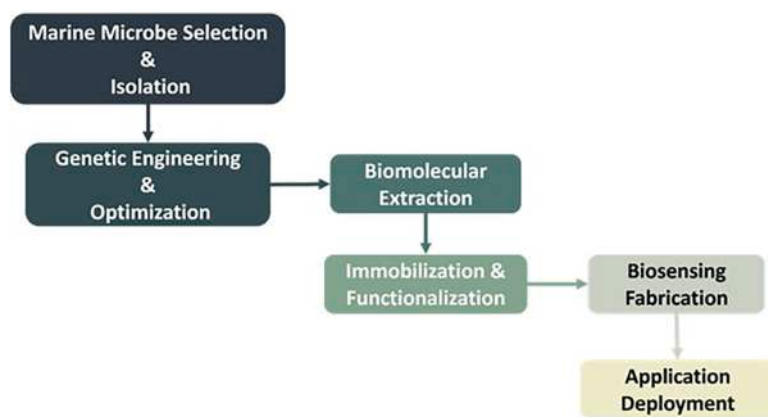
Biosensors are analytical instruments that integrate a biological recognition component, such as an enzyme, antibody, nucleic acid, or microbial cell, with a transducer to produce a quantifiable signal that correlates with the quantity of a given analyte (Barreiros dos Santos et al., 2022). Recently, the incorporation of marine microbial products into biosensor systems has advanced environmental monitoring, medical diagnostics, and food safety, providing benefits in sensitivity, selectivity, and durability under adverse conditions, which are listed in Table 9.1 (Chalklen et al., 2020). The previous decade has shown swift advancements in the creation and use of biosensors originating from marine microbial elements (Fig. 9.1). Whole-cell biosensors have garnered interest for their capacity to detect a diverse array of chemical and biological signals (Moraskie et al., 2021). These biosensors employ living or modified microbial cells, frequently incorporating reporter genes such as *lux*, *gfp*, or *lacZ*, to provide quantifiable outputs such as light or fluorescence in reaction to particular analytes (Moraskie et al., 2021).

Bioluminescent bacteria, such as *Vibrio fischeri*, prevalent in marine ecosystems, have been utilized in biosensors for the detection of harmful chemicals and pollutants. These luminous microbial biosensors provide benefits in speed, simplicity, and real-time analysis, particularly in marine habitats where swift pollutant detection is essential (Olaniyan et al., 2025). Moreover, microbial fuel cell (MFC)-based biosensors utilizing marine sediment microorganisms have exhibited the capacity to transform metabolic data directly into electrical outputs (Sun et al., 2024). Electrochemical biosensors have been utilized for the detection of assimilable organic carbon (AOC) and heavy metals in seawater, underscoring its significance in marine pollution monitoring (Quek et al., 2015).

Recent advancements in synthetic biology have markedly improved the capabilities of marine microbial biosensors. Engineered microbes can now be programmed with synthetic genetic circuits to respond to various analytes with great specificity and little cross-reactivity. Species of *Shewanella* and *Pseudomonas* have been genetically engineered to produce reporter proteins in reaction to particular environmental pollutants, including pesticides, hydrocarbons, and heavy metals (Ruhai & Kataria,

Table 9.1 Types of marine microbial products used in biosensors.

Microbial product type	Examples	Biosensor applications
Enzymes	Laccase, peroxidase, oxidoreductase	Electrochemical detection of phenols, heavy metals
Proteins	Lectins, luciferase, binding proteins	Optical biosensors, target-specific detection
Whole cells	<i>Shewanella</i> , <i>Vibrio</i> , <i>Pseudomonas</i>	Whole-cell biosensors for toxicity and pollution detection
Polysaccharides	Alginate, chitin, fucoidan	Immobilization matrices, biocompatible coatings
Pigments	Violacein, prodigiosin	Redox-active agents for electrochemical sensors
Antibodies	Monoclonal antibodies from marine microbes	Specific binding in SPR and immunosensors
Aptamers	DNA/RNA aptamers from marine bacteria	Toxin/pathogen detection in optical/electrochemical platforms
Biofilms	Marine bacterial biofilms	Environmental monitoring, real-time sensing
Exopolysaccharides	Stabilizing polymers secreted by marine microbes	Enhancing sensor stability and performance
Genetically engineered strains	<i>Vibrio</i> sp. with GFP/lux reporters	Biosensors for pollutant and pathogen detection

**FIGURE 9.1**

General workflow of marine microbial biosensor development.

2022; Steffi et al., 2022). Biosensor-assisted strain engineering has allowed researchers to precisely adjust microbial physiology for enhanced sensing capability. Moon et al. (2024) illustrated the utility of high-throughput biosensor-assisted screening platforms for identifying novel transporters and regulatory pathways in microbial cell factories, a methodology that can similarly be employed to improve marine microbial biosensor design (Moon et al., 2024).

Marine microbial biosensors have numerous applications in environmental monitoring, especially in identifying organic and inorganic pollutants in marine and coastal waters. These biosensors offer an environmentally sustainable and cost-effective alternative to traditional analytical methods, which often need extensive sample preparation and equipment (Thakur & Kumar, 2022). Microbial biosensors have been utilized in biomedical diagnostics to detect pathogenic bacteria, viral agents, and disease biomarkers. Eshaa et al. (2024) emphasized the importance of modified microbial biosensors in healthcare, highlighting their ability to provide cost-effective, field-deployable diagnostics for infectious diseases (Eshaa et al., 2024). Marine microbial derivatives exhibit potential for detecting foodborne toxins and contaminants. Enzyme and aptamer-based biosensors derived from marine microbes have been employed in food safety applications to identify spoilage and pathogenic contamination, hence ensuring product quality and consumer safety.

Despite significant progress, some obstacles persist that impede the extensive implementation of marine microbial biosensors. These encompass restricted scalability, challenges in sustaining biosensor stability across diverse environmental conditions, and regulatory obstacles for commercial use (Moraskie et al., 2021). Furthermore, the methods of action and target specificity of numerous marine-derived bioactive chemicals are inadequately comprehended, constraining their utilization in precise biosensing. Future integration with future technologies, including nanomaterials, artificial intelligence, and Internet-of-Things (IoT) platforms, is anticipated to transform marine microbial biosensor design (Koca & Akan, 2024). These advancements will facilitate the creation of intelligent, self-reporting biosensors with enhanced sensitivity, specificity, and real-time data processing capacities.

The application of marine microbial products in biosensor development constitutes a promising and swiftly advancing domain. Recent studies underscore its extensive potential in environmental, biomedical, and industrial sectors as listed in Table 9.2. Advancements in synthetic biology, sensor engineering, and data analytics position marine microbial biosensors as essential instruments in the forthcoming generation of sustainable and adaptive diagnostic technologies. This chapter explores the potential of marine microbial products as novel biorecognition components for biosensor development, highlighting their varied applications in environmental monitoring, biomedical diagnostics, food safety, and industrial process control.

9.2 Marine microbial products as biorecognition elements

Biosensors are specialized analytical instruments that utilize biological components to identify specific analytes with exceptional sensitivity and specificity (Haleem et al., 2021). Marine microbial products have emerged as fascinating biorecognition elements in biosensor technology owing to their remarkable metabolic variety, stability, and tolerance to extreme environmental conditions (Chakraborty & Krishnani, 2022). Marine microorganisms, including bacteria, fungus, archaea, and

Table 9.2 Biosensors and their application from the marine microbial products.

Marine microbial product	Type of biosensor	Application	References
Bioluminescent bacteria (<i>Vibrio fischeri</i>)	Optical (bioluminescence)	Detection of pollutants in marine environments	Abbas et al. (2018)
Marine sediment electrogenic bacteria	Electrochemical (MFC)	Monitoring AOC in seawater	Zhou et al. (2024)
<i>Staphylococcus aureus</i> (salt-tolerant)	Electrochemical	Heavy metal and pesticide biotoxicity detection	Liu et al. (2023)
Genetically engineered <i>E. coli</i>	Optical (fluorescent/bioluminescent)	Environmental pollutant detection	Zappi et al. (2021)
Anodophilic marine biofilm	Electrochemical (MFC)	AOC detection under oxygenated seawater	Cheng et al. (2014)
General microbial strains (marine-derived)	General microbial biosensors	Environmental, food, biomedical monitoring	Rangesh et al. (2024)
Photosynthetic microalgae	Synthetic biology platforms	Synthetic biology in algae biosensing	Patwari et al. (2023)
<i>P. subcordiformis</i> (microalgae)	Microfluidic motion-based optical	Heavy metal and toxic organic detection	Zhao et al. (2019)
Various marine microbes	General analytical biosensors	Marine pollution, water contaminants	Ma et al. (2022)
Whole-cell biosensors	Electrochemical and optical	Environmental/biomedical monitoring	Luka et al. (2015)
Engineered microbial strains	Electrochemical and fluorescent	High-throughput strain screening	Sarnaik et al. (2020)
Marine <i>Vibrio</i> species	Optical (bioluminescent)	Contaminant detection in seawater	Thacharodi et al. (2019)
Marine microbial consortia	Bioelectronic and fuel-cell based	Marine monitoring and pollution detection	Olias and Di Lorenzo (2021)
Marine microbes (bioluminescent genes)	Optical and genetic circuit-based	Environmental diagnostics and biocomputing	Slomovic et al. (2015)
Marine microbial enzymes	Enzymatic biosensors	Pollutant detection (phenols, metals)	Nigam and Shukla (2015)
Marine microbial strains	Electrochemical (with micro/nanointegration)	Environmental/clinical biosensors	Raditya and O'Hare (2020)
Genetically modified microbial cell factories	Fluorescent/metabolic control-based	Metabolic sensing, strain engineering	Lorenzon (2020)
Marine algae, microbes (macro/microbiota)	Electrochemical, optical, environmental	Pollutant and health monitoring	da Costa Filho et al. (2022)
Marine microbes (GMO and wild-type)	Genetic/electrochemical hybrid biosensors	Pollution and pathogen diagnostics	Zheng et al. (2022)
Marine biological macromolecules (chitin, alginate)	Matrix for various biosensor types	Biomedical, food, and environmental monitoring	Bedi et al. (2022)

viruses, produce a variety of bioactive chemicals such as enzymes, proteins, nucleic acids, and entire cellular systems, which serve as effective biorecognition elements in biosensors (Oon et al., 2023). These components enable rapid and precise identification of target molecules, making them beneficial for environmental monitoring, healthcare diagnostics, and food safety applications.

9.2.1 Bioactive compounds derived from marine microorganisms

Marine microbial compounds possess unique structural and functional attributes that make them appropriate for biosensing applications. A variety of bioactive compounds, such as polysaccharides, peptides, and secondary metabolites, have considerable selectivity and affinity for target analytes (Yao et al., 2023). Marine-derived lectins, a class of carbohydrate-binding proteins, have been utilized in biosensors for the identification of glycan-based biomarkers linked to cancer and viral diseases. Marine-derived antimicrobial peptides (AMPs) have been integrated into biosensing devices for the accurate detection of bacterial infections (Mazurkiewicz-Pisarek et al., 2023).

Marine polysaccharides, such as alginate, chitin, and fucoidan, have been thoroughly examined as biorecognition elements. These natural polymers exhibit remarkable biocompatibility and stability, making them appropriate for the immobilization of enzymes and other biological entities on biosensor surfaces (Aransiola et al., 2024; Sofi et al., 2019). Additionally, particular marine microbial pigments, such as violacein and prodigiosin, have been included into biosensors as redox-active agents for electrochemical detection (Mikhailova, 2024).

9.2.2 Marine-derived enzymes and proteins in biosensing

Enzymes are crucial in biosensor design as they catalyze certain biological events that yield detectable signals. Marine microorganisms constitute an untapped source of extremophilic enzymes that demonstrate stability under harsh conditions, including high salinity, extreme temperatures, and variable pH levels (Mikhailova, 2024). Marine-derived enzymes employed in biosensing include laccases, peroxidases, and oxidoreductases, which have been utilized in biosensors for detecting environmental pollutants, heavy metals, and organic contaminants (Theerachai et al., 2019).

An illustrative example is the utilization of marine microbial laccases in biosensors designed for phenol detection. These enzymes, derived from marine fungi and bacteria, exhibit remarkable catalytic efficiency and stability in organic solvents, making them very suitable for environmental monitoring applications. Additionally, proteases obtained from deep-sea microbes have been integrated into biosensors for the identification of peptide-based biomarkers, indicating potential use in medical diagnostics (Morlighem & Radis-Baptista, 2019).

9.2.3 Role of marine-derived antibodies and aptamers

Antibodies and aptamers generated by marine microorganisms have been examined as biorecognition elements in biosensors due to their high binding specificity and affinity for target molecules. Monoclonal antibodies (mAbs) derived from marine sources have been developed for the identification of marine toxins, heavy metals, and pathogenic microorganisms in environmental and

food safety applications (D'Agata et al., 2021). These antibodies exhibit considerable selectivity, enabling biosensors to distinguish between structurally similar compounds.

Aptamers, concise single-stranded DNA or RNA sequences that selectively attach to specific targets, have been derived from marine microbial sources. Marine-derived aptamers exhibit superior stability and degradation resistance, making them optimal for extended biosensing applications (Acquah et al., 2020). These aptamers have been utilized in optical and electrochemical biosensors for the detection of biomarkers, toxins, and environmental pollutants (Khanmohammadi et al., 2020).

9.2.4 Marine microbial cell-based biosensors

Whole-cell biosensors employing living marine microorganisms as biorecognition components have been thoroughly investigated for the identification of environmental contaminants, pathogens, and metabolic changes in biological systems (Gutiérrez et al., 2015). Marine microbial fuel cell-based biosensors (MFC-Bs) demonstrate the application of electrogenic bacteria from marine sediments to generate electrical signals in response to organic pollutants. These biosensors have been employed for the surveillance of water quality, facilitating real-time identification of biochemical oxygen demand (BOD), heavy metals, and hydrocarbons (Hossain & Mansour, 2019).

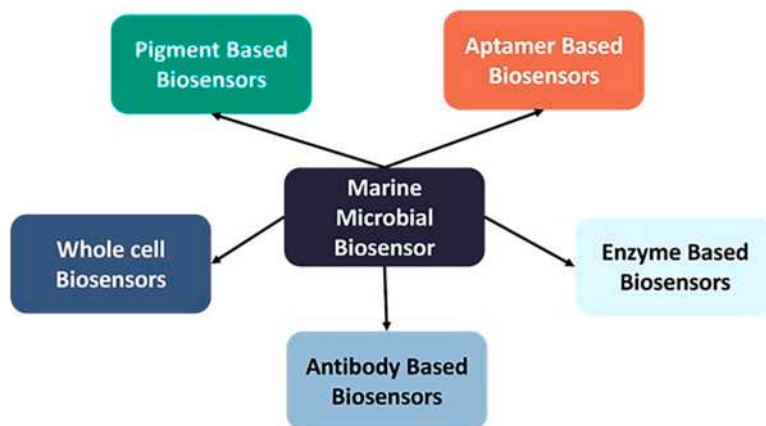
Genetically modified marine-derived bacterial strains, such as *Pseudomonas*, *Shewanella*, and *Vibrio* species, exhibit enhanced biosensing capabilities (Lami, 2019). By including reporter genes that create fluorescent or luminescent proteins, these engineered bacteria can provide measurable optical signals in the presence of certain analytes (Chernov et al., 2017). Microbial biosensors have shown promise in detecting environmental pollutants, medication residues, and disease biomarkers.

9.3 Types of biosensors incorporating marine microbial products

Biosensors are analytical instruments that combine a biological recognition component with a transducer to identify specific analytes. The integration of marine microbial compounds into biosensor technology has transformed their sensitivity, specificity, and functionality. Owing to the biochemical diversity of marine microbes, numerous biosensors have been created, each utilizing distinct microbial components including enzymes, entire cells, and metabolites (Ma et al., 2022). This section examines various biosensor types that utilize marine microbial products, highlighting their operational principles, benefits, and applications as shown in Fig. 9.2 and same listed in Table 9.3.

9.3.1 Electrochemical biosensors

Electrochemical biosensors are among the most prevalent biosensors, providing great sensitivity, swift detection, and possibility for downsizing. These biosensors quantify biochemical events by transducing them into electrical signals utilizing marine microbial enzymes, biofilms, or whole cells (Hu et al., 2022; Khanmohammadi et al., 2020). Marine-derived oxidoreductases, including laccases and peroxidases, are essential in electrochemical biosensors for the detection of environmental contaminants such as phenols, heavy metals, and organic poisons (Ramachandran et al., 2019).

**FIGURE 9.2**

Classification of marine microbial biosensors.

Marine microbial laccases have been integrated into biosensors for the detection of phenol in industrial effluent (Zhang et al., 2022).

A notable example is microbial fuel cell-based biosensors (MFC-Bs), which utilize marine electrogenic bacteria, such as *Shewanella* and *Geobacter* species, to generate energy in response to organic contaminants (Xue et al., 2024). These biosensors have been employed for real-time monitoring of water quality, providing continuous assessment of biochemical oxygen demand (BOD) and heavy metal pollution.

9.3.2 Optical biosensors

Optical biosensors utilize light-based detection methods, such as fluorescence, bioluminescence, and surface plasmon resonance (SPR), to monitor molecular interactions (Shrikrishna et al., 2024). Marine microbial components, particularly luminescent proteins and pigments, have been extensively employed in optical biosensors. One of the most prominent optical biosensors employs *Vibrio* bacteria, which naturally produce bioluminescent proteins such as luciferase. Microbial biosensors have been utilized to identify environmental pollutants, pathogens, and metabolic markers in medical diagnostics. Genetically engineered *Vibrio* strains have been employed in biosensors to produce quantifiable fluorescence in the presence of pollutants, hence offering improved sensitivity for water quality assessments (Ma et al., 2022).

Biosensors employing surface plasmon resonance (SPR) are augmented with marine microbial biorecognition elements, including antibodies and aptamers (Ye et al., 2019). These biosensors provide real-time, label-free detection of analytes, making them suitable for monitoring marine toxins, foodborne infections, and biological markers (Oon et al., 2023).

Table 9.3 Comparison of different biosensor types.					
Biosensor type	Key features	Advantages	Limitations	Common applications	References
Electrochemical	Measures electrical signals from biochemical reactions	High sensitivity, rapid response, easy integration	Requires precise calibration; sensitive to interference	Environmental monitoring, heavy metal detection	Ferrari et al. (2020)
Optical	Uses light-based signals (fluorescence, luminescence, SPR)	Real-time, label-free detection with high specificity	Light sensitivity; can be expensive	Medical diagnostics, toxin and pathogen detection	Shrikrishna et al. (2024)
Piezoelectric	Detects mass changes via resonance frequency shifts	Reagent-free operation, suitable for continuous monitoring	Limited target specificity; complex signal interpretation	Food safety, marine biotoxin detection	Liu et al. (2024)
Nanobiosensors	Integrates nanomaterials for enhanced sensitivity and miniaturization	Ultra-sensitive detection, portable and scalable platforms	Stability concerns; potential nanotoxicity	Cancer diagnostics, pollutant monitoring, portable sensing	Malini et al. (2022)

9.3.3 Piezoelectric biosensors

Piezoelectric biosensors operate by identifying mass changes at the sensor surface, leading to variations in resonance frequency. Marine microbial components, such as whole cells, enzymes, and antibodies, have been immobilized on piezoelectric transducers for the detection of contaminants, toxins, and pathogens (Tang et al., 2023). One use of piezoelectric biosensors is the detection of marine biotoxins, such as brevetoxins and saxitoxins, which are linked to harmful algal blooms (Dutta et al., 2025). The integration of marine-derived antibodies or aptamers as biorecognition elements allows these biosensors to achieve elevated specificity and rapid detection, making them suitable for food safety and environmental monitoring (Arshad et al., 2021).

9.3.4 Nanobiosensors and their marine microbial interfaces

Nanobiosensors amalgamate nanomaterials, such as carbon nanotubes, gold nanoparticles, and quantum dots, with marine microbial biorecognition elements, thereby enhancing the sensitivity and compactness of biosensing platforms (Thakur & Kumar, 2022; Vyshnava et al., 2022). These biosensors have been proficiently employed for the identification of toxins, pathogens, and environmental pollutants. Marine-derived nanoparticles, including biosilica from diatoms and magnetic nanoparticles from magnetotactic bacteria, have been used into biosensors to enhance signal amplification and selectivity (Ibrahim et al., 2022).

These nanobiosensors have exhibited remarkable effectiveness in biomedical applications, such as the identification of cancer biomarkers and antibiotic-resistant bacteria (Bruno et al., 2024). Additionally, carbon-based nanomaterials enhanced with marine microbial enzymes have been utilized in electrochemical nanobiosensors for the detection of organic pollutants in marine environments. These platforms offer advantages such as real-time monitoring, miniaturization, and multiplexed detection, making them appropriate for portable biosensing applications.

9.4 Engineering and functionalization of marine microbial components in biosensors

The integration of marine microbial products into biosensors requires precise engineering and functionalization methods to enhance their stability, sensitivity, and selectivity (Pal et al., 2025). Marine microorganisms produce unique bioactive chemicals, such as enzymes, proteins, polysaccharides, and whole cells, which serve as biorecognition elements in biosensors. Enhancing these components for biosensor applications necessitates genetic modifications, surface immobilization techniques, and hybridization with nanomaterials (Ramesh et al., 2022). This section analyzes current advancements in the engineering and functionalization of marine microbial components in biosensors.

9.4.1 Genetic engineering of marine microorganisms for enhanced sensitivity

Genetic engineering has proven essential in augmenting marine microbial components for biosensing applications. Researchers have enhanced the ability of marine bacterial and fungal strains to produce

specialized biorecognition molecules, such as enzymes, antibodies, and biosurfactants, through alteration. *Shewanella* and *Vibrio* species have been genetically engineered to express fluorescent proteins in response to heavy metal contamination, enabling real-time monitoring of toxins in marine environments (Bhomkar & Naik, 2025).

Synthetic biology methods have been utilized to enhance laccases and peroxidases obtained from deep-sea fungi for superior electrochemical biosensing of organic pollutants (Sodhi et al., 2024). Furthermore, marine microbial whole-cell biosensors have been developed by incorporating genetic circuits that enable microorganisms to respond to specific environmental stimuli. These altered cells emit luminescence, display color changes, or produce electrochemical signals in reaction to the presence of toxins, pathogens, or organic compounds (Sutarlie et al., 2017). These enhancements have augmented biosensor efficacy in environmental and medical applications.

9.4.2 Surface modification and immobilization strategies

The stability and reusability of marine microbial components in biosensors depend on their immobilization on sensor surfaces. Diverse functionalization methods have been developed to enhance the adherence of enzymes, antibodies, and whole cells to transducers. A common technique involves the covalent attachment of marine enzymes to electrode surfaces using functional linkers like as glutaraldehyde, carbodiimide chemistry, and self-assembled monolayers (SAMs) (Mayes, 2002). This technique has been utilized to immobilize deep-sea laccases for the electrochemical detection of phenolic pollutants.

Marine-derived antibodies and aptamers have been conjugated to gold or graphene-based sensors by thiol linkers to enhance signal transduction (Newman, 2021). Marine bacteria and fungi have been immobilized in whole-cell biosensors by biofilm growth techniques, hydrogel encapsulation, and polymer matrix entrapment (Vigués, 2020). These immobilization approaches enhance viability and responsiveness, making them suitable for real-time environmental monitoring.

9.4.3 Hybrid systems: marine microbial products combined with nanotechnology

The amalgamation of marine microbial products with nanomaterials has led to the development of very sensitive and selective biosensors. Nanomaterials, such as carbon nanotubes (CNTs), gold nanoparticles, and quantum dots, have been employed to enhance the performance of marine microbial-based biosensors (Grasso et al., 2019). Carbon-based nanomaterials have been integrated with marine microbial enzymes to develop electrochemical biosensors for the identification of heavy metals and organic pollutants. Graphene-based sensors enhanced with marine-derived oxidoreductases have elevated electron transfer rates, resulting in improved sensitivity.

Gold nanoparticles have been employed to capture marine microbial antibodies, thereby improving the selectivity of biosensors for marine toxins (Bano et al., 2020). The amalgamation of aptamer-functionalized gold nanoparticles with surface-enhanced Raman spectroscopy (SERS) has enabled ultra-sensitive detection of illnesses and contaminants in marine ecosystems (Bilibana et al., 2022). Biosilica obtained from diatoms and other marine microorganisms has been employed in biosensors as a natural, biocompatible matrix for enzyme immobilization (Zobi, 2022). This technique enhances sensor stability and longevity, making it beneficial for extended monitoring applications.

9.4.4 Advances in synthetic biology for marine biosensor development

Synthetic biology has revolutionized marine biosensors by the precise design and engineering of microbial components (Tang et al., 2021). Progress in CRISPR-Cas technology, metabolic engineering, and directed evolution has enabled the enhancement of marine microbial products for biosensing applications (Feng et al., 2023). Researchers have engineered marine microbial strains to produce biosensors with enhanced signal transduction efficacy. Synthetic biology techniques have been utilized to develop bacteria that emit bioluminescence or fluorescence upon exposure to toxic compounds, enabling rapid and real-time environmental monitoring (Parker, 2023).

Moreover, progress in DNA computing has enabled the creation of biosensors functioning as biological logic circuits, leading to the growth of highly programmable biosensing devices (Zhao et al., 2024). Engineered biosensors have prospective uses in personalized medicine, food safety surveillance, and bioterrorism threat assessment.

9.5 Applications and case studies

Marine microbial-derived biosensors have revolutionized environmental monitoring, biomedical diagnostics, food safety, and industrial process regulation (Pal et al., 2025). The unique biochemical properties of marine microbial products, including their robustness under extreme environments, high specificity, and biorecognition capabilities, have facilitated the development of highly sensitive biosensors (Bhatnagar et al., 2024). This section analyzes notable applications and empirical case studies that illustrate the capabilities of marine microbial biosensors across many sectors.

9.5.1 Environmental monitoring

A primary application of marine microbial biosensors is environmental surveillance. Marine ecosystems are especially susceptible to pollutants such as heavy metals, organic contaminants, and toxins from industrial and agricultural runoff (Bashir et al., 2020). Biosensors utilizing marine-derived enzymes and whole-cell systems provide a real-time, cost-effective, and highly sensitive approach for detecting these pollutants (Włodkowiec & Karpiński, 2021). An exemplary case is the utilization of marine microbial fuel cell-based biosensors (MFC-Bs) for the measurement of biochemical oxygen demand (BOD) in wastewater. These biosensors utilize electrogenic bacteria from marine sediments, such as *Shewanella* and *Geobacter*, to generate electrical signals in response to organic pollutants (Zhou et al., 2024). Studies demonstrate that these biosensors can rapidly assess water quality and pollution levels, making them vital tools for environmental agencies.

Additionally, marine microbial biosensors have been employed to detect heavy metals such as lead, cadmium, and mercury in marine ecosystems (Hu et al., 2024). Genetically engineered marine bacteria expressing fluorescent proteins have been employed to assess metal pollution levels in seawater, providing a rapid and portable method for field monitoring (Olaniyan et al., 2025).

9.5.2 Biomedical diagnostics

The application of marine microbial biosensors in biomedical diagnostics has attracted significant attention due to their remarkable selectivity and biocompatibility. Marine microbial enzymes, antibodies, and whole-cell biosensors have been integrated into diagnostic platforms for the detection of infectious diseases, cancer biomarkers, and metabolic disorders (Wan et al., 2022). Marine-derived aptamers have been utilized as biosensors for the identification of viral and bacterial illnesses in clinical samples. Surface plasmon resonance (SPR) biosensors, functionalized with antibodies derived from marine bacteria, have demonstrated considerable sensitivity in identifying viral infections, such as COVID-19 and influenza (Singh, 2018).

Moreover, oxidoreductase enzymes derived from marine creatures have been included into electrochemical biosensors for the identification of cancer biomarkers in blood samples (Pérez et al., 2019). These biosensors offer a noninvasive, rapid, and cost-effective approach for early cancer detection, improving patient outcomes through timely intervention.

9.5.3 Food safety and quality control

Marine microbial biosensors have demonstrated significant potential in guaranteeing food safety and quality. Biosensors utilizing marine microbial products can rapidly identify foodborne pathogens, chemical contaminants, and signs of spoilage. Biosensors utilizing chitinase enzymes derived from marine sources have been developed to detect fungal contamination in food products (Dhevagi et al., 2021). These biosensors facilitate rapid and accurate detection of spoilage microorganisms, allowing food manufacturers to maintain high-quality standards.

Additionally, microbial biosensors have been employed for the detection of marine biotoxins, such as saxitoxin and brevetoxin, associated with harmful algal blooms (Bano et al., 2020). Aptamers derived from marine bacteria have been integrated into biosensor platforms to detect toxins in seafood, thereby ensuring adherence to food safety rules and protecting consumers from harmful exposure (Khan et al., 2024).

9.5.4 Industrial and bioprocess monitoring

Marine microbial biosensors have been employed in industrial bioprocess monitoring to ensure the efficiency and sustainability of production techniques. Biotechnological companies rely on microbial biosensors to oversee fermentation processes, detect contaminants, and improve production efficiency, as listed in Table 9.4 (Neethirajan et al., 2018). A notable use is in biofuel production, wherein microbial biosensors oversee fermentation conditions and metabolic activity (Pontius et al., 2020). Engineered marine bacteria capable of detecting ethanol and other biofuel by-products provide real-time feedback during manufacturing, hence improving process efficiency and reducing waste (Keasling et al., 2021).

Additionally, microbial biosensors have been employed in pharmaceutical manufacturing to detect bacterial contamination in medicinal compositions. These biosensors utilize marine-derived enzymes that selectively bind to microbiological pollutants, ensuring sterility and compliance with industrial standards.

Table 9.4 Industrial applications of marine microbial biosensors—case studies.

Industrial application area	Biosensor type	Microbial source	Analyte/target	Industrial significance	References
Wastewater treatment	MFC-based biosensor	Marine sediment microorganisms	Assimilable organic carbon (AOC)	Prevention of biofouling in seawater desalination plants	Quek et al. (2015)
Marine pollution monitoring	Microfluidic motion-based biosensor	<i>P. subcordiformis</i> (microalgae)	Heavy metals, organic pollutants	Early-warning system for marine pollution	Han et al. (2019)
Carbon capture bioreactors	Biosensor-assisted monitoring	<i>Porosira glacialis</i> (marine diatoms)	Process stability indicators	Monitoring microbial ecology in industrial carbon capture	Aalto et al. (2024)
Toxic gas monitoring	MFC-based biosensor	Marine electroactive biofilm	Carbon monoxide (CO)	Industrial safety monitoring	Zhou et al. (2018)
Industrial wastewater plants	Whole-cell luminescent biosensor	<i>Vibrio fischeri</i>	Phenolic compounds	Toxicity monitoring in industrial wastewater	Philp et al. (2003)
Marine environmental monitoring	Electrochemical biosensor	<i>Staphylococcus aureus</i>	Heavy metals, pesticides	Rapid toxicity assessment in marine waters	Liu et al. (2023)
Organic pollutant detection	Optical biosensor	Bioluminescent marine bacteria	Organic pollutants	Marine pollution management	Balootaki and Hassanshahian (2014)
Food industry applications	Microbial biosensor	Microbial cells	Quality indicators (sugars, toxins)	Real-time food safety monitoring	Meena and Arvind Tripathi (2017)
Microbial corrosion monitoring	Microbial biosensors with microfluidics	Corrosion-associated microbes	Early signs of biocorrosion	Monitoring corrosion in pipelines and marine structures	Ashrafi (2023)

9.6 Challenges and future perspectives

Despite the considerable promise of marine microbial biosensors in environmental monitoring, healthcare, food safety, and industrial applications, several challenges hinder their widespread adoption. Alleviating these constraints will be crucial for ensuring its scalability, reliability, and economic viability. This section analyzes the primary issues associated with marine microbial biosensors and outlines potential research directions to enhance their effectiveness and practical applications.

9.6.1 Technical and regulatory challenges

A critical technical challenge in the advancement of marine microbial biosensors is ensuring their long-term stability and reproducibility. Enzymes, whole-cell systems, and biomolecules derived from marine microbes often experience degradation over time, diminishing sensor effectiveness and sensitivity. The calibration and standardization of biosensors remain substantial issues, particularly when applied to complex real-world materials such as seawater, blood, or food matrices. Regulatory barriers provide significant challenges to commercialization. Biosensors intended for medical diagnostics or environmental monitoring must adhere to rigorous safety and efficacy standards set by organizations such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA). The validation process for marine microbial biosensors can be lengthy and costly, impeding their market entry.

9.6.2 Scalability and commercialization barriers

Although the capabilities of marine microbial biosensors have been shown in laboratory settings, their mass production and practical deployment remain considerable obstacles. The cultivation of marine microbial strains, the extraction of biomolecules, and the building of sensors require cost-effective and scalable methodologies (Huang et al., 2023). Furthermore, integrating marine microbial components into commercial biosensors requires innovative immobilization techniques to enhance sensor longevity and performance. Hybrid systems incorporating nanomaterials, synthetic biology, and microfluidic platforms are emerging as effective ways to tackle scalability issues (Brooks & Alper, 2021).

9.6.3 Future research directions and emerging technologies

Future research should concentrate on addressing these challenges:

- *Improving stability and sensitivity:* Genetic engineering, enzyme immobilization, and synthetic biology techniques can enhance the robustness and efficacy of marine microbial biosensors (Ali et al., 2021).
- *Miniaturization and portability:* Progress in *lab-on-a-chip* technology, wearable biosensors, and microfluidics facilitates real-time, on-site analysis for environmental and healthcare applications (Kuru et al., 2023).

- ## 9.7 Conclusion

Marine microbial biosensors provide effective solutions in environmental, biomedical, food safety, and industrial domains, owing to the distinctive metabolic characteristics of marine microorganisms. These biosensors, which utilize enzymes, antibodies, aptamers, and entire cells, offer remarkable sensitivity and durability in adverse environments. Progress in synthetic biology, nanotechnology, and genetic engineering has improved their efficacy and versatility. Nonetheless, issues including scalability, regulatory permission, and stability require resolution. The prospective amalgamation of AI, microfluidics, and sustainable manufacturing offers significant potential for extensive implementation. Marine microbial biosensors are poised to be integral to the development of next-generation, environmentally sustainable, and high-performance sensing systems.

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Marine microbial products as nutraceuticals

10

Rodrigo Duarte-Casar¹, Juan Carlos Romero-Benavides², Carola Millan³, Natalia Bailon-Moscoso²
and Marlene Rojas-Le-Fort¹

¹Ingeniería en Alimentos, Pontificia Universidad Católica del Ecuador, Portoviejo, Manabí, Ecuador,

²Universidad Técnica Particular de Loja, Loja, Ecuador,

³Universidad Adolfo Ibáñez, Campus Viña del Mar, Viña del Mar, Chile

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10.1 Introduction

Even though misquoted, the “let thy food be thy medicine” topic has gained notoriety in recent years (Cardenas, 2013). This ancient concept, often attributed to Hippocrates, shows the growing recognition of the intrinsic link between diet and health, lately as a reaction to the health hazards posed by the Western dietary pattern (Clemente-Suárez et al., 2023). In modern times, this idea has evolved into the nutraceuticals industry, which stands between nutrition and pharmaceuticals, relying on properties of foodstuffs related to

their health benefits not attributable to nutrition. Nutraceuticals, encompassing functional foods, dietary supplements, and bioactive compounds, are increasingly sought after for their ability to prevent and manage chronic diseases, enhance immune function, and promote overall wellness (Nwosu & Ubaoji, 2020). The rise in lifestyle-related diseases, coupled with a growing preference for natural and preventive healthcare solutions, has fueled the demand for nutraceuticals. As consumers become more health-conscious, the exploration of novel and sustainable sources of these bioactive compounds, such as marine microbial products (MMPs), has become a focus of scientific research and innovation.

The oceans cover more than two-thirds of the Earth's surface. They are a vast reservoir of biological diversity, harboring an immense array of microorganisms that have evolved unique metabolic pathways to thrive in diverse and often extreme environments. Among these microorganisms, marine bacteria, fungi, microalgae, and archaea have emerged as prolific producers of bioactive compounds with significant potential for human health. These MMPs range from specific polysaccharides and peptides to secondary metabolites, such as carotenoids and flavonoids, and are increasingly recognized for their nutraceutical properties. These products, with their unique chemical structures and biological activities, represent a promising, and compared to plant species, an underexplored source of nutraceuticals.

Marine microbes have adapted to survive in environments characterized by extreme temperatures, high salinity, high pressure, and limited light, leading to the production of novel bioactive compounds not found in terrestrial organisms (Li et al., 2019; Viswadeepika & Bramhachari, 2022). These compounds show a wide range of biological activities, including antioxidant, anti-inflammatory, antimicrobial, and anticancer properties, which have made them recognized as pharmacophores (Amanda et al., 2010), also making them ideal candidates for nutraceutical applications. For example, microalgae such as *Spirulina* and *Chlorella* are rich sources of proteins, vitamins, and essential fatty acids. At the same time, marine bacteria, including *Vibrio* and *Pseudomonas* species, produce unique enzymes and metabolites with potential health benefits. The exploration of these microbial products is further supported by advances in biotechnology, such as genomics, metabolomics, and synthetic biology, which enable the identification, optimization, and large-scale production of these compounds. As demand for natural and sustainable health products increases, marine microbes provide a renewable and eco-friendly alternative to traditional nutraceutical sources.

Despite their immense potential, the use of MMPs as nutraceuticals faces several challenges. These include the difficulty of cultivating marine microbes in laboratory settings, the complexity of extracting and purifying bioactive compounds, and the need for rigorous safety and efficacy testing. Additionally, the sustainable harvesting of marine resources without disrupting delicate ecosystems is a critical concern. However, ongoing research and technological advancements are addressing these challenges, paving the way for the commercialization of marine microbial nutraceuticals.

This chapter explores the current state of knowledge on MMPs as nutraceuticals, highlighting their biological activities and potential applications in human health. It also discusses the challenges and opportunities in the field, emphasizing the need for interdisciplinary collaboration to unlock the full potential of these marine treasures.

10.2 Nutraceuticals

“Nutraceutical” is a portmanteau of “nutrition” and “pharmaceutical,” coined in 1989. It refers to any food or food product that provides health and medical benefits, including the prevention and treatment

of disease, with a use more akin to marketing than to a strict definition (Kalra, 2003). Nutraceuticals are bioactive compounds derived from natural food sources that offer health benefits extending beyond essential nutrition, including disease prevention and therapeutic effects. These substances, which include vitamins, minerals, antioxidants, and phytochemicals, are typically marketed as dietary supplements, functional foods, or medical foods. Unlike most pharmaceuticals, nutraceuticals are not chemically synthesized; instead, they are extracted or concentrated from plants, algae, marine organisms, or through microbial fermentation. Examples include omega-3 fatty acids from fish oil, curcumin from turmeric, flavonoids from tropical fruits, and astaxanthin from microalgae (Ambati et al., 2014; de Araújo et al., 2021; Duarte-Casar et al., 2024; Irshad et al., 2017). Their primary appeal lies in their ability to deliver medicinal properties in a food-based format, thereby serving as a bridge between nutrition and medicine.

The regulatory status of nutraceuticals varies globally, influencing how they are developed, marketed, and consumed. In the United States, they are classified as dietary supplements under the Dietary Supplement Health and Education Act (DSHEA), which does not require pre-market approval for efficacy. In contrast, the European Union regulates them as food supplements under the European Food Safety Authority (EFSA), mandating scientific validation for health claims. Canada categorizes them as natural health products (NHPs), requiring licensing for safety and efficacy, while India's Food Safety and Standards Authority (FSSAI) treats them as "foods for special dietary uses" (Bansal et al., 2022; Santini et al., 2018). These differing frameworks impact product availability, labeling, and consumer trust, presenting the need for harmonized standards to ensure quality and efficacy in the expanding nutraceutical industry.

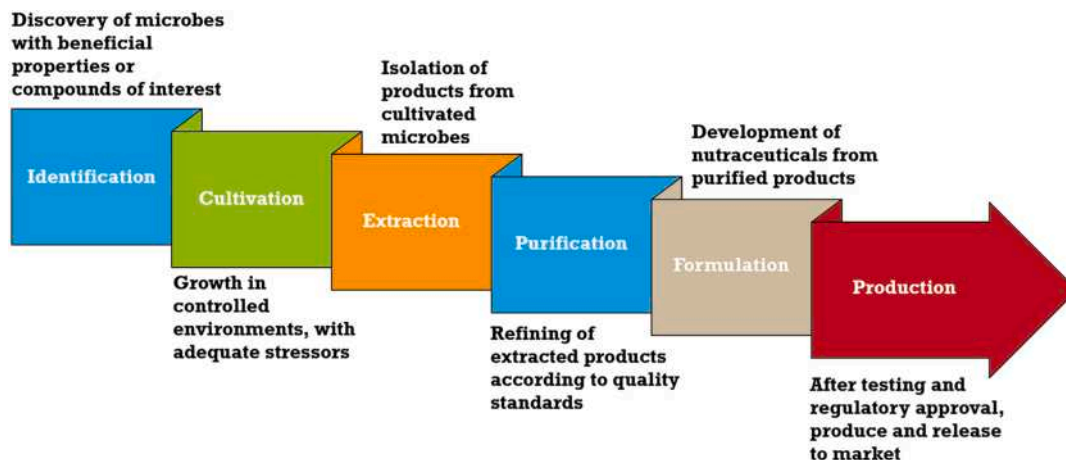
10.3 Current state of the field

Marine microbial nutraceutical products offer promise and challenges: on the one hand, they present an avenue for product development due to their diverse and potent bioactive compounds. On the other hand, such difficulties as extraction efficiency, sustainability, regulatory approval, and market entry need to be addressed to realize their potential in the industry (Santhiravel et al., 2025).

Marine microorganisms produce valuable substances, including peptides, polysaccharides, pigments, and enzymes, that exhibit anti-inflammatory, anticancer, antimicrobial, and antidiabetic effects. The discovery of novel secondary metabolites and advancements in genetic research further expand the possibilities for developing innovative marine-based nutraceuticals. Additionally, the growing market demand for marine-derived supplements—such as omega-3 oils, algal proteins, and bioactive peptides—highlights their increasing commercial viability. With their ability to address chronic diseases and promote overall health, MMPs represent a promising frontier in functional foods and preventive medicine.

The production process of nutraceuticals is outlined in a simplified manner in Fig. 10.1. The stages of this process include discovery, cultivation, extraction, purification, formulation, and production. Each of these stages presents challenges that require solving and fine-tuning to achieve efficient production.

Despite their potential, the widespread adoption of marine microbial nutraceuticals faces several obstacles. One major challenge is the efficient extraction and purification of bioactive compounds, as current methods often lack scalability and cost-effectiveness. Sustainability concerns also arise

**FIGURE 10.1**

Overview of MMP-derived nutraceuticals production. The production process of MMP-derived nutraceuticals can be summarized in six steps: Identification, cultivation, extraction, purification, formulation, and production. *MMP*, marine microbial product.

because overharvesting marine resources could disrupt ecosystems, which require eco-friendly production techniques. Regulatory complexities further slow commercialization down, with rigorous safety and efficacy evaluations an imperative before market approval. Additionally, optimizing fermentation and cultivation processes for marine microbes remains a technical hurdle, often necessitating genetic engineering to enhance compound yields. Finally, consumer awareness and competition with established terrestrial nutraceuticals present market entry challenges, demanding strategic branding and education to drive acceptance. Overcoming these barriers is crucial for unlocking the full potential of marine-derived health products. Continued research and technological advancements are essential to addressing these obstacles and maximizing the benefits of marine-derived nutraceuticals.

10.4 Classes of Marine microbial product nutraceuticals

MMPs represent a diverse and valuable source of nutraceuticals, offering a wide array of bioactive compounds with significant health benefits. These compounds can be broadly categorized into several classes based on their chemical structure and biological functions. Each class of MMP nutraceuticals, including polyunsaturated fatty acids (PUFAs) and carotenoids, as well as polysaccharides, peptides, and secondary metabolites, plays a role in promoting human health. These naturally derived molecules exhibit antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory properties, making them candidates for preventing and managing chronic diseases. This section explores the significant classes of MMP nutraceuticals, highlighting their sources, biological activities, and potential applications in health and wellness. Main classes of nutraceuticals are shown with typical examples in Fig. 10.2.

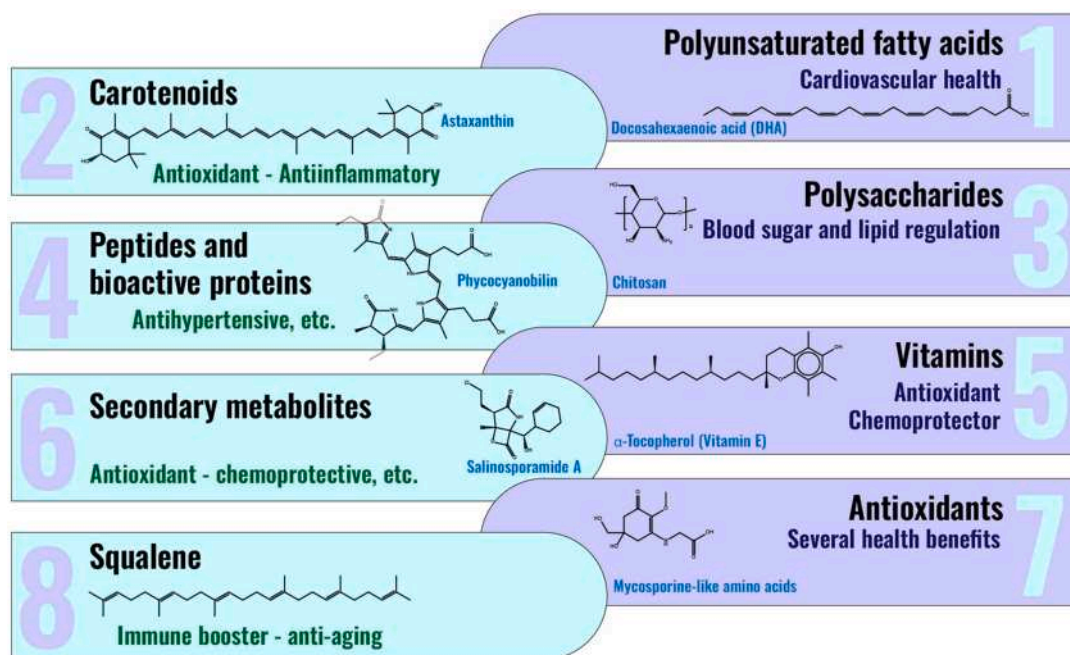


FIGURE 10.2

Main classes of marine microbial nutraceuticals. PUFAs, carotenoids, polysaccharides, proteins and bioactive peptides, vitamins, secondary metabolites, antioxidants and squalene. PUFAs, polyunsaturated fatty acids.

10.5 Polyunsaturated fatty acids

PUFAs are long-chain carboxylic acids characterized by the presence of more than one double carbon-carbon bond, which account for their structural and functional properties. Among the most studied PUFAs are the omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These essential fatty acids are primarily synthesized by marine microalgae, such as *Schizochytrium*, *Phaeodactylum tricornutum*, and *Nannochloropsis*, which serve as the foundational producers in the aquatic food web. These microalgae are increasingly cultivated for their high PUFA content, offering a sustainable and scalable alternative to traditional fish oil sources. The growing demand for omega-3 fatty acids has driven advancements in biotechnological approaches to optimize their production and extraction (Adarme-Vega et al., 2012; Russo et al., 2021).

The health benefits of omega-3 PUFAs are well-documented, particularly in promoting cardiovascular health. EPA and DHA have been shown to reduce triglycerides, lower blood pressure, and improve cholesterol profiles, thereby reducing the risk of heart disease (Endo & Arita, 2016). These effects are attributed to their ability to modulate lipid metabolism and reduce inflammation. Beyond cardiovascular benefits, omega-3 fatty acids exhibit potent anti-inflammatory properties,

making them valuable in managing chronic inflammatory conditions such as arthritis and metabolic syndrome. Their role in modulating inflammatory pathways has been linked to the inhibition of pro-inflammatory eicosanoids, production of specialized pro-resolving mediators (SPMs), which actively resolve inflammation and promote tissue repair, and modulation of gene expression, among others (Molfino et al., 2017).

In addition to their cardiovascular and anti-inflammatory benefits, omega-3 PUFAs are used as supplements to support brain health and cognitive function. DHA is a major structural component of the brain and retina, where it promotes neuronal membrane integrity and synaptic plasticity (Miceli et al., 2020). Adequate intake of DHA has been associated with improved cognitive performance, reduced risk of neurodegenerative diseases, and enhanced mental health. Furthermore, omega-3 fatty acids play a crucial role in fetal development, particularly during pregnancy, as they contribute to the growth and maturation of the fetal brain and visual system. Maternal supplementation with DHA has been shown to improve developmental outcomes in infants (Szajewska et al., 2006).

The applications of omega-3 PUFAs are vast and span multiple industries. In the nutraceutical sector, they are widely used in dietary supplements, often as fish oil or algal oil capsules. Functional foods, such as omega-3 fortified eggs, milk, and bread, have also become popular as convenient ways to increase daily intake. Additionally, infant formula is often enriched with DHA to replicate the nutritional profile of breast milk and support early development (Ni et al., 2024). The versatility and proven health benefits of omega-3 PUFAs underscore their importance as one of the leading marine microbial-derived nutraceuticals.

Despite their numerous benefits, challenges persist in the sustainable production and commercialization of omega-3 PUFAs. Cultivating marine microalgae requires careful optimization of growth conditions, including light, temperature, and nutrient availability, to maximize yield and minimize costs. Advances in genetic engineering and metabolic pathway manipulation hold promise for enhancing PUFA production in microbial systems (Střížek et al., 2024). Furthermore, ensuring the stability and bioavailability of omega-3 fatty acids in nutraceutical products is critical for maintaining their efficacy. Ongoing research and innovation in this field are essential to fully harness the potential of marine microbial-derived PUFAs for human health and nutrition.

10.6 Carotenoids

Carotenoids are a class of naturally occurring pigments synthesized by marine microorganisms, particularly microalgae, with characteristic vibrant colors and potent bioactive properties. Among the most prominent carotenoids are astaxanthin, β -carotene, and fucoxanthin. Astaxanthin is primarily produced by the microalga *Haematococcus pluvialis*, while β -carotene is abundantly found in *Dunaliella salina*. These carotenoids are not only responsible for the red, orange, and yellow hues observed in many marine organisms but also play critical roles in protecting cells from oxidative damage caused by environmental stressors such as UV radiation and reactive oxygen species (ROS).

One of the most significant health benefits of marine-derived carotenoids is their exceptional antioxidant capacity. Astaxanthin is a potent natural antioxidant, with an activity significantly higher than that of vitamin E and β -carotene (Donoso et al., 2021). By neutralizing free radicals and reducing oxidative stress, carotenoids help prevent cellular damage, which is linked to aging, chronic diseases,

and inflammation. Additionally, carotenoids exhibit anti-inflammatory properties by modulating signaling pathways such as NF- κ B and reducing the production of pro-inflammatory cytokines. These properties make them valuable in managing inflammatory conditions such as arthritis and metabolic disorders.

Carotenoids also play a vital role in supporting eye health, particularly in preventing age-related macular degeneration (AMD) and other vision-related issues. Lutein and zeaxanthin, although not exclusively marine-derived, are often found in conjunction with carotenoids such as astaxanthin and β -carotene in marine microalgae. These compounds accumulate in the retina, where they filter harmful blue light and protect photoreceptor cells from oxidative damage. Furthermore, emerging research suggests that carotenoids, particularly fucoxanthin, may possess anticancer properties by inducing apoptosis and inhibiting the proliferation of cancer cells (M  resse et al., 2020). These findings highlight the potential of carotenoids as both preventive and therapeutic agents in combating chronic diseases.

The applications of marine-derived carotenoids are diverse and span multiple industries. In the nutraceutical sector, carotenoids are widely used in dietary supplements to promote overall health and well-being. Astaxanthin, for example, is marketed for its antioxidant and anti-aging benefits, while β -carotene is commonly used as a provitamin A supplement. In the skincare industry, carotenoids are incorporated into products for their ability to protect against UV-induced damage and improve skin elasticity. Additionally, carotenoids are utilized as natural colorants and functional ingredients in various foods, including beverages, dairy products, and snacks, to enhance both nutritional value and visual appeal, besides their functional properties (V  lchez et al., 2011).

Despite their numerous benefits, the production and commercialization of marine-derived carotenoids face several challenges. The cultivation of microalgae for carotenoid production requires precise control of environmental conditions, such as light intensity, temperature, and nutrient availability, to maximize yield and quality. Advances in bioreactor technology and genetic engineering are helping to overcome these challenges by optimizing growth conditions and enhancing carotenoid biosynthesis pathways (Steven et al., 2022). Additionally, ensuring the stability and bioavailability of carotenoids in nutraceutical and functional food products remains a critical area of research. By addressing these challenges, marine-derived carotenoids can continue to play a pivotal role in promoting human health and well-being.

An example of the potential of carotenoids as nutraceuticals is astaxanthin, which is extracted from the microalga *Haematococcus pluvialis*. Astaxanthin is a high-value xanthophyll carotenoid that has emerged as a case of successful biotechnological innovation in the nutraceutical, cosmetic, and aquaculture industries (Fayaazuddin et al., 2023). Natural astaxanthin from *H. pluvialis* is produced through optimized cultivation systems, including photobioreactors and raceway ponds, under carefully controlled stress conditions that maximize yield. Despite challenges such as the microalga's thick cell wall, advancements in cell disruption techniques—ranging from mechanical to enzymatic methods—have significantly improved extraction efficiency (Mota et al., 2022). The resulting product has gained widespread adoption due to its proven health benefits, including photoprotection for skin, neuroprotective effects, and potent anti-inflammatory activity (Ambati et al., 2014). As a result, astaxanthin from *H. pluvialis* has become a key ingredient in premium dietary supplements, anti-aging cosmetics, and aquaculture feeds, demonstrating the commercial viability of microalgal biotechnology.

The outlook of the success of *H. pluvialis*-derived astaxanthin is an example of the importance of continued innovation to viabilize production costs and scalability. Strategies such as biorefinery

approaches and genetic engineering to enhance astaxanthin biosynthesis, hold promise for further improving sustainability and economic feasibility. The case of *H. pluvialis* demonstrates the power of interdisciplinary research, which combines microbiology, engineering, and pharmacology to transform a natural compound into a high-demand global commodity. With growing consumer preference for natural and sustainable products, astaxanthin stands as a prime example for the successful integration of algal biotechnology into industrial applications, paving the way for future advancements in microalgae-based products (Oslan et al., 2021).

10.7 Polysaccharides

Polysaccharides derived from marine microorganisms represent a diverse and versatile class of bioactive compounds that have significant nutraceutical potential, including gastrointestinal modulation, blood sugar and lipid regulation, anti-obesity, anti-aging and others (Carrasqueira et al., 2025). Among the most studied marine polysaccharides are exopolysaccharides (EPS), fucoidans, and chitosan, each with unique structural and functional properties. These compounds are primarily produced by marine bacteria, such as *Alteromonas* and *Vibrio* species, as well as by microalgae and other marine organisms. Marine polysaccharides are characterized by their complex structures, which often include sulfated groups, uronic acids, and other modifications that enhance their biological activities. These structural features enable them to interact with biological systems in ways that terrestrial polysaccharides cannot, making them particularly valuable for health applications.

One of the most notable health benefits of marine polysaccharides is their ability to modulate and enhance the immune system. Fucoidans, for instance, have been shown to stimulate the production of immune cells, including macrophages and natural killer (NK) cells, while also enhancing their activity (Ferreira et al., 2015; Zhang et al., 2025). This immune-boosting effect is especially beneficial for individuals with weakened immune systems or those recovering from illness. Furthermore, marine polysaccharides demonstrate strong antioxidant and anti-inflammatory properties, which help shield cells from oxidative stress and alleviate chronic inflammation. These effects arise from their capacity to scavenge free radicals and block pro-inflammatory signaling pathways, making them valuable for managing conditions such as arthritis, cardiovascular disease, and metabolic syndrome (Rocha De Souza et al., 2007).

Marine polysaccharides also play a critical role in supporting gut health due to their prebiotic properties. Prebiotics are non-digestible compounds that promote the growth and activity of beneficial gut bacteria, such as *Bifidobacteria* and *Lactobacilli*. EPS and chitosan, for instance, have been shown to enhance the production of short-chain fatty acids (SCFAs) in the gut, which are essential for maintaining intestinal barrier function and overall gut health (O'Sullivan et al., 2010). By fostering a healthy gut microbiome, marine polysaccharides contribute to improved digestion, enhanced nutrient absorption, and reduced risk of gastrointestinal disorders. Furthermore, emerging research suggests that these compounds may have anticancer and antiviral properties, with potential applications in cancer therapy and the management of infectious diseases.

The applications of marine polysaccharides are vast and span multiple industries. In the nutraceutical sector, they are used in dietary supplements to support immune function, gut health, and overall well-being. Functional foods enriched with marine polysaccharides, such as yogurt, beverages, and cereals, are gaining popularity for their health-promoting properties (Wang et al., 2023).

In the pharmaceutical industry, marine polysaccharides are being explored for their potential in drug delivery systems, wound healing, and tissue engineering due to their biocompatibility and bioactive properties. Additionally, their antiviral and anticancer activities are being investigated for the development of novel therapeutics.

Despite their immense potential, the production and commercialization of marine polysaccharides face several challenges. The extraction and purification of these compounds from marine sources can be complex and costly, necessitating advanced technologies to achieve high yields and purity. Furthermore, the structural diversity of marine polysaccharides poses challenges in standardizing their biological activities and ensuring consistent quality in nutraceutical and pharmaceutical products. Advances in biotechnology, including genetic engineering and fermentation optimization, are helping to address these challenges and enhance the scalability of marine polysaccharide production. By overcoming these hurdles, marine polysaccharides can continue to play a pivotal role in advancing human health and well-being.

An interesting development is the use of MMP polysaccharides as vehicles for other nutraceuticals such as curcumin and flavonoids ([Barbosa et al., 2019](#); [Huang & Kuo, 2016](#)).

10.8 Peptides and bioactive proteins

Peptides and bioactive proteins derived from marine microorganisms are a rapidly growing area of interest in the nutraceutical and pharmaceutical industries due to their diverse biological activities and health benefits. Marine bacteria, such as *Bacillus* and *Pseudomonas*, as well as microalgae, are prolific producers of bioactive molecules, including peptides, lectins, and enzymes. These compounds are often released through enzymatic hydrolysis or fermentation of marine proteins, resulting in small, highly bioactive fragments that can interact with human physiological systems in beneficial ways. Their structures are often unique, containing rare amino acids or post-translational modifications that contribute to their potent bioactivity and specificity.

One of the most well-studied health benefits of marine-derived peptides is their antihypertensive properties, primarily through the inhibition of angiotensin-converting enzyme (ACE). ACE-inhibitory peptides derived from marine sources, such as fish protein hydrolysates or microalgal extracts, have been shown to effectively lower blood pressure by modulating the renin-angiotensin system ([Montone et al., 2018](#); [Sheih et al., 2009](#)). These peptides are considered a natural alternative to synthetic antihypertensive drugs, with fewer side effects. Additionally, marine peptides exhibit strong antioxidant properties, which help neutralize free radicals and reduce oxidative stress, a key factor in aging and the development of chronic diseases. Their ability to protect cells from oxidative damage makes them valuable in anti-aging formulations and skincare products.

Marine-derived peptides and proteins exhibit significant antimicrobial and antiviral activities, rendering them promising candidates for combating infections. For example, antimicrobial peptides (AMPs) from marine bacteria and microalgae have been shown to disrupt the cell membranes of pathogenic bacteria, fungi, and viruses, offering a potential solution to the growing problem of antibiotic resistance ([Guzmán et al., 2019](#)). These bioactive molecules are being explored for use in both therapeutic and preservative applications, such as in functional foods to extend shelf life and in pharmaceuticals to treat infections. Furthermore, marine peptides have demonstrated antiviral activity

against a range of viruses, including herpes simplex virus (HSV) and human immunodeficiency virus (HIV), highlighting their potential in antiviral drug development.

In addition to their therapeutic properties, marine peptides and proteins play a crucial role in supporting muscle repair and growth, making them ideal ingredients for protein supplements and sports nutrition products. Bioactive peptides derived from marine sources, such as microalgae or fish, are rich in essential amino acids and have been shown to enhance muscle protein synthesis and recovery after exercise (Gorissen et al., 2018). These peptides are often incorporated into protein powders, bars, and shakes to support athletic performance and muscle maintenance. Moreover, their high bioavailability and rapid absorption make them superior to many plant-based protein sources.

The applications of marine-derived peptides and bioactive proteins are extensive and span multiple industries. In the nutraceutical sector, they are used in dietary supplements to promote cardiovascular health, immune function, and muscle recovery. Functional foods enriched with marine peptides, such as fortified beverages and snacks, are gaining popularity for their health benefits (Fernando et al., 2024). In the skincare industry, marine peptides are valued for their antioxidant and anti-aging properties, often incorporated into creams, serums, and masks to improve skin elasticity and reduce wrinkles. Despite their potential, challenges remain in the large-scale production and commercialization of these compounds, including optimizing extraction methods and ensuring stability in final products. Advances in biotechnology and fermentation techniques are helping to address these challenges, paving the way for broader utilization of marine peptides and proteins in health and wellness applications.

10.9 Phycobiliproteins

Phycobiliproteins are a unique class of water-soluble pigments found in cyanobacteria, such as *Spirulina* and *Arthrospira*, and are known for their vibrant blue (phycocyanin) and red (phycoerythrin) colors. These proteins play a crucial role in photosynthesis by capturing light energy, but they also exhibit bioactive properties that make them valuable in nutraceutical and industrial applications (Begum et al., 2016). Phycobiliproteins are not only visually striking but also highly functional, offering a range of health benefits due to their antioxidant, anti-inflammatory, and immune-modulating properties.

One of the most significant health benefits of phycobiliproteins is their potent antioxidant activity, which helps neutralize free radicals and reduce oxidative stress. Phycocyanin, for example, has been shown to scavenge ROS and protect cells from oxidative damage, making it a promising agent for preventing chronic diseases such as cardiovascular disorders and cancer. Additionally, phycobiliproteins exhibit potent anti-inflammatory properties by inhibiting the production of pro-inflammatory cytokines and modulating signaling pathways such as NF- κ B. These effects make them valuable in managing inflammatory conditions like arthritis and metabolic syndrome (Manirafasha et al., 2016).

Phycobiliproteins also play a role in supporting the immune system by enhancing the activity of immune cells, such as macrophages and lymphocytes. Studies have shown that phycocyanin can stimulate the production of antibodies and improve immune responses, making it a potential adjunct in immunotherapy. Furthermore, emerging research suggests that phycobiliproteins may have neuroprotective effects, potentially offering benefits in neurodegenerative diseases such as Alzheimer's and Parkinson's. Their ability to cross the blood-brain barrier and reduce oxidative stress in neural tissues highlights their therapeutic potential (Patel et al., 2022).

The applications of phycobiliproteins are diverse and span multiple industries. In the food industry, they are used as natural colorants in products such as beverages, candies, and dairy, providing a safe and sustainable alternative to synthetic ([Pereira et al., 2020](#); [Vieira et al., 2025](#)). In the nutraceutical sector, phycobiliproteins are incorporated into dietary supplements for their antioxidant and immune-boosting properties. Additionally, their colors and bioactive properties make them popular ingredients in cosmetics, where they are used in skincare products to promote anti-aging and skin repair. Despite their potential, challenges remain in stabilizing phycobiliproteins during extraction and processing, but ongoing research is addressing these issues to harness their benefits entirely.

10.10 The case of spirulina

Spirulina, a cyanobacterium rather than an algae as commonly believed, is one of the most successful and widely recognized MMPs in the nutraceutical market. It is renowned for its high protein content, vitamins, minerals, and antioxidants, and is marketed as a superfood with numerous health benefits. Several companies have commercialized spirulina as a dietary supplement, functional food ingredient, and even a protein source in plant-based diets. Spirulina is particularly valued for its immune-boosting, anti-inflammatory, and detoxifying properties, making it a versatile and nutrient-dense addition to modern diets. Its success as a sustainable and nutrient-rich product exemplifies the potential of marine microorganisms to address global health and nutrition challenges ([Escalante & Pérez-Rico, 2021](#)).

10.11 Vitamins

Vitamins derived from marine microorganisms, particularly microalgae and bacteria, are gaining recognition for their essential roles in human health and nutrition. Among the most notable marine-derived vitamins are Vitamin B12, Vitamin E, and Vitamin D. Marine microalgae, such as *Chlorella* and *Spirulina*, are particularly rich sources of these vitamins, offering a sustainable and bioavailable alternative to synthetic or terrestrial sources ([Coronado-Reyes & González-Hernández, 2023](#)). These vitamins are not only critical for maintaining essential physiological functions but also play specialized roles in preventing chronic diseases and supporting overall well-being.

Vitamin B12, primarily produced by marine bacteria and accumulated in microalgae like *Chlorella*, is essential for energy metabolism, red blood cell formation, and neurological function. Unlike most plant-based foods, marine microalgae provide a reliable source of bioavailable Vitamin B12, making them particularly valuable for vegetarians and vegans who are at risk of deficiency. Deficiency in Vitamin B12 can lead to anemia, fatigue, and neurological disorders. Additionally, Vitamin B12 plays a role in DNA synthesis and methylation processes, further highlighting its significance in cellular health ([Grossman, 2016](#)).

Vitamin E, another critical nutrient found in marine microalgae, is renowned for its potent antioxidant properties. This vitamin helps protect cell membranes from oxidative damage caused by free radicals, thereby reducing the risk of chronic diseases such as cardiovascular disease and cancer. Marine-derived Vitamin E, often in the form of tocopherols and tocotrienols, is more stable and

bioavailable than synthetic versions, making it a preferred ingredient in nutraceuticals and functional foods. Its antioxidant effects also extend to skin health, where it helps prevent UV-induced damage and supports skin repair (Del Mondo et al., 2020).

Vitamin D, synthesized by marine microalgae and found in certain fish oils, is essential for maintaining bone health, supporting immune function, and facilitating calcium absorption. Unlike terrestrial plants, marine microalgae can produce Vitamin D3 (cholecalciferol), the same form synthesized by human skin upon exposure to sunlight. This makes marine-derived Vitamin D a valuable supplement for individuals with limited sun exposure or those living in higher latitudes. Adequate Vitamin D levels are crucial for preventing osteoporosis, supporting immune responses, and reducing the risk of autoimmune diseases (Coronado-Reyes & González-Hernández, 2023).

The applications of marine-derived vitamins are extensive and primarily focused on dietary supplements and fortified foods. Vitamin B12 from *Chlorella* and *Spirulina* is commonly used in vegan supplements and energy-boosting formulations. Vitamin E is incorporated into antioxidant supplements, skincare products, and functional foods such as fortified cereals and beverages. Vitamin D3 from marine sources is widely used in supplements to support bone health and immune function, particularly in regions with limited sunlight. Despite their benefits, challenges persist in optimizing the production and bioavailability of marine-derived vitamins, including the improvement of cultivation techniques and extraction methods. Advances in biotechnology and sustainable aquaculture are helping to address these challenges, ensuring that marine-derived vitamins continue to play a vital role in global nutrition and health (Del Mondo et al., 2020).

10.12 Secondary metabolites

Marine microbial-derived secondary metabolites represent a treasure trove of bioactive compounds with immense potential in both pharmaceutical and nutraceutical applications (Matin et al., 2024). These metabolites, including terpenoids, alkaloids, phenolics, and polyketides, are produced by marine fungi (e.g., *Aspergillus*, *Penicillium*), algae, and bacteria (e.g., *Streptomyces*) as part of their survival mechanisms in the competitive and often extreme marine environment (Sreenikethanam et al., 2022). Unlike primary metabolites, which are essential for growth and development, secondary metabolites are not directly involved in these processes but instead provide ecological advantages, such as defense against predators or competition for resources. Their unique chemical structures and biological activities make them particularly valuable for human health.

Although not nutraceuticals, one of the most promising health benefits of marine-derived secondary metabolites is their anticancer and antitumor properties. Compounds such as salinosporamide A, a polyketide derived from the marine actinomycete *Salinispora*, have shown potent activity against multiple cancer types by inhibiting proteasome function and inducing apoptosis (Russo et al., 2015). Similarly, terpenoids and alkaloids from marine fungi have demonstrated the ability to suppress tumor growth and angiogenesis, making them candidates for the development of novel cancer therapies. These metabolites often target specific molecular pathways involved in cancer progression, offering a more targeted approach to treatment with fewer side effects compared to conventional chemotherapy.

Marine microbial flavonoids are being studied as next-generation nutraceuticals due to their unique structures (sulfated, C-substituted, etc.), potent bioactivities and sustainable production

advantages (Martins et al., 2019). Unlike plant-derived flavonoids, which face scalability and environmental constraints, marine microorganisms, particularly endophytic fungi and symbiotic bacteria, offer a more efficient and eco-friendly production platform. These microbial flavonoids exhibit remarkable anticancer, antioxidant, antidiabetic, and anti-inflammatory properties, making them ideal for functional foods and therapeutic applications. For instance, flavonoids like chrysin and quercetin derivatives from marine fungi have demonstrated tumor-suppressive effects and ROS-scavenging capabilities, while others show promise in modulating metabolic disorders. Biotechnological advancements, such as optimized fermentation (pH, temperature, nutrient stress) and elicitor treatments (yeast extract, UV exposure), significantly enhance yield and functionality. Challenges like low natural production levels and complex extraction processes remain despite their potential (Kamat et al., 2023). However, with continued research into genetic engineering and cultivation optimization, marine microbial flavonoids could revolutionize the nutraceutical industry by providing scalable, cost-effective, and clinically effective bioactive compounds for preventive and therapeutic health solutions.

10.13 Antioxidants

Antioxidants derived from marine microorganisms, such as mycosporine-like amino acids (MAAs) and phenolic compounds, are gaining significant attention for their ability to combat oxidative stress and promote health. These antioxidants are primarily produced by marine microalgae and cyanobacteria as a defense mechanism against environmental stressors like UV radiation and ROS (Vladkova et al., 2022). Their chemical structures and bioactivities make them comparable to terrestrial antioxidants, offering a sustainable solution for preventing oxidative damage and its associated health risks.

One of the most notable health benefits of marine-derived antioxidants is their ability to protect against oxidative stress, a key contributor to chronic diseases such as cancer, cardiovascular disorders, and neurodegenerative conditions. MAAs, for example, are highly effective at scavenging free radicals and neutralizing ROS, thereby reducing cellular damage and inflammation (Tarasuntisuk et al., 2019). Similarly, phenolic compounds from marine microalgae exhibit strong antioxidant activity, helping to maintain cellular integrity and function. These properties make marine antioxidants valuable in preventing and managing diseases linked to oxidative stress.

Marine-derived antioxidants also offer significant benefits for skin health and anti-aging. MAAs, in particular, are known for their ability to absorb UV radiation and protect skin cells from UV-induced damage, reducing the risk of sunburn and skin. Additionally, their antioxidant properties help combat the signs of aging by reducing the formation of wrinkles, improving skin elasticity, and promoting collagen synthesis. Phenolic compounds from marine sources further enhance these effects by inhibiting the degradation of skin proteins and lipids, making them popular ingredients in anti-aging skincare products (Cichoński & Chrzanowski, 2022).

In addition to their skin health benefits, marine antioxidants support cardiovascular health by reducing oxidative damage to blood vessels and improving lipid profiles. Studies have shown that phenolic compounds from marine microalgae can lower LDL cholesterol levels (Arzhang et al., 2024), reduce inflammation in arterial walls, and improve endothelial health. These effects contribute to a reduced risk of atherosclerosis, hypertension, and other cardiovascular diseases. By incorporating marine antioxidants into diets or supplements, individuals can support heart health and overall well-being.

The applications of marine-derived antioxidants are diverse and span multiple industries. In the skincare industry, MAAs and phenolic compounds are used in sunscreens, moisturizers, and anti-aging creams for their UV-protective and antioxidant properties. In the nutraceutical sector, these antioxidants are formulated into dietary supplements to promote overall health and prevent chronic diseases. Functional foods, such as antioxidant-rich beverages and snacks, are also gaining popularity as convenient ways to incorporate these bioactive compounds into daily diets (Vladkova et al., 2022). Despite their potential, challenges remain in optimizing the extraction, stability, and bioavailability of marine antioxidants. Advances in biotechnology and sustainable cultivation methods are helping to address these challenges, ensuring that marine-derived antioxidants continue to play a vital role in health and wellness.

10.14 Squalene

Squalene, a naturally occurring triterpene, is a highly valued compound derived primarily from marine microalgae, such as *Aurantiochytrium*, as well as from shark liver oil, its traditional source. However, marine microalgae have emerged as a sustainable and eco-friendly alternative to shark-derived squalene, addressing both environmental concerns and the growing demand for this versatile compound (Shalu et al., 2024). Squalene is a precursor to sterols and hormones and is widely recognized for its antioxidant, anti-aging, and immune-boosting properties. Its molecular structure allows it to act as a potent scavenger of free radicals, making it a valuable ingredient in nutraceuticals, cosmetics, and pharmaceuticals (Reddy & Couvreur, 2009). Even though squalene can be obtained from plant species (Romero-Benavides et al., 2023), microalgae are a more sustainable option.

One of the most notable health benefits of squalene is its antioxidant and anti-aging properties. As a natural antioxidant, squalene protects cells from oxidative stress caused by free radicals, which are linked to aging and chronic diseases such as cancer and cardiovascular disorders (Dmitrieva et al., 2022).

Squalene also plays a significant role in supporting cardiovascular health. Studies have shown that squalene can help reduce cholesterol levels by inhibiting the absorption of dietary cholesterol and promoting its excretion. This cholesterol-lowering effect contributes to a reduced risk of atherosclerosis and other cardiovascular diseases. Additionally, squalene's antioxidant properties help protect blood vessels from oxidative damage, further supporting heart health. Regular supplementation with squalene has been associated with improved lipid profiles and overall cardiovascular function (Kim & Karadeniz, 2012).

Another important benefit of squalene is its ability to enhance the immune response in human health and animal husbandry. Squalene is a key component of certain vaccine adjuvants, where it helps stimulate a stronger and more durable immune response to antigens. This property has made squalene an essential ingredient in vaccines for influenza and other infectious diseases. Beyond its role in vaccines, squalene has been shown to boost the activity of immune cells, such as macrophages and lymphocytes, enhancing the body's ability to fight infections and diseases (Du et al., 2024).

The applications of squalene are diverse and span multiple industries. In the nutraceutical sector, squalene is used in dietary supplements to support cardiovascular health, boost immunity, and provide antioxidant protection. In the cosmetics industry, it is a key ingredient in moisturizers, anti-aging products, and sunscreens due to its skin-repairing and protective properties. Despite its numerous

benefits, challenges remain in optimizing the production of squalene from marine microalgae, including improving yield and reducing costs. Advances in biotechnology and fermentation techniques are helping to address these challenges, ensuring that squalene continues to play a vital role in health, wellness, and medicine (Yarkent & Oncel, 2022).

10.15 Calcium

Although most marine-derived calcium sources are not microbial, (Xu et al., 2020; Vincent et al., 2021), there is potential in marine microbes, such as *Spirulina* (*Arthrospira platensis*) and *Chlorella*, which, are known to accumulate calcium inorganic forms that are more easily absorbed by the human body compared to inorganic calcium sources (Ekantari et al., 2017). These microbial sources offer a sustainable and eco-friendly alternative to traditional calcium sources, with the added benefit of providing other essential nutrients like vitamins, antioxidants, and omega-3 fatty acids, useful both as food and feed (Prates, 2025).

10.16 Promising marine microbial species for nutraceutical obtention

Marine microorganisms represent an untapped reservoir of bioactive compounds with immense potential for nutraceutical applications. Among the most promising species are microalgae, cyanobacteria, marine bacteria, and marine fungi, each offering unique metabolites that contribute to human health and wellness. Microalgae such as *Spirulina*, *Chlorella*, *Dunaliella*, *Haematococcus*, and *Nannochloropsis* are particularly notable for their rich content of proteins, vitamins, antioxidants, and PUFAs (Adarme-Vega et al., 2012). For example, *Spirulina* and *Chlorella* are widely used in dietary supplements for their high protein content and immune-boosting properties, while *Haematococcus* is a primary source of astaxanthin, a potent antioxidant. *Dunaliella* is valued for its β -carotene, and *Nannochloropsis* is a key producer of omega-3 fatty acids, making these microalgae indispensable in the nutraceutical industry. The most notable species are presented in Table 10.1

Cyanobacteria, such as *Arthrospira* (commonly known as spirulina) and *Synechococcus*, are significant contributors to nutraceutical development. *Arthrospira* is renowned for its high protein content, essential amino acids, and phycocyanin, a bioactive pigment with antioxidant and anti-inflammatory properties (Patel et al., 2022). *Synechococcus*, on the other hand, produces unique secondary metabolites with potential anticancer and antimicrobial activities. These cyanobacteria thrive in diverse marine environments, making them a sustainable source of bioactive compounds for functional foods and supplements.

Marine bacteria, including *Bacillus*, *Pseudomonas*, *Vibrio*, and *Streptomyces*, are prolific producers of enzymes, peptides, and secondary metabolites with diverse health benefits. *Bacillus* species, for instance, produce bioactive peptides with antihypertensive and antimicrobial properties, while *Pseudomonas* and *Vibrio* species are known for their production of exopolysaccharides and PUFAs. *Streptomyces*, a well-known genus of marine bacteria, is a rich source of polyketides and alkaloids with anticancer, antimicrobial, and anti-inflammatory activities. These bacteria are being explored for their potential in developing novel nutraceuticals and pharmaceuticals (Debbab et al., 2010).

Table 10.1 Notable nutraceutical-producing marine species.

Microbial Group	Species	Key Bioactive Compounds	Nutraceutical Applications	References
Microalgae	<i>Spirulina</i>	Proteins, phycocyanin, vitamins	Immune support, antioxidant, anti-inflammatory	Manzoor et al. (2024)
	<i>Chlorella</i>	Proteins, chlorophyll, PUFAs	Detoxification, immune modulation, cholesterol management	Chiellini et al. (2022)
	<i>Dunaliella</i>	β -carotene, antioxidants	Vision health, antioxidant protection	Garofalo et al. (2022)
	<i>Haematococcus</i>	Astaxanthin	Anti-aging, joint health, UV protection	Fayaazuddin et al. (2023)
	<i>Nannochloropsis</i>	Omega-3 PUFAs (EPA)	Cardiovascular health, brain function	Adarme-Vega et al. (2012)
Marine Bacteria	<i>Bacillus</i> spp.	Bioactive peptides	Antihypertensive, antimicrobial	Debbab et al. (2010)
	<i>Pseudomonas</i> spp.	Exopolysaccharides, PUFAs	Gut health, anti-inflammatory	Debbab et al. (2010)
	<i>Vibrio</i> spp.	PUFAs, enzymes	Metabolic health, marine-derived omega-3s	Debbab et al. (2010)
	<i>Streptomyces</i> spp.	Polyketides, alkaloids	Anticancer, antimicrobial, anti-inflammatory	Debbab et al. (2010)
Marine Fungi	<i>Aspergillus</i> spp.	Lovastatin, terpenoids	Cholesterol-lowering, neuroprotective	Burja and Radianingtyas (2005)
	<i>Penicillium</i> spp.	Bioactive peptides, enzymes	Antioxidant, anticancer	Burja and Radianingtyas (2005)

Marine fungi, such as *Aspergillus* and *Penicillium*, are another promising group of microorganisms for nutraceutical applications. These fungi produce a wide range of secondary metabolites, including terpenoids, alkaloids, and polyketides, which exhibit antioxidant, anticancer, and neuroprotective properties. For example, *Aspergillus* species have been shown to produce lovastatin, a compound with cholesterol-lowering effects, while *Penicillium* species are known for their production of bioactive peptides and enzymes. Marine fungi are increasingly being studied for their potential in developing functional foods and therapeutic agents (Debbab et al., 2010; Kim & Li, 2012).

The variety of marine microbial species, including microalgae, cyanobacteria, marine bacteria, and marine fungi, offers a diverse and sustainable source of bioactive compounds for nutraceutical applications. Their unique adaptations to marine environments enable them to produce metabolites with potent health benefits, ranging from antioxidant and anti-inflammatory effects to anticancer and immune-boosting properties. Advances in biotechnology and sustainable cultivation methods are helping to unlock the full potential of these microorganisms, paving the way for innovative nutraceutical products that promote human health and well-being (Burja & Radianingtyas, 2005).

10.17 Challenges

The development and commercialization of MMPs as nutraceuticals hold immense promise, but they also face significant challenges that must be addressed to fully realize their potential. One of the primary hurdles is the production and scalability of bioactive compounds from marine microorganisms. Many marine microbes, such as microalgae and extremophiles, require specific environmental conditions—such as controlled light, temperature, and nutrient availability—to thrive and produce high yields of target metabolites (Amanda et al., 2010). Cultivating these organisms on a large scale often involves complex and costly bioreactor systems, and optimizing growth conditions to maximize productivity remains a significant challenge. Additionally, the extraction and purification of bioactive compounds can be technically demanding and expensive, particularly for compounds that are present in low concentrations or require specialized processing techniques.

Sustainability is another critical challenge in the development of MMP nutraceuticals. While marine microorganisms offer a renewable source of bioactive compounds, their large-scale cultivation must be carefully managed to avoid ecological disruption. For example, the overharvesting of marine resources or the introduction of non-native species for cultivation could harm marine ecosystems. Furthermore, the energy and resource inputs required for large-scale production, such as water, nutrients, and electricity, must be minimized to ensure environmental sustainability. Advances in biotechnology, such as genetic engineering and synthetic biology, are being explored to enhance the efficiency and sustainability of MMP production, but these approaches must be balanced with ethical and regulatory considerations.

The stability and bioavailability of MMP-derived nutraceuticals also pose significant challenges. Many bioactive compounds, such as omega-3 fatty acids, carotenoids, and peptides, are sensitive to environmental factors like heat, light, and oxygen, which can degrade their efficacy during processing and storage. Ensuring the stability of these compounds in final products, such as supplements and functional foods, requires innovative encapsulation and delivery systems. Additionally, the bioavailability of MMP-derived compounds (how effectively they are absorbed and utilized by the human

body) can vary widely, necessitating further research to optimize their formulation and delivery (Escalante & Pérez-Rico, 2021; Kim, 2013).

Despite these challenges, the future of MMP nutraceuticals looks highly promising. Advances in biotechnology, including metabolic engineering, high-throughput screening, and omics technologies, are accelerating the discovery and optimization of bioactive compounds from marine microorganisms. Sustainable cultivation methods, such as integrated multi-trophic aquaculture (IMTA) and utilizing waste streams as nutrient sources, are being developed to minimize the environmental impact of MMP production. Moreover, growing consumer demand for natural and sustainable health products is driving investment and innovation in this field (D'Orbecastel et al., 2022).

While challenges related to production, sustainability, and product stability persist, the future of MMP nutraceuticals looks promising. By tackling these challenges through interdisciplinary research, technological innovation, and sustainable practices, MMPs can revolutionize the nutraceutical industry, offering novel solutions for enhancing human health and well-being while safeguarding marine ecosystems.

10.18 Sustainable development goals

Sustainable Development Goals (SDGs) are interconnected. Nonetheless, the topics discussed in this chapter mainly address SDG 3: Good Health and Well-being by exploring MMPs as a source of nutraceuticals with various previously discussed health benefits. The increasing demand for natural and preventive healthcare solutions drives the focus on these marine resources.

The chapter significantly relates to SDG 14: Life Below Water by highlighting the potential of marine microorganisms as valuable and biodiverse resources. It emphasizes the importance of sustainably utilizing these marine organisms, including bacteria, fungi, and microalgae, for their unique bioactive compounds. Additionally, the chapter acknowledges the challenges of ensuring sustainable harvesting and promotes advancements in biotechnology and aquaculture as responsible production methods.

Furthermore, the chapter connects to SDG 8: Decent Work and Economic Growth. The nutraceuticals industry, driven by the concept of food as medicine, holds significant economic importance. The exploration of MMPs and the development of innovative nutraceuticals derived from them create opportunities for economic growth, particularly in biotechnology and marine-related sectors. The growing market demand for these marine-derived supplements highlights their commercial potential.

Although it is less central, the chapter also addresses SDG 9: Industry, Innovation and Infrastructure by highlighting the need for biotechnological advancements in the efficient production of MMPs. The challenges in cultivation, extraction, and purification necessitate innovative solutions and infrastructure development that focus on sustainable production practices for MMPs. This aligns with SDG 12: Responsible Consumption and Production, advocating for the environmentally sound use of marine resources and applying biotechnology to obtain products with minimal impact on the ecosystem.

10.19 Conclusions

Marine microbial species represent a rich and largely untapped source of bioactive compounds with significant potential for nutraceutical applications, offering diverse health benefits. These unique

metabolites, evolved in the marine environment, hold promise for developing innovative nutraceuticals that can improve human health and help manage chronic diseases. However, the path to widespread use of MMPs as nutraceuticals is fraught with substantial hurdles. Significant challenges exist in the large-scale cultivation of demanding marine organisms, the complex and costly processes required for extracting and purifying valuable bioactive compounds, and the critical need to implement sustainable production methods that protect delicate marine ecosystems.

To overcome these obstacles and fully leverage the potential of MMPs, future efforts must prioritize several key areas. This includes ongoing research and development of more efficient and cost-effective cultivation and extraction technologies, along with a strong commitment to sustainable and environmentally responsible production practices.

Furthermore, it is crucial to focus on rigorous scientific validation through comprehensive preclinical and clinical trials to confirm the health benefits of these novel nutraceuticals. Concurrent efforts are necessary to engage with regulatory bodies to establish clear and harmonized regulatory frameworks that ensure the safety and quality of marine-derived products. Effective market development and consumer education strategies will also be essential for successful commercialization.

Ultimately, realizing the transformative potential of MMPs for the nutraceutical industry requires strong interdisciplinary collaboration among various scientific and industry experts. By strategically addressing the challenges and focusing on key areas of development, marine microorganisms promise to provide novel and sustainable solutions for promoting global health and well-being.

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Algae in renewable energy production for the sustainable environment

**K. Swetha¹, Vyshnava Satyanarayana Swamy¹, Gayathri Pandluru¹, M. Srinivasulu²,
Dineshkumar Krishnamoorthy³ and Kameshpandian Paramasivam⁴**

¹*Department of Biotechnology, University College of Sciences, Sri Krishnadevaraya University, Anantapuramu, Andhra Pradesh, India,*

²*Department of Biotechnology, Yogi Vemana University, Kadapa, Andhra Pradesh, India,*

³*Center for Genomics and Systems Biology, New York University Abu Dhabi, Saadiyat Campus, Abu Dhabi, United Arab Emirates,*

⁴*DMI St. John The Baptist University, Lilongwe, Malawi*

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11.1 Introduction

The global community faces increasing energy demands, climate change, and degradation of the environment, necessitating an urgent transition from fossil fuels (Gimba et al., 2024; Johnsson et al., 2019). Conventional energy sources including coal, oil, and natural gas, despite their long-standing prevalence, are now broadly acknowledged for their considerable carbon emissions and finite sustainability (Aransiola et al., 2024; Holechek et al., 2022). Researchers and governments are progressively adopting renewable energy technologies that have both environmental and economic advantages. Among the several renewable resources being studied, algae have emerged as a notably attractive potential for sustainable energy solutions (Aransiola et al., 2023; Torres & De-la-Torre, 2022).

Algae, particularly microalgae, have received significant attention for their exceptional ability to produce biomass efficiently, frequently in conditions unfit for traditional agriculture (Samoraj et al., 2024). In contrast to terrestrial biofuel crops, algae do not compete with food production and can flourish in saline water, wastewater, or dry environments, thereby substantially alleviating pressure on freshwater and arable land resources (Abideen et al., 2023). Moreover, algae can sequester ambient CO₂ via photosynthesis, providing the combined benefit of energy generation and greenhouse gas reduction.

Recent investigations into algal biofuels have proliferated, concentrating on the generation of diverse sources of energy like biodiesel, bioethanol, biogas, and biohydrogen. These advancements establish algae as a third-generation biofuel feedstock, exceeding previous generations that depended on food crops and lignocellulosic biomass (Aransiola et al., 2024; Powar et al., 2022). Research indicates that microalgae exhibit far greater oil yields per hectare than terrestrial crops, and their quick growth rates render them optimal for high-density biofuel production (Auta et al., 2024; Show et al., 2017).

Besides their elevated lipid content, algae have a varied biochemical composition comprising carbohydrates and proteins, facilitating the generation of numerous energy sources via different conversion routes (Choudhary et al., 2020). Methods including transesterification for biodiesel, anaerobic digestion for biogas, and fermentation for bioethanol are perpetually being optimized to enhance efficiency and decrease expenses. Furthermore, innovations in bioreactor design and strain optimization are demonstrating potential in improving large-scale algae culture. Despite these benefits, numerous technological and economic obstacles persist. Substantial capital and operational expenses associated with algae culture, harvesting, and lipid extraction have hindered commercial scaling (Khoo et al., 2023).

Nevertheless, continuous advancements in genetic engineering, photobioreactor efficiency, and biorefinery integration are systematically mitigating these limitations, suggesting a feasible trajectory forward. This chapter seeks to investigate the several functions of algae in renewable energy generation, analyzing existing technologies, ecological advantages, obstacles, and future possibilities.

By integrating latest discoveries and technical advancements, we seek to offer a thorough comprehension of the role of algae in fostering a sustainable energy future.

11.2 Algal biomass and its potential in renewable energy

Algal biomass is a highly promising and diverse feedstock for renewable energy generation, owing to its rapid development, elevated photosynthetic efficiency, and capacity to amass substantial quantities of lipids and carbohydrates, as shown in Fig. 11.1 (Pandey et al., 2018). In contrast to conventional bioenergy crops, algae can be grown on nonarable land utilizing saline, brackish, or wastewater, hence reducing conflict with food production and freshwater supplies. These characteristics render algae a feasible and sustainable choice for fulfilling future global energy requirements while reducing impacts on the environment.

11.2.1 Types of algae

Algae are classified into two primary categories: microalgae and macroalgae, as listed in Table 11.1. Microalgae are minuscule, unicellular entities proficient at photosynthesis (Heimann & Huerlimann, 2015). They are deemed the most appropriate for biofuel production owing to their elevated lipid and carbohydrate content, rapid growth rates, and facilitation of genetic manipulation. Common genera including *Chlorella*, *Spirulina*, and *Nannochloropsis* are extensively researched for their bioenergy potential (Choudhary et al., 2022).

Macroalgae, also referred to as seaweeds, are substantial multicellular algae located in maritime ecosystems. Despite having a lower lipid content than microalgae, they are abundant in polysaccharides including alginate, carrageenan, and agar, rendering them suitable for bioethanol and biogas generation by fermentation and anaerobic digestion (Milledge et al., 2019). The growth of macroalgae in ocean farms aids in carbon sequestration and the regeneration of marine habitats.

11.2.2 Algal biomass composition and its significance

The biochemical composition of algal biomass, consisting primarily of lipids, carbohydrates, and proteins, dictates its suitability for various biofuel routes. Lipids, especially triacylglycerols (TAGs), are essential for biodiesel synthesis via transesterification. Some species can amass lipids constituting up to 60% of their dry weight during nutritional stress situations (Mallick et al., 2016). Carbohydrates, mostly as starch or cellulose, are appropriate for fermentation into bioethanol, while proteins can be employed for coproducts or animal feed within a biorefinery framework (Formann et al., 2020).

The elevated productivity of algae per unit area and their capacity to double biomass within days substantially enhance their potential as a renewable resource. Algae are proficient at sequestering CO₂, with certain strains capable of fixing multiple times more CO₂ than terrestrial plants (Zhang & Liu, 2021). This not only contributes to the reduction of greenhouse gas emissions but also improves the environmental sustainability of algae biofuel systems.

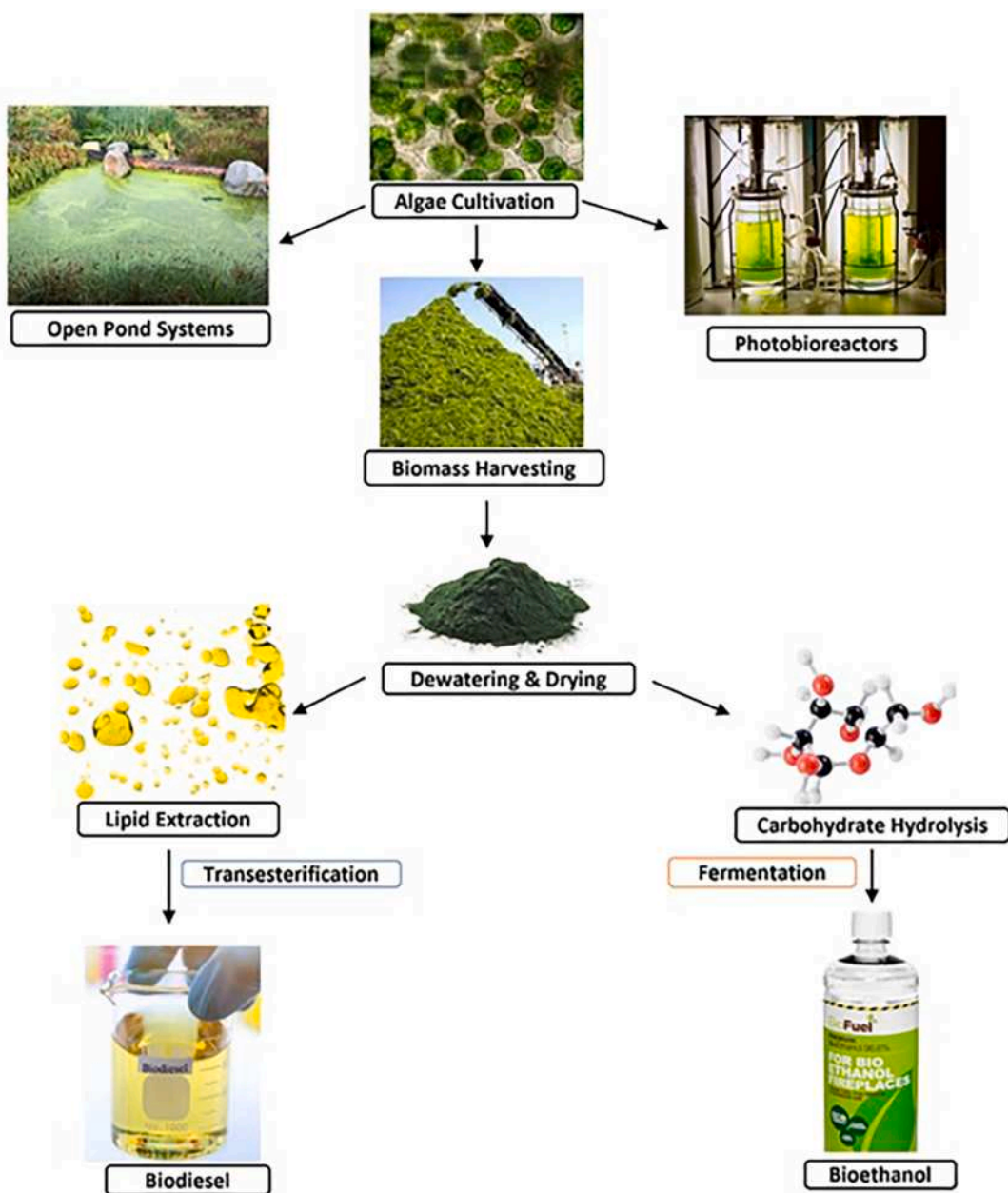


FIGURE 11.1

Algal biofuel production process.

Table 11.1 Comparison of microalgae and macroalgae.

Feature	Microalgae	Macroalgae
Size	Microscopic (unicellular)	Large (multicellular, seaweeds)
Habitat	Freshwater, marine, brackish waters	Predominantly marine environments
Growth rate	Very high (can double in 24 h)	Moderate
Lipid content	High (up to 60% dry weight)	Low to moderate
Carbohydrate content	Moderate	High (suitable for bioethanol/biogas)
Cultivation system	Photobioreactors, raceway ponds	Seaweed farming, ocean lines
Suitability	Biodiesel, biohydrogen, biogas	Bioethanol, biogas, biochar
Harvesting	Energy-intensive (due to small size)	Easier due to large biomass

11.2.3 Factors affecting algal growth and biofuel yield

Various environmental and operational parameters affect algal proliferation and the quality of biomass generated. Essential criteria comprise:

- *Illumination intensity and photoperiodicity*: Algae necessitate adequate illumination for photosynthesis. Natural sunshine and artificial light are utilized in open ponds and photobioreactors, with light quality and duration directly influencing biomass productivity (Nwoba et al., 2019).
- *Nutrient accessibility*: Nitrogen and phosphorus are essential nutrients. Although abundant nutrients facilitate growth, nitrogen scarcity frequently triggers lipid buildup, hence augmenting biodiesel potential (Gumbi et al., 2022).
- *Carbon dioxide provision*: Enhancing CO₂ levels augments photosynthetic efficiency. Industrial flue gases serve as an economical source of CO₂ and provide a synergistic approach for carbon mitigation (Viswanaathan et al., 2022).
- *Temperature and pH levels*: The ideal temperature and pH ranges differ among species. Most microalgae flourish at temperatures ranging from 20°C to 30°C and a pH of 7–9, while certain extremophiles can endure more severe circumstances (Rojas-Villalta et al., 2024).

Effective regulation of these parameters in cultivation systems, particularly in closed photobioreactors, can substantially enhance biomass yield and fuel production, rendering commercial-scale manufacturing more viable.

11.3 Algal biofuels: production pathways and technologies

Algae are recognized for their adaptability in producing several types of biofuels via different biochemical and thermochemical conversion methods. Algae, as third-generation biofuel feedstocks, present notable advantages over traditional crops: superior yield per unit area, accelerated development, independence from arable land, and the capacity to utilize waste or saline water, as shown in Fig. 11.2 (Mahmood et al., 2023). These characteristics render algae especially conducive to

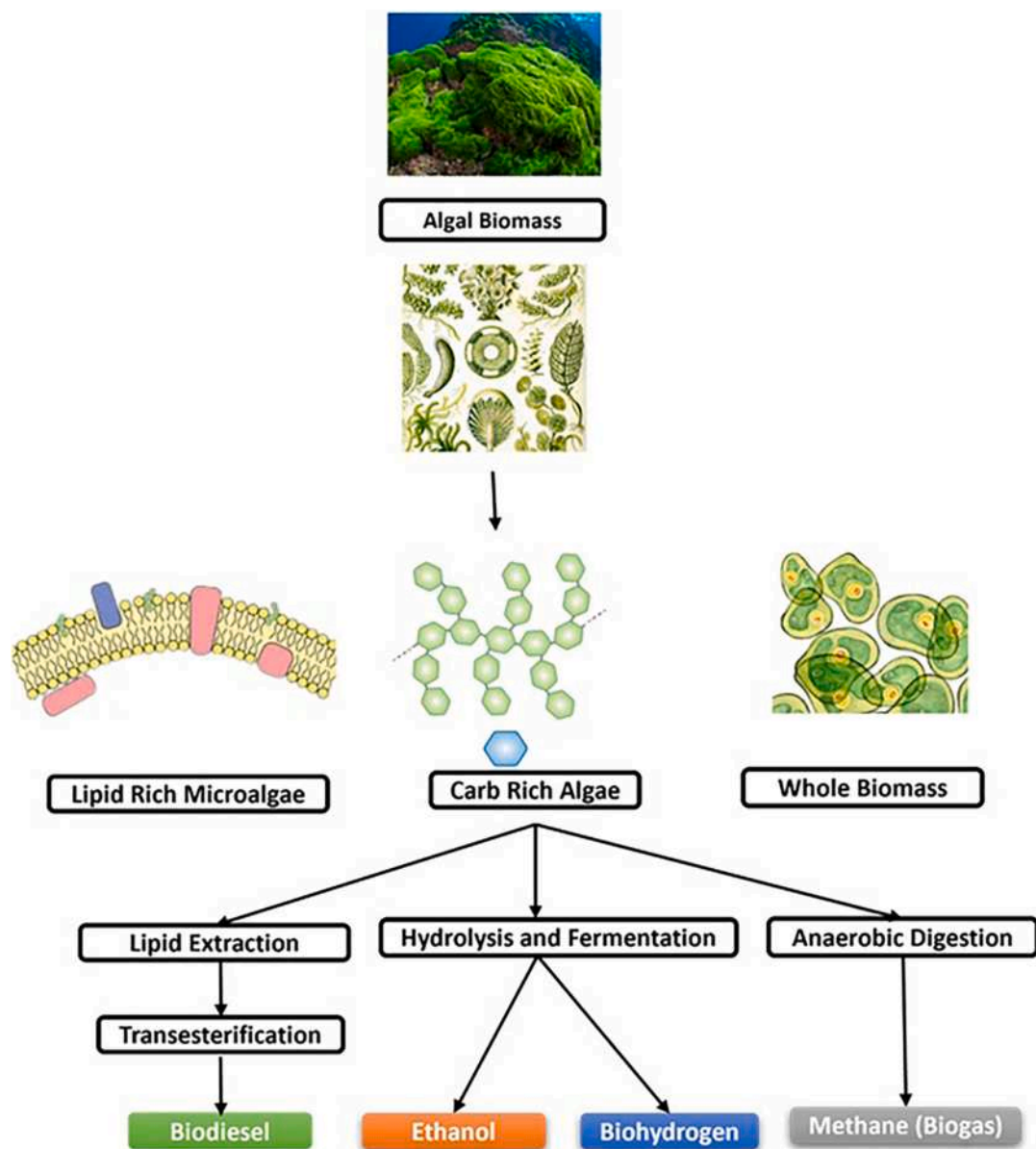


FIGURE 11.2

Pathways for algal biofuels.

sustainable energy advancement. This section examines the primary technological methods employed to transform algal biomass into biofuels, emphasizing both biological and thermochemical strategies (Ashokkumar et al., 2024).

11.3.1 Bioethanol from algae: fermentation-based production

Bioethanol synthesis from algae predominantly utilizes carbohydrate-dense species of microalgae and macroalgae. The procedure has three primary stages: pretreatment (to disintegrate cell walls), hydrolysis (to transform polysaccharides into monosaccharides), and fermentation (to generate ethanol utilizing microbial cultures). Macroalgae, including *Laminaria* and *Ulva*, are abundant in polysaccharides such as laminarin and mannitol, which can be transformed into fermentable sugars through enzymatic or acid hydrolysis (Lakatos et al., 2019; Sirajunnisa & Surendhiran, 2016).

Microalgae, despite typically having reduced carbohydrate levels, can be genetically engineered or grown under stress conditions to enhance starch accumulation. Yeast strains like *Saccharomyces cerevisiae* are frequently utilized for fermentation, however alternative modified microorganisms are being investigated for enhanced conversion efficiency (Parapouli et al., 2020). Despite its potential, the economic viability of algal bioethanol is impeded by elevated pretreatment expenses and inferior sugar yields relative to starch-based crops.

11.3.2 Biodiesel production: transesterification and lipid extraction

Biodiesel derived from algae is among the most extensively studied biofuels, attributable to the elevated lipid content of specific microalgal strains, as listed in Table 11.2. Species such as *Nannochloropsis*, *Chlorella*, and *Botryococcus braunii* can accumulate lipids that may comprise up to 60% of their dry weight in nutrient-deficient environments (Hasnain et al., 2023; Nazloo et al., 2024). The biodiesel production process entails the collection of algal biomasses, the extraction of lipids utilizing solvents such as hexane, and the conversion of these lipids into fatty acid methyl esters (FAMES) by transesterification (Cheng et al., 2014).

Catalysts, whether chemical (acid/base) or enzymatic, are employed to expedite this conversion. Research is being conducted on advancements in wet extraction and supercritical CO₂ methods to minimize energy usage in lipid recovery. Biodiesel produced from algae possesses a superior energy density compared to ethanol and is compatible with current diesel engines (Ali et al., 2021). Nonetheless, obstacles including scalability, elevated cultivation and extraction expenses, and the necessity for resilient bioreactors persist in hindering commercial acceptance.

11.3.3 Biogas and biohydrogen from algae: anaerobic digestion and dark fermentation

Algal biomass can be utilized for biogas production, predominantly methane, by anaerobic digestion (AD). During this process, microorganisms break down organic materials anaerobically, producing biogas and digestate, as listed in Table 11.3. This technique is especially suitable for low-lipid or leftover algal biomass following lipid extraction (Abomohra et al., 2022). Algae such as *Chlorella* and

Table 11.2 Biochemical composition of selected algal species.

Algal species	Lipid content (% dry weight)	Carbohydrate content (% dry weight)	Protein content (% dry weight)	Primary biofuel potential	References
<i>Chlorella vulgaris</i>	28%–32%	20%–30%	40%–50%	Biodiesel, bioethanol	Agwa et al. (2017) , Salman and Ali (2014)
<i>Nannochloropsis</i> sp.	30%–60%	10%–15%	30%–40%	Biodiesel	Paramasivam et al. (2021)
<i>Spirulina platensis</i>	6%–13%	14%–19%	55%–70%	Biogas, co-product (protein)	Hultberg et al. (2017)
<i>Scenedesmus obliquus</i>	20%–40%	25%–45%	30%–50%	Biodiesel, bioethanol	Xu et al. (2019)
<i>Botryococcusbraunii</i>	25%–75%	10%–15%	15%–20%	Hydrocarbons, biodiesel	Nazloo et al. (2024)
<i>Ulva lactuca</i> (macro)	2%–4%	40%–50%	10%–20%	Bioethanol, biogas	Allouache et al. (2021)
<i>Laminaria japonica</i>	3%–5%	45%–55%	10%–15%	Bioethanol	Moenaert et al. (2023)

Table 11.3 Summary of algal biofuel types and production technologies.				
Biofuel type	Feedstock component	Conversion process	End product	Technology type
Biodiesel	Lipids (triglycerides)	Lipid extraction → transesterification	Fatty acid methyl esters (FAME)	Chemical/ biochemical
Bioethanol	Carbohydrates (starch, cellulose)	Hydrolysis→ fermentation	Ethanol	Biochemical
Biogas	Whole biomass or residues	Anaerobic digestion	Methane (CH ₄) + CO ₂	Biological (microbial)
Biohydrogen	Whole cells (under anaerobic/sulfur-starved conditions)	Dark fermentation or biophotolysis	Hydrogen (H ₂)	Biological (enzymatic)
Bio-oil	Wet algal biomass	Hydrothermal liquefaction	Crude bio-oil	Thermochemical
Biochar	Dried algal biomass	Pyrolysis	Solid biochar	Thermochemical

Scenedesmus have demonstrated efficacy in codigestion systems with various organic wastes, enhancing overall methane production (Zhen et al., 2016).

Constraints encompass ammonia toxicity and the necessity for balancing the carbon-to-nitrogen ratio. Pretreatment techniques, including ultrasound, thermal hydrolysis, and alkaline conditioning, enhance digestibility and biogas yield. Simultaneously, biohydrogen can be produced through dark fermentation or photofermentation with green algae such as *Chlamydomonas reinhardtii* (Putatunda et al., 2023). In sulfur-limited and anaerobic environments, these algae generate hydrogen gas via hydrogenase enzymes. Although biohydrogen is a clean and high-energy fuel, its production is still limited to laboratory scale due to enzyme sensitivity and low yields (Razu et al., 2019).

11.3.4 Algal biochar and bio-oil: pyrolysis and hydrothermal liquefaction

Thermochemical conversion methods such as pyrolysis and hydrothermal liquefaction (HTL) can convert algal biomass into bio-oil, charcoal, and syngas. Pyrolysis entails the thermal degradation of biomass at elevated temperatures (300°C–600°C) in an anoxic environment. Rapid pyrolysis generates substantial quantities of bio-oil, while gradual pyrolysis results in increased biochar production, which is beneficial as a soil amendment and carbon sequestration agent (Pandit et al., 2023).

HTL, conversely, functions under aqueous circumstances (200°C–350°C, 10–20 MPa), obviating the necessity for biomass desiccation. This approach is very beneficial for algae because of their elevated moisture content. HTL generates bio-crude that may be refined into drop-in fuels utilizing standard refinery methods. It also produces aqueous, gaseous, and solid coproducts that can be further exploited or processed. Despite the potential of these technologies, problems encompass substantial capital investment, reactor corrosion, and the optimization of production and product quality.

11.3.5 Comparative analysis of algal biofuels and traditional fossil fuels

Algal biofuels provide numerous environmental and strategic benefits compared to fossil fuels. Algae possess the largest yield potential among biofuel crops, with estimations indicating up to 30 times more oil per acre than terrestrial oilseed crops (Perona, 2017). They also sequester CO₂ during growth, facilitating net carbon neutrality when utilized as fuels. From an emissions standpoint, biodiesel and bioethanol derived from algae produce markedly less pollutants than diesel and gasoline, notably reduced sulfur oxide and particulate matter emissions (Sarwer et al., 2022). Furthermore, algae-derived biogas and biohydrogen produce negligible greenhouse gas emissions during combustion.

Economically, algae biofuels remain more costly than fossil fuels due to expenses associated with production, harvesting, and processing. Although fossil fuel infrastructure is well-established and subsidized, algae systems necessitate further investment and innovation for economically viable scale. The life cycle assessment (LCA) of algal biofuels frequently demonstrates a good energy return on investment (EROI), particularly when included into closed-loop systems that employ waste CO₂, heat, and water (Bessette et al., 2020). When integrated with wastewater treatment and flue gas collection, algae-based systems can yield net beneficial effects on environmental health and resource circularity.

11.4 Environmental and economic sustainability of algal biofuels

The quest for sustainable energy solutions involves both minimizing environmental effect and ensuring long-term economic sustainability. In this perspective, algal biofuels are seen as a comprehensive answer as they concurrently tackle various challenges renewable energy production, carbon dioxide reduction, water conservation, and land-use optimization, as shown in Fig. 11.3 (Olabi et al., 2023). This section assesses the environmental and economic sustainability of algae biofuels by analyzing their roles in climate mitigation, resource efficiency, economic viability, and practical use.

11.4.1 Carbon sequestration and algae's role in climate mitigation

One of the most notable environmental advantages of algae is their capacity to sequester and store atmospheric carbon dioxide. During photosynthesis, algae convert CO_2 into organic biomass at a significantly greater rate than terrestrial plants. Certain microalgae strains may sequester CO_2 with up to 50 times more efficiency than higher plants (Prasad et al., 2021). Additionally, algae can be cultivated adjacent to industrial facilities, employing flue gases as a carbon source, thus directly mitigating greenhouse gas emissions from power plants and manufacturing units (Chia et al., 2021).

Besides diminishing carbon emissions, algae-based systems facilitate oxygen production and enhance water quality. Certain systems are combined with wastewater treatment facilities, wherein algae eliminate fertilizers and pollutants while sequestering CO_2 , thereby establishing a closed-loop model that advances climate objectives.

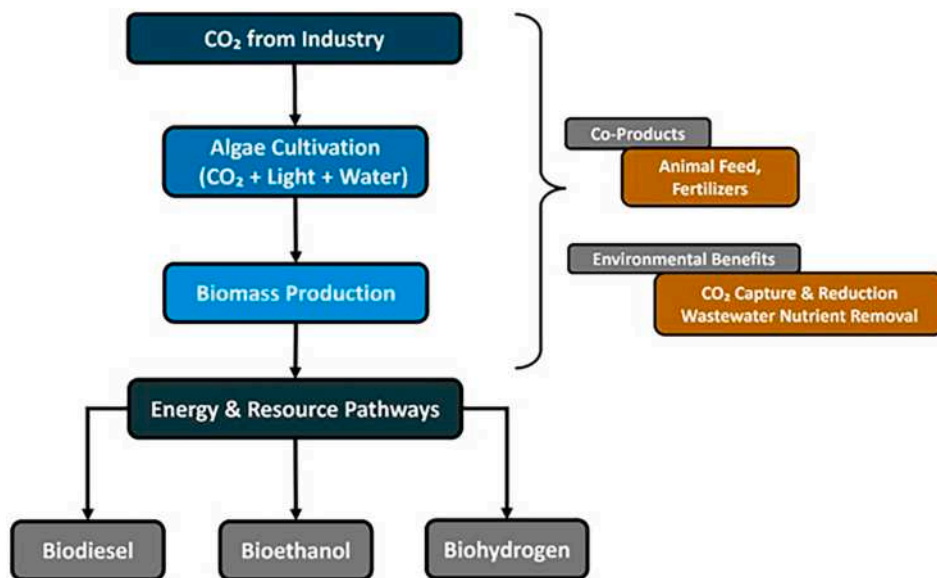


FIGURE 11.3

Integrated algal bioenergy and environmental system.

11.4.2 Water and land use considerations in algae cultivation

In contrast to conventional bioenergy crops such as corn or sugarcane, algae necessitate far less land and can be grown in nonarable or marginal regions, including deserts and salt flats. This trait renders algae farming particularly appealing in areas where arable land is limited or excessively exploited. Moreover, algae do not vie with food crops on arable land, so mitigating the food-versus-fuel discourse prevalent with first-generation biofuels (Samoraj et al., 2024).

Algae can thrive in salt, brackish, or effluent, hence diminishing reliance on freshwater supplies. Nonetheless, extensive cultivation continues to face difficulties concerning evaporation losses in open pond systems and water reclamation in closed photobioreactors. Technologies that combine wastewater treatment with algal biomass production offer a sustainable solution for simultaneous water management and energy generation (Madhubalaji et al., 2019).

11.4.3 Cost-effectiveness and commercial viability of algal biofuels

Although its many environmental benefits, algal biofuels encounter various economic obstacles that have constrained their extensive commercialization (Dębowski et al., 2022). Principal cost determinants comprise:

- *Cultivation*: The cultivation of algae necessitates meticulous regulation of light, nutrients, temperature, and carbon dioxide levels. Photobioreactors, while more efficient, are costly to build and sustain.
- *Harvesting and dewatering*: The processes are energy-intensive because of the dilute composition of algal colonies.
- *Lipid extraction and conversion*: Solvent-based extraction and transesterification techniques increase operational complexity and expenses.

Numerous studies indicate that the production cost of algal biodiesel presently varies between \$5 and \$10 per liter, markedly exceeding that of fossil diesel. Integrated biorefinery models that generate several coproducts, including animal feed, cosmetics, bioplastics, and fertilizers, can enhance economic viability.

A further cost-reduction technique involves the utilization of industrial waste streams. For instance, harnessing CO₂ emissions from power plants or nutrient-dense wastewater can lower input expenses while delivering ecological benefits. Progress in synthetic biology and strain engineering demonstrates potential for enhancing yield and minimizing input requirements (Bharathiraja et al., 2019).

11.4.4 Case studies: successful implementations of algal biofuel projects

Numerous pilot and commercial-scale initiatives globally demonstrate the potential and challenges associated with the implementation of algal biofuels:

- *Sapphire Energy (United States)*: Sapphire Energy, a highly recognized enterprise, produced “green crude” from algae, which can be converted into drop-in fuels. The company generated in excess of 1 million gallons of algae biofuel and showcased its application in commercial

transportation. Notwithstanding technological achievement, exorbitant expenditures ultimately necessitated a strategic turn ([Perona, 2017](#)).

- *Algenol (United States)*: Algenol concentrated on ethanol generation from algae, employing a unique photobioreactor method and utilizing saline water along with collected CO₂. Despite initial encouraging results, the company encountered difficulties in growing and obtaining long-term financing ([Legere et al., 2017](#)).
- *IHI Corporation of Japan*: This initiative cultivates microalgae in external ponds for the production of jet fuel. The initiative, in collaboration with government and scientific organizations, has demonstrated successful flight testing utilizing a mixture of algal biojet fuel, highlighting the potential of algae in aviation ([Herrador, 2016](#)).
- *CSIR-CIMFR of India*: This research, in collaboration with NTPC, India's largest power producer, investigates algae culture utilizing wastewater and flue gas from thermal power plants. Preliminary findings suggest a dual advantage of less pollution and enhanced biofuel production ([Ansari et al., 2020](#)).
- *NRC and NREL (Canada and United States)*: A global partnership shown that colocating algae production with sources of CO₂, heat, and wastewater can enhance sustainability and cost-effectiveness. The project created a decision-support tool to evaluate the feasibility and location selection for algae biofuel facilities ([Karim & Faissal, 2022](#)).

These case studies underscore the technological preparedness and systemic obstacles associated with algae biofuel production. Although several projects encountered financial or scalability challenges, they offer significant insights into technology optimization, cost reduction, and sustainability integration ([Dębowski et al., 2022](#)).

11.5 Challenges and future prospects in algal bioenergy

Although algae possess significant potential as a renewable energy source, the practical feasibility of algal biofuels is hindered by various technical, biological, regulatory, and economic obstacles. Although many pilot projects and laboratory-scale research have established feasibility, large-scale implementation remains behind more established renewable technologies such as solar and wind ([Shuba & Kifle, 2018](#)). Nevertheless, increasing global interest in sustainable bioenergy, along with advancements in biotechnology and favorable policy frameworks, is creating new opportunities for the future of algal biofuels. This section delineates the principal difficulties and the nascent opportunities that may influence the future direction of algae-derived renewable energy.

11.5.1 Technical and biological challenges in algal biofuel production

A significant challenge in algal biofuels is the optimization of cultivation and conversion processes ([Khan et al., 2018](#)). Principal challenges encompass:

- *Suboptimal biomass yield and lipid productivity*: Numerous algae strains inherently lack the capacity to generate adequate lipids or carbohydrates for economically feasible biofuel generation.

Furthermore, increasing lipid yield frequently undermines growth rate, resulting in a productivity trade-off (Hoang et al., 2023).

- *Collection and moisture removal:* The microscopic size and dilute growth medium of microalgae necessitate energy-intensive harvesting techniques, such as centrifugation or filtration, hence elevating operational expenses.
- *Downstream processing:* The conversion of algal biomass into useable fuels by transesterification, fermentation, or pyrolysis often entails several energy-intensive processes. Ensuring cost-effectiveness and productivity during these transformations remains an ongoing problem.

11.5.2 Policy and regulatory framework for algae-based renewable energy

Policy support is essential for promoting innovation and investment in algae biofuels. Current legislative frameworks frequently lack explicit recommendations for algae as a separate category within bioenergy. Numerous subsidies, tax incentives, and research grants predominantly target first- and second-generation biofuels, so placing algae-based technology at a disadvantage (Liu, 2016).

Furthermore, rules concerning environmental safety, genetically modified organisms (GMOs), and wastewater reuse may impede project approvals and elevate compliance expenses. A comprehensive and algae-specific regulatory framework, with established criteria for growing, processing, and fuel quality, is crucial to facilitate commercial deployment.

11.5.3 Advances in genetic engineering and synthetic biology for high-yield algal strains

Recent advancements in genetic engineering and synthetic biology have significant potential for improving algal biofuel production (Jagadevan et al., 2018). By precisely manipulating metabolic pathways, researchers are developing strains that can:

- Increase fat accumulation without hindering growth
- Enhance resilience to environmental variations
- Minimize photorespiration and enhance photosynthetic efficacy.

These alterations are facilitated by techniques like as CRISPR-Cas9, metabolic pathway reconfiguration, and high-throughput strain selection (Okoro et al., 2022). These advances may decrease production expenses and enhance commercial scalability. Nonetheless, ethical considerations and legislative obstacles pertaining to GMOs must be confronted concurrently with scientific advancement.

11.5.4 Future trends and opportunities in algal biofuel industry

The future of algal bioenergy is rooted in integrated, multiproduct biorefinery models that coproduce biofuels and high-value chemicals, including pigments, proteins, medicines, and bioplastics. This strategy improves economic sustainability by diversifying income sources. Furthermore, the increasing focus on decarbonization and net-zero objectives worldwide is expected to enhance both

public and private investment in carbon-negative technologies, such as algae systems combined with carbon capture and wastewater treatment (Tiwari et al., 2024).

Artificial intelligence and automation offer prospects for optimizing culture conditions, reducing resource consumption, and improving real-time monitoring of algal systems. Given these trends, algae may not only serve as a fuel source but also become a fundamental component of the circular bioeconomy.

11.6 Recommendations

Algal biofuels signify a highly promising pathway in the shift toward sustainable and renewable energy sources. Algae have considerable environmental benefits compared to traditional fossil fuels and first- and second-generation biofuels due to their capacity for rapid growth in nonarable land utilizing saline or wastewater, high photosynthetic efficiency, and potential for carbon sequestration. Algae function as a diverse feedstock, facilitating the production of many energy products, including biodiesel, bioethanol, biogas, and biohydrogen (Padder et al., 2024).

The commercial scalability of algal biofuels is impeded by elevated production costs, technological constraints in harvesting and conversion, and inadequate legislative assistance. Nonetheless, progress in genetic engineering, bioreactor design, and integrated biorefinery models is progressively resolving these challenges. As global objectives transition toward decarbonization and climate resilience, the significance of algae in circular bioeconomy frameworks is becoming progressively pertinent with following recommendations (Errera et al., 2025).

- *Incentives for policy implementation:* Governments ought to implement algae-specific rules, financing initiatives, and tax incentives to promote research and commercialization.
- *Integration of technology:* The advancement of low-energy harvesting, efficient downstream processing, and AI-driven agricultural systems will improve economic viability.
- *Collaboration between public and private sectors:* Collaborative alliances across academia, industry, and government are crucial for enhancing output and implementing pilot initiatives.
- *Multiproduct biorefineries:* Concentrating on coproducts such as animal feed, pigments, and biofertilizers can enhance the profitability of algae biofuel enterprises.
- Through concentrated innovation and policy endorsement, algae can significantly contribute to the attainment of global sustainability and energy security objectives.

11.7 Conclusion

Algal biofuels signify a pivotal opportunity in the shift toward sustainable energy sources. Their capacity to thrive in nonarable terrain, utilize wastewater, and sequester substantial quantities of CO₂ renders algae a preferable alternative to conventional fossil fuels and first-generation biofuels. Despite significant environmental benefits, the industry encounters technological and economic challenges, such as expensive harvesting, processing inefficiencies, and inadequate legislative backing. Nonetheless, continuous advancements in synthetic biology, photobioreactor design, and integrated

biorefinery models are progressively bridging these gaps. Global case studies illustrate the viability of algae-based systems integrated with carbon capture and waste management. For algae to emerge as a prevalent energy alternative, coordinated initiatives in policy development, public-private investment, and cross-sector collaboration are essential. Through ongoing innovation and focused assistance, algae can play a pivotal role in attaining global energy security and climate resilience objectives in a resource-efficient and sustainable way.

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Marine microbial products and global food safety: benefits, threats, and future guidelines

Mariam Iyabo Adeoba¹, Thanyani Pandelani², Harry Ngwangwa² and Tracy Masebe³

¹*Biomechanics Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, College of Science, Engineering and Technology (CSET), University of South Africa (UNISA), Florida, South Africa,*

²*Unisa Biomedical Engineering Research Group, Department of Mechanical, Bioresources and Biomedical Engineering, School of Engineering, College of Science Engineering and Technology, University of South Africa, Science Campus, Florida, South Africa,*

³*Department of Life and Consumer Sciences, College of Agriculture and Environmental Sciences, University of South Africa (UNISA), Florida, Johannesburg, South Africa*

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12.1 Introduction

Bioactive substances produced by microorganisms that flourish in marine environments, including bacteria, fungi, and algae, are referred to as marine microbial products (MMPs) (Li et al., 2019). Numerous secondary metabolites are produced by these microbes, which can be found in various marine environments, from coastal waters to deep-sea hydrothermal vents. These metabolites, often referred to as marine natural products, contain distinct biological activity and include peptides, polysaccharides, enzymes, and antibiotics. Because of its potential uses in various industries, most notably food safety and global food systems, MMP research and exploitation have grown dramatically in recent decades.

Because MMPs can solve some of the most urgent issues in food safety, they have grown in significance within global food systems. MMPs provide a creative and long-lasting way to improve food security and safety in a time of expanding global population, heightened food trade, and growing worries about antibiotic resistance and foodborne illnesses (El-Saadony et al., 2023). Due to their antibacterial, antioxidant, and antifungal qualities, several MMPs are helpful in reducing food

spoilage, avoiding pathogen contamination, and prolonging the shelf life of perishable goods. These properties are particularly valuable in combating foodborne illnesses caused by pathogens such as *Salmonella*, *Listeria*, and *Escherichia coli* (*E. coli*), which are major contributors to global food safety concerns. Moreover, MMPs have the potential to serve as natural preservatives, replacing synthetic chemicals that may pose health risks or environmental hazards (Zorić et al., 2022).

The relevance of food safety in today's globally interconnected supply chain cannot be overstated (Aransiola et al., 2024a). The modern food supply chain is characterized by complex logistics and trade networks that span continents, leading to increased contamination risks and foodborne diseases. The rapid movement of food products across borders, coupled with varying safety standards and practices, has heightened concerns about the safety and quality of food on a global scale (Charlebois et al., 2021). In this context, MMPs represent a promising tool to ensure the safety of food products, offering an alternative to conventional methods of preservation and pathogen control. By harnessing the antimicrobial and preservative properties of MMPs, food producers can enhance product safety, reduce reliance on synthetic preservatives, and address challenges posed by evolving microbial threats. This chapter aims to examine the importance of MMPs in relation to international food safety. A thorough description of MMPs, including their types, origins, and biological activities, will be given in the first part. MMPs' ability to solve problems with foodborne infections, spoiling, and preservation will be highlighted in the second section, which will also cover their function in enhancing food safety. The final portion will examine the risks and difficulties of using MMPs, such as the possibility of antibiotic resistance, environmental sustainability, and safety issues. The chapter will conclude by outlining the future rules and regulations required to safely incorporate MMPs into food systems, guaranteeing their sustainability and long-term effectiveness. By the end of this chapter, readers will have a clear understanding of the benefits, challenges, and future directions for using MMPs in global food safety.

12.2 Understanding marine microbial products

Naturally occurring bioactive substances called MMPs are created by microorganisms that live in marine habitats (Ding et al., 2022). These microorganisms, which include cyanobacteria, fungi, bacteria, and archaea, produce a wide variety of metabolites with substantial potential for use in a wide range of industrial processes. Microorganisms that can produce bioactive substances with specific qualities have evolved due to the special conditions found in marine habitats, including high salinity, pressure, and a variety of biological interactions. Due to their many benefits, including antibacterial, antioxidant, antiinflammatory, and anticancer properties, MMPs have attracted more and more attention. As a result, they are highly valued in industries including food preservation, aquaculture, and agriculture. Based on their chemical make up and biological role, the diverse range of biochemicals that make up MMPs can be divided into multiple groups. Enzymes, antibiotics, bioactive chemicals, biopolymers, and pigments are among them; each has a specific function in the microbial environment as well as in industrial settings.

Marine microorganisms produce numerous enzymes with significant biotechnological uses. Usually, these enzymes are extremophiles, meaning they can work in harsh environments like high salinity, high pressure, or fluctuating temperatures (Mesbah, 2022). Marine enzymes are widely desired in industrial operations, especially in waste treatment, biofuel production, and food

processing. Proteases, lipases, and cellulases are a few examples that are crucial for the breakdown of intricate chemical molecules. Numerous new antibiotics produced by marine microorganisms have demonstrated effectiveness against diseases resistant to multiple drugs (Aransiola et al., 2024b). The hunt for novel and powerful antimicrobial agents has turned to marine ecosystems due to growing concerns about antibiotic resistance in both clinical and agricultural settings. Compounds such as marinomycin, inecalcitol, and others derived from marine bacteria and fungi exhibit significant antibacterial, antifungal, and antiviral properties, making them vital tools in medicine and food safety. Bioactive compounds from marine microbes include molecules with antimicrobial, antioxidant, anticancer, and antiinflammatory properties. These compounds, including peptides, polysaccharides, and terpenoids, have wide applications in developing functional foods, pharmaceuticals, and nutraceuticals. Marine microorganisms are also sources of various biopolymers, such as exopolysaccharides, which have applications in food, pharmaceuticals, and the cosmetics industry (Qi et al., 2022). These biopolymers are often used for their emulsifying, gelling, and stabilizing properties. Alginate, a biopolymer derived from marine algae, is widely used as a thickening agent in food products. In contrast, chitosan, obtained from marine crustaceans, has applications in wound healing and food preservation. Marine microorganisms produce a variety of pigments, such as carotenoids, chlorophylls, and phycobiliproteins, which are known for their antioxidant and UV-protective properties. These pigments are not only crucial for the survival of microbes but have applications in the food, cosmetic, and pharmaceutical industries due to their health benefits and ability to enhance the appearance of products.

Marine microbes, the producers of MMPs, thrive in various marine habitats, from the deep ocean to coastal zones. These microbes include bacteria, fungi, archaea, and cyanobacteria, each contributing to the diversity of MMPs available for biotechnological exploitation. Marine bacteria are one of the most prolific producers of bioactive compounds. Many marine bacteria belong to genera such as *Bacillus*, *Pseudomonas*, and *Streptomyces*, known for their ability to produce antibiotics and other bioactive metabolites (Ameen et al., 2021). Seawater, sediment, and symbiotic connections with marine species like corals and sponges are just a few maritime settings where these bacteria can be found. Novel bioactive chemicals can be abundant in marine fungi, especially those found in coastal and deep-sea environments. *Aspergillus*, *Penicillium*, and other marine-derived fungi produce a range of secondary metabolites, bioactive peptides, and enzymes that have potential uses in food, medicine, and agriculture. Numerous species of marine mushrooms are currently poorly understood, indicating a substantial potential for the discovery of novel chemicals. The biodiversity of these organisms is still being investigated. Extremophilic microbes known as Archaea live in hostile settings such as hot springs, deep-sea vents, and hypersaline lakes (Kumar et al., 2022). These microorganisms have evolved to survive extreme conditions, producing unique enzymes and metabolites useful in industrial applications. Marine archaea are studied for their ability to synthesize thermophilic enzymes useful in high-temperature industrial processes. Cyanobacteria, or blue-green algae, are photosynthetic microorganisms in marine environments, particularly coral reef ecosystems. They produce a range of bioactive compounds, including pigments and peptides, many of which have shown promise in medical and nutritional applications. Cyanobacteria also play a crucial role in nitrogen fixation in marine ecosystems, contributing to the overall health of marine environments.

The use of MMPs for biotechnological purposes in food preservation, aquaculture, and agriculture is growing (Fig. 12.1). MMPs are helpful in various industries because of their unique qualities, which

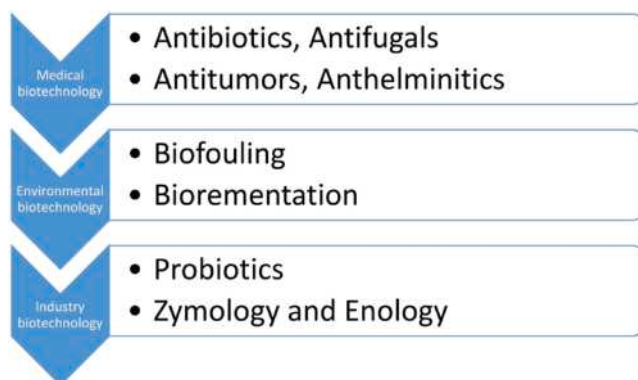
**FIGURE 12.1**

Illustration showing various marine microbial sources and their biotechnological applications in medical biotechnology, environmental biotechnology, and industry biotechnology.

include their enzymatic activities, antibacterial activity, and capacity to improve food quality. In agriculture, MMPs are used to create biopesticides and biofertilizers. It has been demonstrated that some marine fungi and bacteria can prevent plant diseases, which lessens the need for chemical pesticides. Alginate and chitosan, two biopolymers produced from marine sources, are also used as organic soil conditioners and growth boosters. Compared to synthetic fertilizers, these products help raise agricultural yields, promote soil health, and lessen their negative environmental effects. MMPs are employed in aquaculture to improve water quality, boost growth, and suppress bacterial infections. Marine-derived antibiotics, enzymes, and probiotics are particularly useful in maintaining healthy fish populations and preventing diseases caused by pathogenic microbes (Eze et al., 2023). The use of MMPs in aquaculture also reduces the reliance on chemical treatments, which can harm both environment and consumer. Food preservation is among the most potential uses of MMPs. Natural preservatives and antimicrobial peptides obtained from marine sources can prolong the shelf life of perishable food items without artificial chemicals. By preventing the growth of foodborne pathogens and spoilage microorganisms, these bioactive chemicals can improve the safety and quality of food. Additionally, the food sector uses enzymes generated from marine microbes for activities including brewing, the fermentation of dairy products, and creating functional meals. Products from marine microbes are a vast and mostly unexplored source of bioactive substances with enormous potential for use in biotechnological applications. Marine microbes provide creative solutions for sectors including agriculture, aquaculture, and food preservation because of their capacity to create enzymes, antibiotics, bioactive chemicals, biopolymers, and colors. The unique properties of these compounds, derived from microorganisms that thrive in extreme marine environments, position MMPs as valuable tools for addressing some of the world's most pressing challenges, such as food safety, sustainability, and disease control (Porzani & Nowruzi, 2023). As research into MMPs continues to expand, discovering new metabolites will undoubtedly lead to novel applications that will benefit both human health and the environment (Table 12.1).

Table 12.1 Common types of MMPs and their functional roles in food safety and nutrition.

Types of MMP	Source	Functional role in food safety	Functional role in nutrition
Enzymes	Marine bacteria, fungi, algae	Breakbone of foodborne pathogens Control food spoilage (e.g., amylases, cellulases)	Aid in digestion (e.g., proteases, lipases) Enhance nutrient bioavailability
Antibiotics	Marine bacteria, fungi	Combat foodborne pathogens (e.g., <i>Marinomycin</i> , <i>Inecalitol</i>) Control bacterial contamination in food products	Support gut health by reducing pathogenic bacteria in food
Bioactive peptides	Marine bacteria, fungi, algae	Antimicrobial and antifungal activity (e.g., <i>Lactoferrin</i> , <i>Bacteriocins</i>) Inhibit pathogenic growth in food	Improve immune function and reduce inflammation Antioxidant effects, lowering risk of chronic diseases
Polysaccharides	Marine algae, bacteria	Form biofilms that prevent microbial contamination Enhance shelf life by acting as natural preservatives	Provide prebiotic effects, enhancing gut health Aid in digestion and immune modulation
Pigments	Cyanobacteria, algae	Act as natural colorants with antioxidant properties Protect against UV-induced food spoilage	Protect against oxidative stress, supporting cellular health May have potential anticancer effects (e.g., <i>Astaxanthin</i>)
Fatty acids	Marine bacteria, algae	Control oxidative spoilage in seafood and other fats	Omega-3 fatty acids for cardiovascular and cognitive health Antiinflammatory effects
Chitin and chitosan	Marine crustaceans, fungi	Natural preservative, reducing microbial contamination Enhance food texture and stability	Promote healthy cholesterol levels and weight management Antioxidant and antiinflammatory properties

12.3 Benefits of marine microbial products in global food safety

Derived from microorganisms that flourish in marine conditions, MMPs are a fast-expanding topic of study with numerous implications for global food safety. Marine microorganisms like bacteria, fungi, cyanobacteria, and algae produce a wide range of bioactive compounds, including antimicrobials, enzymes, biopolymers, and bioactive peptides. These compounds are being used increasingly to improve food safety, quality, and sustainability in the global food system. Because of their special

attributes, MMPs are vital resources for addressing several food safety issues, including contamination, spoiling, and foodborne illnesses (Aransiola et al., 2024a; Santos et al., 2023). These advantages are especially noteworthy in an era of growing food trade, population development, and environmental issues.

Their capacity to act as natural antimicrobials, essential for reducing foodborne infections and prolonging the shelf life of perishable food items, is one of MMPs' most significant contributions to global food safety. Peptides, fatty acids, and bacteriocins are examples of marine-derived antimicrobial compounds with broad-spectrum activity against bacteria, fungi, and viruses that cause food deterioration and foodborne diseases (Rani et al., 2021). These bioactive substances stop the growth of dangerous microorganisms in food products by rupturing microbial cell membranes or interfering with cellular functions. Other MMPs, such as organic acids (like lactic acid) and fatty acids (like omega-3 fatty acids), function as efficient preservatives in addition to antimicrobial peptides. By incorporating these MMPs into food systems, producers can reduce the need for synthetic preservatives and enhance the safety and quality of food. These natural antimicrobials have been successfully used in various food products, including dairy, meat, seafood, and ready-to-eat meals, to extend shelf life and reduce the risk of contamination (Fig. 12.2).

Another essential advantage of MMPs for global food safety is the inclusion of bioactive substances from marine microorganisms into functional foods. These substances, including fatty acids, polysaccharides, and bioactive peptides, enhance food's nutritional content and positively impact health. Probiotics with marine origins, like strains of *Lactobacillus* and *Bifidobacterium*, have demonstrated potential in regulating the gut microbiota, enhancing digestion, and lowering inflammation. These probiotics can improve general health and lower gastrointestinal problems' prevalence when introduced to functional food products like yogurt, fermented drinks, and dietary supplements. Other bioactive substances obtained from marine microbes, like peptides, omega-3 fatty

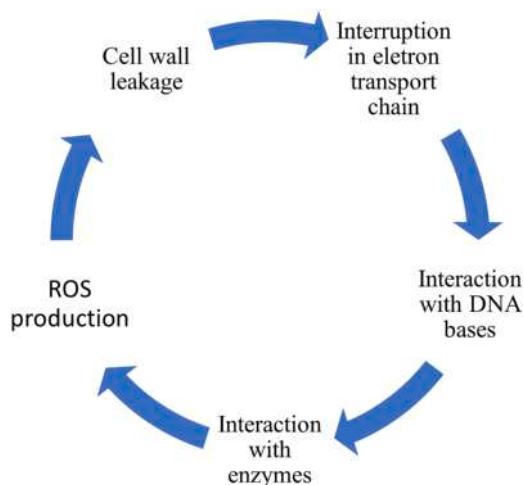


FIGURE 12.2

Mechanism of action of a marine-derived antimicrobial compound in inhibiting foodborne pathogens.

acids, and antioxidants, provide a variety of health advantages in addition to probiotics. The cardiovascular, cognitive, and antiinflammatory properties of omega-3 fatty acids, which are obtained from marine algae and fish, are widely recognized. Carotenoids and polyphenols from marine algae and cyanobacteria are examples of antioxidant-rich substances that aid in preventing oxidative stress, which has been connected to many chronic illnesses, such as cancer, heart disease, and neurodegenerative diseases (Ferdous & Yusof, 2021). In addition to increasing the nutritional profile of food products, adding these bioactive chemicals helps to prevent diet-related disorders and improve public health (Table 12.2).

The bioremediation of environmental pollutants, such as poisons that build up in the food chain, is another crucial function of marine microorganisms. Marine microbes have developed systems to break down various contaminants that might enter the marine environment and then build up seafood products, including pesticides, heavy metals, and petroleum hydrocarbons (Tufail et al., 2022). By lowering the concentrations of dangerous pollutants in the food chain, this procedure, known as bioremediation, can guarantee that marine foods like fish, shellfish, and algae are safe for human

Table 12.2 Examples of marine-derived probiotics and their health claims.		
Marine-derived probiotic (MMP)	Source	Health claims
<i>Lactobacillus plantarum</i>	Marine fish and seaweed	Improves gut health by balancing intestinal microbiota
<i>Bacillus subtilis</i>	Marine sediment, sea sponges	Enhances digestion, boosts immune response
<i>Enterococcus faecium</i>	Marine fish, crustaceans	Supports gastrointestinal health, reduces symptoms of IBS
<i>Streptococcus thermophilus</i>	Marine bacteria, seawater	Supports lactose digestion, promotes gut flora balance
<i>Lactobacillus rhamnosus</i>	Marine algae, sea plants	Improves intestinal health, reduces stress and inflammation
<i>Pediococcus acidilactici</i>	Marine fish, shellfish	Enhances immunity, lowers cholesterol levels
<i>Lactobacillus rhamnosus</i>	Marine algae, sea plants	Improves intestinal health, reduces stress and inflammation
<i>Bifidobacterium animalis</i>	Marine sources, fish	Enhances immune system function, improves gut microbiota diversity
<i>Vibrio spp.</i> (nonpathogenic)	Marine environments, fish	Promotes digestion, balances the gut microbiome
<i>Micrococcus luteus</i>	Marine animals, fish	Anti-inflammatory properties promote skin health
<i>Carnobacterium maltaromaticum</i>	Marine fish, crustaceans	Antioxidant effects boost gut immunity
MMP, marine microbial product.		

consumption. By utilizing these natural processes, marine microbes can contribute to the detoxification of contaminated aquatic environments and prevent the transfer of toxins into the human food chain. Furthermore, marine-derived enzymes and biosurfactants can clean up oil spills and other environmental contaminants, protecting both marine ecosystems and food safety.

The growing demand for seafood makes sustainable aquaculture essential to global food security. Environmental contamination, antibiotic resistance, and disease outbreaks are just a few of aquaculture's many difficulties. By offering natural alternatives to pharmaceutical treatments for disease control, MMPs present a viable answer to these problems. Probiotics, enzymes, and antimicrobials originating from marine sources are being utilized increasingly in aquaculture systems to improve fish health and stop the development of infections. To protect fish from harmful bacteria and to boost general health, these probiotics function by encouraging a healthy gut microbiota. In addition, marine-derived antibiotics and antifungal compounds are being explored as natural alternatives to traditional synthetic antibiotics, which are often overused in aquaculture and contribute to the development of antimicrobial resistance (Deng et al., 2022). Moreover, MMPs can help improve water quality in aquaculture systems. Enzymes produced by marine microorganisms can break down organic matter in water, reducing the build up of toxic substances such as ammonia and nitrites, which can harm fish. By incorporating MMPs into aquaculture practices, producers can reduce the environmental impact of fish farming, enhance fish health, and promote sustainability in the seafood industry (Fig. 3). (Table 12.3).

Additionally, MMPs help to improve food processing techniques and increase nutritional bioavailability. Marine microorganism-derived enzymes are being utilized more and more in food processing to boost the body's absorption of complex nutrients. These enzymes can be used to enhance the nutritional value and digestibility of food in processed food products, dietary supplements, and functional foods. MMPs can also improve how nutrients are extracted and used from diets derived from plants and animals. Additionally, by facilitating the fermentation process, these enzymes can enhance the nutritional value of fermented foods like kimchi, sauerkraut, and yogurt all of which are high in probiotics and bioactive substances. MMPs offer a wealth of benefits in the context of global food safety, ranging from natural antimicrobial properties to health-promoting bioactive compounds. By harnessing the power of marine microorganisms, industries can improve food preservation, enhance the nutritional value of foods, and promote sustainability in aquaculture and agriculture. The use of MMPs in food safety represents an innovative and environmentally friendly approach to addressing some of the most pressing challenges facing the global food system (Sridhar et al., 2023). As research continues to uncover new marine-derived compounds and their applications, MMPs will undoubtedly play an increasingly important role in ensuring the global food supply's safety, quality, and sustainability.

12.4 Potential threats and concerns

In recent years, there has been a lot of interest in marine-derived probiotics (MMPs) to improve food safety in aquaculture and food preservation. These microbes have enormous potential to enhance food quality, advance human health, and maintain the sustainability of aquaculture systems, but their employment also raises several serious issues (Diwan et al., 2022). These dangers include biotoxin

Table 12.3 Applications of MMPs in aquaculture and outcomes for food safety.

Application of MMPs in aquaculture	MMP type/source	Outcome for food safety
Disease prevention in fish farms	<i>Lactobacillus plantarum</i> , <i>Bacillus subtilis</i>	Reduces incidences of bacterial infections such as <i>Vibrio</i> and <i>Aeromonas</i>
Enhancing gut health in fish	<i>Pediococcus acidilactici</i> , <i>Lactobacillus rhamnosus</i>	Strengthens immune response, promotes healthy gut flora
Water quality improvement	<i>Bacillus subtilis</i> , <i>Carnobacterium maltaromaticum</i>	Improves water quality by controlling pathogenic microbes and reducing ammonia levels
Promoting growth and feed efficiency	<i>Enterococcus faecium</i> , <i>Streptococcus thermophilus</i>	Enhances feed digestion and nutrient absorption in farmed fish
Bio-preservation of seafood products	<i>Lactobacillus plantarum</i> , <i>Bifidobacterium animalis</i>	Extends shelf life of processed seafood products
Reduction of antibiotic usage	<i>Vibrio spp. (non-pathogenic)</i>	Reduces dependency on antibiotics, preventing antibiotic resistance
Reduction of stress and inflammation in fish	<i>Lactobacillus rhamnosus</i> , <i>Bifidobacterium animalis</i>	Modulates stress responses, improving health and survival rates
Improved biosecurity measures	<i>Micrococcus luteus</i> , <i>Carnobacterium maltaromaticum</i>	Enhances biosecurity by outcompeting harmful pathogens
Fermentation in aquaculture feeds	<i>Lactobacillus plantarum</i> , <i>Bacillus subtilis</i>	Improves nutritional content of feeds through fermentation

MMPs, marine microbial products.

contamination, antibiotic resistance, hazardous marine bacteria, regulatory loopholes, and ethical and environmental ramifications. These attempts to thoroughly examine these issues illuminate the possible dangers of applying MMPs in food safety.

The possibility of harmful marine microorganisms infiltrating the food supply chain is one of the main risks connected to using probiotics originating from marine sources. Numerous bacteria, some dangerous to humans, can be found in the maritime environment. Common in maritime environments, pathogenic bacteria, including *Salmonella*, *E. coli*, and *Vibrio*, can contaminate seafood items and result in foodborne diseases. There is a chance that some marine microbes may host pathogenic strains, even if some marine probiotics are advantageous and aid in the fight against dangerous germs. When MMPs are applied in aquaculture or food production systems, improper screening, handling, or accidental contamination may cause seafood products to include these hazardous infections, putting consumers' health at risk. Furthermore, certain marine microorganisms used as probiotics may become pathogenic under certain conditions, such as when the host fish is stressed or

immunocompromised (Mondal & Thomas, 2022). While probiotic strains are typically nonpathogenic in controlled environments, there is always a potential for shifts in microbial behavior that could lead to unintended health consequences. Therefore, thorough screening and quality control measures are essential to prevent the introduction of pathogenic microbes into food products.

The possibility of horizontal gene transfer (HGT) between marine microbes is a major worry when using marine probiotics. Genes that provide antimicrobial resistance (AMR) can be exchanged between species thanks to HGT. Because resistant diseases may spread resistance genes to other dangerous bacteria, making them challenging to treat with traditional antibiotics, this presents a serious risk to public health and food safety. The enormous diversity of species and genetic material found in marine microorganisms, particularly those originating from marine habitats, is recognized to have a significant potential for gene transfer (Rotter et al., 2021). The concern is that introducing probiotic strains into aquaculture environments could create an ecosystem where AMR genes are transferred to pathogenic bacteria, creating superbugs that are resistant to the antibiotics commonly used to treat foodborne illnesses. This would undermine efforts to control bacterial infections in aquaculture and human health and could lead to a significant public health crisis (Table 12.4).

The possibility of biotoxin contamination is a serious issue with marine probiotics. Toxins produced by some marine creatures, such as algae and some marine bacteria, can build up in seafood. When taken by humans, these toxins—which include domoic acid, saxitoxin, and brevetoxin—can cause serious foodborne illnesses and even death. Even though many marine probiotics are healthy and safe to eat, there is still a chance that some marine microbes could produce or shelter toxic biotoxins. If adequate screening and purifying procedures are not followed, MMPs may occasionally unintentionally release these poisons into the food supply. In aquaculture systems, where marine probiotics are commonly applied, there is a risk that marine organisms could become carriers of these harmful biotoxins, especially in areas prone to toxic algal blooms. This could compromise the safety of the seafood and lead to widespread health issues. Consequently, stringent monitoring for potential biotoxin contamination is essential to ensure that the use of MMPs does not inadvertently jeopardize food safety (Bergwerff & Debast, 2021). (Table 12.4)

Currently, there is little regulation governing the use of marine probiotics in food safety. The use of MMPs in aquaculture and fisheries is frequently not effectively controlled, even though numerous nations have developed criteria for using probiotics in food items. A significant obstacle to guaranteeing the safe use of marine-derived microorganisms in food systems is the absence of uniform laws and precise standards for their safety evaluation (Daniotti & Re, 2021). Adverse health effects could arise from the widespread use of untested or inadequately evaluated probiotic strains if suitable regulation is not in place. Without sufficient safety assessments, dangerous bacteria could be introduced into food systems due to inconsistent standards and an opaque certification process. This lack of oversight also makes it difficult for consumers to make informed decisions about seafood's safety and quality. The global nature of the seafood trade further complicates regulatory oversight, as different countries have varying standards for the approval of marine probiotics. A lack of international harmonization of these standards could result in inconsistent safety protocols, exposing consumers to increased contamination risks. Therefore, there is an urgent need for more robust regulatory frameworks that govern the use of MMPs in food production and aquaculture, as well as international cooperation to standardize these guidelines.

It is also necessary to consider the ethical and environmental ramifications of employing probiotics obtained from marine sources in food safety. Environmentally speaking, producing marine

Table 12.4 Major marine biotoxins, associated organisms, and health effects.

Biotoxin	Associated organisms	Health effects
Domoic Acid	<i>Pseudo-nitzschia</i> (diatoms)	Causes amnesic shellfish poisoning (ASP), leading to memory loss, seizures, and gastrointestinal distress.
Saxitoxin	<i>Alexandrium</i> , <i>Gymnodinium</i> , <i>Pyrodinium</i> (dinoflagellates)	Causes paralytic shellfish poisoning (PSP), resulting in paralysis, respiratory failure, and even death.
Brevetoxin	<i>Karenia brevis</i> (dinoflagellates)	Causes neurotoxic shellfish poisoning (NSP), leading to nausea, vomiting, diarrhea, and neurological symptoms.
Ciguatoxin	<i>Gambierdiscus</i> (dinoflagellates)	Causes ciguatera fish poisoning (CFP), with symptoms including nausea, vomiting, diarrhea, neurological effects, and cardiovascular symptoms.
Okadaic Acid	<i>Dinophysis</i> and <i>Prorocentrum</i> (dinoflagellates)	Causes diarrhetic shellfish poisoning (DSP), with symptoms such as diarrhea, nausea, and vomiting.
Pectenotoxin	<i>Dinophysis</i> (dinoflagellates)	Causes DSP-like symptoms, including diarrhea and vomiting.
Marine Tetrodotoxin	<i>Fugu</i> (pufferfish), <i>Spheroides</i> (marine organisms)	Causes paralysis, respiratory failure, and death, with no known antidote.
Azaspiracids	<i>Azadinium</i> (dinoflagellates)	Causes azaspiracid shellfish poisoning (AZP), leading to gastrointestinal distress and potentially liver damage.
Ciguatoxin	<i>Gambierdiscus</i> (dinoflagellates)	Causes ciguatera fish poisoning (CFP), resulting in nausea, vomiting, and neurological symptoms.
Tetrahydroisoquinoline	<i>Phytoplankton</i> (some marine algae)	Neurotoxic effects, including convulsions, vomiting, and gastrointestinal distress.
Maitotoxin	<i>Gambierdiscus toxicus</i> (dinoflagellates)	Severe food poisoning, including nausea, vomiting, diarrhea, respiratory distress, and cardiovascular collapse.

probiotics for aquaculture systems may lead to the overuse of marine environments and disturb native microbial communities. Furthermore, releasing significant amounts of marine probiotics into the atmosphere may have unforeseen ecological effects, such as changing natural microbial populations or upsetting local biodiversity. Concerns regarding the possibility of unintentional harm to marine ecosystems and wildlife are raised by the ethical use of probiotics produced from marine sources (Knowlton et al., 2021). If probiotics are not carefully selected and controlled, they could pose a risk to marine species that rely on the balance of microbial communities for survival. Furthermore, there is the ethical issue of whether it is appropriate to manipulate natural marine ecosystems for the benefit of human food production, potentially compromising the integrity of these environments for future

generations. While marine-derived probiotics offer promising solutions to improving food safety, their application has significant risks. The safety and sustainability of using MMPs in aquaculture and food production systems are seriously threatened by pathogenic marine microbes, antimicrobial resistance and HGT, biotoxin contamination, regulatory gaps, and ethical and environmental issues (Haldar et al., 2022; Varello & Cima, 2022). To address these concerns and ensure that the advantages of marine probiotics exceed any possible hazards, extensive study, strict safety regulations, and worldwide cooperation are needed. The potential of MMPs may be maximized while reducing the risks they pose to global food safety by creating efficient monitoring systems, guaranteeing stringent regulatory control, and taking the environment into account.

12.5 Case studies and real-world applications

MMPs have drawn much interest in food safety, especially in aquaculture, food preservation, and microbiome management (Jagannathan et al., 2021). These naturally occurring microorganisms, which include bacteria, fungi, and algae, are used because they may help reduce the spread of diseases, prolong the shelf life of food, and improve the health of aquatic and human species. Although applying MMPs has frequently produced encouraging outcomes, there have also been examples when unanticipated issues have jeopardized food safety initiatives. This compares the use of MMP in food safety procedures worldwide and examines noteworthy successes and failures.

One of the most notable successful applications of MMPs in food safety is using *Lactobacillus plantarum* (*L. plantarum*) in seafood preservation (Yap et al., 2021). In a case study conducted in South Korea, *L. plantarum* was used to enhance the shelf life and safety of marinated fish products. The bacterium was found to inhibit the growth of spoilage and pathogenic bacteria, including *E. coli* and *Vibrio* species, which are commonly associated with seafood contamination. The results demonstrated that MMPs could extend the shelf life of fish products by up to 50%, thereby reducing food waste and improving the safety of available seafood products. Another successful example is using *Bacillus subtilis* (*B. subtilis*) in aquaculture to promote fish health and reduce disease incidence. In a large-scale trial in Norway, *B. subtilis* was incorporated into the feed of farmed salmon. The probiotic strain was shown to enhance gut health, reduce the prevalence of gastrointestinal infections, and improve immune responses in the fish. As a result, using this MMP reduced the need for antibiotics and improved the overall safety of farmed salmon, ensuring that the seafood product met the stringent food safety regulations in place. Additionally, *Pediococcus acidilactici*, as a probiotic in aquaculture, has been successfully implemented in shrimp farming in Thailand. This marine-derived bacterium was used to balance the gut microbiota of farmed shrimp, enhancing their immune system and preventing bacterial infections caused by pathogens such as *Vibrio harveyi* (Du et al., 2022). This approach has resulted in healthier shrimp populations, reducing the need for antibiotics and chemicals and ensuring safer shrimp products for the global market.

While MMPs have shown promise, there have also been notable failures in applying marine-derived probiotics that have led to food safety concerns (Dashputre et al., 2023). One such case

occurred in 2016 when an outbreak of *Vibrio parahaemolyticus* contamination in raw oysters in the United States was linked to improper handling of probiotics in the aquaculture industry. Despite using probiotics to enhance water quality and improve fish health, insufficient control measures allowed pathogenic bacteria to proliferate, leading to foodborne illness outbreaks. This case highlighted the importance of strict monitoring and quality control procedures, even when probiotics are used to maintain food safety. Another failure occurred in using marine-derived Ciguatera toxin in the tropical fish trade. Ciguatera toxins are neurotoxins produced by marine dinoflagellates, such as *Gambierdiscus toxicus*. These toxins accumulate in reef fish, particularly herbivores, and can cause ciguatera fish poisoning in humans when consumed. Despite awareness of the risks associated with ciguatera, there have been several cases of foodborne illness in regions where monitoring of these toxins was insufficient. One such incident in the Caribbean in 2017 led to multiple cases of food poisoning after consumers ate contaminated reef fish. This failure underlined the need for proper monitoring and detection methods to prevent the inclusion of toxic fish in the food supply chain, emphasizing the importance of comprehensive safety measures for marine organisms.

The use of MMPs in food safety practices varies widely across different regions, reflecting disparities in technology, regulation, and public awareness. In countries like Norway and Japan, with well-established aquaculture industries, marine probiotics and other MMPs have been more successfully integrated into food safety practices. These nations have stringent regulatory frameworks for aquaculture, ensuring that MMPs are applied with robust safety protocols in place. For instance, Norway has successfully used *Lactobacillus* strains to reduce microbial contamination in farmed salmon. Japan has effectively used marine-derived probiotics to enhance fish products' shelf life and quality. In contrast, developing nations where aquaculture is rapidly growing, such as Vietnam and Thailand, face challenges in implementing MMP-based food safety practices. While probiotics like *Pediococcus acidilactici* have been successfully used in shrimp farming, these countries often struggle with inconsistent quality control, lack of infrastructure for monitoring biotoxins, and limited regulatory oversight (Goh et al., 2023). In these regions, the adoption of MMPs is promising, but their potential is undermined by insufficient resources for effective implementation, resulting in occasional food safety failures. A comparative study between European Union (EU) countries and China reveals further differences. In the EU, regulatory bodies such as the European Food Safety Authority (EFSA) closely monitor the use of marine probiotics and the presence of biotoxins in seafood, creating a relatively safe environment for applying MMPs. Conversely, in China, rapid industrialization of aquaculture has led to the overuse of antibiotics and less attention to probiotics' role in food safety. Though some MMPs are used, the lack of stringent regulation and monitoring mechanisms raises concerns about the potential risks of aquaculture products entering the global market.

Using MMPs in food safety has promising benefits and notable risks. While successful case studies demonstrate their role in extending shelf life, enhancing food quality, and promoting health in aquaculture, there are also cautionary tales of foodborne illness outbreaks and failures in safety protocols. Global comparisons indicate that the success of MMPs in food safety is highly dependent on regulatory frameworks, monitoring infrastructure, and technological advancements

(Sharma et al., 2021). Integrating MMPs into global food safety practices will require stronger international collaboration, standardized safety protocols, and improved monitoring systems to ensure that the benefits outweigh the risks, leading to a safer and more sustainable food system.

12.6 Future guidelines and recommendations

There is no denying the potential advantages of MMPs for aquaculture, food preservation, and food safety. But when MMPs are used more frequently, several issues need to be resolved to ensure their use doesn't endanger the environment, human health, or the sustainability of marine ecosystems. Creating thorough guidelines and suggestions is essential to maximizing the advantages of MMPs while reducing potential risks. This highlights important areas for future attention, such as public awareness and education, surveillance and monitoring systems, regulatory frameworks, sustainable harvesting and biodiversity conservation, and research and development. To guarantee that MMPs can be utilized in food safety applications safely and efficiently, research and development (R&D) is essential. To achieve this, more funding for scientific research is required to find novel marine-derived microbes with probiotic potential and to comprehend their implications for food safety and human health. The main research areas should be the safety and effectiveness of various marine microbial strains, their capacity to suppress foodborne pathogens, and their effects on the microbiomes of farmed creatures and consumers. Moreover, R&D must explore the interaction between MMPs and other microorganisms in aquaculture environments, including their ability to balance microbial ecosystems and reduce the need for chemical treatments or antibiotics. Additionally, studies on the mechanisms of biotoxin production and their presence in marine organisms should be prioritized to prevent contamination in the food supply. Developing advanced genetic tools and analytical techniques, such as high-throughput sequencing and metabolomics, will also aid in understanding the complex interactions between MMPs, pathogens, and the environment.

Creating strong regulatory frameworks is crucial as MMPs become more and more common in international food safety procedures. Precise and uniform regulations should be implemented to guarantee the safe and controlled use of MMPs. Regulatory agencies must establish standards for determining the safety of marine probiotics for human consumption and rules for their selection, manufacture, and application in aquaculture. The regulatory supervision of MMPs is still lacking in many areas, and various national regulations could result in unequal seafood trade practices. To solve this, global norms for using MMP must be established through international cooperation through agencies like the Codex Alimentarius Commission. These recommendations should cover protocols for safety testing, traceability systems, and acceptable MMP application levels in food products. Regulatory frameworks must also address the potential of biotoxin contamination in seafood to protect consumers by establishing acceptable level limits and ensuring the correct detection techniques are in place.

Efficient surveillance and monitoring systems are essential to guarantee the safe use of MMPs and stop outbreaks of foodborne illness. To identify dangerous microbial contamination, such as

pathogenic bacteria and biotoxins, these systems should include routine monitoring of aquaculture environments and sporadic testing of seafood products. Rapid diagnostic tools and biosensors are examples of real-time monitoring technology that can give quick information on the microbial levels in seafood and water, enabling prompt intervention in the event of contamination. Furthermore, surveillance should focus on infections and track any possible gene transfer of antimicrobial resistance (AMR) between pathogenic bacteria and marine probiotics. Monitoring systems must be linked to regulatory authorities and food safety agencies that can quickly respond to potential risks and enforce corrective actions when necessary to ensure food safety. By establishing a global network of surveillance systems, countries can share data and collaborate in tracking emerging risks related to MMPs and food safety.

Future guidelines must prioritize sustainable harvesting practices, ensuring that the collection of marine microbes does not harm marine ecosystems, such as by enacting regulations to regulate the extraction of microorganisms from vulnerable marine areas and promoting the use of cultured microorganisms instead of wild collection. Because MMPs are derived from marine environments, their use raises concerns about the sustainability of marine ecosystems. Harvesting marine microorganisms for use in food safety applications should be done in a way that minimizes environmental impact and protects marine biodiversity. Overexploitation of marine resources for MMP production can result in habitat destruction, depletion of key species, and marine food web disruptions. Furthermore, marine protected areas (MPAs) and ecosystem-based management techniques should be used to maintain marine biodiversity, and marine-based MMP production should be incorporated into more significant conservation initiatives. Additionally, the concepts of ecosystem health should be carefully balanced with the use of marine bacteria in aquaculture. Before implementing any MMP-based interventions into aquaculture or the food supply chain, thorough environmental studies must be conducted. Public awareness and education are crucial to successfully integrating MMPs into global food safety practices. Consumers need to understand the benefits and risks of MMP-based food safety solutions and how these products contribute to healthier seafood and safer food systems. Public education campaigns can help raise awareness about the role of probiotics in food production, dispel misconceptions about marine-derived products, and encourage responsible seafood consumption. Additionally, education programs targeting aquaculture professionals, food safety authorities, and researchers are essential for fostering a deeper understanding of the scientific and regulatory aspects of MMPs. Training programs should emphasize the importance of safe practices in using probiotics, the need for rigorous monitoring, and the environmental impact of marine microbial harvesting. Promoting global collaboration and knowledge-sharing will ensure that MMPs are used effectively while minimizing risks to public health, the environment, and the economy. The future of MMPs in food safety depends on the continued advancement of research and the establishment of clear regulatory frameworks, robust monitoring systems, and sustainable harvesting practices. To ensure the safe and effective use of MMPs, investing in research that expands our understanding of marine microorganisms and their interactions with pathogens and ecosystems is essential. Regulatory frameworks must be strengthened, and global surveillance systems must be established to monitor the safety of seafood products. Sustainable harvesting and biodiversity conservation must remain central to MMP applications to protect marine environments. Lastly, public awareness and education are key to building trust in these products and ensuring their responsible use. By addressing these critical areas, the potential of MMPs in improving global food safety can be realized while minimizing potential risks ([Table 12.5](#)).

Table 12.5 Summary of future guidelines and best practices for safe MMP integration in food systems.	
Area	Guidelines and best practices
Research and development	Invest in continuous scientific research to identify new marine-derived microorganisms with beneficial properties. Focus on understanding marine microbes' safety, efficacy, and mechanisms in food safety applications. Develop advanced genetic tools and detection methods to monitor the impact of MMPs on microbial ecosystems and food safety.
Regulatory frameworks	Establish clear, standardized global regulations for MMP use in food safety, including production, testing, and application guidelines in aquaculture. Implement safety protocols to assess the impact of marine probiotics and biotoxins on human health and the environment. Encourage international cooperation (e.g., Codex Alimentarius) to harmonize safety standards for MMPs across regions and industries.
Surveillance and monitoring	Implement real-time monitoring systems for MMP application, focusing on pathogen detection, antimicrobial resistance, and biotoxin levels in seafood products. Develop robust, globally coordinated food safety surveillance networks to track MMPs in food systems and identify emerging risks.
Sustainable harvesting and biodiversity	Ensure sustainable practices in collecting marine microorganisms by promoting cultured microbes over the wild collection to prevent ecosystem disruption. Protect marine biodiversity by adhering to ecosystem-based management practices and marine-protected areas (MPAs). Incorporate biodiversity conservation measures in the harvesting guidelines to safeguard ocean health.
Public awareness and education	Launch public education campaigns to inform consumers about the benefits and potential risks of MMPs in food safety, focusing on responsible seafood consumption. Educate aquaculture professionals, researchers, and food safety authorities about best practices in MMP use, including monitoring, regulations, and sustainable harvesting. Promote transparency in MMP use in the food supply chain to increase consumer trust and ensure the responsible use of marine resources.

12.7 Conclusion

A promising new area in food safety is represented by MMPs, which provide ways to improve seafood quality, support aquaculture health, and lessen dependency on chemical treatments.

Throughout this conversation, we have emphasized the advantages of MMPs, such as their capacity to suppress dangerous infections, extend food storage, and promote sustainable aquaculture methods. However, these benefits come with certain drawbacks, such as potential pathogenic contamination, antibiotic resistance (AMR), and the buildup of biotoxins in seafood. There are also associated risks such as ecological impact, ethical concerns, or unintended consequences. The necessity of a balanced approach to using marine resources is underlined as a crucial aspect. Sustainable harvesting methods, strict monitoring, and preserving marine biodiversity are crucial to stopping the overexploitation of marine ecosystems and ensuring that using MMPs does not upset the delicate balance of marine environments. Furthermore, to oversee the safe implementation of MMPs, efficient regulatory frameworks that fill the gaps in food safety regulations, quality control, and surveillance must be implemented internationally. To guarantee the judicious and equitable application of MMPs in the future, scientific inquiry must persist in enhancing comprehension of the efficacy and safety of marine microorganisms. MMPs can facilitate the establishment of safer, more resilient food systems that benefit consumers by promoting international collaboration, standardized regulations, and sustainable practices. Public awareness and education will ensure that MMPs are adopted responsibly, enhancing comprehension of their advantages and potential hazards. Through meticulous planning and administration, MMPs possess the capacity to transform food safety while safeguarding the health of our oceans for posterity.

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Bacteriocins from the marine environment: production, detection and applications

Farida Mohammed Ado¹, Abdulkabir Danlami Muhammad¹, Bolaji Oluwatosin Akanbi¹,
Roseline Rumi Ideh², Salamatu S. Machunga-Mambula¹, Sesan Abiodun Aransiola^{3,4} and
Naga Raju Maddela⁵

¹*Department Of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria,*

²*Food and Industrial Biotechnology Department, National Biotechnology Research and Development Agency, Abuja, Nigeria,*

³*Centre for Artificial Intelligence & Multidisciplinary Innovation Studies, College of Accounting Sciences, University of South Africa, Pretoria, South Africa,*

⁴*Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria,*

⁵*Departamento de Ciencias Biológicas, Facultad la Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador*

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13.1 Introduction

Bacteria produce a variety of secondary metabolites during growth, some of which possess antimicrobial properties. Bacteriocins are short polypeptides or proteins that are mostly produced at the ribosome and exhibit antibacterial properties, usually against strains that are linked to the producer. Bacteriocins usually exhibit antibacterial activity against closely related strain while some have broad spectrum activity. However, the bacteria responsible for producing these bacteriocins remain unaffected, as they typically generate self-protective immunity proteins that shield them against the detrimental effects of self-bacteriocins (Verma et al., 2022). The discovery of bacteriocins dates back nearly a century, and subsequent research have revealed their widespread presence across most eubacterial families and numerous actinomycete species (Hammami et al., 2013). Despite being initially thought to be universally produced, bacteriocins have actually been found to be produced by some, but not all, microorganisms, including certain members of the Archaea domain. (Riley & Wertz, 2002). The bulk of documented bacteriocins were gotten from Gram-positive bacteria with just a limited number identified in Gram-negative bacteria. A group of Gram-positive bacteria known as lactic acid bacteria (LAB) have attracted a lot of interest due to their production of bacteriocins, which hold considerable promise (Lopetuso et al., 2019), due to their probiotic properties, food safety and preservative ability, Generally Regarded as Safe (GRAS) status, natural origin, biotechnological application, and cost effectiveness. Studies have demonstrated the efficacy of bacteriocins in inhibiting an appreciable number of food spoilage bacteria as well as the pathogenic ones, across diverse food systems such as dairy products, meats and vegetables (Gálvez et al., 2011). Furthermore, numerous bacteriocins have proven to be therapeutic, with demonstrated potential effectiveness against a wide range of human and animal infections (Campion et al., 2013; Aransiola et al., 2025).

Like other bioactive compounds produced by microorganisms, bacteriocins have distinct characteristics that set them apart from other biologically synthesized molecules. Most bacteriocins are tasteless, colorless, and odorless, making them more acceptable in various applications (Verma et al., 2022).

Bacteriocins are ribosomally synthesized by their producer strains to gain a competitive advantage in their ecological niche (Perez et al., 2018). While certain bacterial species generate bioactive peptides nonribosomally, bioactive peptides synthesized at the ribosome and afterward modified (RiPPs) have attracted greater interest due to their benefits, such as enhanced scalability in production and increased amenability to bioengineering (Perez et al., 2014).

Most bacteriocins are small, cationic molecules with hydrophobic, or amphiphilic properties, exhibiting a range of inhibitory activities against closely related and nonrelated species (Eijsink et al., 2002).

Notably, bacteriocins tend to display maximum activity against organisms within the same species. Bacteriocins are sensitive to degradation by proteolytic enzymes, which can inactivate their antimicrobial properties. For example, proteolytic enzymes like chymotrypsin, proteinase K, trypsin, and pepsin have been shown to inactivate the antimicrobial activity of *L. murinus* AU06 bacteriocin (Elayaraja et al., 2014). On the other hand, enzymes that are not involved in proteolysis, including catalase and α -amylase, have no impact on the bacteriocin's ability to inhibit microbial growth. Bacteriocins are typically heat-stable, with some, like those from LAB, retaining their antibacterial activity after 15 minutes exposure to a temperature of 121°C (Campos et al., 2006). However, certain bacteriocins, such as colicins, are heat-sensitive. The heat sensitivity of bacteriocins depends on their type. Additionally, storage at 4°C for three months or in a frozen state at -20°C has been shown to preserve the antibacterial activity of bacteriocins (Fatima & Mebrouk, 2013).

Bacteriocins exhibit antimicrobial activity, including the inactivation of bacteria. For example, Enterocin AS-48 has been shown to inactivate cells of *L. monocytogenes* on surfaces of fruit and slices, as well as entirely or incompletely inactivate *S. aureus* in various fruit and vegetable sauces (Montalban-Lopez et al., 2011). Additionally, some bacteriocins possess sporicidal properties. Bovicin HC5, for instance, is effective against heat-tolerant spores of *Geobacillus stearothermophilus* in coconut milk and *Alicyclobacillus acidoterrestris* in juices containing acid (Ovchinnikov et al., 2017). Bacteriostatic properties of bacteriocins produced by LAB have also been reported. Research has shown that the cell-free supernatant of 48 LAB isolates from various sources were able to inhibit the growth of one or more indicator strains, including *E. coli* ATCC 25922, *Staphylococcus aureus* ATCC 43306, *Enterococcus faecalis* ATCC 10541, and *Bacillus subtilis* NCTC 8236 (Elyass, 2010).

A significant number of bacteriocins exhibit bactericidal activity. For example, the probiotic strain *Lactobacillus salivarius* UCC118, which is of human origin, produces the bacteriocin Abp118, which has been shown to be effective in destroying *Listeria monocytogenes* cells (Sun et al., 2018). Certain bacteriocins have shown potential in targeting cancer cells. Research has demonstrated that cytotoxic bacteriocins can rapidly depolarize and increase the permeability of sensitive eukaryotic cells, leading to cell death (Zimina et al., 2020). Additionally, various colicins, including A, E1, U, and E3, have been found to trigger pro-apoptotic and cytotoxic effects on a range of cultured cancer cells, including colon cancer (HT-29), leiomyosarcoma (SKUT-1), breast cancer (BT549, BT474, MDAMB-231, T47D and SKBR3), osteosarcoma (HOS) and fibrosarcoma (HS913T) (Chumchalová & Smarda, 2003).

Bacteriocins function by binding to and damaging cells that possess particular surface receptors (Sugrue et al., 2020). These antimicrobial peptides have been found to employ a range of mechanisms, including increasing cytoplasmic membrane permeability through pore formation, degrading peptidoglycan precursors to inhibit cell wall biosynthesis, exhibiting activity against phosphatase, RNA (often targeting specific tRNAs and 16 S rRNA), DNA, as well as interfering with various metabolic pathways (Hols et al., 2019; Cascales et al., 2007). The diverse chemical structures of bacteriocins enable them to affect multiple vital cellular functions such as gene expression, protein synthesis, DNA replication, and the construction of the cell wall. However, majority of bacteriocins primary mode of action typically involves creating channels or pores in the cell membrane, leading to a loss of membrane potential (Bindiya & Bhat, 2016). The interaction between bacteriocin and target cell is thought to occur in two phases. The initial phase, which can be reversed, involves the bacteriocin attachment to cell surface through receptors. If the bacteriocin is removed at this point, the cell seems to stay intact without any lasting physiological harm. The subsequent phase causes

irreversible pathological alterations due to targeted biochemical damage to the cell (Bindiya & Bhat, 2016).

13.2 Bacteriocins-producing bacteria in the marine environment

The marine environment is home to diverse microorganisms including bacteria that produce bacteriocins. These bacteria can be found in various marine ecosystems such as the coral reefs, seawater, and marine sediments. The bacteriocin-producing bacteria help maintain the balance of marine ecosystems and also help to control bacterial population (Aransiola et al., 2024a).

13.2.1 Benefits of bacteriocins in the marine environment

Novelty: Marine bacteriocins can exhibit novel structures and mechanisms of action thereby offering new opportunities for antimicrobial development.

Antimicrobial potential: Bacteriocins extracted from organisms isolated from marine environment have shown great promise in inhibiting the growth of various pathogens, including antibiotic-resistant bacteria.

Activity against specific pathogens: Marine bacteriocins have targeted activity against specific pathogens, reducing the risk of disrupting the normal microbiome.

Diversity: The marine environment is a very rich source of diverse bacteriocin-producing bacteria, increasing the possibility of discovering new compounds.

13.2.2 Types of bacteriocins in the marine environment

Depending on the type of organism that produces them, bacteriocins are categorized into three main types: those from Gram-negative bacteria, those from Gram-positive bacteria, and archaeocins. The antibacterial peptide products of marine bacteria are grouped into three classes including class I, II and III. Bacteriocin production in marine environments is attributed to a variety of microbial genera, including *Pseudomonas*, *Bacillus*, *Photobacterium*, *Lactococcus*, *Streptomyces*, *Serratia*, *Carnobacterium*, *Enterococcus*, *Aeromonas*, *Pediococcus*, *Stenotrophomonas*, *Burkholderia*, and *Pseudoalteromonas*, along with certain archaeal species (Zimina et al., 2020).

13.2.3 Gram-positive antibacterial peptides

Three different groups of antibacterial peptides (bacteriocins) produced by bacteria with thick peptidoglycan have been identified: Class I bacteriocins (lantibiotics): characterized by modifications after translation, Class II (nonlantibiotics): which are unmodified bacteriocins and class III bacteriocins (high molecular weight bacteriocins). The classification of bacteriocins is according to their genetic traits, molecular weight and primary structures, as well as any post-translational modifications they may undergo (Mokoena, 2017).

13.2.3.1 Class I bacteriocins (lantibiotics)

Class I bacteriocins (lantibiotics) are antibacterial peptides having low molecular mass (less than 5 kDa) and are post-translationally modified with the amino acids, lanthionine or methyllanthionine, which contribute to their stability and antibacterial effect (Cotter et al., 2005). A distinctive feature of these peptides is the presence of β -methyllanthionine or lanthionine afterward translation. (Ng et al., 2020). The mechanism of action of these peptides involves attachment to lipid II, a crucial molecule for cell wall synthesis in bacteria, ultimately leading to death of cell. Lantibiotics are mainly produced by bacteria with thick peptidoglycan cell wall together with some lactic acid bacteria species (*Lactococcus lactis*, *Lactobacillus* sp, *Streptococcus* sp), some *Bacillus* sp (*B. subtilis*, *B. Licheniformis*) and some *Staphylococcus* sp such as *S. aureus*. An example of a lantibiotic found in marine environments is subtilin, produced by *Bacillus subtilis* which possess potent antibacterial effect against Gram-positive bacteria (Desriac et al., 2010). Nisin is predominantly found in terrestrial bacteria, but similar peptides have been discovered in marine bacteria, including *Lactococcus lactis* (Sahl & Bierbaum, 2008). Nisin is the most studied and established Lantibiotics (LeLay et al., 2016).

13.2.3.2 Class II bacteriocins (nonlantibiotics)

Bacteriocins grouped as class II are characterized by their small molecular weight (under 10 kDa) and resistance to heat. They exert their inhibitory and bactericidal effects by damaging the membrane structure of target bacteria. (Cotter et al., 2005). They are not modified afterward translation and are hydrophobic peptides. These bacteriocins are additionally categorized into sub-class a, b, and c.

Antibacterial peptides of the sub-class IIa bacteriocins, also known as pediocin-like bacteriocins, are characterized by their potent activity against *Listeria* species, which they achieve by forming pores in the bacterial membranes. (Yang et al., 2014). Piscicocin CS526 produced by *Carnobacterium piscicola* CS526 and Enterocin P produced by some marine *Enterococcus* species are some of the sub-class IIa antibacterial peptides obtained from gram positive marine bacteria.

Bacteriocins of the sub-class IIb are antibacterial peptides that require the combined action of a pair of complementary peptides to exhibit antibacterial properties, of which enterocin X and plantaricin A are good examples (Hu et al., 2010). Plantaricin A and Enterocin X are typically produced by Gram-positive terrestrial bacteria, but some marine-derived strains of *Lactobacillus* and *Enterococcus* species have also been found to produce similar Class IIb bacteriocins. The genes that code for the two distinct peptides are genetically linked and located within the same operon. (Diep et al., 2009).

Sub-class IIc bacteriocins also called circular bacteriocins are antibacterial peptides having a head-to-tail cyclized structure, making them highly stable in extreme marine conditions. Examples include Enterocin AS-48, produced by marine *Enterococcus* species (Abriouel et al., 2011). Enterocin AS-48 is an antibacterial protein synthesized by the Gram-positive bacterium *Enterococcus faecalis*, commonly found in terrestrial environments, fermented foods, or the gastrointestinal tract of animals. *Enterococcus* species inhabit a range of environments, including marine environments, but Enterocin AS-48 is not specifically attributed to marine bacterial production.

13.2.3.3 Class III bacteriocins

Antibacterial proteins grouped into Class III are characterized by their big size (greater than 30 kDa) and heat-lability, with helveticin J being a notable example (Parada et al., 2007). Antibacterial

proteins of the class III category typically target cells of Gram-negative bacteria and function similarly to lysozymes (Yang et al., 2014). This class includes helveticin J, Lacticin Q and enterocin A. Lacticin Q isolated from *Lactobacillus sakei*, is one of the antibacterial proteins synthesized by a Gram-positive bacterium that can be found in the marine environments.

13.2.4 Gram-negative antibacterial peptides

Four types of antibacterial peptides (bacteriocins) are synthesized by Gram-negative bacteria: colicins, colicin-like bacteriocins, tailocins, and microcins. (Ge et al., 2019). In the marine environment, all the three types of bacteriocins exist except colicins produced by *E. coli*, since *E. coli* are not typically found in the marine environment. Gram negative bacteriocins are sub-categorized into three major classes, class I, II, and III.

13.2.4.1 Colicins

The most researched class of gram-negative bacteriocins is represented by colicins. Certain *E. coli* strains produce large molecular mass (≥ 30 kDa) protein molecules called colidins, which have antibacterial properties against other *Enterobacteriaceae* and other *E. coli* strains. (Cascales et al., 2007). Colicins belong to the class III bacteriocins. The majority of *E. coli* strains with a single colicinogenic plasmid produce them (Zimina et al., 2020). Two types of colicinogenic plasmids have been identified in *E. coli* strains that produce colicins, the Type I colicinogenic plasmids which are small size plasmids with large frequency per cell (e.g., pColE1, 6.6 Kb) and the Type II which are large size plasmids with a frequency of one per cell (e.g., pColH, 94 Kb).

Colicins are not produced in bacterial cells under normal conditions, but a limited number of colicin molecules are constantly present in the cell (Marković et al., 2022). However, studies are yet to reveal the production of colicins in the marine environment. Colicin synthesis is carried out under stress and is fatal to the producing cells, due to co-expression with lysis protein (Alvarez-Sieiro et al., 2016). Colicins exert its effect against target cell by firstly attaching to a complementary receptor on the surface of cell, after which it move into the cell and finally destroy the cell. Colicins eliminate target cells using three main strategies: forming voltage-dependent channels in the inner membrane of the target bacteria, acting as nucleases in the cytoplasm (such as DNase, 16 S rRNase, and tRNase), or blocking the synthesis of peptidoglycan (Barreteau et al., 2010).

13.2.4.2 Colicin-like bacteriocins

Bacteriocins synthesized by Gram-negative bacteria other than *E. coli*, which share similar structural and functional characteristics with colicin, are termed colicin-like bacteriocins (Tracanna et al., 2017). Similar to colicins, their antimicrobial activity can be due to pore formation or nuclease activity (Michel-Briand & Baysse, 2002). Colicin-like bacteriocins are categorized as Class III bacteriocins because of their structural and functional similarities to colicins. Colicin-like antibacterial peptides include Colicins E2, E3, A, and B.

13.2.4.3 Tailocins (phage tail-like bacteriocins)

Tailocins are massive protein complexes (ranging from 2×10^6 to 1×10^7 Da) composed of around eight to fourteen different polypeptide subunits, and they share structural similarities with various

bacteriophage tails (Scholl, 2017). These structures are encoded within bacterial genomes by gene clusters exceeding 40 kilobase pairs (Zimina et al., 2020). Within these regions, genes are typically found that code for structural proteins as well as assembly-related proteins or chaperones, which assist in the proper construction of the tailocin (Scholl, 2017). This type of bacteriocin is classified into two categories—R and F types. R-type tailocins are evolutionarily linked to the tails of Myoviridae phages and feature a long tube encased in a sheath, ending in a complex baseplate equipped with receptor-binding proteins (Sun et al., 2018). F-type bacteriocins, which are part of the tails of phages in the Siphoviridae family, lack a shell (Zimina et al., 2020). The best-known bacteriocins in this group are R-pyocins and F-pyocins, which are produced by *Pseudomonas aeruginosa*. Their mode of action involves disrupting the membrane potential, resulting in the formation of pores in the bacterial membrane (Simons et al., 2020). S-pyocin produced by *P. aeruginosa* in the marine environment is a tailocin that inhibits the growth of other *Pseudomonas* sp., thereby giving the producing bacteria a competitive advantage in their ecological niche.

13.2.4.4 Microcins

Microcins are antibacterial peptide compounds synthesized by *Enterobacteriaceae*, mainly strains of *E. coli* under stress conditions and in most cases undergo diverse post-translational modifications. They are peptides smaller than 10 kDa and are also strongly resistant to high temperatures, as well as proteases, and extreme pH levels (Duquesne et al., 2007). Two classes of microcins exist and are defined by differences in molecular mass, disulfide bonding, and possession of modifications after translation. Class I microcins (e.g., microcin J25, B17, and C) are peptides encoded in plasmid usually less than 5 kDa and have post-translational modifications attached to their backbone structure (Duquesne et al., 2007). Microcins of the class II group are characterized by higher molecular mass of 5–10 kDa and are sub-grouped into a and b. Class IIa microcins are plasmid-encoded peptides that do not undergo modifications after translation, they include microcins N, L, and V, that possess varying numbers of disulfide bonds. Class IIb, on the other hand, comprises chromosome-encoded linear microcins, such as microcins E492, M, and H47, which may possess modification in the C-terminal (Rebuffat, 2012). Marine bacteria produce microcins including Microcin MccC7-like compounds (found in marine *Enterobacter* species) and microcin E492-like compounds (identified in marine *Klebsiella* species).

13.3 Group of bacteriocins isolated from marine animals and environment

13.3.1 *Aeromonas* sp. bacteriocin-like inhibitory substance (BLIS)

According to a study by Messi et al. (2003), all strains of *Aeromonas hydrophila* tested, produced antibacterial peptides (Bacteriocin-like Inhibitory Substance) inhibited the growth of multiple strains of *Staphylococcus aureus*, as well as *Streptococcus agalactiae*, *Listeria* species and *Lactobacillus* sp. However, the BLIS produced by *A. hydrophila* failed to inhibit the growth of Gram-negative strains tested alongside closely related species such as *A. caviae* ATCC 13137 and *Aeromonas sobria* ATCC 43979, indicating a narrow range of activity that spares closely related species.

13.3.2 *Vibrio* sp. BLIS

Species of *Vibrio* are widespread in marine ecosystem and are frequently obtained from shellfish and fish (Morris, 2003). While certain species can cause disease in marine organisms, others seem to have no significant impact. The ability of *Vibrio* species to survive and thrive in marine environments has led researchers to investigate their ability to produce antibacterial peptides or protein. A study by Zai et al. (2009), identify 50 *Vibrio* strains obtained from the gut and gills region of infected and healthy giant sea catfish. Several *Vibrio* species have been found to produce BLIS, including *V. harveyi*, *V. mediterranei*, *V. fluvialis*, and *V. vulnificus* (Table 13.1).

13.3.3 BLIS from marine *Pseudoalteromonas* sp

A strain of *Pseudoalteromonas* sp., designated as X-153, was isolated from various substrates in the littoral zone of Brittany. The purified active protein P-153, determined to have a molecular mass of 280 kDa, exhibited antibacterial effects against various bacterial groups. These included firmicutes (such as *Staphylococcus epidermidis*, *P. granulosum*, and *Propionibacterium acnes*) and gracilicutes (Particularly *ichthyopathogenic Vibrio*) (Ng et al., 2015). Notably, the broad-spectrum property of the antibacterial peptides produced by *Pseudoalteromonas* sp. deviates from the traditional definition of a bacteriocin, which typically targets closely related species. A summary of some marine associated bacteriocins and their producing species/strains is presented in the accompanying Table.

13.4 Bacteriocins from lactic acid bacteria

Research has identified and characterized two specific bacteriocins, divercins and piscicocins, which are produced by *Carnobacterium* sp. isolated from the intestines of fish. These bacteriocins are classified as class IIa bacteriocins, a subgroup of bacteriocins produced by LAB. The gut microbiota of healthy fish typically consists of LAB from the genera *Streptococcus*, *Lactobacillus*, *Carnobacterium*, and *Leuconostoc*. A summary of some bacteriocins produced by LAB isolated from marine environments is presented in Table 13.2.

13.4.1 Archaeocins

Archaeocins are bacteriocin-like antimicrobial proteins or peptides produced by archaea. Currently, there are two recognized types of archaeocins: halocins, which are produced by *Halobacteriales* (Euryarchaeota) archaea and sulfolobocins, which are produced by *Sulfolobales* (Crenarchaeota) archaea (Zou et al., 2018).

13.4.2 Halocins

Halocins are a type of archaeocin produced by halophilic archaea, specifically those belonging to the class Halobacteria, which inhabit extremely salty environments. These antimicrobial compounds vary widely in size, ranging from small peptides like halocin S8 (~3 kDa) to larger proteins such as halocin

Table 13.1 Antibacterial peptides produced by bacteria isolated from marine animal and surrounding.					
Antibacterial peptides	Producerspecies/strain	Species/strains inactivated	Source of producer	Molecularmass (kDa)	References
Harveyicin SY	<i>Vibrioharveyi</i> (Beneckea harveyi SY)	<i>V. harveyi</i>	Galveston Island region	24	McCall and Sizemore (1979)
Vibriocin AVP10	<i>Listonellaanguillarum</i> AVP10	<i>Escherichia coli Listonella anguillarum</i> AVS9	Healthy and infected catfishes	?	Zai et al. (2009)
BC1	<i>Vibrio vulnificus</i>	<i>V. parahaemolyticus</i>	Water samples from Wilmington	75	Shehane and Sizemore (2002)
BLIS	<i>Vibrio mediterranei</i>	<i>V. parahaemolyticus</i> <i>V. mediterranei</i> 5	Fresh and frozen seafood	63–65	
Antibiotic protein P-153	<i>Pseudodalteromonas</i> Species Strain X153	<i>chthyopathogenic Vibrio Propionibacteriumacnes</i> <i>Staphylococcuspepidemidis</i> <i>Propionibacteriumgranulosum</i>	Substrates in Brittany	280	Longeon et al. (2004)
BLIS	<i>Aeromonas hydrophila</i>	<i>S. aureus</i> strains	Water tank containing alligator	?	Messi et al. (2003)

Table 13.2 Antibacterial peptides produced by lactic acid bacteria isolated from marine animal.					
Antibacterial peptide	Producerspecies/ strain	Species/strains inactivated	Source of producer	Molecularmass (kDa)	References
Divercin V41	<i>Carnobacterium divergens</i>	<i>Listeria monocytogenes</i>	Salmon intestine	4,509	Richard et al. (2004)
Enterocin P	<i>Enterococcus faecium</i> LHICA 28.4, 34.5, 40.4, 46	<i>Carnobacterium maltaromaticum</i> , <i>Listeria monocytogenes</i> , <i>Staphylococcus aureus</i>	Turbot muscle	?	Hosseini et al. (2009)
Piscicocin V1a Piscicocin V1b bac ALP57	<i>Carnobacterium piscicola</i> V1 <i>Pediococcus pentosaceus</i> ALP57	<i>Listeria monocytogenes</i> <i>Listeria innocua</i> , <i>Bacillus subtilis</i> , <i>Lactobacillus brevis</i> <i>gravenisii</i> ; <i>Lactobacillus curvatus</i> and <i>Enterococcus faecalis</i> <i>L. monocytogenes</i>	Trout intestine Shellfish including clams, oysters and mussels that are non-fermented	4,416 4,526 < 10	Bhugalloo-Vial et al. (1996) Pinto et al. (2009)
bac ALP7	<i>Enterococcus faecium</i> ALP7		shellfish including clams oysters and mussels that are non-fermented	< 10	Pinto et al. (2009)

Table 13.3 Classification of bacteriocins.

Bacteriocin producing microbe	Bacteriocin Category	Molecular weight (kDa)	Examples	References
Gram-negative bacteria	Colicins	≥30	Colicins E2, E3, A, B	(Ge et al., 2019)
	Colicin-like bacteriocins	≥30	klebicins, S-pyocins	(Wencewicz & Miller, 2017)
	Tailocins	20–100	F-and R-pyocins	(Egan et al., 2017)
	Microcins	< 10	MicrocinC7, microcinB17, colicinV	(Acedo et al.,2018)
	ClassI	< 5	Nisin, mersadicin, lacticin 3147	(Wencewicz & Miller, 2017)
Gram-positive bacteria	ClassII	< 10	Pediocin RA1, carnobacteriocinB2	(Wencewicz & Miller, 2017)
	ClassIII	> 10	Helvecin, enterocin AS-48	
	Halocins	> 5	HalocinA4,C8,H1,H4	(Zou et al., 2018)
Archaea	Sulfolobicin	~20	Sulfolobicin	

H6/H7 (~36 kDa) (Atanasova *et al.*, 2013). Halocins typically exert their antimicrobial effects by disrupting the membrane integrity of target cells, resulting in the leakage of cellular contents and ultimately, cell death. Notably, halocins have been shown to be effective not only against closely related species but also across different genera within the Halobacteria class. Halocin H1, produced by *Haloferax mediterranei*, has been found to inhibit a range of haloarchaeal species, demonstrating a broad spectrum of antimicrobial activity (Torreblanca *et al.*, 1994). Interestingly, some halocins are stable under extreme salt conditions and high temperatures, reflecting their adaptation to harsh environments. Harveycin is an example of marine halocin isolated from *Vibrio harveyi*.

13.4.3 Sulfolobocins

Sulfolobocins are produced by *Sulfolobus* species, which are thermoacidophilic archaea belonging to the Crenarchaeota phylum. These organisms typically inhabit hot, acidic environments such as sulfur-rich springs. Sulfolobocins differ from halocins in their mode of action; they are cell-associated and not secreted into the environment. Instead, they mediate contact-dependent inhibition of sensitive cells (Ellen *et al.*, 2011). Unlike halocins, which are usually active in liquid media, sulfolobocins require direct cell-cell contact and are thus believed to play roles in biofilm development, niche protection, or competition for surfaces in geothermal environments. Table 13.3 below contains the classification of bacteriocins.

13.5 Advantages of bacteriocins in the marine environment

Bacteriocins provide several ecological and biotechnological advantages in the marine ecosystem. These advantages include microbial competition, potential therapeutic applications, aquaculture benefits, food preservation, and environmental sustainability.

13.5.1 Role in microbial competition and ecological balance

In the marine environment, bacteria compete for limited nutrients and space, bacteriocins help producer bacteria establish dominance by inhibiting the growth of competing species (Desriac *et al.*, 2010). This competitive advantage allows bacteriocin-producing bacteria to colonize specific niches and maintain microbial diversity within the ecosystem. For example, in coral reef microbiomes, bacteriocin-producing *Pseudomonas* and *Vibrio* species regulate microbial populations, preventing pathogenic bacteria from overpopulating and disrupting coral health (Chakraborty *et al.*, 2021).

13.5.2 Potential in antibiotic development

The discovery of marine bacteriocins provides promising alternatives to conventional antibiotics. Many marine bacteriocins have novel structures and mechanisms of action, making them effective against antibiotic-resistant bacteria (Desriac *et al.*, 2010). For instance, pyocins from *Pseudomonas* species have been explored as therapeutic agents against other *Pseudomonas aeruginosa* a common pathogen in cystic fibrosis patients (Michel-Briand & Baysse, 2002).

13.5.3 Application in aquaculture

Bacteriocins play a crucial role in disease control in aquaculture. Bacterial infections, such as vibriosis caused by *Vibrio* species, are a significant challenge in fish and shrimp farming. Marine bacteriocins, such as those produced by *Lactobacillus* and *Enterococcus* species, have been used as probiotics to reduce pathogenic bacterial populations, thereby improving fish health and reducing the need for antibiotics (Ringø et al., 2018).

13.5.4 Food preservation and safety

Marine bacteriocins have potential applications in food preservation by inhibiting foodborne pathogens and spoilage bacteria. Nisin and pediocin-like bacteriocins have been tested for use in seafood preservation, extending shelf life and ensuring food safety (Abriouel et al., 2011; Aransiola et al., 2024b). These bacteriocins provide a natural substitute for synthetic preservatives, meeting consumer demand for organic and chemical-free food products.

13.5.5 Environmental sustainability

The use of bacteriocins in disease control and food preservation reduces the reliance on chemical antibiotics and preservatives, minimizing environmental pollution. Unlike conventional antibiotics, bacteriocins degrade naturally and do not contribute to antibiotic resistance in microbial communities (Cotter et al., 2005).

13.6 Production of bacteriocins by different microorganisms

Bacteriocins are antimicrobial peptide produced by different microorganisms, including bacteria, archaea, and fungi, to inhibit the growth of other microorganisms. Some examples of microorganisms that produces bacteriocins include: lactic acid bacteria: is a class of bacteria that is well known for producing bacteriocins, the genus *Lactobacillus* contains bacteria that are used as oral probiotics. These bacteria are frequently prescribed to patients following antibiotic treatments or in cases of stomach infections caused by resistant pathogenic microorganisms. Their purpose is to restore the balance of the microbiome by using their capacity to secrete bacteriocins, which combat colonizing foreign microorganisms (Ye et al., 2021; Xu et al., 2021). A food preservative called Nisin, which is produced by *Lactococcus lactis* subsp. *lactis* KT2W2L, has been licensed for use in halting the growth of *Listeria monocytogenes* and other Gram-positive bacteria (Prangishvili et al., 2000). *Lactobacillus helveticus* produce non lytic bacteriocin Helveticin J (37 kDa) (Joerger & Klaenhammer, 1986). *Lactobacillus fermentum* produces fermenticin which have a broad spectrum of activity against pathogenic organisms.

- Halobacteria: produces bacteriocins called halocins. Halocins may be categorized into two groups according to their size. The tiny microhalocins (3.6 kDa) and the bigger 35 kDa halocins (O'Connor & Shand, 2002). The first halocin to be identified was S8, a 36-amino acid hydrophobic peptide that was generated from a bigger 34-kD pro-protein. A common

characteristic of halo bacteria is the production of halocin (Torreblanca et al., 1994). Halocin genes are found on minichromosomes, also known as megaplasmids. Approximately 200 and 300 kbp plasmids encode halocins S8 and H4, respectively (Cheung et al., 1997; Prince & Shand, 2000). Typically, their activity is observed during the late exponential to early stationary growth phase.

- *Sulfolobus* genus: they are known for the production of sulfolobocins bacteriocins. Sulfolobocin bacteriocins have not been thoroughly investigated. The synthesis of sulfolobocin from *Sulfolobus islandicus* isolated from volcanic vents around Iceland was tested by Prangishvili et al. (2000). According to this study, sulfolobocin is a protein that is connected with membranes. Additionally, sulfolobocins are linked to membrane vesicles that have a diameter of 90–180 nm.

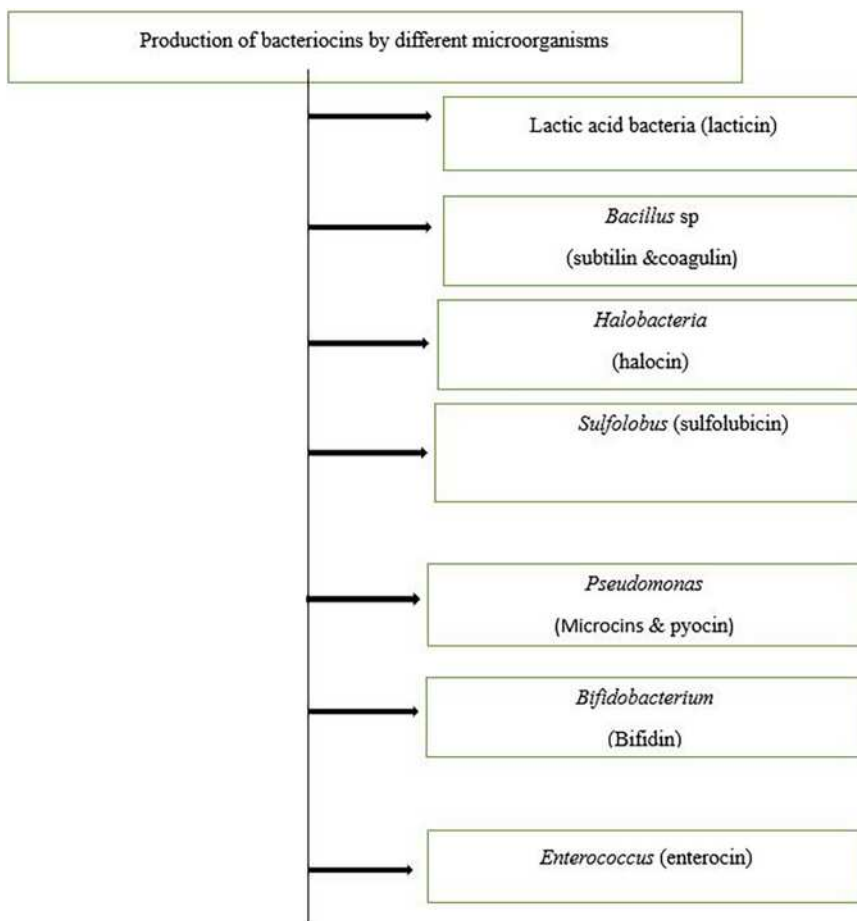


FIGURE 13.1

Bacteriocin produced by different microorganisms.

They are susceptible to protease treatment and thermostable, like many bacteriocins their mode of action is still yet known (Ellen et al., 2011).

- The *Bacillus* genus: generates bacteriocins with appealing properties (Salazar-Marroquín et al., 2016), different species of *Bacillus* produce different kind of bacteriocins examples are *Bacillus coagulans*-produced coagulin and *Bacillus subtilis*-produced subtilin. Broad-spectrum bacteriocins produced by *Bacillus thuringiensis* suppress a variety of disease, including the *Aspergillus fungus*, *Staphylococcus aureus*, *L. monocytogenes*, *Klebsiella pneumoniae*, *Vibrio cholerae*, and *Pseudomonas aeruginosa*. (Salazar-Marroquín et al., 2016).
- Genus *Pseudomonas*: produces bacteriocins of a high molecular weight, including pyocins of the S, F, and R types (Oluyombo et al., 2019). Along with type B microcins (Ghequire et al., 2018), tailocins, and pyrocins, they are distinguished by their complex structure that resembles phage tails. Their mechanism of action is based on the recognition of specific receptors on the cell surface, which results in lipid II-degradation, pore formation, or nonspecific nucleic acid degradation.
- Genus *Bifidobacterium*: First identified in 1980, bacteriocins linked to *Bifidobacterium* have antibacterial effect against varieties of pathogenic microorganisms including *Escherichia coli*, *C. perfringens* and *Listeria monocytogenes*. Bifidin, which was made by *Bifidobacterium bifidum* NCDC 1452, was the first *Bifidobacterium*-associated bacteriocin to be identified. Growing this strain in skim milk was found to have the highest antibacterial activity; it was then isolated using methanol-acetone and partially purified using Sephadex G-15 chromatography. There was no decrease in activity when the filtered product was kept in the refrigerator for at least three months. (Anand et al., 1985). *Bifidobacterium*-associated bacteriocins, such as lantibiotic bisin from *Bifidobacterium longum* DJO10A, bifidin I from *Bifidobacterium infantis* BCRC 14602z (Cheikhoussef et al., 2010), and bifidocin B from *Bifidum* NCFB 1454, have been extensively documented. These are the only bacteriocins that have undergone thorough characterization and have had at least some of their amino acid sequences clarified.
- Genus *Streptococcus*: The Studies of bacteriocins produce by streptococci was first carried out in the year 1960s. Recently researchers focused on the isolation and characterization of streptococcal bacteriocins of disease-causing streptococci instead of nondisease causing *Streptococci* species. Streptococci's most common peptide bacteriocins are lantibiotics, and the majority of them belonged to the elongated cationic type A lantibiotics. The first bacteriocin of *Streptococcus salivarius* to be characterized was lantibiotic salivaricin A (Ross et al., 2021), and it strongly inhibited the growth of *Streptococcus pyogenes* strains. *Streptococcus pyogenes* is an organism that is common and known to cause different kind of diseases in human. salivaricin A has up to five structural variations (salivaricin A1 to A5) (Wescombe et al., 2006). SalA1 activity predominated among the SalA-type peptide bacteriocins generated by a wide variety of species which include *S. dysgalactiae*, *S. agalactica* and *S. pyogenes* (De Kwaadsteniet et al., 2006). Peptide bacteriocins produced by *Streptococcus* mutans are called mutacins, and the incidence of such antimicrobial activities was reported to vary from 11% to 100% among *Streptococcus* mutans isolates. 145 oral *Streptococcus mutans* isolates from mothers and their young children were studied for mutacin production. The results indicated that 88% of the strains exhibited antimicrobial activity against at least one of the 14 indicator bacteria (Gronroos et al., 1998). Production of bacteriocins by different microorganisms are summarized in Fig. 13.1.

13.7 Detective innovations of bacteriocin in the marine environment

In recent years, advances in detection methods, referred to here as “detective innovations,” have facilitated the identification, isolation, and characterization of novel bacteriocins from marine environments. These innovations span various disciplines, including genomics, proteomics, metabolomics, and synthetic biology, and they have significantly enhanced our understanding of marine microbial interactions and the potential applications of bacteriocins.

13.7.1 Detective innovations in bacteriocin discovery

13.7.1.1 *Metagenomics and high-throughput sequencing*

One of the most transformative detective tools in marine bacteriocin research is metagenomics. Traditional methods of bacteriocin discovery relied on culturable microbes, limiting the diversity of bacteriocins that could be studied. However, it is estimated that more than 99% of marine bacteria are unculturable using standard laboratory methods (Amann et al., 1995). Metagenomic sequencing bypasses the need for culturing by directly extracting and analyzing DNA from environmental samples, thereby revealing novel biosynthetic gene clusters (BGCs) that encode for bacteriocins.

Through shotgun metagenomic sequencing, researchers can identify bacteriocin-producing genes, such as those responsible for lantibiotic and nonlantibiotic peptide production, from seawater, sediments, sponges, and marine biofilms (Wang et al., 2020). Tools like antiSMASH (antibiotics and Secondary Metabolite Analysis Shell) are used to scan metagenomic data for bacteriocin-related BGCs (Blin et al., 2019).

13.7.1.2 *Genome mining and bioinformatics tools*

Genome mining has revolutionized the discovery of bacteriocins by enabling researchers to scan bacterial genomes for gene clusters involved in antimicrobial peptide production. The increasing availability of marine microbial genomes in public databases has made genome mining a highly efficient detective tool.

Bioinformatics tools such as BAGEL (Bacteriocin Genome Mining Tool) and antiSMASH help identify putative bacteriocin genes, predict their structures, and determine their potential antimicrobial activity (van Heel et al., 2018). These tools can also reveal regulatory genes, immunity proteins, and transporter systems associated with bacteriocin biosynthesis. Novel bacteriocin-producing gene clusters have been discovered in marine *Bacillus*, *Pseudoalteromonas*, and *Streptomyces* species using these techniques (Desriac et al., 2010; Wang et al., 2020).

13.7.1.3 *Proteomics and mass spectrometry-based detection*

Proteomic approaches are essential for validating and characterizing bacteriocins predicted through genome mining. MALDI-TOF (Matrix-Assisted Laser Desorption Ionization-Time of Flight) spectrometry is commonly employed to directly analyze the molecular weight and structure of bacteriocin peptides from bacterial cultures (Joo et al., 2016).

Liquid chromatography combined with mass spectrometry helps identify post-translational modifications in bacteriocins, such as cyclization, methylation, or lanthionine bridge formation.

Table 13.4 Detective Innovations of bacteriocins in the marine environment.

S/ N	Innovation/method	Description	Application/impact	Reference
1	Metagenomic Approaches	Use of environmental DNA to discover bacteriocin genes without culturing	Enables discovery of novel bacteriocins from unculturable marine microbes	(Desriac et al., 2010)
2	Genome Mining	Analyzing sequenced genomes for biosynthetic gene clusters (BGCs)	Accelerates the identification of bacteriocin-producing marine organisms	(Barbosa et al., 2015)
3	Mass Spectrometry (MALDI-TOF, LC-MS)	Used for rapid profiling and identification of bacteriocin structures	Provides precise molecular weight and structure of marine bacteriocins	(Yang et al., 2014)
4	Bioinformatics Tools (e.g., BAGEL, AntiSMASH)	Software platforms for detecting and classifying bacteriocin gene clusters	Enhances automated screening and classification of bacteriocins	(Van Heel et al., 2018)
5	Co-culture Techniques	Culturing marine microbes together to stimulate bacteriocin production	Reveals cryptic bacteriocins induced by microbial interactions	(Meade et al., 2020)
6	CRISPR-Cas Systems	Gene editing tools to activate silent bacteriocin genes	Unlocks hidden bacteriocins in marine microbial genomes	(Meade et al., 2020)
7	High-Throughput Screening (HTS)	Rapid screening of microbial isolates for antibacterial activity	Allows large-scale discovery of marine bacteriocin producers	(Yang et al., 2014)
8	NMR Spectroscopy and X-ray Crystallography	Structure elucidation of bacteriocins	Aids in understanding function and stability of marine-derived bacteriocins	(Desriac et al., 2010)
9	AI and Machine Learning Models	Predictive modeling for bacteriocin activity and synthesis pathways	Improves efficiency in discovering functional bacteriocins	(Meade et al., 2020)
10	Bioprospecting in Extreme Marine Environments	Exploring deep-sea vents, polar regions, etc., for unique microorganisms	Leads to discovery of novel bacteriocins with unique properties	(Desriac et al., 2010)

These modifications are essential for bacteriocin stability and bioactivity, especially in the challenging marine environment (Cotter et al., 2005).

Combined with tandem mass spectrometry (MS), researchers can map peptide sequences and compare them against known bacteriocin databases to determine novelty and function.

13.7.1.4 Synthetic biology and heterologous expression systems

One major challenge in marine bacteriocin discovery is the difficulty of culturing native bacteria in laboratory conditions. To overcome this, synthetic biology has enabled the heterologous expression of marine bacteriocin genes in well-characterized host organisms like *Escherichia coli* and *Bacillus subtilis*.

Synthetic gene synthesis and cloning technologies allow researchers to synthesize bacteriocin genes identified from marine metagenomes and insert them into suitable expression vectors. These engineered systems can produce bacteriocins in large quantities for functional analysis and therapeutic testing (Zhao et al., 2016). Furthermore, synthetic biology enables the optimization of bacteriocin genes for improved expression, stability, and activity, which is vital for industrial applications.

13.7.1.5 Microfluidics and lab-on-a-chip technologies

Microfluidic systems offer miniaturized, high-throughput platforms to screen marine bacteria for antimicrobial activity in real-time. These lab-on-a-chip devices can simulate marine conditions, allowing for co-culture experiments that detect bacteriocin-mediated inhibition of target bacteria (Whitesides, 2006). These systems use small sample volumes and automated analysis to rapidly identify bacteriocin producers without the need for large-scale culturing. They also allow time-resolved imaging of bacterial interactions, helping researchers visualize how bacteriocins act within marine biofilms and microbial communities. Table 13.4 presents the detective innovations of bacteriocins in the marine environment and their applications/impact.

13.7.2 Applications and implications of detective innovations

13.7.2.1 Unlocking the unculturable majority

Many marine microbes remain uncultivable using conventional methods. Detective innovations like metagenomics and synthetic biology have allowed scientists to bypass this limitation and access the vast genetic reservoir of unculturable bacteria. This has led to the identification of bacteriocins with novel structures and unique modes of action, increasing the pool of candidates for antimicrobial drug development.

13.7.2.2 Tackling antibiotic resistance

Bacteriocins discovered using modern detective tools often possess activity against multidrug-resistant pathogens. For instance, pyocins from *Pseudomonas* spp. and colicins from marine *E. coli* strains have demonstrated potent effects against Gram-negative bacteria (Michel-Briand & Baysse, 2002). These bacteriocins can be further modified using synthetic biology to enhance their spectrum and reduce resistance development.

13.7.2.3 Enhancing aquaculture health

The application of bacteriocins in aquaculture is another major benefit of detective innovations. Marine-derived bacteriocins are being incorporated into probiotic formulations to reduce pathogenic bacteria in fish and shellfish farming (Ringø et al., 2018). This approach decreases antibiotics usage in aquatic organism farming, minimizing pollution in aquatic environment and resistance transfer.

13.7.2.4 Marine biodiversity conservation

Understanding bacteriocin production in marine ecosystems helps in the conservation of marine biodiversity. By mapping bacteriocin-producing species and their ecological roles, researchers can monitor shifts in microbial communities caused by pollution, climate change, or human activity (Chakraborty et al., 2021). This knowledge informs marine conservation policies and sustainable resource management.

13.8 Challenges and future directions

Despite the progress, several challenges remain. Metagenomic datasets often contain fragmented gene clusters, making it difficult to predict complete bacteriocin structures. Similarly, the lack of standardized protocols for functional validation can delay the transition from discovery to application.

Future directions involve integrating machine learning with genome mining to predict bacteriocin function more accurately. Additionally, improvements in single-cell genomics and culturomics may allow for the cultivation of previously unculturable marine bacteria.

International collaborations and data sharing among marine microbiologists, bioinformaticians, and synthetic biologists are crucial for unlocking the complete potential of marine bacteriocins.

13.8.1 The use of bacteriocins derived from marine organisms

Bacteriocins produced by marine organisms have potential applications in various field and industries, which include food industry, aquaculture, medicine, and agriculture among others.

13.8.1.1 Application in aquaculture

The use of marine-derived bacteriocins in aquaculture is predicated on the observation that the producer strains and the pathogens of interest have nearly the same ecological habitat (Prasad et al., 2005 and Zai et al., 2009). Due to the fact that the properties of terrestrial bacterial strains rely on their environment, their use as probiotics in aquaculture has not been very successful (Nikapitiya, 2013). Cultivating probiotic microorganisms that produce bacteriocin from the marine environment where they thrive is therefore the best strategy as these strains are predicted to be more efficient for use in aquaculture as opposed to bacteria that are not marine based. Additionally, it's worth noting that fish are a key source of bacteriocin-producing bacteria among marine mammals. Some examples of marine bacteriocins include divercins and piscicocins, which are produced by *Carnobacterium* species that have been isolated from the intestine of fish. (Desriac et al., 2010), the bacterium *Enterococcus faecium* which was isolated from turbot produced enterocin p, lastly *Vibrio anguillarum*

isolated from catfishes produces *Vibrio* AVP10 bacteriocin (Zai et al., 2009). Strains of bacteria that are members of the genera, *Lactobacillus*, *Carnobacterium*, *Leuconostoc* and *Streptococcus*, are often found in healthy fish's gut microbiome. This rich microbiota largely explains why fishes frequently include bacteriocin-producing strains that may be advantageously cultivated for aquaculture applications, such as adding probiotic strains to feeds for easy introduction into the fishes' digestive system. Numerous isolated marine bacterial strains have demonstrated the qualities that might make them viable substitutes for antibiotics in aquaculture. (Joerger, 2003; Gillor et al., 2008). These have demonstrated inhibitory effects on a number of recognized pathogenic microbial strains of both Gram-positive and Gram-negative bacteria (Ghanbari et al., 2012; Singh et al., 2013). MMB2 strain. Although it is known that the bacteriocins of the *Bacillus* species only have activity against Gram-positive bacteria, recent screening findings have revealed that they also have an inhibitory spectrum against Gram-negative bacteria, which mostly represent aquaculture pathogens. (Kim et al., 2014). Not only does this group have the ability to sporulate, but it also has antagonistic activity against Gram-negatives, which makes it a potential candidate for development as aquaculture probiotics (Martinez Cruz et al., 2012). Studies carried out by Irianto and Austin, found that the Atlantic salmon gastrointestinal system contained *Carnobacterium inihbens* K1, which generated inhibitory compounds that were effective against bacterial fish infections *in vitro*. Robertson (2000) confirmed the benefit of *Carnobacterium* K by demonstrating antagonism against a variety of fish infections and confirming its effectiveness in lowering salmonid mortality caused by *Yersinia ruckeri*, *Vibrio ordalii*, and *Aeromonas salmonicida*. Furthermore, rainbow trout were given the human probiotic *Lactobacillus rhamnosus* 53101 at doses of 109 and 1012 cells/g of feed for 51 days. This decreased the mortality rate from 52.6 to 18.9% (109 cells/g of feed) and to 46.3% (1012 cells/g of feed) after being challenged with *Aeromonas salmonicida*. (Nikoskelainen et al., 2001).

13.8.1.2 Application in food industry

Marine bacteriocins are predicted to provide potential benefits for a wide range of industries outside aquaculture. Interest in finding more bacteriocins for the food business has increased with the discovery of nisin and its subsequent permitted usage as a food preservative in more than 40 countries (Cleveland et al., 2001). Smitha and Bhat (2013), reported that bacteriocins or live culture preparations of strains that produce can be utilized as food preservative if they satisfy the standards set by the European Food Safety Authority. Many bacteriocins exhibit properties that are advantageous for food preservation, while only a small number are marine in origin. The thermostable, wide-pH range bacteriocin BL8 from *Bacillus licheniformis* strain BHT8 has antimicrobial action against harmful Gram-positive bacteria linked to food-borne infections (Smitha & Bhat, 2013). A bacteriocin produced by *Lactobacillus fermentum* SBS001 can be utilized as a protective culture to increase the microbiological safety of fermented foods like yogurt and pickle (Singh et al., 2013). Additionally, the ability of *Lactobacillus casei* and *Lactobacillus plantarum* to suppress food-rotting bacteria was demonstrated by their production of AP8 and H5, respectively (Ghanbari et al., 2012). These bacteriocins have been directly added to foods like cheese to guard against *Listeria monocytogenes* and *Clostridium perfringens* (Cleveland et al., 2001). Karthik et al. studied the effectiveness of bacteriocin-producing strain of *Lactobacillus* sp. (AMET1506), in the role of bio preservative for shrimp in various storage settings (Karthik et al. (2013). Plastic sheets coated with nisin inhibited the growth of other anaerobic and aerobic food spoiling organisms in a manner

that depends on concentration (Neetoo et al., 2008). Diop et al. outlined that, to enhance the traditional Senegalese fermented fish guedj, a starting culture of the nisin producing *L. lactis* subsp. *lactis* strain CWBIB1410 was utilized (Diop et al., 2009).

13.8.1.3 Agricultural application of bacteriocin

Agrochemical misuse has seriously harmed both the environment and human health. Many researchers aim to look for methods to combat diseases and pests in a more sustainable way. Marine organisms that generate inhibitory compounds have been utilized as inoculants to target plants pathogens or to stimulate the growth of crop plants. Few examples of bacteriocins of marine inception used in agriculture include thuricin 17 and enterocin UNAD 04 (David & Onifade, 2018). Enterocin UNAD, bacteriocin produced by a marine organism known as *Enterococcus faecalis* has antibacterial activity against *Botrydiplodiatheobromae*, *Aspergillus niger*, and *Pseudomonas expansum* phytopathogenic fungi (David & Onifade, 2018). The bacteriocin Thuricin 17 generated by marine organism *Bacillus thuringiensis* strain NEB17 is a biological stimulant of plant that has no negative impacts on rhizobia that is nodulating (Nazari & Smith, 2020). NCPPB2355 strain of *Pseudomonas syringae* subspecie *ciccaronei* generate bacteriocin with antibacterial activity against *Pseudomonas-syringae* subspecie (*Savastanoi*) that causes Olive knot disease (Kim et al., 2006). Marine bacteriocin 32Y produce by *Pseudomas aeruginosa* RsB29 inhibit the main plant pathogenic fungi, *Fusarium*, that impact a variety of plants, such as watermelon, cucumbers, tomatoes, cucumbers, cantaloupe, spinach, eggplant, celery, bananas, and cabbage. When bacteriocin is directly applied to plants, it creates a defense mechanism against abiotic stressors and infections. (Nazari & Smith, 2020).

13.8.1.4 Application in medicine

In the medical profession, penicillin's antibacterial action against a wide variety of pathogens was thought to have made a significant advance to the treatment of illnesses brought on by microorganisms. A startling number of novel antibiotics were developed and utilized to cure illnesses throughout the 1950s and 1960s. However, after 1985, the number of new antibiotic discoveries started to decline. At the same time, more and more antibiotic-resistant microorganisms are being discovered, endangering human health. It has been demonstrated that human pathogens can evolve novel defense mechanisms against antibiotic, such as altered drug binding sites that prevent antimicrobial drugs from reaching their target location (Munita & Arias, 2016). Methicillin-resistant *Staphylococcus aureus* is an example of a drug-resistant bacterium that was initially identified in hospitals in the 1960s when methicillin was used to treat several skin infections. Because of this resistance problem, researchers are searching for substitute antimicrobial medicines that can eradicate infections. Because of its low toxicity, numerous researchers suggested using bacteriocin instead of antibiotics to treat infectious diseases (Mathur et al., 2018; Abanoz & Kunduhoglu, 2018). Numerous investigations have been conducted to look at bacteriocins that can be utilized to treat conditions including cancer, mastitis, respiratory tract infections, lung infections, urinary tract infections, skin infections, diarrhea, dental cavities, and bloodstream infections.

13.8.1.5 The bacteriocin subtilisin

Some *Bacillus* species, which can be found in soil, water, or as normal gut flora, generate bacteriocin called subtilisin. Subtilisin A is composed of 32 amino acids and additional nonamino acid residues,

with a molecular weight of 3398.9. It was reported to possess ability to combat a variety of both Gram-positive and Gram-negative disease-causing bacteria. This bacteriocin demonstrated an inhibitory impact against *Enterococcus faecalis* that causes urinary tract infections in human. High inhibitory action against *Enterococcus faecalis* OGX1 was demonstrated by subtilisin A at the minimal inhibitory dose of 3.125 mg L⁻¹. In addition, it was demonstrated that subtilisin A might be utilized to stop *P. gingivalis* from growing, at MIC of 3.125 mg L⁻¹. This pathogen causes periodontitis which may lead to tooth loss. Additionally, it was demonstrated that subtilisin A inhibited the growth of *Klebsiella pneumoniae*. The causative agent of infections of the skin, urinary tract, meningitis, and pneumonia. The lowest concentration of the bacteriocin subtilisin A that inhibited the growth of *Klebsiella pneumoniae* strain UMN1, UMN5, UMN3, UMN4, and ATCC 4352, were > 200, 1.25, 5.0, 25.0 mg L⁻¹, and > 200, respectively.

13.8.1.6 Mersacidin

This bacteriocin belongs in the lantibiotic group, their structure consists of a lanthionine group and 20 amino acids. It has been discovered that this bacteriocin, which is generated by *Bacillus* species, has inhibitory action against Gram-positive disease-causing bacteria. The *Bacillus* sp. strain HIL Y-85, 54728 mersacidin was shown to have antimicrobial effects on some strains of *Staphylococcus aureus*, including *Staphylococcus aureus* R33 MRSA, SA137/93 G, SH1000, SA137/93 A, and SG511. It was found that the minimum inhibitory concentration of 32, 30, 32, 35, and 1 mg mL⁻¹ of mersacidin were required to stop the development of *Staphylococcus aureus* SH1000, R33 MRSA, SG511, SA137/93 A, and SA137/93 G, respectively. Further, it was demonstrated that mersacidin had inhibitory action against *Streptococcus pneumoniae* BAA-255, which is the causative agent of human respiratory infections. Mersacidin's MIC of 2 mg mL⁻¹ was found to prevent *Streptococcus pneumoniae* BAA-255 from growing. Additionally, mersacidin also shows inhibitory activity against *Micrococcus luteus*, that causes pneumonia and meningitis. It was shown that a 1.2 mg mL⁻¹ MIC of mersacidin inhibits the growth of *Micrococcus luteus* ATCC4698 (Barbosa et al., 2015). Mersacidin was reported to have an inhibitory activity against *Enterococcus faecalis* and *Enterococcus faecium* strains, that causes infections of the skin, circulation, urinary tract, and abdomen.

13.9 Conclusion

Bacteriocins of marine origin represent a rich source of novel antimicrobial peptides, lantibiotics with numerous applications. The marine environment's vast array of microbes offers a unique opportunity for discovering new bacteriocins with potential application in medicine, aquaculture, food industry, biotechnology, cosmetic industry, pharmaceutical industry, phytoremediation, and for use in bioremediation of the environment. Further research should be conducted to understand the full extent of bacteriocin production and their ecological significance in marine environment. Lastly, bacteriocins present an intriguing avenue for discovering novel ways to combat bacterial pathogens of both human, animals, and phytopathogens and to promote ecological balance in the marine environment.

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Marine microbial products as emerging antimicrobials

Magdalene Akhere Osaghae^{1,2}, Tracy Uyigue¹, Aduba Osaretin¹, Oyindamola Esan¹ and Stephen Olori¹

¹Department of Microbiology, Faculty of Life Sciences, University of Benin, Benin, Edo, Nigeria,

²Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria

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14.1 Introduction

The marine environment is rich with life forms, from the microscopic to the very large living thing. It houses more than 80% of life on the planet (Kasanah & Hamann, 2004). This rich environment is also very diverse in terms of microorganisms. These microbes play important roles in sustaining the environment from the microalgae, bacteria, actinomycetes, fungi, which could be found inhabiting the

surface and the deep sea regions. These organisms also dwell on larger organisms found in the ocean (Aransiola, Oyewole, et al., 2024).

The different living conditions present in the ocean have equipped marine microbes with special survival skills; these skills include the ability to produce bioactive metabolites with various natural activities (Li et al., 2022). These metabolites are often used for defense mechanisms, communication, and other adaptation purposes (Aransiola, Bamisaye, et al., 2024; Manivasagan et al., 2014). They have attracted interest for their potentials as antimicrobials. For example, amino acids, terpenoids, polysaccharides, and some other metabolic compounds with varying antimicrobial activities have been extracted from marine microbes.

The brisk and widespread effects of resistance to common antimicrobials have called for new antimicrobials. The necessitated call for new sets of antimicrobial agents is due to the surfacing and spread of resistant pathogens, which are pathogens evolving resistance to commonly used antimicrobials (Muteeb et al., 2023). The efficacy of traditional antimicrobials has been compromised by the emergence of resistant pathogens posing a threat to countless lives. According to the World Health Organization (WHO), “antimicrobial resistance is one of the most significant threats to global health” (World Health Organization W.H.O., 2019). By 2050, it is estimated to force up to 24 million people into extreme poverty and claim the lives of over 10 million people yearly (World Health Organization W.H.O., 2019) prompting the need for novel and effective antimicrobial agents. The capability of marine microorganisms to produce biological active compounds with the potential to combat resistant strains of pathogens has placed them as a key focus of research. Marine microbial products have taken the interests of scientists as potential antimicrobials. The extreme conditions of the marine environment would pressure microbes to produce unique compounds, which could be manipulated as alternative antimicrobials. The complex structures and functions of these compounds stand out for their uniqueness (Bharathi & Lee, 2024). Unique biochemical pathways to survive are evolved by these compounds, which correlate with their functions (Bharathi & Lee, 2024).

Some examples of marine microbe produced antimicrobials are “1-Hydroxy-1-norresistomycin” from *Streptomyces chinaensis*, “Chandranamycin” from *Actinomadura* sp, “Pyridinium” from *Amycolatopsis alba*, “Marinomycins” from *Marinospora* sp, (Dasari et al., 2012; Kwon et al., 2006; Maskey et al., 2003). These compounds often act in mechanisms similar to the terrestrial counterparts. For example, Abyssomicin C (a polyketide) produced from *Verrucosipora* sp prevents the production of at an early stage (Riedlinger et al., 2004), which is an essential metabolic pathway in bacterial cells.

The extraction of these compounds from their microbial source is often challenging as most of these microorganisms do not thrive well in standard culture medium, a novel technique or special medium is often added to enrich production of these compounds. These antimicrobial-producing marine microbes are isolated from sediments of the oceans, free swimming, and sessile organisms like sponges and fishes (Ward & Bora, 2006). Due to the unculturable character of some of these isolates, the use of molecular techniques for detection has been adopted (Mincer et al., 2005). This challenge limits the adoption of marine microbial products as alternative antimicrobials. Genome-based bioprospecting have been employed to tackle this setback but, the success depends on varying factors like the creation of the effective programs and tools for the bioinformatic analysis of the genomes (Manivasagan et al., 2014). The use of modified culture environment that simulates the marine environment and its physicochemical features to cultivate marine microbes has been successful so far (Stewart, 2012). The gelling agent could be modified to suit the bacterial isolates,

for example, [Bech et al., 2020](#); discovered that more marine bacterial products were recovered due to the switch from agar to gellan gum as gelling agents. The slow growth and adaptation rates, the sensitivity, competition, diversity of other isolates in the enriched media, and low yields are often challenges encountered in the isolation and extraction of these products ([Sedeek et al., 2022](#)).

The antimicrobial products of these marine microbes have been applied to different clinical settings. The application of these products as antimicrobials shows promising results even in drug resistant infection cases. Drug-resistant infection is one of the most difficult cases under antimicrobial control. It presents health challenges both locally and globally by complicating treatment outcomes and increasing morbidity and mortality rates. Some of the marine microbial products used for resistant infections include “coumarin-6-ol, 3,4 dihydro-4, 4, 5, 7-tetramethyl from *Streptomyces* VITAK1 exhibited activity against drug-resistant methicillin-resistant *Staphylococcus aureus* (MRSA) ATCC 33591 (IC₅₀, 40 µg/mL) and other Gram-positive and Gram-negative bacteria pathogens” ([Abirami et al., 2015](#)), *S. rochei* produced a sulfanyl like metabolite prevented the growth of multi drug resistant and extended spectrum Betalactamases producing ATCC strains ([Shanthi et al., 2015](#)), “*Bacillus velezensis* strain RP137 produced an aminoglycosides that inhibited the growth of MRSA at MIC of 150 ± 5 µg/mL” ([Pournejati et al., 2019](#)). It goes beyond antibiotics even to chloroquine resistant plasmodium which was inhibited by salinipostins A-K produced by *Salinospora* sp ([Schulze et al., 2015](#)) and to fungal isolates like the *C. albicans* ATCC 10231 inhibited by *Streptomyces* sp. strain SMS_SU21.

This chapter explores antimicrobial compounds derived from marine microorganisms, detailing their diverse types, mechanisms of action, and extraction techniques. It further examines their clinical and industrial applications, the challenges associated with their production and commercialization, and the future prospects of marine-derived antimicrobials in medicine

14.2 Marine microbial products: types, mechanisms of action, and challenges of antimicrobials

The aquatic environment has always been the most diverse ecosystem. The ocean takes up more than 60% of the earth surface and it houses over 300,000 species of organisms. A lot of areas remain unexplored. [Ruginescu et al. \(2022\)](#) estimates that approximately 0.01% of marine bacteria species have been characterized so far. The extreme environmental condition of the marine environment has led to specific adaptive mechanisms adopted by these organisms ([Barzkar et al., 2024](#)). The recent discovery of marine microbes as sources of antimicrobial agents has placed them at the front option to combating antimicrobial resistance outbreaks. The widespread outbreaks of resistance to conventional antimicrobials have led to the exploration of alternatives and new sources of antimicrobials. The marine microbes are still fully unexplored but show promising effect in the treatment of diseases ([Penesyan et al., 2010](#)).

14.2.1 Types of antimicrobials produced by marine microbes

Marine microbes, for example, marine bacteria, fungi, and actinomycetes produce biologically active metabolites. These organisms sometimes dwell on the surface of higher marine life forms (plants and

animals) in a symbiotic relationship. Microbes on the surface of sponges constitute about 40% of the body mass and work symbiotically for the benefit of the sponge (Bayer et al., 2008).

These natural compounds from marine microbes have unique function and structure (Karthikeyan et al., 2022). “Approximately 28,500 natural products have been identified at the end of 2016” (Blunt et al., 2016; 52. Cedeño Muñoz et al., 2024). They present a wide range of activities as antimicrobials; antifungal, antiviral, antibiotics, antiprotozoan (Ji et al., 2018; Mohie et al., 2023). Some of which will be discussed in this section.

Examples of marine bacteria with antibacterial activities include *Micromanospira harpali* which produces spirotetromate analogs against some Gram-positive bacteria, marine derives actinomycetes *Streptomyces* sp produces chromomycins against “Methicillin Resistant *Staphylococcus aureus* (MRSA)” (Cho et al., 2020; Gui et al., 2017), Streptoseomycin from *Streptomycesseoulensis* A01 (Zhang et al., 2016) and many more. Marine fungi can also be found on the surface sea level and at the deep sea level. A number of marine fungi show promising sources of antibacterials (Table 14.1). For example, *Aspergillus* sp fungus produces dehydrochlorofusaricin B against multidrug resistant *S. aureus* (Gladfelter et al., 2019). A good source of antimalarial is discovered in a marine fungus *Chaetomium* sp (Barone, 2022) some bioactive compounds belong to known structures while others are complex in structures. Many of these agents are yet to pass clinical trials but have shown slow progress in their discovery and development.

Table 14.1 describes some selected antimicrobials produced by certain marine microbes with promising effects as alternative therapy. While other reviews focus on common marine antimicrobials, this table reveals products that were selected because of their novelty, diversity of action, and the multipurpose biotechnological use of the source organisms.

14.2.2 Mechanism of action

The research for novel antimicrobials with distinctive structures and mechanisms of action is critical due to the overwhelming increase in resistance to commercial antimicrobials. Marine microorganisms live in highly stressed environment with extreme conditions and this has equipped them with the ability to survive by producing secondary metabolites discovered to possess essential biological properties such as antifungals, antibacterial, and antitumors. Marine antimicrobials with their complex structures offer diverse mode of action reducing the possibility of cross resistance (Labes, 2018). Antimicrobials derived or isolated from marine microorganisms usually act in mechanisms similar to conventional antimicrobials from terrestrial sources (Fig. 14.1). Some antimicrobials function by inhibiting biofilm formation, cell adhesion, fungal metabolism, ATP production in bacterial cell leading to its death (Bharathi & Lee, 2024).

Fig. 14.1 represents the major pathways or mechanisms of actions these marine antimicrobials exhibit. It varies from the prevention of cell wall synthesis, the interruption of bacterial cell membrane integrity, inhibition of metabolic pathways, and interference with nucleic acid synthesis (Bharathi & Lee, 2024).

Certain marine antimicrobials have been discovered as work alongside with commercial antibiotics in a synergistic manner. For example, an antimicrobial agent isolated from marine microbes could prevent efflux pump, a resistant mechanism in bacterial pathogens thereby enabling the effect of the prescribed antibiotics. It is also important to note that in addition to the biological

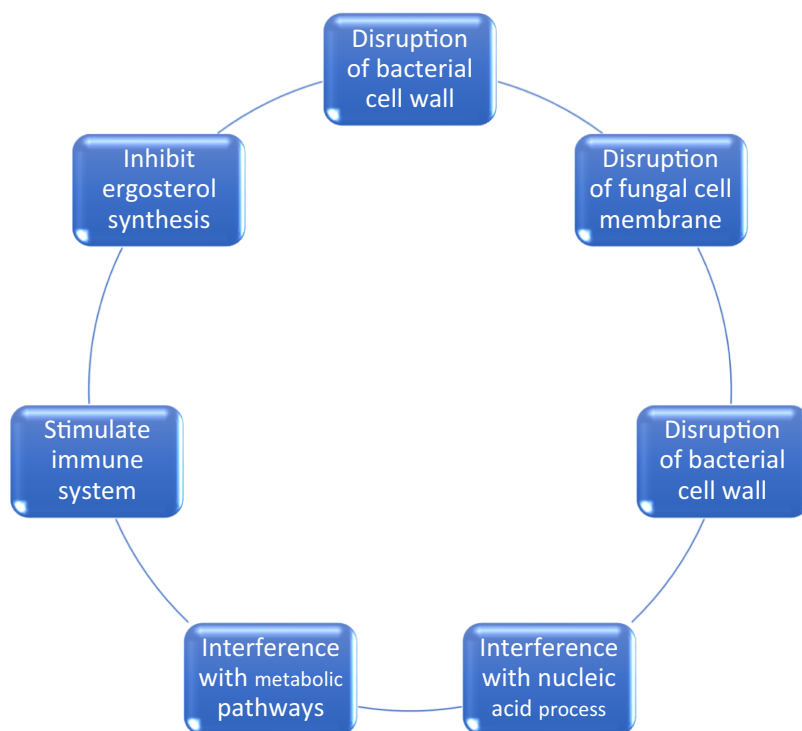
Table 14.1 Types of marine microbial products as antimicrobials agents.

Antimicrobial product	Source	Biological activity	Structural classification	References
Macrolactin A	<i>Bacillus subtilis</i>	Antibacterial	(Macrolide) Polyketide	Chakraborty et al. (2018)
Surfactin	<i>Bacillus amyloliquefaciens</i> , <i>B. subtilis</i>	Antibacterial and Antifungal	Lipopeptide	Xu et al. (2014)
Chromacilin, Methyl chromenoate	<i>Bacillus amyloliquefaciens</i>	Antibacterial, antifungal	Polyketide, chromone	Chakraborty et al. (2018)
Tropodithietic acid	<i>Pseudovibrio</i> sp.	Antibacterial	Dithietane	Raina et al. (2016)
Tirandamycins	<i>Streptomyces amycinicus</i>	Antibacterial	Polyketide	Huang, Kong, et al. (2019) , Huang, Song, et al. (2019)
PCA (Phenazine-1-carboxylic acid)	<i>Pseudomonas aeruginosa</i>	Antibacterial	Polyketide	Zhang et al. (2017)
Penicisimpin A, B, C	<i>Penicillium simplicissimum</i>	Antifungal	Terpenes	Xu et al. (2016)
Fusolanone B	<i>Fusarium solani</i>	Antifungal	Polyketide	
Arenimycin	<i>Salinispora arenicola</i>	Anticancer and antibacterial	Polyketide	Asolkar et al. (2010)
Pacificanones A & B	<i>Salinispora pacifica</i>	Antibacterial	Polyketide	Oh et al. (2008)
Polymyxin	<i>Bacillus polymyxa</i>	Antibacterial	Lipopeptide	
Pseudomononic acid	<i>Pseudomonas fluorescens</i>	Antibacterial	Polyketide	Gao et al. (2024)
Bacitracin	<i>Bacillus laterosporus</i>	Antibacterial	Polypeptide	Zhang et al. (2023)
Manzamine A	<i>Micromonospora</i> sp	Antibacterial and antifungal	Macrolides	Lin et al. (2023)
Actinomycins D, collismycin C	<i>Streptomyces</i> sp	Antibacterial	Peptides	Zhang et al. (2016) , Lee et al. (2017)

(Continued)

Table 14.1 Types of marine microbial products as antimicrobials agents. *Continued*

Antimicrobial product	Source	Biological activity	Structural classification	References
Quinomycin G, Echinomycin	<i>Streptomyces sp.</i> , <i>Gelliodes carnosasp</i>	Antibacterial	Cyclic dipeptides	Zhen et al. (2015)
Basiliskamides A Basiliskamides B	<i>Bacillus laterosporus</i>	Antifungal	Lipopeptides	Gouda et al. (2016)
Ascochyatin	marine-derived fungus, <i>Ascochyta sp.</i>	Antibacterial	Polyketides	Rateb and Ebel (2011)
Ceratinadins A Ceratinadins B	<i>Pseudoceratina sp.</i>	Antifungal	Terpenes	Olatunji (2014) , Gotsbacher and Karuso (2015)
Dicitrinones	<i>Pennicillin sp.</i>	Antifungal	Polyketide	Yin et al. (2023)
Ilamycins	<i>Streptomyces atratus</i>	Antibacterial	Peptides	Cheung et al. (2015)

**FIGURE 14.1**

Major mechanism of actions of antimicrobials derived from marine microorganisms.

activity of these metabolites, their structural properties also play a role in their potent nature. This could be seen in lipopeptides whose antibacterial and antifungal activity increases due to a change in the chemical structure like the addition of carbon chains and lipid moiety (Mandal et al., 2013),

Some examples of antimicrobials (Table 14.2) that have been derived from marine bacteria and fungi with distinct features and modes of actions are listed in the table below. This table focuses on the most common modes of actions exhibited by some marine microbial antimicrobial agents.

14.2.3 Challenges of marine microbial-derived antibiotics

In spite of the immense potential of marine microbes as sources of antimicrobials, there are still challenges that hinder their development and commercialization. It spans from technological to scientific and political as well as economic concerns.

Challenges of studying marine microbes: Marine microorganisms which are resident of the marine environment at deep sea level and surface sea levels are often difficult to reach. It is a critical point in marine drug discovery to have significant amount of organisms and other raw materials from the sea in a sustainable manner. Hence, most researches were carried out in mangroves and coastal

Table 14.2 List of antimicrobials derived from marine microbes and the mode of action they exhibit.

Antimicrobials	Source	Mode of action	References
Streptoidole A, B, C, D	<i>Streptomyces</i> sp ZZ1118	Disrupt cellular processes like DNA replication and protein synthesis	Newaz et al. (2022)
Ilamycin	<i>Streptomyces atratus</i>	Disrupt bacterial cell wall	Jiang et al. (2023)
Surfactin	<i>Bacillus</i> sp	Disrupting bacterial cell membrane by inserting lipid tail and increasing the permeability the membrane	Meena and Kanwar (2015)
Ophiobolin	<i>Emericella varicolor</i> strain GF- 10	Inhibits biofilm formation	Arai et al. (2013)
Penicisteroid A and B	<i>Penicillium chrysogenum</i> QEN-24s	Disrupt fungal membrane and the production of ergosterol	Gao et al. (2011)
Collismycin C	<i>Streptomyces</i> sp MC025	Iron chelating properties interferes with biofilm formation	Lee et al. (2017)
Aspulvinones B, H, R, and S	<i>A flavus</i> KUFA1152	Prevent biofilm formation	Takahashi et al. (1978)

regions (Baharum et al., 2010). With the financial burden of researching, these marine microbes have made this aspect of alternative medicine not feasible.

Cultivation challenges: A considerable number of marine microorganisms are difficult to culture under standard laboratory conditions. It often requires specialized equipments or techniques to replicate the marine suitable environment. Microorganisms inhabiting the deep sea level are usually chemolithoautotrophs and cultivating them is often challenging (Tortorella et al., 2018). Although progress has been made to address this with the use of technology to modify culture environment or bioreactor to allow for more cultivation and production. For example, using mixed fermentation method to mimic the complex marine environment in order to boost production (Lindequist, 2016).

Low yield of compounds: Many marine microbial bioactive products are produced in minimal quantities making extraction and purification challenging. This could in turn hinder the feasibility of large scale production and commercialization. The alternative solution to this was to chemically synthesize these compounds with similar biochemical pathways. For this to be successful, proper studies should be carried out on the target organisms and their products beforehand. These products with biological activity are often unique and complex in structure, making it difficult to replicate them unless with simpler structures (Lindequist, 2016). The same genetic and technological selection techniques used for strain selection for terrestrial microbes can be applied to marine isolates (Kasanah & Hamann, 2004).

Environmental and ethical issues: Isolating microbes producing antimicrobials from the marine space would shift the balance of the ecosystem, microbes cover most parts of this environment and are still yet to be explored and discovered making them more abundant than any sea life form. Microbes play an essential part in the continuation of life in the oceanic environment; they are responsible for decomposition and nutrient cycling, photosynthesis, and detoxification.

Regulatory issues: The path to the implementation and commercialization of marine antimicrobials is an expensive one. From the clinical trials to regulations, all these processes often slow down research and deter investors from making contributions.

14.3 Antimicrobial products of marine microbes: current detection and control

Marine compounds possess distinct structural features, such as unconventional ring systems, halogenation, and branching, as well as sulfated polysaccharides. Their interaction with biological targets in novel ways differs from traditional antibiotics and is being enabled by these unique features. The likelihood of cross-resistance which is a major obstacle in the battle against antimicrobial resistance is being tackled by the diversity and uniqueness in function and structure (Labes, 2023).

Copper, zinc, and cadmium are heavy metals present in the aquatic environment and microbes have discovered elaborate mechanisms to coexist with them. The triggering of the defensive mechanisms in marine microbes is a result of the exposure to these substances which then act as stressors to improve the synthesis of secondary metabolites (Shams et al., 2022). This response yields a diverse array of biologically active compounds including antimicrobials, pigments, and antimicrobials, which play vital roles in ensuring the survival of microorganisms. The production of these compounds serves as a form of protection against the harsh environment like damage caused by metallic ions and stress. Furthermore, novel metabolites could also be produced by the presence of these compounds, which fuel complex biochemical pathways. This could in turn favor drug discovery as it unveils new leads for innovative therapies (Ul Hassan et al., 2021).

The productions of stress metabolites are influenced by several factors and to enhance their yields, these factors should be optimized. Metabolite production is influenced by temperature, pressure, nutrient composition, heavy ion supplementation, culture time, and other external factors. While other researches focus on traditional methods of up-scaling culture time and enriching media, this session focuses on the extraction by the use of novel methods like heavy metals and omics technology.

14.3.1 Extraction of antimicrobial products: use of heavy metals

Bioactive compounds production is enhanced by the exposure to stress factors like the presence of heavy metal ion, which is a new method in natural products drug discovery in natural products. For example, the production of enterocin, a broad spectrum antimicrobial peptide by *Actinobacterium Streptomyces* sp. H-1003 is another example of a study that investigates the effect of heavy metals (Hassan et al., 2017). The addition of 2 mM cobalt ions to a customized Gause's medium containing 20 mg/L starch, followed by a 10-day fermentation period at 180 rpm were discovered as the optimal conditions for enterocins production. The enterocin production was greatly optimized, reaching

5.33 mg/L, whereas it was not detectable under normal culture conditions. This method presents a promising approach for novel antibiotic discovery.

14.3.2 Analytical techniques

A photodiode array detector (Waters 996) that was equipped in a “High-performance liquid chromatography (HPLC) system,” “UV detector (SHIMADZU UV-2550)” as well as an autosampler (Waters 717 plus) were used to conduct chemical analysis. Additionally, an “Agilent 1290 infinity II HDR-DAD” and “SHIMADZU LC-2010AHT” systems were employed. A “Bruker AVANCE DRX 500 NMR” spectrometer was used to conduct a nuclear magnetic resonance (NMR), using tetramethylsilane (TMS) as an internal standard. The “ ^1H NMR (500 MHz)”, “ ^{13}C NMR (125 MHz)”, and “DEPT (135) spectra” were recorded at 25°C. The heavy metals used were dependent on the marine microbe of choice (Hassan et al., 2024).

14.3.3 Omics technologies and drug discovery

The conduction of comprehensive analysis of biological systems at the molecular level is now possible with omics technology which has in turn revolutionized drug discovery. Researchers can optimize compound selection, model and predict chemical interactions, and streamline experimental workflows by leveraging computational tools and chemoinformatics. The prediction of drug efficacy and specificity is enhanced by molecular docking simulations, which enable researchers model and bind small molecules to target proteins.

14.3.4 Antimicrobials and common extraction methods

Optimizing the concentration of zinc sulfate in a culture medium was used to improve the synthesis of five novel antibiotics by marine *Streptomyces* sp (Wu et al., 2024). The antibacterial activities of these metabolites were evaluated against multiple Gram-negative and Gram-positive pathogens using in vitro assays. Molecular docking simulations, chemoinformatics approaches, and transcriptomics were employed to elucidate the mechanisms underlying the antibacterial activity of the most promising compound. The identification of the most effective compound, insights into its mode of action, paving the way for the development of novel antibiotics was possible via these strategies (Wu et al., 2024).

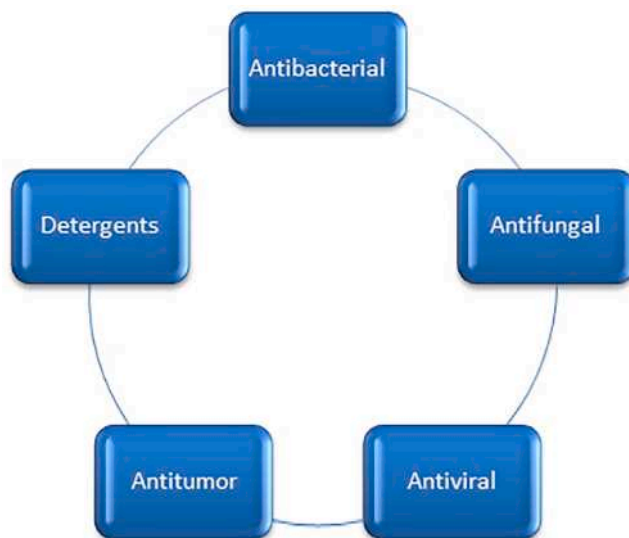
Some antimicrobials produced by marine microbes (Table 14.3) have been selected based in their novel extraction methods.

14.4 Applications of emerging antimicrobials from marine microbes

The widespread of resistant pathogens have called for the exploitation of new source of antimicrobials. The marine microbial community not yet fully explored promising applications in medicine. The production of major secondary metabolites which has been applied to the field of medicine is solely by them. “In 2016, 179 new natural products of marine bacteria were discovered” (Blunt et al., 2016). These natural products have shown various potentials in their applications (Fig. 14.2) as antibacterial, antifungal, antiviral, antiprotozoan, detergents, and antitumor agents.

Table 14.3 A number of current metabolic compounds produced by marine microbes, with the extraction method.

Antimicrobial product	Source	Extraction method	References
penicisteroid A	<i>Penicillium chrysogenum</i>	Solvent based, isolation and cultural	Gao et al. (2011)
Dicitrinones	<i>Penicillium</i> sp	Chemical extraction, DNA and isolation and culturing	Fan et al. (2022)
ilamycin B1–F and ilamycins G–R.	<i>S. atratus</i>	Chemical solvent, heavy metals	Ma et al. (2017)
Propolone Streptazolin streptazone B1 and C	<i>Streptomyces</i> sp.	Solvent based	Chung et al. (2007) , Mothana et al. (2022) , Puder et al. (2000)

**FIGURE 14.2**

Applications of marine microbial products as antimicrobials.

Fig. 14.2 summarizes the use of emerging microbial products as antimicrobials. The marine products have been applied in the above aspects with varying levels of progress. The applications as antifungal and antibacterial have been addressed in the previous sessions. We shall be detailing the use as antiviral, antitumor, and detergents.

14.4.1 Antivirals

Viruses inhabit the ocean, many of which are bacteriophages. Since the phages and bacteria co-habit the aquatic environment, the bacteria are pressured to devise various mechanisms of actions against viral attacks. This could in turn be harnessed as antivirals. Examples of antivirals produced by marine bacteria include *Streptomyces koyangensis* SCSIO802 in which was isolated three novel abyssomicins D, E, and A2, two dimer neoabyssomicins F & G that showed effects on herpes simplex viruses and vesicular stomatitis (Huang, Kong, et al., 2019; Huang, Song, et al., 2019). Wailupemycin J, and [®]-wailuemyacin K isolated from *Streptomyces* sp OUCMDZ-3434 shows effect against influenza virus (Liu et al., 2017). A marine fungus *Aspergillus terreus* OUCMDZ-1925 produced Rubiolide S, which showed inhibition towards H₁N₁ virus (Zhu et al., 2014), *Cladosporium sphaerospermum* 2005-01-E3 isolated from sediments collected in the pacific ocean produced “Cladocin C” which has antiviral activity against “Influenza A virus” (Wu et al., 2014), *Penicillium chrysogenum* isolated from soft coral at terra bay, produced novel sorbicillinoids that showed inhibitory activity against H₁N₁ virus (Peng et al., 2014)

14.4.2 Antitumor agents

The anticancer potential of marine microbial products remains a promising field for future research and therapeutic development. Marine microbes are also reservoirs for cytotoxic natural products (Santos et al., 2020). Several marine-derived compounds have already shown substantial antitumor activity and continue to be explored for their clinical applications. Salinosporamide A is an example, Dentigeromycin E isolated from *Streptomces albogriseolus* JB5 showed moderate toxicity against “colorectal cancer HCT116”, “breast cancer MDA-MB-231” and lung carcinoma (Shin et al., 2018). Bryostatin 1, originally isolated from *Bugulaneritina*, modulates protein kinase C activity and has been investigated in clinical trials for various cancers (Kollár et al., 2014). Marizomib, in addition to its role as a proteasome inhibitor, has the unique “ability to cross the blood-brain barrier, making it a strong candidate for treating central nervous system malignancies” (Gazzaroli et al., 2023). Although challenges remain in its clinical development, ongoing studies are evaluating its potential in combination therapies, particularly for hematologic malignancies and solid tumors.

14.4.3 Detergents and surface active compounds

The production of emulsifiers, wetting agents, dispersants, and detergents by marine microorganisms has positioned them as potential sources of detergents. An example of active surface compounds is the biosurfactant. The production of a crude oil emulsifier by *Flavobacterium myroides* (Maneerat et al., 2006) and fatty acids by marine yeast (Luepongpatana et al., 2017) are examples of marine microbes producing surface active compounds. Examples of low-molecular weights surface active molecules produced by marine microorganisms include Rubiwettin R1 synthesized by *Serratia rubidaea* (Matsuyama et al., 1990), Pumilactin by *Bacillus pumilus* (Saggese et al., 2018), Surfactin from *Bacillus licheniformis* isolated from sponges at North bay, Port Blair (Anburajan et al., 2015).

14.5 Prospects of marine microbial products as antimicrobials

The applications of marine microbial bioactive products in diverse industries and fields like the cosmetics, vaccine development pharmaceuticals have positioned them as priceless (Corinaldesi et al., 2017). The development of vaccines and cosmetics is now the research focus of these compounds which will pave way for groundbreaking advancements and revolution of the industries. This session focuses on the future opportunities and applications of marine microbial products as antimicrobials.

14.5.1 Drug development

Marine-derived bioactive compounds are continuously being researched as potential candidates for novel therapeutics. The future of drug discovery is likely to be significantly influenced by marine microorganisms due to the rapid increase in antimicrobial resistance (Gerwick & Fenner, 2013). An example can be seen in the synthesis of “Salinosporamide A” by the marine bacterium *Salinispora tropica*. It is seen as a potent proteasome inhibitor showing great potential against multiple myeloma and glioblastoma (Mandlik & Mandlik, 2021; Rai et al., 2024). Though research is still underway to understand its mechanism and efficacy, this compound could be considered an effective treatment against treatment resistant malignancies.

A marine fungus produced Plinabulin which is a microtubule destabilizing agent, and undergoing Phase III clinical trials for non-small-cell lung cancer. The ability of Plinabulin to enhance antitumor efficacy reduce chemotherapy-induced neutropenia while presents an exciting avenue for future combination therapies (Albahde et al., 2021; Wang et al., 2020). Further research and advancement may lead to personalized therapy.

14.5.2 Advancements in vaccine development

Vaccine development is another area of research marine microbes that are on the brink of revolutionizing (Gogineni et al., 2015). The immunomodulatory effects of certain marine-derived compounds propose that they could serve as vaccine adjuvants or be incorporated into novel immunotherapies. For example, the demonstration of the ability of Bryostatins, synthesized by marine bryozoans, to modulate protein kinase C activity essential for immune system regulation (Kollár et al., 2014; Raghuvanshi & Bharate, 2020; Trenn et al., 1988). Further research could lead to their insertion in vaccines for infectious diseases and cancer immunotherapy.

Due to the increasing threat of global pandemics, the need for novel vaccine strategies which marine microorganisms offer cannot be overemphasized. Future studies may expose novel immunostimulants which will be marine-microbial derived peptides and polysaccharides.

14.5.3 Cosmeceutical and cosmetic

Marine microbial products are now considered sources of natural and effective ingredients by the cosmetic industry. The bioactive compounds may greatly influence skincare and dermatological treatments (Corinaldesi et al., 2017).

The development of photoprotective agents from marine microorganisms is now one of the main areas of focus. Example of a natural sunscreen is “Mycosporine-like amino acids (MAAs),” derived from marine bacteria and fungi, which exhibit strong UV-absorbing properties, making them potential candidates as natural sunscreens. MAAs could replace synthetic UV filters as more sustainable and safer option offering minimal environmental impact and enhanced skin protection (Corinaldesi et al., 2017).

The antiaging and skin-rejuvenating properties of marine microbial derived exopolysaccharides have continuously positioned them as viable alternatives. These are ideal as antiaging creams and serums haven displayed their moisturizing and skin barrier-enhancing capabilities, (Polshettiwar et al., 2025). Biotechnological approaches may further enhance the extraction and modification of these compounds, leading to next-generation skincare products with superior efficacy.

14.5.4 Clinical trials and future prospects

Numerous marine-derived bioactive compounds have advanced through clinical trials. An example is Marizomib, which is currently in Phase I and II trials, showing activity against multiple myeloma and glioblastoma. With further research it may revolutionize the oncology field. Another example is seen in Plinabulin’s ongoing Phase III trials for non-small-cell lung cancer. Further studies suggest that it could soon be incorporated into standard cancer treatment regimens, particularly in combination therapies.

Marine microorganisms will likely remain at the forefront of biopharmaceutical and biotechnological research due to its potentials and sustainable impact. With continued investments, marine biotechnology will open novel opportunities for human health improvement.

14.6 Conclusion

Marine microorganisms represent a rich reservoir of compounds with diverse applications in vaccines, cosmetics, anticancer therapies, and pharmaceuticals. These marine-microbial-derived antimicrobials show great potentials as alternative therapies against drug resistant infections, which is now a global threat. Biotechnological and synthetic biology advancements will enhance the discoveries and production of these antimicrobials, paving the way for novel therapeutic agents. Some of the challenges like production, extraction, purifications, and study limit this progress. Future research should focus on the optimization of these biologically active compounds while overcoming the challenges associated. The potentials of marine-derived bioactives will continue to expand and revolutionize medicine, once again positioning the ocean as the richest source of resources.

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Current innovations in
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Marine microbial products and corrosion mitigation

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Kingsley Erhons Enerijiofi¹, Soumitra Nath², Jonathan Inetianbor³ and Daniel Makolo⁴

¹*Department of Biological Sciences, College of Basic, Applied and Health Sciences, Glorious Vision University, Ogwa, Edo State, Nigeria,*

²*Department of Biotechnology, Gurucharan College, Silchar, Assam, India,*

³*School of Health and Life Sciences, Coventry University Group, Coventry, United Kingdom,*

⁴*Department of Microbiology, Baze University, Abuja, Nigeria*

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15.1 Introduction

Corrosion occurs when materials usually metal slowly break down due to chemical or electrochemical reactions with their surroundings. Electrons transfer from the metal to an oxidizing agent, resulting in ion loss and the accumulation of corrosion byproducts (Al-Baghdadia & Alamierya, 2025). It is a costly nuisance, hitting industries, infrastructure, and the environment hard with damaged equipment, safety risks, and hefty repair bills (Bhaskaran et al., 2018; Wang et al., 2019; Wang, Zheng, et al., 2019).

The marine environment; spanning oceans, seas, and coastlines covers more than 70% of our planet (Ifi et al., 2019). It is a dynamic, life-giving system, dishing out food, storing carbon, shielding shores, and cradling biodiversity (Ajuzie et al., 2015). At its core, tiny powerhouses like phytoplankton, seaweeds, and seagrasses churn out organic matter via photosynthesis, kicking off the food web (Field et al., 1998). The ocean also doubles as a climate hero, soaking up about a quarter of the CO₂ we pump into the air (Sabine et al., 2004). However, it is increasingly threatened by climate change, pollution, overfishing, and habitat destruction (Enerijiofi et al., 2018). Saving it calls for teamwork, sustainable thinking, and global cooperation. Often flying under the radar, though, are the microbes; bacteria, archaea, viruses, and fungi that keep this whole show running. They handle nutrient recycling, break down organic materials, distort the climate, and juggle biogeochemical cycles (Arnosti et al., 2014; Flombaum et al., 2013). Without them, the ocean’s delicate balance would collapse.

15.2 Composition and diversity of marine microbial communities

Marine microbes are a wildly varied bunch, with bacteria and archaea dominating the ocean’s microbial crowd. You have got heavy hitters like *Proteobacteria*, *Cyanobacteria*, and *Bacteroidetes*, alongside archaea like *Thaumarchaeota*, which keep the nitrogen cycle humming (Ajuzie et al., 2015; Fuhrman, 2009). These tiny survivors pop up everywhere from sun-drenched coastal waters to the pitch-black depths of hydrothermal vents adapting to whatever the ocean throws at them. In shallow waters, *Cyanobacteria* like *Prochlorococcus* and *Synechococcus* soak up sunlight to churn out organic matter, fueling life on a massive scale. Down in the deep sea, it is a different story chemoautotrophic bacteria and archaea tap into sulfur or methane to power their existence, thriving where most life would not dare (Jørgensen & Boetius, 2007). Extremophiles and psychrophiles, halophiles, laugh in the face of freezing temps or salty extremes (Bhowmik et al., 2023). Also, viruses should not be overlooked especially bacteriophages, which shake up microbial life by infecting bacteria, swapping genes, and recycling nutrients. When they burst their hosts open, they spill organic goodies into the water, keeping the food web spinning (Suttle, 2007).

15.3 Functional roles of marine microbes in corrosion and mitigation

Marine microbes are the unsung heroes (and sometimes villains) of the ocean's carbon, nitrogen, and sulfur cycles, tying it all into Earth's bigger systems. They are behind processes like biofilm buildup, acid production, redox reactions, and even hydrogen embrittlement (Beech & Sunner, 2004; Videla & Herrera, 2005). Photosynthetic champs like *Prochlorococcus* and *Synechococcus* churn out heaps of organic matter (Partensky et al., 1999), while biofilms think microbial cities sprout on ship hulls, offshore rigs, and rocks, sparking biofouling and corrosion. Sulfate-reducing bacteria (SRB), *Desulfovibrio* species are major contributors to corrosion, generating hydrogen sulfide that severely degrades metal surfaces (Videla & Herrera, 2005). But it is not all bad news. We can fight back with biocides, coatings, cathodic protection, and MIC-specific inhibitors like benzalkonium chloride (Ashassi-Sorkhabi et al., 2017; Zhang et al., 2018). Researchers are developing corrosion-resistant materials, better monitoring tools, and sustainable fixes think nanotech coatings, microbial fuel cells, and genomic deep dives into these communities (Enerijiofi, Musa, et al., 2024; Probandt et al., 2017; Zhang et al., 2020a, 2020b).

15.4 Microbiologically influenced corrosion

Microbiologically influenced corrosion (MIC) occurs when microbes like bacteria, archaea, or fungi team up to corrode through metals. It is a problem in water, soil, and industrial setups alike (Liu et al., 2022, 2023).

15.4.1 Key microbial species involved in corrosion

Certain microbes are crucial in producing corrosion's, especially in wet environments. These include:

1. **Sulfur-reducing bacteria:** *Desulfovibrio* and *Desulfobacter* produce hydrogen sulfide, a metal-degrading threat (Liu et al., 2023).
2. **Iron-oxidizing bacteria:** *Gallionella* and *Sideroxydans* build-up iron oxides that wear metals down (Liu et al., 2022).
3. **Acid-producing bacteria:** *Acidithiobacillus* and *Leptospirillum* secrete acids that react with the surfaces of iron pipes (Butar et al., 2024; Liu et al., 2023).

15.4.2 Mechanisms of microbiologically influenced corrosion

MIC is a complex interaction between microbes, metals, and their surroundings. Here's how it breaks down:

1. **Biofilm formation:** Microbes stick to metal, building slimy biofilms with extracellular goo (EPS) to anchor their colonies (Aransiola et al., 2022, 2024; Liu et al., 2022, 2023).
2. **Electrochemical mechanisms:** Anodic reactions involve microbes accelerating metal degradation through corrosive byproducts, while cathodic reactions, such as oxygen or hydrogen reduction, further drive the corrosion process (Shu et al., 2024; Zhang et al., 2024).

15.4.3 Environmental factors affecting microbiologically influenced corrosion

The ocean's mood swings like temperature, pH, nutrient levels, and electrolyte makeup call the shots on MIC. Warmer water enhances microbial activity, pH tweaks their growth, nutrients feed, and ion-heavy water amps up the electrochemical chaos (Al-Baghdadia & Alamierya, 2025; Xu et al., 2025).

15.4.4 Case studies of microbiologically influenced corrosion in marine industries

MIC is a serious issue, as evidenced by the Alaska Pipeline oil spill in 2006. A tiny hole courtesy of SRB pumping out hydrogen sulfide ripped open a BP pipeline, spilling 267,000 gallons of crude across Alaska's North Slope. The fallout? A \$255 million fine, a 2% stock drop, and a pricey pipeline swap. This is a stark reminder of MIC's real-world sting.

15.5 Marine bacteria as a source of antimicrobial compounds

Marine bacteria like those from the *Pseudomonas*, *Bacillus*, and *Vibrio* crews are naturals at churning out antimicrobial compounds that can take down a wide range of nasty pathogens. Living in the ocean's tough neighborhoods has pushed these microbes to evolve some clever metabolic tricks, producing secondary metabolites with unique chemical flair. Take *Pseudomonas*, for example, it whips up *pyrrolnitrin*, a heavy-hitting antifungal that is been put through its paces against *Candida* and *Aspergillus* (Subramani & Aalbersberg, 2012). Then there is *Bacillus*, pulled from marine muck, crafting lipopeptides like surfactin and fengycin that pack a punch against multidrug-resistant bugs (Jiang et al., 2020). *Vibrio*, meanwhile, brings halogenated furanones to the table compounds that mess with bacterial chatter (quorum sensing) and stop biofilms in their tracks, hinting at some exciting antiinfection potential.

15.5.1 Actinomycetes and their bioactive treasures

Actinomycetes, especially the *Streptomyces* crew, are the heavy hitters of the antibiotic world, churning out over 70% of the stuff you'd grab at the drugstore. The marine branch of these stringy bacteria has everyone talking, thanks to finds like salinosporamide, a compound that is got some serious muscle against microbes and cancer cells (Fenical & Jensen, 2006). Then there is a lineup of other stars from marine actinomycetes:

- Marinopyrrole A: A MRSA-slaying machine.
- Abyssomicin C: Takes on vancomycin-resistant *Enterococcus* (VRE) like a champ.
- Daryamides: A solid hitter against Gram-positive bacteria.

These bioactive treasures are goldmines for drug discovery, especially as we scramble to tackle resistant infections.

15.5.2 Marine fungi and their antimicrobial products

Marine fungi are a force to be reckoned with, flourishing in the ocean's salty, high-pressure chaos and spitting out a crazy array of bioactive compounds. *Penicillium*, *Aspergillus*, and *Fusarium* species have researchers researching on their potential use. Deep-sea *Penicillium* keeps it old-school, pumping out penicillins and cephalosporins, the kind of game-changers that rewrote medical history (Wang et al., 2019; Wang, Zheng, et al., 2019). *Aspergillus* throws down with terrein and gliotoxin, landing solid punches against bacteria and fungi alike (Li et al., 2018; Li, Zhang, et al., 2018). And *Fusarium*? It contains fusaric acid, a broad-spectrum antimicrobial compound that effectively targets both Gram-positive and Gram-negative bacteria with equal potency.

15.6 Corrosion mitigation using marine microbial products

Marine microbial products are shaking things up in clever, planet-friendly ways to fight corrosion, especially in the brutal marine environment. By leaning into what microbes do naturally, their metabolic flair and bioactive tricks, these solutions ditch the nasty side effects of traditional chemical inhibitors. We will examine the mechanisms of bio-based inhibitors, biosurfactants, biopolymers, and biofilms are rewriting the corrosion protection playbook, with hard science and real-world results to back them up.

15.6.1 Bio-based corrosion inhibitors

Bio-based inhibitors from marine microbes are flipping the script on corrosion control. They either neutralize the troublemakers or throw up a protective barrier on metal surfaces. Consider *Bacillus subtilis*, which exhibits a remarkable process known as biomineralization, laying down a calcite layer on steel that is like a suit of armor. This does not just put the brakes on corrosion; it can seriously extend a material's shelf life. Lab tests show it cuts corrosion rates by 80% after a month in seawater, positioning it as a heavy hitter for marine equipment (Guo et al., 2019). Then you have got quinoline-based biocides, squaring off against SRB the usual suspects behind corrosion—and coming out ahead. Seawater experiments pegged them at over 75% corrosion reduction, making them a slick, greener swap for synthetic options (El-Shamy et al., 2009). And if you want something with a little pizzazz, green nanomaterials like graphene oxide-silver composites swoop in, smothering biofilms and shaving uniform corrosion on marine steel by up to 60% (Taghavi Kalajahi et al., 2021). These concepts are not merely theoretical; they are well positioned to play a crucial role in protecting essential materials (Table 15.1).

15.6.2 Applications of biosurfactants and biopolymers

Biosurfactants and biopolymers are like the unsung heroes of microbial corrosion defense, pulling double duty by keeping microbes from setting up camp on metal surfaces and throwing up protective shields. Take rhamnolipids, for instance, produced by *Pseudomonas aeruginosa*, these biosurfactants are champs at breaking up biofilms on metals. Research shows they can slash biofilm-driven corrosion

Table 15.1 Summary of corrosion mitigation techniques using marine microbial products.				
Technique	Mechanism	Efficiency (%)	Application environment	References
Biom mineralization	EPS and calcite deposition	80	Steel in seawater	Guo et al. (2019)
Biosurfactant	Glycolipids	87	Carbon steel in high salinity	Parthipan et al. (2018)
Green nanomaterials	Graphene oxide-silver composite	60	Marine steel	Taghavi Kalajahi et al. (2021)
Encapsulated biofilms	<i>Paenibacillus polymyxa</i> biofilms	70	Aluminum alloys	Gittens (2011)
EPS-based barriers	EPS secretion by <i>Bacillus</i> species	50	Marine steel	Li, Cheng, et al. (2021) , Li, Zhou, et al. (2021)

on steel by up to 80%, especially in salty, marine settings (Seter et al., 2012). Then there is chitosan, a biopolymer that is a real team player when mixed into zinc coatings. It knocks microbial adhesion down by 70% and boosts corrosion resistance crucial when SRB are lurking around. Compared to plain old zinc coatings, chitosan-zinc combos hold up way better in tough conditions (Das et al., 2024). And do not sleep on extracellular polymeric substances (EPS) from marine microbes like *Bacillus* species, these biofilms create dense, robust barriers on metal surfaces, effectively protecting against chemical corrosion and microbial activity. Extracellular polymeric substances could be a natural solution for corrosion control.

15.6.3 Potential use of biofilms in corrosion protection

Biofilms usually get a bad rap for causing corrosion, but flip the script, and they can actually be protective allies. When noncorrosive microbial strains are in charge, biofilms turn into shields against environmental and microbial threats (Nath et al., 2024). For example, biofilms from *Tenacibaculum* sp. have been shown to cut corrosion rates on marine steel by 50%, thanks to EPS secretions that act like a buffer against the nasty stuff (Li, Cheng, et al., 2021; Li, Zhou, et al., 2021). There is also a cool twist with sol-gel coatings, think of them as high-tech wrappers for biofilms. When *Paenibacillus polymyxa* biofilms get tucked into these coatings, they block microbial squatters while toughening up metal surfaces. Real-world tests show these setups can hit 70% corrosion inhibition on aluminum alloys in marine conditions (Gittens, 2011). It is a smart way to borrow from nature's playbook, using microbial teamwork to build sustainable corrosion defenses.

15.7 Marine microbes in bioengineering and biotechnology

Marine microbes are like the Swiss Army knives of bioengineering and biotech that are adaptable, versatile, and loaded with tricks from surviving the ocean's extremes. Bacteria, archaea, fungi, and microalgae are driving breakthroughs in bioremediation, drug development, biomaterials, and bioenergy (Enerijiofi, Onuoha, et al., 2024). Their wild metabolic pathways and enzyme skills are opening doors for industrial and environmental wins (Jensen & Fenical, 2019). With a treasure chest of unique genes and processes, plus tools like omics and synthetic biology, these microbes are ready to supercharge innovation across the board.

15.7.1 Marine microbial bioproducts in biotechnology

Marine microbes are biotech goldmines, pumping out enzymes, antibiotics, pigments, and biosurfactants shaped by the ocean's harsh vibes. These compounds often have quirky structures and functions that terrestrial microbes cannot touch, making them perfect for jobs needing extra grit and staying power.

15.7.1.1 Marine microbial enzymes

These microbes dish out extremophilic enzymes that laugh at high salt, scorching heat, or crushing pressure. Proteases, lipases, and cellulases from marine sources are workhorses in bioremediation,

pharmaceuticals, and food processing (Singh & Reddy, 2021). Cold-adapted enzymes from *Pseudoalteromonas* exhibit exceptional efficiency in low-temperature catalysis, offering energy-saving advantages for industries such as detergent production (Auta et al., 2022; Trincone, 2017). Meanwhile, marine DNA polymerases and ligases hold strong in salty settings, making them MVPs for molecular biology and genetic engineering.

15.7.1.2 Marine microbial antimicrobials and pharmaceuticals

Marine bacteria like *Streptomyces* and *Salinispora* are antibiotic and anticancer heavyweights. Salinosporamide A from *Salinispora tropica*, for instance, is showing big promise as a cancer fighter (Fenical et al., 2020). Marine fungi like *Aspergillus* and *Penicillium* chip in with secondary metabolites tackle microbes and inflammation (Zhang et al., 2022). With antibiotic resistance on the rise, these finds are clutch, and they do not stop the antiviral, antifungal, and immunosuppressive powers, which widen their reach (Ekozin et al., 2025). Even marine sponges, teeming with microbial roommates, are re-emerging as key sources of bioactive compounds with potential antimalarial, TB, and brain diseases.

15.7.1.3 Marine microbial polysaccharides and biomaterials

Marine polysaccharides like alginates, EPS, and chitin spin-offs are bioengineering stars, shining in wound healing, drug delivery, and tissue engineering. EPS from *Alteromonas* species, with their biofilm-building knack, are handy for biotech and clean-up jobs (Casillo et al., 2018). Their flowy properties and biocompatibility give them an edge over land-based options. Plus, marine bacterial cellulose and bioplastics are stepping up as green alternatives to petroleum plastics, tackling pollution.

15.8 Case studies and applications

Marine microbial products are shaking up corrosion protection across industries—think marine setups, oil and gas pipelines, and industrial gear. By tapping into these microbes' natural defenses, researchers are crafting sustainable, high-impact solutions for some of the roughest environments out there. They boost durability and cut reliance on harsh chemical fixes, making them a smart bet for keeping assets safe long-term.

15.8.1 Real-world applications in marine industries

Marine microbes are proving their worth in the field. Take *Pseudoalteromonas lipolytica* biofilms woven into hybrid organic–inorganic coatings on steel they slash corrosion rates by 80% and even self-heal, making them tough enough for long-haul marine duty (Liu et al., 2018). Then there is biomineralization with *Bacillus subtilis* in marine concrete, it drops sulfate diffusion by 40%, keeps SRB in check, and stretches concrete life by over 30% (Sun et al., 2023). As Table 15.2 shows, these microbial fixes are cost-effective and adaptable, poised to replace old-school methods across marine and industrial scenes.

Table 15.2 Applications of marine microbial products for corrosion mitigation.

Application	Microbial product	Efficiency (%)	Environment	References
Steel protection	<i>Pseudoalteromonas lipolytica</i> biofilm	80	Marine steel	Liu et al. (2018)
Concrete corrosion prevention	Biom mineralized films	40	Marine concrete	Sun et al. (2023)
Pipeline corrosion mitigation	Organic corrosion inhibitors	70	Oil pipelines	Skovhus et al. (2017)
Aluminum alloy protection	Sol-gel coatings with biofilms	90	Marine infrastructure	Akid et al. (2008)
Multifunctional coating	Extracellular polymeric substances	90	Carbon steel	Tuck et al. (2021)
Florida bridge steel protection	Antifouling coating	Varies	Steel piles in seawater	Permeh, Lau, and Duncan (2020)

15.8.2 Success stories and challenges

Consider sol–gel coatings enhanced with *Paenibacillus polymyxa* biofilms. They enhanced the corrosion resistance of carbon steel by an impressive 90% in a 6-month test in tidal estuaries (Alcantara-Garcia et al., 2020). That is a solid win, showing how microbial coatings can hold their own in brutal marine conditions and keep things protected for the long haul. In the oil and gas world, Where *Desulfovibrio* spp. biofilms actively contribute to pipeline degradation, smart microbial treatments are stepping up. A North Sea field study showed a multifunctional inhibitor slashing SRB activity by 70%, tacking an extra 15 years onto pipeline life (Skovhus et al., 2017). But it is not all smooth sailing as steel piles in Florida coated with protective layers started breaking down over time, losing their edge against biofouling and SRB (Permech, Lau, & Duncan, 2020). It is a reminder that we need tougher, more adaptable materials to make these solutions stick in the real world.

15.8.3 Economic and environmental wins

Corrosion runs the global economy dry to the tune of 3%–4% of GDP every year (Lobo et al., 2024; Schmitt et al., 2009). A massive hit that screams for smart, sustainable fixes. Marine microbial products are stepping in as wallet-friendly heroes, cutting maintenance costs and stretching infrastructure life. Take cetrimonium trans-4-hydroxy-cinnamate (CTA-4OHcinn), it wiped out biofilms across multiple strains on carbon steel, outshining traditional chemical inhibitors while keeping the environment happy (Tuck et al., 2021). It's a practical and green option that could save industries big time.

15.9 Future directions and challenges

Marine microbial products are a bright spot for tackling corrosion in harsh marine and industrial settings, but there is work to do to unlock their full potential. We need to beef up the staying power of microbial coatings, fine-tune biomineralization tricks, and sharpen bio-based inhibitors against a range of corrosive threats. Synthetic biology and omics tech could fast-track the hunt for microbial strains with killer protective skills, while pairing them with nanomaterials might enhance resistance while maintaining its environmentally friendly properties. Scaling up production and running long-term field tests would be key to turning lab wins into everyday solutions—bridging that gap could make these microbial strategies the go-to over old-school corrosion control.

15.9.1 Innovations in marine microbial research

The next big leaps in fighting corrosion are all about getting under the hood of marine microbial ecosystems and their biochemical magic. Tools like high-throughput sequencing and metagenomics have changed the game, letting us zero in on the microbial gangs driving corrosion or standing guard against it. *Zetaproteobacteria* and *Epsilonproteobacteria*, for example, have been caught red-handed playing key roles in biofilm buildup and corrosion chaos (Dang et al., 2011). Meanwhile, metabolomics and proteomics are pulling back the curtain on treasures like EPS and biosurfactants

that beef up resistance. A prime case? *Pseudoalteromonas lipolytica*'s biofilm-powered biomineralization, it slashed steel corrosion by over 80%, offering a green, practical fix for marine equipment (Liu et al., 2018). Blending these high-tech molecular tricks with synthetic biology and machine learning could be a game-changer. Imagine engineering specialized microbial consortia with exceptional protective capabilities and self-healing coatings are highly durable and scalable for industrial applications.

15.9.2 Artificial Intelligence and bioinformatics in product discovery

Artificial intelligence and bioinformatics are set to flip the script on how we hunt down and harness marine microbial products. Machine learning acts as a powerful analytical tool, processing complex datasets to identify the most effective microbial strains or consortia for specific applications. It is already sniffed out winning combos that boost corrosion resistance no matter the salinity or pH, fast-tracking bioengineered wins (Finny, 2024; Tarolli et al., 2024). On the flip side, bioinformatics is mapping out the genetic breadcrumbs linked to EPS production and biofilm grit, opening the door to tweaks that crank up the juice. Take *Bacillus subtilis*, genetic modifications enhanced its calcite deposition efficiency by 30%, turning it into a biomineralization beast (Sun et al., 2023).

15.9.3 Barriers to large-scale applications

Marine microbial products have huge promise, but scaling them up for industrial and marine use comes with some serious hurdles like production bottlenecks, environmental durability, and regulatory hoops. Clearing these would be make-or-break for getting microbial tech into the field.

15.9.3.1 Production challenges

Ramping up microbial output for industry is tricky, keeping things consistent and affordable is not a walk in the park. Fermenting EPS or biosurfactants hinges on nailing nutrient levels, pH, temperature, and oxygen, all of which mess with yield and quality. Tweaking conditions can boost EPS production by 60%. However, it often requires advanced equipment and continuous monitoring, jacking up costs (Gaur et al., 2021). Rhamnolipids, a corrosion-busting biosurfactant, run \$4–6 per kilogram to produce, compared to \$1–2 for chemical surfactants. With biosurfactant demand growing at 5.1% yearly, there is pressure to slash costs using waste glycerol from biodiesel cut production by 30%, pointing to a greener and cheaper path forward (Chilakamarry et al., 2021; Tuck et al., 2021).

15.9.3.2 Environmental stability

Marine environments are brutal shifting temps, high salt, and biofouling can tank microbial product performance. EPS coatings start to falter above 40°C, limiting their use in hot zones (Sun et al., 2023), and biofouling organisms can gum up biofilm coatings, cutting resistance by 20% in 6 months (Perme, Lau, Tansel, & Duncan, 2020). Hybrid materials blending microbial goodies with tough polymers, or encapsulating biofilms in sol–gel matrices that holds 90% resistance in salty conditions are promising fixes (Akid et al., 2008).

15.9.3.3 Regulatory and safety concerns

Rolling out microbial products in the wild means navigating a regulatory maze agencies like the ECHA demand rigorous testing to avoid ecological blowback, stretching approval times and costs (Puri et al., 2023; Williams et al., 2009). Genetically modified microbes, like *Bacillus subtilis* with 30% better calcite output, raise extra flags, horizontal gene transfer or ecosystem shake-ups need tight monitoring to keep risks in check.

15.9.4 Emerging technologies to tackle challenges

New tech is stepping up to boost microbial product durability. Encapsulating biofilms in sol-gel matrices kept 90% corrosion resistance after 6 months in high salt (Akid et al., 2008), while self-healing coatings with smart materials and active microbes fix cracks on their own, cutting upkeep costs. Omics advancements are crafting specialized strains for specific conditions, making them sharper and more adaptable (Li & Ning, 2019).

15.10 Conclusion

Marine microbes such as actinomycetes, fungi are a goldmine of antimicrobial compounds, ripe for tackling MIC. Tapping into these bioactive wonders could slash economic losses and toughen up infrastructure for the long haul. Future efforts should hunt for fresh compounds and polish their biotech potential to push sustainability forward. Artificial intelligence and bioinformatics would speed up the search for new MIC fighters, while teaming up across academia, industry, and environmental groups would turn these discoveries into scalable, green corrosion solutions that are good for the planet and public health alike.

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Applications of machine learning in marine microbial products prediction and monitoring

Jogipeta Harihara¹, P. Gnana Deepu¹, Anjaneyulu Musini¹, Jogipeta Pruthvi Raj², Boje Gowd B.H¹ and Kondakindi Venkateswar Reddy¹

¹Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India,

²Central Institute of Agricultural Engineering, Bhopal, Madhya pradesh, India

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16.1 Introduction to marine microbial products

16.1.1 Marine microbes and their secondary metabolites

Marine microorganisms such as bacteria, fungi, and algae are a rich source of secondary metabolites, which are bioactive substances that are not necessary for their growth but vital for survival in different marine ecosystems. These metabolites play numerous ecological functions, including mediating interactions with other organisms and tolerating extreme environments. Marine microbes have enormous diversity, with an estimated 103 bacteria and 102 fungi per milliliter of seawater.

Literature shows that microorganisms in marine environments produce an array of bioactive compounds, such as polyketides, alkaloids, peptides, and glycosides, which carry high therapeutic value. For example, research has established that secondary metabolites in marine bacteria and fungi have antimicrobial, antitumor, and antiinflammatory activities ([Corinaldesi et al., 2017](#)). Even with the enormous potential, few compounds have been studied, making research in this area necessary ([Barzkar et al., 2024](#)).

16.1.2 Industrial importance

Industrial uses of marine microbial products cut across a number of industries, particularly pharmaceuticals, agriculture, and biotechnology:

Pharmaceuticals: The compounds derived from the sea have resulted in new antibiotics and anticancer drugs. For instance, some marine bacteria yield metabolites that can be used to fight drug-resistant diseases (Srinivasan et al., 2021).

Agriculture: Marine microorganisms are being considered biocontrol agents and natural fertilizers. Their metabolites are used to promote plant growth and disease resistance (Waters et al., 2010).

Biotechnology: The unique properties of marine microbial products make them valuable for various biotechnological applications. This includes the development of sustainable materials and bioactive substances for cosmetics and personal care products (Bhatnagar & Kim, 2010).

Their prospects to contribute to such industries are huge because these microbes can be able to yield structurally new compounds that cannot be found among terrestrial organisms.

16.1.3 Emerging role of machine learning

ML is becoming a revolutionary tool in the discovery and manufacture of marine microbial products. With access to large numbers of data from genomic research and metabolomic analyses, ML algorithms are able to detect patterns and foretell the occurrence of bioactive compounds among marine microorganisms. This method increases the efficacy of screening procedures for novel drugs and bioproducts from marine origins (Jordan & Mitchell, 2015).

Moreover, ML can also optimize the fermentation processes employed in the production of such metabolites, resulting in enhanced yields and lower costs. The combination of ML with research on marine microbial products is an important leap toward biotechnological innovation (Ding et al., 2022).

The discovery of marine microbial products uncovers a treasure trove of biodiversity with immense industrial potential. The incorporation of ML into this field of research promises to speed up discoveries that can impact different industries from medicine to agriculture. Table 16.1 provides the overview of applications of marine microbial products.

Table 16.1 Applications of marine microbial products.

Industry	Applications
Pharmaceuticals	– New antibiotics – Anticancer drugs
Agriculture	– Compounds to fight drug-resistant diseases – Biocontrol agents – Natural fertilizers
Biotechnology	– Promote plant growth and disease resistance – Development of sustainable materials – Bioactive substances for cosmetics – Personal care products

16.2 Machine learning in marine microbial applications

16.2.1 Efficiency versus traditional methods

ML techniques greatly improve efficiency in marine microbial applications over conventional methodologies. These include:

Data handling: ML algorithms are capable of handling enormous amounts of intricate data from diverse sources, including genomic sequences, environmental parameters, and acoustic signals, much more quickly than traditional methods. This enables real-time analysis and decision-making, which is vital in dynamic marine ecosystems ([Sadaiappan et al., 2023](#)).

Predictive modeling: ML has the capability of developing predictive models that are capable of recognizing patterns and associations within data that can be obscure by using conventional statistical techniques. For example, ML has been utilized to forecast hypoxic events and toxic algal blooms based on environmental data to enable early intervention environments ([Sadaiappan et al., 2023](#)).

Real-time decision-making: Since it can analyze data streams in real-time, ML facilitates real-time monitoring and decision-making. This is especially useful for applications such as ocean health monitoring, where prompt responses can reduce negative impacts on marine ecosystems ([Waters et al., 2010](#)).

16.2.2 Key applications of machine learning in marine microbial applications

ML has successfully been applied to a number of key fields concerning marine microbes:

Drug discovery: ML plays a key role in discovering new antibiotics from marine microorganisms. Through the analysis of large microbial metabolite datasets, ML algorithms can predict which compounds are likely to possess antimicrobial activity, accelerating the drug discovery process.

- **Bioremediation:** When it comes to pollutant breakdown, ML models assist in the identification of marine microbes that can degrade toxic compounds. Through prediction of the ability of certain microbial strains to degrade pollutants, ML enables the best bioremediation approaches to be chosen ([Rubbens et al., 2023](#)).
- **Environmental monitoring:** ML methods are being employed more and more to track ocean health indicators. For instance, algorithms can scrutinize satellite data and other environmental information to gauge chlorophyll levels and forecast shifts in marine ecosystems. Such an application is crucial for monitoring the effects of climate change and human activities on ocean health ([Jiang et al., 2022](#)).

ML optimizes the effectiveness of marine microbial applications by utilizing better data processing, predictive model performance, and real-time decision-making. Its successful application in drug discovery, bioremediation, and environmental monitoring makes it poised to revolutionize marine science and biotechnology.

16.3 Data collection and preprocessing

16.3.1 Sources and challenges of marine data

Marine microbial product research entails gathering information from diverse sources, each with its own set of challenges:

- **Environmental data:** This comprises parameters like temperature, salinity, and pH, which are essential for the comprehension of microbial habitats. The variability of these factors in different marine environments, however, makes data collection and interpretation difficult. (Glockner et al., 2012).
- **Chemical composition:** Examining the chemical composition of marine habitats, including nutrient levels and pollutants, is crucial for evaluating microbial activity. The problem is the heterogeneity of marine ecosystems, which may result in nonuniform data (Chen et al., 2024).
- **Microbial genomic data:** Genomic sequencing reveals information about microbial diversity and functionality. The enormous amount of genomic data produced (e.g., from metagenomic analysis), however, may overwhelm conventional data processing techniques to the point that it becomes impossible to identify significant patterns and relationships.

16.3.2 Metadata and quality assurance

Good data management is important for guaranteeing the reliability of marine microbial research. Major challenges involve:

- **Data consistency:** Differences in data collection tools and techniques may result in inconsistencies. It is necessary to have standardized protocols to harmonize datasets from multiple sources.
- **Integration:** Integrating data from various sources (e.g., environmental sensors, genomic databases) needs strong integration methods to ensure data integrity.
- **Significance of metadata:** Metadata—information on information—is critical to achieving valid and reproducible outcomes. Metadata gives meaning to how data were gathered, processed, and analyzed, so that researchers can determine the quality and appropriateness of datasets with ease.

16.3.3 Data preprocessing

Data preprocessing is an essential step in readying marine microbial data for analysis. Some of the main steps are:

- **Cleaning:** It refers to removing noise and outliers from data sets to increase accuracy. Removing erroneous readings, for instance, from environmental sensors means that any analysis that follows is done from reliable data.
- **Normalization:** Data value standardization is important for the comparison of various datasets. Normalization corrects for differences in scale or units so that analyses across different samples are more accurate.
- **Feature engineering:** Development of meaningful features from raw data can enhance model performance in predictive analyses. This could include extracting new variables that represent key features of the microbial communities or environmental factors.
- **Augmentation:** Increasing datasets via synthetic data creation can alleviate problems of small sample sizes. Methods like oversampling minority classes or creating artificial samples from current data distributions improve the resilience of analyses. (Duncan, 2023).

Accurate data collection and preprocessing are central to pushing the science of marine microbial products. Handling data sources issues, quality control, and preprocessing methods will better the consistency and usability of conclusions in this subject (Mioduchowska et al., 2022).

16.4 Feature selection and engineering

16.4.1 Significant variables identification

Identification of key variables is important for the prediction of microbial product yields from marine microorganisms. Several statistical methods and ML algorithms can be used to identify the most important features.

- Correlation analysis: This analysis tests the interrelationships among various variables, determining which of the environmental factors (such as temperature, salinity, and pH) have high correlation with microbial product yields. Strong correlation coefficients suggest potential predictors that can be explored further.
- Feature importance ranking: ML algorithms, including random forests, give information on feature importance by analyzing the extent to which each variable impacts the predictive power of the model. The ranking aids in the prioritization of the most significant factors for further analysis and model building (Xiong et al., 2013).

By using these methods, researchers can highlight the most influential variables and optimize model performance and interpretability.

16.4.2 Advanced techniques

There are some advanced techniques for feature selection and dimensionality reduction that are critical for handling high-dimensional datasets in marine microbial research:

- Lasso regression: Lasso regression makes use of L1 regularization that, in addition to supporting feature selection through shrinking coefficients of less influential features to zero, also enhances interpretability of the model. Through penalizing the absolute value of coefficients, Lasso essentially shrinks the number of variables included in the model, resulting in lesser and more stable predictions (Chen et al., 2024).
- Random forest feature selection: Random forests are not only applicable for classification and regression but also for feature importance assessment. Through examining how frequently a feature appears in decision trees across the forest, scientists can order features by their predictive power contribution to model accuracy, enabling good dimensionality reduction (Corinaldesi et al., 2017).
- Principal component analysis (PCA): PCA is a common dimensionality reduction technique that converts original variables to a reduced set of uncorrelated variables (principal components). The technique preserves the maximum amount of variance in the data by decreasing complexity and facilitating easier visualization and analysis of relationships between features (Ding et al., 2022).

The integration of these advanced methods into the feature selection process increases the potential for accurate prediction of microbial product yields while coping with the complexities of marine datasets. By targeting meaningful variables and using advanced methods of dimensionality reduction, scientists are able to enhance the efficiency and effectiveness of their analyses in marine microbial research.

16.5 Model building and training

16.5.1 Overview of machine learning algorithms

Among the algorithms for predicting marine microbial products, several ML models have proven to be very effective. Each model has its strengths that can be harnessed to solve very particular problems in predicting yields of microbes. In this article, we review four models: decision trees, random forests, support vector machines (SVMs), and neural networks. [Table 16.2](#) provides the overview of the strength and applications four models of ML.

- **Decision trees:** It is an interpretable and intuitive algorithm that is widely used for the first steps in predictive modeling. Decision trees divide the data into subsets by feature values, resulting in a tree-like structure that ends with predictions. Though simple to visualize and comprehend, decision trees tend to overfit, particularly when dealing with complex data typical in marine science ([Moitinho-Silva et al., 2017](#)).
- **Random forests:** A variant of decision trees, random forests reduce overfitting by building multiple trees and averaging their predictions. This ensemble approach improves accuracy and stability,

Table 16.2 Machine learning algorithms for marine microbial product prediction.		
Algorithm	Strengths	Applications
Decision trees	– Interpretable and intuitive – Good for initial predictive modeling	– Simple visualizations - Easy to understand
Random forests	– Reduces overfitting – Improves accuracy and stability	– Predicting ecological outcomes – Handling noisy and complex data
Support vector machines	– Effective in high-dimensional spaces – Works well with more features than samples	– Classifying microbial communities – Ecological investigations
Neural networks	– Can identify complex patterns – Learns nonlinear relationships	– Predicting microbial product yields – Modeling interactions of multiple variables

making it especially useful for marine microbial product predictions where data may be noisy and complicated. Research has demonstrated that random forests can attain high accuracy levels in predicting ecological outcomes from environmental features (Dutta et al., 2022).

- Support vector machines: SVMs work well in high-dimensional spaces and are especially effective when the number of features is larger than the number of samples. They perform by determining the optimal hyperplane for classifying diverse classes in the data. SVMs have been utilized in marine applications to classify microbial communities according to environmental factors and have been successful in numerous ecological investigations (Rubbens et al., 2023).
- Neural networks: They are biological neural network-inspired models that can identify complex patterns in multiple layers of interconnected nodes. Although they need large datasets to train on, neural networks have been successful in predicting microbial product yields from complex datasets, especially when combined with deep learning algorithms (Riekeles et al., 2021). Their nonlinear relationship-learning capacity makes them fit for modeling the interactions of many variables in marine ecosystems.

16.5.2 Model optimization

In order to improve model performance and avoid overfitting throughout the training phase, various techniques of hyperparameter tuning are used:

- Grid search: Exhaustively searching over a defined subset of hyperparameters for the best combination of parameters to maximize model performance is what this approach entails. Grid search may be computationally intensive but works well for finding the optimal parameter settings for models like SVMs and random forests (Miller et al., 2023).
- Random search: In contrast to grid search, which tries all combinations systematically, random search randomly samples a set number of hyperparameter combinations. This can be more effective than grid search, particularly in the case of high-dimensional parameter spaces, as it tends to discover good configurations sooner.
- Cross-validation: In order to make sure that the model can generalize to data not seen during training, cross-validation methods like k-fold validation are employed during training. This is the process of dividing the dataset into k subsets and training the model k times, with each time a different subset being used as the validation set and the rest being trained upon. This ensures reliable assessment of model performance and eliminates risks of overfitting (Hernández Medina et al., 2022).
- Regularization methods: Techniques like Lasso or Ridge regression impose penalties on overly complex models by adding regularization terms to the loss function. These methods regulate model complexity and enhance generalization by deterring dependence on irrelevant features (Domingos, 2012).

Bleeding these optimization techniques into model construction not only improves predictive accuracy but also prevents models from degenerating into spurious overfits—a paramount consideration when dealing with heterogeneous and usually sparse marine datasets.

The integration of ML algorithms in predicting marine microbial products is a profound innovation in marine science. With the application of decision trees, random forests, SVMs, and neural networks suited to particular difficulties in this sector, researchers will be able to further improve their predictability. Further, utilizing strong model optimization practices guarantees that these models provide robust outputs while attempting to avoid the possibility of overfitting. With ongoing advances in research, refinement of such methodologies will continually exploit the prospect of ML for comprehending and tapping the potential of marine microbial biodiversity.

16.6 Model validation and evaluation

16.6.1 Performance metrics

Assessing the performance of ML models is an important process in the model development cycle. It informs one about the generalization ability of a model to new data and points out areas that need to be addressed. Important performance measures are accuracy, precision, recall, F1 score, and AUC-ROC, each having a particular function in measuring model performance.

- **Accuracy:** This metric measures the proportion of correctly classified instances out of the total evaluated cases. While it provides an overall assessment of the model's correctness, accuracy can be misleading in the presence of imbalanced datasets where one class significantly outnumbers another (Otten, 2024). For example, in a dataset where 95% of instances belong to one class, a model that always predicts this majority class could achieve 95% accuracy without being useful.
- **Precision:** Precision measures the number of actual positive predictions made by the model out of all positive predictions it has made. Precision is especially vital in situations where there are high costs associated with false positives, for example, medical diagnosis or detection of fraud (Kanerika, 2024). High precision shows that if the model predicts a positive result, there is a high chance it is correct.
- **Recall (Sensitivity):** Recall is calculated as the number of true positive predictions out of all actual positive cases in the dataset. It is an important metric in cases where lost positive cases (false negatives) are catastrophic, for instance, disease detection or detection of security threats (Otten, 2024).
- **F1 score:** The F1 score is the harmonic mean of precision and recall. It gives an equitable measure of a model's performance, particularly when there is an imbalance in the class distribution or when precision and recall are mutually contradictory. A large F1 score means both precision and recall are fairly high (Rainio et al., 2024).
- **AUC-ROC:** Area under the receiver operating characteristic curve (AUC-ROC) measures binary classification models through a plot of the true positive rate against the false positive rate at different levels of thresholds. The better the model's performance at different levels of classification thresholds, the greater the AUC value (Otten, 2024). This is a very good measure to get an idea of how well a model can differentiate between classes.

Utilizing a blend of such metrics provides scholars with an integral picture of model performance and facilitates well-informed model selection and tuning decisions.

16.6.2 Cross-validation

Cross-validation is a key method of determining the generalizability and robustness of ML models. It consists of dividing the dataset into subsets to provide each instance a chance to be utilized for both validation and training. One such common method is k-fold cross-validation:

K-fold cross-validation: Here, the dataset is split into k subsets (or folds). The model is trained on $k - 1$ folds and validated on the rest of the fold. This is done k times, with each fold being used as the validation set once. The ultimate performance measure is usually averaged over all k iterations to yield a better estimate of model performance (Kumar, 2025).

Cross-validation prevents overfitting by making sure that models are tested on data they have not been exposed to while training. It also gives an idea of how well a model can perform on unseen data, and hence it is a useful tool for checking predictive models.

16.6.3 Handling model overfitting

Overfitting is the phenomenon by which a model not only learns the inherent patterns in the training data but also its noise and outliers. Therefore, whereas it works well with training data, its performance on unseen data significantly degrades. In order to ensure model integrity and avoid overfitting, a number of methods can be utilized:

- Regularization: Regularization involves methods like Lasso (L1 regularization) and Ridge (L2 regularization), which impose penalties on the loss function to avoid over completeness. Regularization prevents overfitting by capping the value of coefficients corresponding to features in linear models (Bajaj, 2025).
- Pruning: Pruning in decision trees and ensemble techniques such as random forests entail the removal of branches that are unimportant or cause overfitting. Simplification of the tree structure following the initial training, pruning adds generalization strength without a loss of predictive ability.
- Ensemble methods: Techniques such as bagging and boosting combine predictions from multiple models to improve overall performance. For instance, random forests aggregate predictions from numerous decision trees to produce more robust outcomes than any single tree could achieve alone. This approach reduces variance and enhances stability against overfitting (Kanerika, 2024).

Model testing and validation are essential parts of creating efficient ML models to predict marine microbial products or for other purposes. Using the right performance measures such as accuracy, precision, recall, F1 score, and AUC-ROC, scientists can evaluate their models thoroughly. Cross-validation strategies such as k-fold give proper estimates of generalizability of the model along with preventing the overfitting issue using regularization, pruning, and ensemble strategies ensures that the models remain effective and predictive in nature.

As ML advances in marine science and other disciplines, these assessment methods will continue to be crucial to driving innovation and making sure models provide useful information from complicated datasets.

16.7 Developing predictive models for marine microbial products

Predictive modeling of marine microbial metabolites is a new area that utilizes computational methods to predict the yield of useful biochemical products from marine microbes. Predictive models combine microbial diversity, environmental conditions, and molecular information to comprehend and anticipate microbial metabolic outputs. A step-by-step description of the procedure for developing predictive models for marine microbial products follows (Hernández Medina et al., 2022) in Fig. 16.1

16.7.1 Importance of marine microbial metabolites

Marine microbes are important agents of global nutrient cycling and a treasure trove of bioactive molecules, such as antibiotics, enzymes, and secondary metabolites. It is important to predict their metabolic products for biotechnological, pharmaceutical, and environmental applications. The heterogeneity of marine ecosystems and the variety of microbial populations require sophisticated prediction models to utilize their full potential.

16.7.2 Steps to develop predictive models

Defining objectives: The initial step toward building predictive models is to set the precise objectives:

- What to predict: Such as predicting the production of certain metabolites such as antibiotics or enzymes.
- Why to predict: Applications may vary from drug discovery to environmental monitoring.

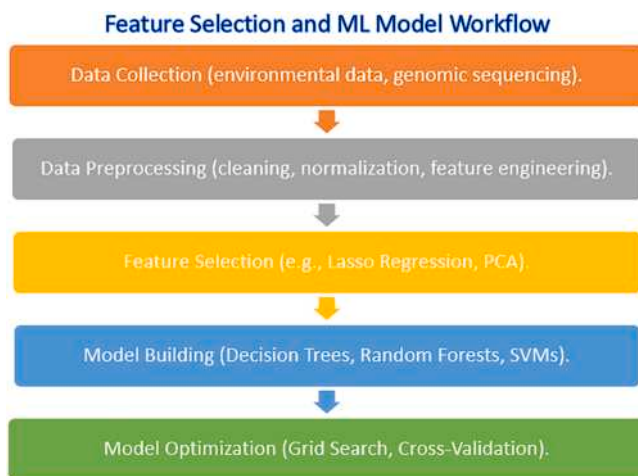


FIGURE 16.1

Feature selection and ML model workflow.

Data collection: Data collection forms the basis of predictive modeling. It entails collecting data on, microbial diversity employing methods such as 16 S rRNA sequencing to determine microbial taxa. Environmental parameters temperature, salinity, pH, nutrient gradients, and oxygen.

Molecular data: Multiomic datasets comprising genomics, transcriptomics, proteomics, and metabolomics (Connors et al., 2024; University of British Columbia, 2016).

Preprocessing data: Raw data needs to be cleaned and preprocessed for analysis, removing outliers and noise. Normalizing data to give equal relevance across samples. Annotations of sequences with functional data e.g., KEGG pathways.

Feature selection: Characteristics that play a key role in microbial metabolite production are determined, taxonomic make-up: Target microbial taxon associated with metabolite formation (Connors et al., 2024). Environmental factors: factors that promote or suppress microbial activity. Interaction effects: synergistic or inhibitory interactions between the microbes (Stadler et al., 2024).

Model selection: The choice of the modeling strategy is a function of the data complexity. ML models random forest regression, SVM, or neural networks can be used for predicting microbial function from community composition. (Connors et al., 2024). Mathematical models differential equations modeling nutrient cycling and energy flux in microbial networks. Hybrid models integration of statistical approaches with mechanistic models to enhance accuracy.

Training the model: The chosen model is learned on historical datasets. Supervised learning methods demand labeled data (e.g., known metabolite levels). Cross-validation is employed to avoid overfitting and achieve generalizability across datasets.

Validation: Model validation is carried out by assessing its predictive capability on independent datasets, measures such as R2R2 (coefficient of determination) and RMSE (root mean square error) are employed to quantify accuracy (Connors et al., 2024). Validation guarantees that predictions conform to observed trends in microbial metabolite formation.

Iterative refinement: Predictive models are iteratively improved by adding new data or modifying parameters, adding more environmental variables or interaction terms, and enhancing algorithms for improved management of complex datasets.

16.7.3 Challenges in predictive modeling

16.7.3.1 Marine ecosystem complexity

Marine ecosystems are extremely dynamic, with changing environmental conditions that affect microbial activity. It is challenging to capture this variability in models.

16.7.3.2 Unavailability of data

Although sequencing technologies have improved, there are many areas where there are no complete datasets connecting microbial community composition to metabolic outputs (Connors et al., 2024).

16.7.3.3 Effects of interactions

Microbial interactions—both intra-community and with the environment—are frequently nonlinear and hard to quantify precisely (Stadler et al., 2024).

16.7.3.4 Model generalization

Models developed in one area can fail in another because of variations in microbial communities or environmental conditions ([Connors et al., 2024](#)).

16.7.4 Uses of predictive models

- Drug discovery marine microorganisms are a reservoir of new antibiotics and anticancer compounds. Predictive models assist in the identification of potential candidates by correlating genetic data with metabolite profiles.
- Environmental monitoring models are able to predict shifts in microbial activity because of climate change or pollution, supporting ecosystem management ([Robaina-Estévez et al., 2024](#); [University of British Columbia, 2016](#)).
- Biotechnological innovation anticipating enzyme production or other metabolites enables industries to streamline processes such as biofuel production or waste breakdown ([Robaina-Estévez et al., 2024](#)).

16.7.5 Case studies

Microbiome prediction in oceans, a model created at the University of British Columbia combines molecular sequence information with environmental variables to forecast nutrient cycling by marine microbes ([University of British Columbia, 2016](#)). The model offers information on how microbial processes react to climate change.

Bacterial production prediction using random forest regression, scientists showed that bacterial community composition is a strong predictor of bacterial production in all ocean ecosystems ([Connors et al., 2024](#)). This method exceeded the performance of conventional environmental models, emphasizing the significance of data on community composition.

Predictive modeling advancements will target the use of real-time sensor data from deployments in the marine environment. The creation of global models that combine heterogeneous datasets across various regions. The application of artificial intelligence (AI) methods such as deep learning to improve prediction. The extension of multiomic analysis to include the entire range of microbial metabolic pathways ([Heasley et al., 2021](#)).

The creation of predictive models for marine microbial products entails the integration of varied datasets, from genetic sequences to environmental factors, and the use of advanced computational methods such as ML and mathematical modeling. Although obstacles such as ecosystem complexity and data limitation remain, these models are highly promising for enhancing biotechnology, environmental sustainability, and scientific knowledge of marine ecosystems ([Ross, 2000](#)).

16.8 Monitoring and real-time application

Real-time monitoring and ML applications in marine microbial communities. ML algorithms are transforming the real-time monitoring and analysis of marine microbial communities and metabolites. Combining environmental data, microbial activity, and metabolite production, ML-driven systems

enable data-driven decision-making for environmental management, optimization of bioproduction, and public health. The mechanisms of real-time monitoring using ML algorithms and applications in process and environmental control are discussed in this article.

Role of ML algorithms: ML algorithms allow continuous surveillance of ocean microbial communities by examining intricate sensor data, satellite imagery, and autonomous robots. They can identify patterns in microbial behavior, predict the production of metabolites based on environmental conditions, and learn to respond to dynamic oscillations in ocean ecosystems.

16.8.1 Key components of real-time monitoring

- **Data acquisition:** Physico-chemical parameters (oxygen levels, salinity, temperature) are measured by sensors in the sea and biological processes (chlorophyll content, microbial gene expression). Autonomous vehicles with sophisticated sampling equipment take in water samples and analyze microbial assemblages within the ocean directly (Cunha et al., 2008).
- **Data integration:** ML algorithms combine multisource data (e.g., satellite remote sensing, underwater sensors) to construct an integrated image of microbial dynamics. Environmental factors like the availability of nutrients, light intensity, and water currents are incorporated into the calculation (Grimes et al., 2014).
- **Real-time analysis:** Algorithms analyze incoming data streams to identify anomalies or trends. Predictive models predict microbial metabolite production or ecosystem shifts based on present observations (Larsen et al., 2015).
- **Feedback mechanisms:** Systems give relevant information to decision-makers or researchers for intervention. For instance, early warning for harmful algal blooms initiates mitigation measures (Grimes et al., 2014).

16.8.2 Applications in environmental control

16.8.2.1 Tracking ocean health

ML-based systems are crucial for evaluating the health of marine ecosystems:

- **Satellite remote sensing:** Satellites track microbial activity from space by quantifying parameters such as sea surface temperature (SST) and chlorophyll content. These observations are utilized to forecast harmful algal blooms and evaluate primary production (Grimes et al., 2014).
- **Autonomous robots:** Armadas of autonomous robots monitor microbial communities in open-ocean eddies. The robots harvest genetic material and environmental information to examine how microbes react to shifting conditions (Visceral_Dev_Admin, 2022).

16.8.2.2 Detecting harmful algal blooms

Harmful algal blooms (HABs) are of great hazard to both marine and human health. ML techniques assist in the detection of HABs by identifying bloom-forming species from satellite imagery, forecasting bloom formation from environmental conditions such as temperature and nutrient concentrations (Grimes et al., 2014), and offering early warnings to reduce effects on fisheries and coastal communities.

16.8.2.3 Climate change impact assessment

Marine microbes contribute significantly to global carbon cycling. ML models examine past trends in the analysis of microbial populations based on ocean warming to determine long-term patterns. Forecast future shifts in microbial dynamics across various climate scenarios (Brown et al., 2018).

16.8.3 Applications in process control

- **Optimizing large-scale bioproduction:** Marine microbes are exploited in industrial processes for the manufacture of enzymes, biofuels, and pharmaceuticals. ML-driven real-time monitoring systems enhance these processes by monitoring metabolite production rates under different conditions, optimizing environmental parameters (e.g., pH, temperature) to achieve maximal yields, and detecting high-performance microbial strains for bioproduction (van den Engh et al., 2019)
- **Water quality improvement:** ML algorithms enhance water quality measurement by studying the microbial community profile and activity, identification of pollution or contamination impact on microbial groups, and predictive modeling of variations in water quality due to man-made processes or natural occurrences (Bergamasco et al., 2021).

16.8.4 Real-world examples

Autonomous robotic fleets for microbial tracking: Scientists at MBARI showed how autonomous robots can be used to follow microbial communities in open-ocean eddies off Hawaii. The robots took seawater samples at depths of more than 100 meters with onboard processors analyzing genetic material and proteins. The system gave real-time feedback on environmental conditions affecting microbial activity (Visceral_Dev_Admin, 2022).

Satellite-based remote sensing: Satellite remote sensing has been used effectively to track cyanobacteria and *Vibrios* that are linked to harmful algal blooms. By integrating SST data with predictive models, scientists created early warning systems for disease outbreaks caused by these microbes (Grimes et al., 2014).

Continental-scale monitoring networks: The Australian Marine Microbial Biodiversity Initiative (AMMBI) developed a standardized network for the monitoring of marine microbiota in various climatic zones. The data from this initiative is utilized to hindcast past trends and predict future shifts in microbial assemblages under climate change scenarios (Brown et al., 2018).

16.8.5 Challenges in real-time monitoring

In spite of its promise, real-time monitoring is confronted with a number of challenges. Marine environments produce enormous quantities of disparate data that call for sophisticated processing methodologies. Constantly shifting ocean conditions necessitate adaptive algorithms that can cope with such fluctuations. Nevertheless, the expense of installing sensors, robots, and satellites is a major barrier that dampens accessibility to smaller research groups. Moreover, fusing data from a variety of sources, for example, satellites and autonomous vehicles, into an integrated model is a challenging task.

ML-based real-time monitoring is revolutionizing our capacity to analyze marine microbial communities and their metabolites. By bringing together a variety of datasets and prediction models, such systems offer decision-relevant insights for the management of ocean health, early detection of harmful algal blooms, and the optimization of bioproduction processes. Despite challenges, continued improvements envision a day when continuous monitoring will be an essential tool to evaluate and safeguard marine ecosystems.

16.9 Challenges and limitations in machine learning for marine microbial applications

ML is now a highly useful tool in the study of marine microbial populations, the modeling of metabolite production, and the assessment of ocean health. Its application to marine microbiology is, nevertheless, hampered and constrained by data availability issues, interpretability of models, and ethics. These problems should be overcome if the field has to advance and if ML will be used properly in marine science.

16.9.1 Data paucity and quality problems

16.9.1.1 Sparsity of data in remote marine environments

Marine environments are large, complex, and undersampled. Many regions lack rich datasets due to the practical challenges of sampling remote areas like deep-sea environments or polar oceans. This sparsity hampers the ability of ML models to generalize across a range of marine environments.

- **Sparse genomic databases:** While databases like MarRef hold curated marine microbial genomes, they represent only a fraction of the microbial communities present in the ocean. Uncharacterized microbes lead to incomplete training datasets, which reduce model accuracy.
- **Sparse temporal data:** Continuous monitoring is rare, resulting in datasets that fail to reflect seasonal or long-term patterns in microbial activity (Park et al., 2023).

16.9.1.2 Impact of poor-quality data

The purity of data has a direct bearing on ML model performance:

- **Noise and bias:** Unpredictable sampling protocols or environmental noise introduce biases in datasets, leading to wrong predictions.
- **Class imbalance:** Asymmetrical representation of microbial taxa or environmental conditions in training datasets skew model outputs.
- **Incomplete metadata:** Inadequate contextual information (e.g., nutrient levels or water currents) limits the ability of models to account for environmental interactions (Walsh et al., 2024).

16.9.1.3 Solving data challenges

Efforts to circumvent these limitations include expanding genomic databases by international cooperation, employing autonomous robots and sensors to record data on a continuous basis, and standardizing sampling regimes to enable comparability among studies (Walsh et al., 2024).

16.9.2 Model interpretability

16.9.2.1 Interpretability challenges

ML models tend to be “black boxes,” and their predictions are not easily understandable by domain experts such as marine biologists or ecologists. This opacity raises various problems:

- **Biological understanding:** Results can be nonintuitive, deviating from known ecological principles and generating doubt in the scientific community.
- **Actionability:** Without explanations, model outputs become difficult to convert to actionable information for conservation or management purposes (Weller et al., 2021).

16.9.2.2 Strategies for increasing interpretability

- **Simplified models:** Employing interpretable algorithms such as decision trees or linear regression rather than intricate neural networks. For instance, decision trees have been demonstrated to solve taxonomic trends with great accuracy while being interpretable.
- **Feature importance analysis:** Determining influential variables that are driving predictions (e.g., certain microbial taxa or environmental variables).
- **Explainable AI (XAI):** Creating frameworks that give human-interpretable explanations of model outputs without sacrificing accuracy.

16.9.2.3 Balancing accuracy and interpretability

Although intricate models such as deep learning tend to deliver better accuracy, less complicated models might be superior in applications involving transparency. As an example, shallow decision trees have proved highly effective within the field of marine ecology for attaining balance between interpretability and predictive power (Wang et al., 2024).

16.9.3 Ethical and regulatory issues

Environmental Implication of manipulation extensive interference in marine microbiomes—like enhancing targeted microbes for bioproduction—carries ethical concerns:

- **Ecological risks:** Altering microbial communities can interfere with natural processes such as nutrient cycling or carbon sequestration.
- **Unintended consequences:** Release of engineered microbes might have unforeseen effects on indigenous species or ecosystem stability (Wang et al., 2024).

Regulatory challenges marine biotechnology is subject to a multifaceted regulatory environment:

- **International laws:** Operations in international waters have to be in accordance with treaties such as the United Nations Convention on the Law of the Sea (UNCLOS).
- **Environmental safeguards:** Maintaining compliance with regulations meant to safeguard biodiversity and avoid pollution.

Encouraging ethical practice to resolve these issues conducts comprehensive risk assessments prior to enforcing mass interventions, establishes guidelines for ethical marine biotechnology

research, and encourages transparency in decision-making involving stakeholders from the science, policy, and industry communities ([Mahynski et al., 2022](#)).

16.10 Future directions and research opportunities

The future of ML in marine microbial applications is in developing computational methods, merging emerging technologies, and encouraging interdisciplinary research.

16.10.1 Developments in machine learning and artificial intelligence methods

- **Deep learning** architectures like convolutional neural networks (CNNs) and recurrent neural networks (RNNs) provide greater functionality for processing complex data. CNNs are best for the treatment of spatial data like satellite imagery or water sensor readings. RNNs deal with temporal data, allowing prediction of seasonal patterns in microbial activity.
- **Reinforcement learning** can fine-tune real-time monitoring systems by adjusting sampling methods according to environmental feedback.
- **Explainable AI** creation of explainable AI frameworks will make ML models more transparent, enabling domain experts to comprehend predictions without compromising on accuracy.

16.10.2 Internet of Things and big data analytics

- **IoT sensors:** The Internet of Things (IoT) makes possible the real-time gathering of data through networked sensors installed all over oceans, monitoring physical parameters such as temperature or salinity and monitoring microbial activity through biosensors.
- **Big data analytics:** Merging IoT-generated data with big data analytics enables researchers to identify global patterns in microbial dynamics and predict ecosystem changes under various climate scenarios.

Integration of IoT and big data analytics has the potential to revolutionize HABdetection using real-time satellite monitoring and large-scale bioproduction optimization through automation of process control systems ([D'Elia et al., 2024](#)).

16.10.3 Interdisciplinary collaboration

Interdisciplinary cooperation is needed to further marine microbial science: marine biologists offer ecological insight to inform model development. Data scientists create algorithms specifically suited for microbiome data. Environmentalists align research with conservation objectives. Initiatives such as the Australian Marine Microbial Biodiversity Initiative show the benefits of interdisciplinary collaboration through integrating ecological observation with computational modeling ([Salman, 2023](#)).

16.11 Conclusion

In conclusion, ML has unprecedented potential to revolutionize the investigation and exploitation of marine microbial resources in biotechnology, pharmaceutical, and agricultural areas. Through an improvement in drug discovery, bioremediation, and ecological monitoring, ML presents promising fields for the exploration of new bioactive compounds, environmental cleanup procedure optimization, and real-time oceanic ecosystem observation. But challenges like data paucity, model explainability, and ethical issues of ecological effects need to be resolved to be able to tap the full potential of ML in this field. The future of marine microbial applications will be in breakthroughs in deep learning, IoT technologies integration, and more interdisciplinary work. Coupled, these advances will result in more precise predictive models, effective monitoring systems, and sustainable marine resource utilization strategies, eventually guiding the future of marine microbial science and applications.

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MMP and drug development: prospects and shortcomings

17

Vyshnava Satyanarayana Swamy¹, K. Swetha¹, Gayathri Pandluru¹, Shiva Prasad Panajala²,
Kameshpandian Paramasivam³, Govindhasamay R. Varatharajan⁴, P. Deepalakshmi⁵ and
M. Srinivasulu^{5,6}

¹*Department of Biotechnology, University College of Sciences, Sri Krishnadevaraya University, Anantapuramu, Andhra Pradesh, India,*

²*Department of Genetics and Biotechnology, University College of Sciences, Osmania University, Hyderabad, Telangana, India,*

³*DMI St. John The Baptist University, Lilongwe, Malawi,*

⁴*Faculty of Biology, Shenzhen MSU-BIT University, Shenzhen, P.R. China,*

⁵*Department of Chemistry, Nadar Saraswathi College of Arts and Science, Theni, Tamil Nadu, India,*

⁶*Department of Biotechnology, Yogi Vemana University, Kadapa, Andhra Pradesh, India*

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17.1 Introduction

Marine microbes are a mostly unexplored source of biochemical diversity found beneath the vast expanse of Earth's oceans. The pursuit of bioactive chemicals has traditionally focused on terrestrial bacteria, but the marine biosphere, which makes up more than 70% of the planet's surface, has become a field with enormous medicinal promise (Das & Mondal, 2024). Numerous distinct microbial species that have developed in this understudied environment, which includes high hydrostatic pressure, high salinity, and cold temperatures, are found there (Shu & Huang, 2022). The production of structurally unique and frequently extremely powerful secondary metabolites has been fueled by these selection pressures; many of these compounds have biological activities that are superior to those of their terrestrial counterparts (Kiran et al., 2018; Aransiola et al., 2024a). Therefore, marine microorganisms are an important and potential source for therapeutic and biotechnological advancements in the foreseeable future.

The concept of the marine microbes as a prolific source of innovative pharmaceuticals has transitioned from speculation to a swiftly advancing domain at the confluence of microbiology, pharmacology, and biotechnology. As antimicrobial resistance advances and the need for novel chemotherapeutics increases, researchers are increasingly searching marine sources for alternatives (Muteeb et al., 2023; Aransiola et al., 2024b). Marine microorganisms are especially fascinating because of their ability to produce complex secondary metabolites, many of which exhibit promise antiviral, antibacterial, antifungal, anticancer, and antiinflammatory effects (Barzkar et al., 2019; Li et al., 2019). In recent decades, there has been a rise in the discovery of novel chemicals sourced from marine microbes. From 2010 to 2016, over 895 unique bioactive compounds were identified from marine bacteria, actinomycetes, and fungi, highlighting the considerable untapped potential of these organisms (Raimundo et al., 2018; Alharbi, 2016). Notable examples of marine-derived pharmaceutical candidates include salinosporamide A (an anticancer agent in clinical studies), thiocoraline, and didemnin B (AplidineTM), all generated from marine microorganisms and shown considerable efficacy against neoplastic cells (Khalifa et al., 2019; Mandlik & Mandlik, 2021).

The biopharmaceutical sector has shown significant interest in this domain. More than 30 drugs sourced from marine microorganisms are presently undergoing clinical or preclinical evaluation, predominantly targeting cancer and infectious illnesses, some are listed in Table 17.1 (Anjum et al., 2017). Notwithstanding the initial potential, barely a few have attained entry into the pharmaceutical industry. Cytarabine, a chemotherapeutic treatment derived from marine microbes, stands as one of the early success stories among authorized medications and continues to motivate marine bioprospecting initiatives (Das & Mondal, 2024). The evolution of bacteria in extreme deep-sea environments has resulted in the development of highly specialized metabolic pathways, producing compounds with novel methods of action (Roda-Garcia et al., 2023). Many secondary metabolites first ascribed to sponges or tunicates have subsequently been traced to their symbiotic microbial partners, supporting the theory that microorganisms, rather than their hosts, are the true biochemical builders (Lo Giudice & Rizzo, 2022).

However, despite the encouraging progress, the transition from microbial metabolite to commercially viable medicine is far from straightforward. Challenges including the low cultivability of marine microorganisms (with about 1–5% being culturable using traditional techniques), challenges in large-scale production, and regulatory complications have resulted in substantial bottlenecks (Zhang et al., 2021). Technological advancements, including metagenomic sequencing, biosynthetic gene cluster (BGC) mining, and heterologous expression systems, are currently utilized to surmount these challenges and expedite discovery processes (Xu et al., 2023). Furthermore, the

Table 17.1 Representative bioactive compounds from marine microbes.

Compound name	Microbial source	Chemical class	Bioactivity	Development status	References
Salinosporamide A	<i>Salinispora tropica</i>	γ -lactam- β -lactone	Proteasome inhibitor (anticancer)	Clinical trials (Phase I/II for myeloma)	Barreca et al. (2020)
Marinopyrrole A	<i>Streptomyces</i> sp. CNQ-418	Halogenated pyrrole	Antibacterial (MRSA)	Preclinical	Genilloud (2017)
Thiomarinol A	<i>Pseudoalteromonas</i> sp.	Hybrid PK-NRP	Broad-spectrum antibiotic	Preclinical	Rahman et al. (2010)
Cytarabine (Ara-C)	Sponge symbionts (e.g., <i>Verrucosisspora</i>)	Nucleoside analog	Antileukemic	FDA-approved	Shakeel et al. (2018)
Lynamicins A–E	<i>Marinispora</i> sp.	Indole alkaloid	Antibacterial (Gram-positive)	Experimental/preclinical	Kasanah and Triyanto (2019)
Alteramide A/B	<i>Alteromonas</i> sp.	Tetramic acid	Antitumor, immunosuppressive	Preclinical	Cho (2012)
Didemnin B	Symbiotic bacteria in <i>Trididemnum</i>	Cyclic depsipeptide	Antiviral, anticancer	Clinical trials (as Aplidine)	Xu et al. (2012)

increasing utilization of artificial intelligence (AI) and high-throughput screening (HTS) has introduced a novel aspect to the exploration of marine-derived pharmaceuticals, enabling researchers to anticipate bioactivity and therapeutic significance prior to laboratory experimentation (La Paglia et al., 2023). Marine microbial natural products currently occupy a promising intersection of environmental science, synthetic biology, and pharmaceuticals.

This chapter provides an overview of the various bioactive chemicals recognized so far, the methods employed for their identification and development, and the technical advancements that have facilitated progress in this domain. Simultaneously, it rigorously evaluates the deficiencies and persistent scientific, logistical, and ethical challenges that impede the complete realization of the marine microbial pharmacopeia. This analysis seeks to provide a fair viewpoint on the future of a significant frontier in drug discovery (Fig. 17.1).

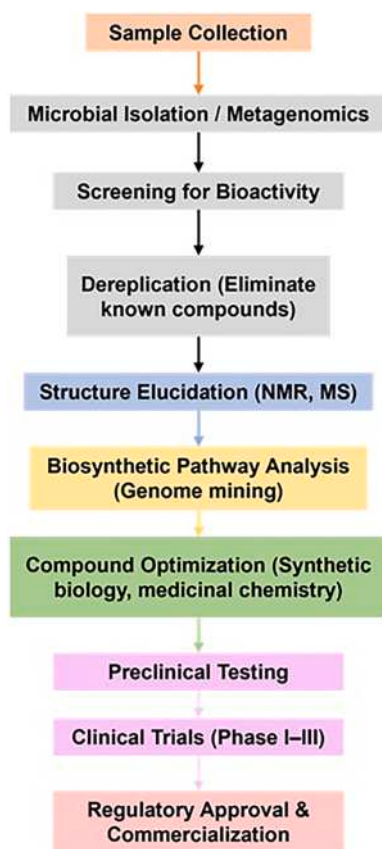


FIGURE 17.1

Marine microbial drug discovery pipeline.

17.2 Marine microbes as a source of bioactive compounds

Marine microorganisms represent an essential and generally underutilized resource of bioactive compounds, providing distinctive chemical diversity with considerable potential for medicinal, agricultural, and industrial uses.

17.2.1 Unique adaptations and secondary metabolite production

Marine microorganisms endure severe and fluctuating habitats, ranging from lighted coral reefs to the profound pressures of the abyssal plain (Munn & Munn, 2019). These species have adapted to withstand higher pressures, fluctuating temperatures, and diverse salinity levels. Environmental influences contribute to the formation of distinct metabolic pathways, facilitating the production of structurally varied and physiologically active secondary metabolites. In contrast to primary metabolites, which are crucial for growth and survival, secondary metabolites frequently execute ecological functions, including chemical defense, competition, and signaling (Petersen et al., 2020). The potential to generate these advantageous compounds is often encoded by BGCs, which are increasingly revealed through metagenomics and bioinformatics (Viju et al., 2021).

Multiple examples demonstrate that compounds initially derived from marine microorganisms, such as sponges or tunicates, can be traced back to their microbial symbionts, underscoring the microbial origin of various marine bioactivities (Ramesh et al., 2021). Such microorganisms employ their metabolic array to produce molecules with antibacterial, antifungal, cytotoxic, and antiinflammatory properties, making them highly attractive for drug discovery. Additionally, marine bacteria often possess genes for polyketide synthases (PKSs) and nonribosomal peptide synthetases (NRPSs), enzymatic systems prevalent in terrestrial microbes, however occasionally producing chemically distinct scaffolds in marine species due to adaptive evolution (Giordano et al., 2015; Machado, 2016). These methods enable the synthesis of highly specialized and therapeutically relevant compounds.

17.2.2 Major classes of bioactive compounds

Marine microorganisms are abundant producers of various kinds of bioactive secondary metabolites. This encompasses, but is not limited to:

- *Alkaloids*: Compounds containing nitrogen that frequently exhibit significant pharmacological action. Marine-derived alkaloids have been recognized for their antiviral, anticancer, and neuroactive effects (Mayer et al., 2024). Certain marine *Aspergillus* and *Neosartorya* species have produced diverse alkaloids exhibiting cytostatic and antibacterial properties (de Sá et al., 2022).
- *Peptides*: Marine fungus and bacteria synthesize ribosomal and nonribosomal peptides, encompassing cyclic and linear forms (Sukmarini, 2022). These compounds frequently exhibit cytotoxic or antibacterial properties, and their comparative safety in humans renders them interesting candidates for pharmacological development.
- *Polyketides*: Polyketides, a prominent class of marine-derived chemicals, demonstrate various biological activities, including anticancer and antiinflammatory properties (Papikinou et al., 2024).

Marine fungus and bacteria exhibit significant polyketide variety, with certain species generating compounds with novel carbon structures.

- *Terpenoids*: These chemicals are generated from isoprene and are particularly prevalent in marine fungi. Terpenoids frequently have antiinflammatory and antiviral properties, and current research indicates they may possess immunomodulatory capabilities ([Sanapala et al., 2022](#)).

Marine fungi have produced numerous novel compounds within these chemical classes, including various hybrid structures (e.g., polyketide-terpenoids) that exhibit potential as lead therapeutic candidates.

17.2.3 Comparison with terrestrial microbial sources

While marine and terrestrial bacteria generate structurally analogous groups of secondary metabolites, marine microbes' ecological pressures and unique evolutionary trajectories yield distinct chemical characteristics, as detailed in [Table 17.2](#). For instance:

Table 17.2 Comparison of marine versus terrestrial microbial natural products.			
Feature	Marine microbes	Terrestrial microbes	References
Habitat conditions	High pressure, salinity, low temperatures, nutrient-scarce, extreme environments	Soil, decaying vegetation, animal hosts; relatively stable and nutrient-rich	Bertrand et al. (2018)
Cultivability	Low (~1–5% culturable with standard methods)	Moderate (~20–30% cultivable in lab conditions)	Kapinusova et al. (2023)
Structural novelty	High—frequent halogenation, sulfation, unique ring systems	Moderate—less halogenation or novel functional groups	Sallam (2013)
Secondary metabolite diversity	Rich in alkaloids, polyketides, peptides, terpenoids; often hybrid structures	Predominantly polyketides, peptides, and alkaloids	Phukan et al. (2023)
Biosynthetic gene cluster (BGC) diversity	High modular diversity; many silent or cryptic clusters	Well-characterized; some redundancy in known pathways	Reen et al. (2015)
Bioactivity potency	Often highly potent due to ecological pressure (e.g., antibiosis, predation)	Potent but generally less structurally complex	Wang et al. (2024)
Challenges in drug development	Difficult to cultivate, complex structures, limited supply, regulatory hurdles	Easier cultivation and synthesis; rediscovery of known compounds is a major issue	Atanasov et al. (2021)
Sustainability	Increasing focus on metagenomics, heterologous expression, digital bioprospecting	More established fermentation platforms and synthetic biology workflows	Ezeako (2024)

- *Structural novelty*: Marine-derived compounds frequently contain halogenated groups, sulphated moieties, and atypical ring structures uncommon in terrestrial metabolites. These characteristics augment their biological efficacy and pharmacokinetic profiles (Carroll et al., 2021).
- *Potency*: Marine bacteria have developed extraordinarily potent compounds to establish ecological supremacy in response to the dilute and competitive coastal environment. This potency is beneficial in pharmaceutical development but may potentially pose toxicity challenges.
- *Biosynthetic complexity*: Marine microbial BGCs frequently exhibit greater modular diversity compared to those in terrestrial organisms. This enhances the possibilities for combinatorial biosynthesis and the generation of structural analogs.

Despite the similarities in metabolic machinery (PKS and NRPS systems), the final products in marine microorganisms sometimes vary in structure, stereochemistry, and bioactivity providing distinct benefits for fulfilling unmet medical requirements.

17.3 Drug discovery and development from marine microbial products

Marine microbial products have become a significant asset in drug discovery and development, offering new molecules with distinctive structures and powerful biological activity that meet essential medical requirements.

17.3.1 Screening strategies for bioactive compounds

Traditionally, drug development from marine microbes depended on phenotypic screening, which involved cultivating organisms, collecting compounds, and evaluating them against target disorders (Maghembe et al., 2020). This approach is labor-intensive, susceptible to the rediscovery of established compounds, and constrained by the inability to cultivate multiple marine microorganisms. Current methodologies now use chemical dereplication, bioassay-guided fractionation, and metabolomics to surmount these obstacles.

HTS tools facilitate the swift assessment of microbial extracts or purified compounds for bioactivity through cell-based assays or target-specific in-vitro systems (Stuart et al., 2020). These are being augmented with functional genomics tools and biosensor-based tests that directly associate biological activity with metabolic profiles. Sequence-based screening has gained significance, especially for targeting specific BGCs encoding PKS and NRPS (Mohan et al., 2024). This facilitates the anticipation of metabolite categories before cultivation, enhancing the efficacy of novel compound identification.

17.3.2 Key marine-derived drugs in clinical use

Marine microbial metabolites have significantly contributed several prominent drugs to clinical application or advanced clinical trials:

- *Cytarabine (Ara-C)*: This nucleoside analog, initially extracted from a marine sponge but synthesized by microbial symbionts, is a primary treatment for leukemia and lymphoma (Paniagua-Michel et al., 2015).

- *Trabectedin (Yondelis)*: This compound, derived from symbiotic microbes in tunicates, binds to DNA and disrupts transcription; it is approved for the treatment of soft tissue sarcomas and ovarian cancer (Cooreman et al., 2023).
- *Eribulin (Halaven)*: A synthetic analog of halichondrin B, derived from marine sponges and produced by associated microbes, it targets microtubules and is approved for metastatic breast cancer (Mahaddalkar & Lopus, 2017).
- *Salinosporamide A*: This proteasome inhibitor, derived from *Salinispora tropica*, is currently in clinical trials for multiple myeloma and glioblastoma (Seyed & Ayesha, 2021).

These examples illustrate the potential and difficulties of converting marine microbial products into therapeutic applications. Numerous additional compounds are in preclinical or clinical development, particularly addressing antimicrobial resistance and cancer.

17.3.3 Advances in biotechnological tools

Modern biotechnology advancements have transformed the quest for marine microbial pharmaceuticals, especially in addressing the constraints of conventional cultivation methods.

- *Genomic Mining*: With a drop in sequencing costs, researchers may now investigate marine microbial genomes for BGCs probable sources of novel bioactive compounds. Tools like antiSMASH and ARTS predict metabolite classifications based on gene structure, enabling targeted investigations (Kaari et al., 2022).
- *Metagenomics*: Metagenomics enables the direct extraction of biosynthetic genes from environmental materials due to the unculturable characteristics of many marine microbes (Liu et al., 2022). This enables the discovery of new bioactive chemicals without isolating individual organisms.
- *Synthetic Biology*: Biosynthetic pathway-encoding genes can now be cloned and produced in heterologous hosts like *Streptomyces* or *Escherichia coli*, which are more conducive to modification and scaling (Zhang et al., 2019). This is particularly advantageous for accessing cryptic or silent gene clusters that stay unexpressed in laboratory conditions.

These technologies enhance compound discovery, enable structural alteration, improve yield, and facilitate studies on resistance mechanisms.

17.3.4 Role of high-throughput screening and AI-driven drug discovery

HTS has become a vital component in marine drug discovery. Automation now facilitates the evaluation of hundreds of marine microbial extracts or fractions against disease models within days (West & Crawford, 2016). Cytological profiling and multiparameter cell imaging yield extensive datasets that elucidate structure–activity correlations prior to drug isolation.

AI is augmenting this process by:

- Predicting bioactivity based on molecular structure.
- Detecting novel BGCs in genomic datasets.
- Ranking lead compounds utilizing machine learning (ML) algorithms informed by pharmacokinetic and toxicological data.

- AI is especially adept at addressing the "*rediscovery problem*," the recurrent isolation of previously identified compounds that has historically hindered natural product research (Liu & Yu, Fan, et al., 2024).

Furthermore, integrated systems already merge AI (Refer Table 17.3 for some of AI tools used in the drug discovery) with synthetic biology to engineer novel biosynthetic pathways or enhance existing ones for improved yields and activity, signifying a new epoch in "*smart bioprospecting*" (Almaliti & Gerwick, 2023).

17.4 Challenges and shortcomings in marine microbial drug development

Despite the substantial medicinal potential of marine microorganisms, the progression of their metabolites from discovery to licensed therapeutic products entails considerable scientific, logistical,

Table 17.3 HTS and AI-driven drug discovery.			
Tool/study name	Technology used	Application	References
Protein Sequencing and Drug Discovery by HTS	HTS, mass spectroscopy, crystallography	Protein structure analysis and drug screening	Cronk & Shearer, 2021
HTS for New Drug Discovery	Robotics, Laboratory Information Management Systems (LIMS)	Screening of natural products and combinatorial libraries	Liu and Zhang (2024)
High Content and Throughput Drug Discovery	Ultra-High-throughput Screening (uHTS), microfluidics	Screening biological and chemical perturbations	Williams et al. (2024)
High-throughput and In Silico Screening in Drug Discovery	HTS, in silico tools	Bioactive molecule identification, lead development	Thrithamarassery Gangadharan et al. (2017)
HTS Data Analysis	HTS data quality analysis, statistical modeling	Hit validation and error reduction in drug screening	Zhong et al. (2015)
HTS Technologies for Drug Discovery	Virtual screening, image analysis, microarray screening	Compound identification, drug development	Wang (2023)
Role of AI in Accelerating Drug Discovery	ML, deep learning	Target identification, screening, toxicity prediction	Sarkar et al. (2023)
Molecular Representations in AI-driven Drug Discovery	Graph neural networks, chemical descriptors	Chemical representation for AI drug models	Satheeskumar (2024)

HTS, High-throughput screening; AI, artificial intelligence; ML, machine learning.

and regulatory challenges. These problems encompass the entire drug research process, from acquiring microbial biodiversity to manufacturing and commercialization [Fig. 17.2](#).

17.4.1 Biodiversity and sampling challenges

The ocean constitutes Earth's most extensive repository of microbial diversity; nevertheless, only a small portion has been investigated due to restricted accessibility and technological limitations. Numerous marine microorganisms reside in severe or isolated settings such as deep-sea sediments, hydrothermal vents, and polar waters, which are logistically and monetarily challenging to sample ([Radziejewska et al., 2023](#)). Sampling frequently necessitates specialized apparatus like remotely operated vehicles (ROVs) or deep-sea pressurized containers, which are typically inaccessible to most research organizations ([McLean et al., 2020](#)).

Furthermore, marine microbial populations are dynamic and can be substantially modified by environmental alterations, including temperature, salinity, and pollution. These variations complicate biodiversity evaluations and impede consistency in investigations. Extensive initiatives such as the Sorcerer II Global Ocean Sampling trip uncovered significant uncharacterized genetic diversity, highlighting the limited understanding of marine microbial ecosystems ([Venter & Duncan, 2023](#)).

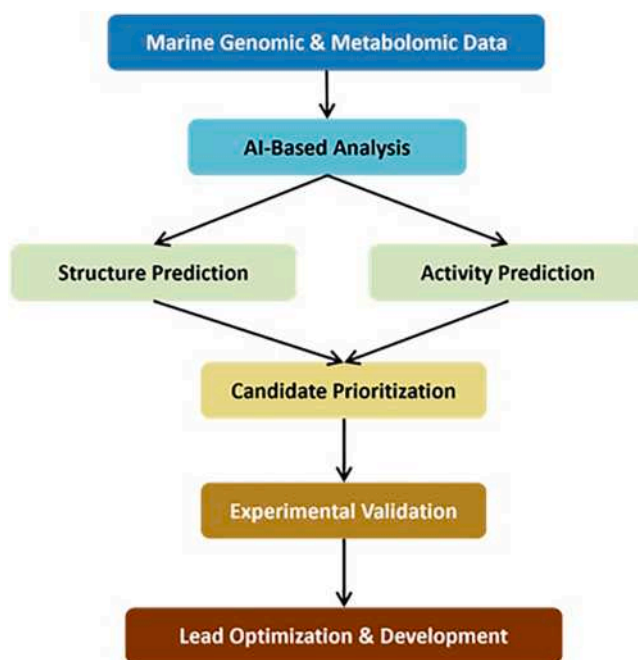


FIGURE 17.2

Integration of AI in marine drug discovery. *AI*, Artificial intelligence.

17.4.2 Cultivation and production limitations

The culture of microbial strains constitutes a significant bottleneck in marine microbial medication development. Fewer than 1% of marine bacteria are predicted to be easily cultivable using conventional laboratory methods, while the remainder exists as "microbial dark matter" (Lok, 2015; Jiao et al., 2021). These unculturable microbes may possess the potential for novel bioactive chemicals; yet they remain inaccessible without optimal growth environments.

Scaling up extraction can be challenging, even for cultivable strains. Marine bacteria frequently synthesize secondary metabolites in negligible amounts or solely in response to environmental stress. This poses challenges for preclinical testing and commercial production. Although synthetic biology and heterologous expression systems provide specific options, converting of a complex marine BGC onto a terrestrial host presents significant technological challenges, potentially leading to diminished yields or loss of function (Wibowo et al., 2023).

17.4.3 Chemical and structural complexity

Marine microbial metabolites are distinguished by their remarkable structural diversity, frequently exhibiting complex scaffolds, atypical functional groups, and unique stereochemical configurations (Carroll et al., 2021). These properties support their potent and selective bioactivities; yet they also provide significant challenges throughout the therapeutic development process, from isolation to synthesis and optimization.

17.4.3.1 Unique chemical features

Marine natural products often comprise halogenated atoms (e.g., bromine, chlorine), sulfated groups, polycyclic structures, or bridged ether linkages (Blunt et al., 2018). These characteristics are uncommon in terrestrial metabolites and enhance pharmacological interest in marine compounds. However, this chemical innovation also leads to:

- Inadequate solubility or stability in physiological conditions
- Challenges in extensive chemical synthesis
- Incompatibility with conventional formulation techniques

Moreover, intricate stereochemistry demands meticulous regulation during synthetic replication, frequently requiring multistep, low-yield procedures that elevate both time and expense.

17.4.3.2 Isolation challenges

Marine microbial isolates display a multifaceted and varied chemical makeup. Target compounds often exist in minute levels, concealed by other dominant metabolites. Advanced extraction technologies, such as high-performance liquid chromatography (HPLC), ultra-performance liquid chromatography (UPLC), and multidimensional chromatography, are essential for isolating pure bioactive compounds from crude extracts. These methods need substantial resources and demand advanced expertise (Ebada et al., 2008).

17.4.3.3 Structural characterization

Understanding the structure of complex marine metabolites is a challenging task. Traditional analytical methods often demonstrate insufficiency due to the size, symmetry, or instability of the compounds. High-resolution nuclear magnetic resonance (NMR) spectroscopy, mass spectrometry (MS), cryo-electron microscopy (cryo-EM), and X-ray crystallography are commonly utilized simultaneously to explain structural ambiguity. Notwithstanding advanced instruments, thorough characterization may necessitate months and yet yield partial results, especially for compounds with several chiral centers or unstable intermediates.

17.4.3.4 Chemical modification and optimization

Medicinal chemistry is crucial for improving drug-like properties such as solubility, stability, and bioavailability. The presence of reactive or labile functional groups in marine compounds sometimes complicates derivatization. Sulfated or highly oxidized compounds may degrade under standard reaction conditions, hence limiting options for structural change. Furthermore, many marine compounds function via mechanisms that are poorly understood, hindering rational design and structure–activity relationship (SAR) studies (Dinarvand & Spain, 2021).

17.4.3.5 Limited mechanistic understanding

Diverse marine microbial compounds demonstrate potential biological activity; however, their cellular targets and mechanisms of action remain poorly defined. This is often due to their novelty, lack of similar terrestrial counterparts, or limitations in bioassay techniques. Without a molecular knowledge, optimizing selectivity, efficacy, or reduced toxicity becomes a trial-and-error process, impeding therapeutic progress (Romano et al., 2018).

17.4.4 Regulatory and economic hurdles

The journey from discovery to commercialization for any pharmaceutical compound is arduous and expensive, and marine microbial products are no exception. The typical duration for medication development surpasses 10 years and incurs expenses in the billions of dollars. Marine-derived chemicals encounter heightened regulatory oversight owing to their novelty and ecological origins (Daniotti & Re, 2021; Musa et al., 2024).

- *Regulatory Concerns:* Regulatory bodies such as the FDA and EMA mandate comprehensive data on safety, efficacy, and environmental impact. The intricacy of marine natural products may necessitate supplementary toxicological or pharmacokinetic investigations, hence extending development times and expenses.
- *Intellectual Property:* Establishing and safeguarding patents for natural substances is notoriously challenging. In some instances, the same or analogous chemicals may be synthesized by various marine creatures, prompting issues over patent eligibility and ownership.
- *Economic Viability:* Creating a sustainable and scalable supply chain presents a significant challenge. A significant number of marine goods cannot be sustainably collected from their natural habitats, requiring synthetic or biotechnological substitutes, which may be expensive and technically impractical.

Furthermore, financing for nascent marine natural product research is constrained relative to other therapeutic domains, hindering commercial investment. Public-private partnerships (PPPs) and government-supported incentives may alleviate these obstacles; however, such frameworks are not yet prevalent.

17.5 Prospects and emerging trends

As the demand for novel therapies grows, particularly due to increasing antimicrobial resistance and treatment-resistant malignancies, marine microbial drug development is advancing through technological convergence. Future advancements in genomics, synthetic biology, AI, microbiome research, sustainability, and collaborative frameworks are poised to transform the sector, facilitating more intelligent, rapid, and ethical medication development.

17.5.1 Advances in microbial genomics and synthetic biology

The decreasing cost and enhanced throughput of DNA sequencing have catalyzed remarkable advancements in genome mining and functional genomics. Utilizing bioinformatics methods like antiSMASH and BiG-SCAPE, researchers may detect BGCs in marine microbial genomes and anticipate their capacity to synthesize bioactive secondary metabolites (Di et al., 2024).

Synthetic biology contributes to these findings by facilitating the production of gene clusters in well-characterized host organisms such as *E. coli* or *Streptomyces*. Heterologous expression systems are essential for extracting compounds from unculturable marine microorganisms. Novel host species, including as marine bacteria like *Vibrio natriegens*, are currently being investigated for their rapid proliferation and compatibility with synthetic circuits (Buijs et al., 2019). Genomics and synthetic biology are transforming marine natural product development from a laborious, empirical approach to a predictive, design-focused field.

17.5.2 Marine microbiome research and microbiota-based therapeutics

The marine microbiome is being explored for its therapeutic potential, paralleling the attention on the human microbiome. Marine microbiotas are recognized for their production of bioactive compounds and their ecological functions, such as nutrient cycling, symbiosis, and biofilm regulation, which may exhibit biological similarities (Tan, 2023).

Advanced meta-omics, encompassing metagenomics, metatranscriptomics, and metaproteomics, enable the analysis of entire microbial communities without culturing, allowing researchers to delineate functional gene networks and identify "core" marine microbiomes responsible for chemical synthesis (Bharti & Grimm, 2021). Future therapeutic strategies may include engineered marine microbial consortia for use in regenerative medicine, wound healing, or immunomodulation, inspired by the effectiveness of human microbiome therapies like fecal transplants or live biotherapeutics (Hahn et al., 2024).

17.5.3 Artificial intelligence and machine learning in bioactive compound discovery

Recent advances indicate that AI and ML are markedly improving the identification of marine bioactive chemicals. [Moret et al. \(2019\)](#) showed that deep learning algorithms can produce tailored libraries of novel bioactive compounds derived from natural products, significantly enhancing pharmacologically pertinent chemical domains ([Moret et al., 2019](#)). [Beyan and Browman \(2020\)](#) emphasized that ML, especially deep learning, facilitates the discovery of concealed patterns in extensive marine datasets, hence expediting the identification of possible bioactive chemicals ([Beyan & Browman, 2020](#)). [Schneider et al. \(2022\)](#) advanced this domain by creating AI-driven techniques for the de novo design of bioactive compounds inspired by natural products, presenting a novel strategy for drug discovery ([Schneider et al., 2022](#)). [La Paglia et al. \(2023\)](#) introduced novel AI-driven computational methods to investigate innate immunity mechanisms in marine invertebrates, such as ascidians, with the objective of identifying new bioactive compounds ([La Paglia et al., 2023](#)). In addition to these findings, [Park et al. \(2022\)](#) conducted a thorough analysis of ML methodologies employed for the identification and assessment of bioactive chemicals, with specific emphasis on natural products as a valuable source ([Park et al., 2022](#)).

17.5.3.1 Prediction of bioactivity and target identification

AI significantly contributes to marine drug discovery by predicting biological activity from molecular structure. AI models, utilizing algorithms trained on extensive chemical libraries, can discern molecules that are likely to engage with specific molecular targets, hence minimizing the necessity for comprehensive experimental screening ([Goshisht, 2024](#)). Platforms such as PandaOmics and Chemistry42 exemplify how AI-driven models can expedite hit identification by merging structure-based design with biological pathway research ([Pushkaran & Arabi, 2024](#)). Moreover, AI models can analyze genomic data to identify novel BGCs with medicinal potential. This facilitates the quick prioritization of strains and gene clusters, hence improving the effectiveness of later drug isolation and synthesis efforts.

17.5.3.2 Dereplication and novelty assessment

AI enhances the dereplication process by rapidly comparing new compounds with existing chemical databases, aiding researchers in avoiding the re-isolation of known molecules. Advanced cheminformatics algorithms can detect structural analogs and suggest potential scaffolds for more investigation. This is particularly advantageous in marine microbial research, where considerable chemical redundancy often arises.

17.5.3.3 AlphaFold for structural prediction and functional analysis

A notable progress in AI-assisted medicine development was realized with the introduction of AlphaFold, a deep learning system developed by DeepMind that predicts protein structures with atomic accuracy. AlphaFold's capability to model protein targets, especially those lacking prior structural data, has considerably expanded the range of proteins available for virtual screening and docking studies. AlphaFold-predicted structures have effectively facilitated the identification of inhibitors for targets such as CDK20 within 30 days of target selection, showcasing its capability to

substantially reduce drug discovery timeframes (Gangwal & Lavecchia, 2024). In marine environments, where numerous microbial enzymes and regulatory proteins have unresolved structures, AlphaFold facilitates functional investigation and biosynthetic engineering of hidden pathways.

17.5.3.4 Integration with robotics and high-throughput screening

AI can enhance entire discovery operations when integrated with robots and automated HTS systems. Models can select chemical libraries for evaluation, forecast off-target effects, and propose optimal synthesis pathways. AI-driven algorithms are currently being trained not only to identify hits but also to iterate on molecular design to enhance potency and drug-likeness, a notion referred to as generative chemistry.

17.5.3.5 Limitations and future directions

Although AI technologies such as AlphaFold have transformed protein structure prediction, they possess inherent limits. AlphaFold primarily produces static structures and is unable to comprehensively represent protein dynamics or allosteric binding interactions crucial for elucidating complicated molecular activities (Raisinghani et al., 2024). Consequently, the combination of molecular dynamics simulations with wet-lab validation is imperative. In the future, AI is anticipated to transition from a mere tool to a fully integrated co-pilot in marine natural product research, facilitating automated bioactivity prediction, compound optimization, and biosynthetic pathway design.

17.5.4 Sustainable bioprospecting and marine conservation strategies

The critical need to utilize marine biodiversity must be reconciled with sustainable methodologies. The overexploitation of marine animals and harmful sampling techniques can jeopardize fragile ecosystems, particularly coral reefs and deep-sea environments. Consequently, novel methodologies prioritize noninvasive, in situ sampling and ex situ culture, complemented by digital bioprospecting, extracting genomic data instead of physical specimens.

Metagenomics provides a sustainable method by isolating and analyzing microbial DNA from seawater or sediment samples, eliminating the necessity to culture or harvest complete organisms. Synthetic biology enhances sustainability by facilitating the manufacture of marine substances in laboratory-cultivated hosts, hence eliminating the need for environmental extraction (Flaviani, 2017). Furthermore, conservation principles consistent with the Nagoya Protocol are progressively incorporated into marine bioprospecting agreements to guarantee fair and equitable distribution of benefits, particularly for biodiversity-rich areas in the Global South.

17.5.5 Potential collaboration between academia, industry, and regulatory bodies

The intricacy and expense of marine drug research necessitate strong collaboration across sectors. Academic research institutes provide basic information, whereas industry offers resources, scalability, and commercialization skills. Concurrently, regulatory authorities are essential in formulating safety, efficacy, and environmental protection frameworks.

PPPs and consortia such as the EU's Horizon Blue Growth initiatives showcase effective collaborative research models in marine biotechnology (Theis & van Liempd, 2024). These programs

may be broadened to encompass global marine biodiversity databases, open-access biogeochemical libraries, and collaborative biofoundries for synthetic biology research. Efforts must be undertaken to synchronize research aims with regulatory timelines and market demands to enhance translational efficiency from laboratory to clinical application. Interdisciplinary training programs could equip a new generation of scientists proficient in genomics, AI, environmental legislation, and pharmaceutical research.

17.6 Conclusion

Marine microbes present an underutilized reservoir of structurally unique and physiologically active natural compounds with considerable potential for pharmacological advancement. Their distinctive evolutionary adaptations have led to biosynthetic pathways that can generate various secondary metabolites, many of which lack terrestrial counterparts. Although many substances, like cytarabine, trabectedin, and salinosporamide A, have attained clinical application or development, most marine microbial metabolites remain underexploited due to significant difficulties.

Challenges include obtaining deep-sea microbial biodiversity, the low cultivability of numerous strains, intricate chemical structures, and regulatory and economic obstacles. Recent advancements in genomics, metagenomics, synthetic biology, and AI are surmounting innumerable obstacles. Furthermore, incorporating sustainable bioprospecting techniques and global regulatory collaboration fosters a more ethical and scalable future.

The ongoing integration of microbiology, bioinformatics, pharmacology, and environmental research is crucial to realize the medicinal potential of the marine microbiome fully. Collaborative frameworks across academia, industry, and politics will be essential for turning marine microbial research into practical medicines. The oceans could provide the next generation of life-saving pharmaceuticals through focused innovation and prudent management.

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Biomining of waste materials using marine microbial products

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Anjaneyulu Musini¹, P. Gnana Deepu¹, Mariam Ahmed¹, Gandikota Sardhika¹,
Gedela Sandhya Rani¹, Pilli Aishwarya¹, Prathipati Supriya¹, Kondakindi Venkateswar Reddy¹,
Venkateshwarlu Musini² and Himanshu Narayan Singh³

¹Centre for Biotechnology, University College of Engineering, Science and Technology, Jawaharlal Nehru
Technological University, Hyderabad, Telangana, India,

²Department of Civil Engineering, CMR College of Engineering and Technology, Hyderabad, Telangana, India,

³Department of Systems Biology, Columbia University Irving Medical Centre, New York, NY, United States

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18.1 Introduction to biomining

A little conference titled “Drugs from the Sea” was organized in 1967 in Rhode Island, United States. Although the first real medication from the sea took a while to create, the symposium’s tagline has persisted throughout the years as a metaphor for drug development from marine natural resources. The intense search for new substances from marine organisms is supported by the need for novel substances to treat severe human diseases like cancer, microbial infections, and inflammatory processes, as well as the realization that marine organisms offer a rich potential source of such substances (Saeed et al., 2021). Algae and marine creatures have been studied a lot in the past. But contemporary marine biotechnology has shifted its emphasis to microorganisms, including the development of novel drugs from marine microbes. Particularly, bacteria and fungus found in marine microorganisms like sponges, corals, and algae are powerful makers of biologically active compounds

that have notable actions against tumor cells in addition to pathogenic bacteria, fungi, and viruses (Penesyan et al., 2010). The hunt for therapeutic leads in marine creatures is highly appealing due to the exceptionally high hit rates of marine chemicals. In general, natural products are crucial to the creation of pharmaceuticals. Naturally derived pharmaceuticals (unmodified natural product, modified natural product, or synthetic molecule containing a natural product as pharmacophore) accounted for 63% of newly developed medications. Between January 1981 and mid-October 2008, 68% of anti-infectives (antiviral, antifungal, antibacterial, and antiparasitic) and 63% of medications used to treat cancer were obtained from natural sources (Newman & Cragg, 2020). There are two main facets to research on biologically active chemicals and how they are produced. The ecological importance of microbe-microbe and microbe-host interactions is one thing; the other is their potential use in disease therapy and other applications. Apart from their usage as medications, marine microorganisms and their byproducts find applications in bioremediation, materials technology, and as model organisms for marine biomedicine. In this overview, we go over the potential and uses of marine microbes in marine biotechnology and natural product manufacturing (Haripriya & Suthindhiran, 2024). The more generic term “biomining,” which can be used to describe both procedures, primarily refers to the utilization of microbial activities in the mining sector for large-scale economic recovery. The principles of bioleaching, biomining, and other biomining techniques are discussed in this book along with their mechanics and commercial uses. Additionally addressed are the case studies and potential technological paths (Chen et al., 2024).

18.2 Marine microbes and their unique properties

Marine microbes are fascinating and diverse organisms that play crucial roles in marine ecosystems. Marine microbes, which include bacteria, archaea, viruses, protists, and fungi, play essential roles in ocean ecosystems and have a variety of unique properties that make them distinct from terrestrial microbes. These properties are vital for maintaining oceanic health, biogeochemical cycling, and the overall functioning of marine environments. Below is a detailed exploration of these unique properties

18.2.1 Adaptations to extreme environments

- **Salinity tolerance:** Marine microbes have evolved to thrive in high-salinity environments. Halophilic (salt-loving) bacteria and archaea can survive in hypersaline environments, such as salt flats, deep-sea brines, and tidal pools. These organisms possess specialized osmoregulatory mechanisms to maintain cell integrity and function despite the high osmotic stress.
- **High-pressure adaptation:** Deep-sea microbes, which live at great depths, experience extreme pressure (up to 1000 times that at the surface). Psychrophilic (cold-loving) and piezophilic (pressure-loving) bacteria and archaea have adapted to this extreme environment by producing proteins and enzymes that maintain their structure and function under pressure.
- **Temperature Resilience:** Many marine microbes are psychrotolerant or psychrophilic, meaning they can survive or thrive in cold ocean waters, typically ranging from -2°C to 20°C . These microbes have specialized enzymes that function at low temperatures, such as antifreeze proteins that prevent the formation of ice crystals (Azam & Malfatti, 2007).

18.2.2 Diverse metabolic pathways

- **Chemosynthesis:** In the absence of sunlight, marine microbes like *Sulfur bacteria* and *Methanogens* perform chemosynthesis, where they use chemical reactions, often involving hydrogen sulfide or methane, to produce energy. These microbes are often found in deep-sea hydrothermal vent communities, where sunlight cannot penetrate.
- **Nitrogen fixation:** Some marine cyanobacteria, such as *Trichodesmium*, can fix atmospheric nitrogen into forms usable by other organisms, contributing to the nitrogen cycle in the ocean. This is essential in areas where the nitrogen supply is limited, such as oligotrophic (nutrient-poor) waters.
- **Denitrification and nitrate reduction:** Marine microbes are involved in the process of denitrification, where they convert nitrate into nitrogen gases, such as N_2 and N_2O , which are then released back into the atmosphere. This process is critical for regulating nitrogen levels in the ocean and preventing eutrophication (Falkowski & Raven, 2007).

18.2.3 Role in biogeochemical cycles

- **Carbon cycling:** Marine microbes, particularly phytoplankton, are responsible for much of the ocean's primary productivity through photosynthesis. These organisms take in carbon dioxide and convert it into organic matter, which is then either consumed by marine consumers or sinks to the deep ocean, contributing to the "biological pump" of carbon sequestration.
- **Sulfur and methane cycling:** Sulfate-reducing bacteria (SRB) and methane-producing archaea (methanogens) are integral to sulfur and carbon cycling in marine environments. For instance, SRB play a role in the reduction of sulfate to hydrogen sulfide, which is utilized by other microbes, including sulfur-oxidizing bacteria. These processes are crucial in maintaining the balance of sulfur and methane in marine systems (Yutin & Galperin, 2013).

18.2.4 Genetic and functional diversity

- **Horizontal gene transfer:** Marine microbes exhibit a high degree of genetic exchange via horizontal gene transfer (HGT), which allows them to rapidly adapt to changing environments and acquire resistance to pollutants or antibiotics. This can occur through transformation, conjugation, or transduction, making marine microbial communities highly dynamic.
- **Phylogenetic diversity:** The ocean is home to a vast diversity of microorganisms, including novel species that have yet to be fully characterized. Marine metagenomics has revealed previously unknown microbial lineages, particularly in extreme environments like hydrothermal vents or the deep sea. This diversity is crucial for maintaining ecosystem services such as nutrient cycling and the breakdown of organic matter (Whitman et al., 1998).

18.2.5 Symbiosis and mutualistic relationships

- **Symbiotic associations:** Marine microbes engage in numerous symbiotic relationships with larger marine organisms. For example, marine sponges harbor microbial communities that assist in nutrient cycling, while coral reefs host cyanobacteria (like *Symbiodinium*) that photosynthesize and provide energy to corals. In return, the corals provide shelter and nutrients to the microbes.

- **Marine microbiomes:** The microbiomes of marine organisms (such as fish, whales, and invertebrates) play key roles in digestion, immune system function, and protection against pathogens. These microbiomes are often highly specialized and can vary significantly across different marine species and habitats ([Suttle, 2007](#)).

18.2.6 Resistance to environmental stressors

- **Antibiotic and chemical resistance:** Marine microbes, particularly those living in polluted areas such as coastal zones and the deep sea, have developed mechanisms to resist a wide range of natural and anthropogenic toxins, including antibiotics and heavy metals. This resistance can arise from genetic adaptations or the production of biofilms, which protect the microbial communities.
- **UV radiation protection:** Marine microbes living near the ocean's surface are exposed to high levels of ultraviolet (UV) radiation. To protect themselves, many marine bacteria and algae produce UV-absorbing pigments, such as carotenoids, or have specialized DNA repair mechanisms to counteract the damage caused by UV exposure ([Falkowski & Raven, 2007](#)).

18.2.7 Biological interactions with viruses

- **Viral dynamics:** Marine viruses play a crucial role in the regulation of microbial populations. Phages (viruses that infect bacteria) are involved in controlling bacterial abundance and diversity by lysing their hosts. This viral-mediated mortality contributes to nutrient cycling and helps shape microbial community structures.
- **Viral shunting:** The process by which viral lysis of microbial cells releases organic matter back into the water column is referred to as viral shunting. This process leads to the release of dissolved organic matter (DOM) that can be utilized by other microbes, which has implications for oceanic carbon cycling ([Azam & Malfatti, 2007](#)).

18.2.8 Marine microbial biomarkers

- **Biomarkers for climate change:** Marine microbes, particularly those in the planktonic realm, are used as bioindicators of oceanic health and climate change. For example, changes in the abundance and diversity of certain microbial groups, such as diatoms, can indicate shifts in nutrient availability or ocean acidification. Additionally, microbial lipids and isotopic signatures can be used to track historical climate change ([Suttle, 2007](#)).

18.3 Marine microbes products for biomining

We use marine microbes products for the extraction of important compounds a sustainable process for extracting metals and minerals from ores using biological organisms. These microbes are capable of leaching metals, such as copper, gold, and uranium, from ores through various biochemical processes. The unique properties of marine environments make marine microbes an attractive source of novel biotechnological applications, including biomining ([Saldaña et al., 2023](#)).

18.3.1 Types of marine microbes in biomining

Marine microorganisms involved in biomining typically include:

- **Acidophilic bacteria:** These bacteria thrive in acidic environments, often found in metal-rich marine waters, and are key in the extraction of metals like copper, gold, and iron.
- **Sulfate-reducing bacteria:** These microbes can reduce sulfate to sulfide and are often used to extract heavy metals like uranium and gold.
- **Fungi and algae:** Marine fungi and algae are also used for bioaccumulation and biosorption of metals from the environment (Bhatt et al., 2022).

18.3.2 Mechanisms of marine microbes in biomining

Marine microbes contribute to biomining through various mechanisms, including:

- **Bioleaching:** Some marine bacteria, such as *Acidithiobacillus ferrooxidans*, produce acids (e.g., sulfuric acid) that dissolve metals from ores, making them easier to extract. The bacteria oxidize the metal sulfides, converting them into soluble forms.
- **Biosorption:** Marine algae and fungi can absorb heavy metals through their cell walls, concentrating them in their bodies. This mechanism is used for bioremediation and metal extraction from contaminated water.
- **Bioaccumulation:** Some marine organisms, such as algae and bacteria, accumulate metals inside their cells. This is useful for extracting metals from polluted marine environments or low-concentration ore bodies.
- **Biotransformation:** Marine microbes can convert metals into more accessible forms through enzymatic processes. For example, *Pseudomonas* species may reduce toxic metal ions (e.g., hexavalent chromium) into less toxic or insoluble forms, aiding in their extraction (Alabssawy & Hashem, 2024).

18.4 Waste material as resource for biomining

Biomining refers to the process of using microorganisms to extract metals from ores or waste materials. The concept of using waste materials as resources for biomining has gained traction as a sustainable and eco-friendly alternative to traditional mining. Waste materials—such as industrial byproducts, sewage sludge, agricultural residues, and e-waste—can be rich in valuable metals like copper, gold, zinc, or rare earth elements (REEs). Biomining utilizes microorganisms, especially bacteria and fungi, to solubilize these metals and recover them from waste streams.

18.4.1 Electronic waste

Electronic waste (E-waste) refers to discarded electrical or electronic devices, including computers, smartphones, televisions, circuit boards, and batteries. These devices often contain valuable metals such as gold, silver, palladium, copper, and platinum, which can be recovered through biomining.

Biomining role E-waste presents a substantial environmental problem because of the toxic substances such as lead, mercury, and cadmium it contains. However, the valuable metals within E-waste make it a prime candidate for biomining. Microorganisms are used to recover precious metals from E-waste, reducing the need for traditional, environmentally harmful extraction methods.

Example: Certain bacteria like *Thiobacillusferrooxidans* and *Leptospirillumferrooxidans* have been used to bioleach gold and other metals from the components of E-waste.

18.4.2 Mining tailings

Mining tailings are the residual materials left over after extracting valuable metals from ores. These often consist of finely ground rock and mineral particles and can contain trace amounts of valuable metals that remain after the primary mining process. Biomining role tailings often contain metals such as gold, copper, and REEs. The biomass from microorganisms can help recover these metals through bioleaching, potentially turning these waste products into valuable resources (Opara et al., 2022).

Example: Copper and gold recovery from mining tailings is a well-established application, where bacteria like *Leptospirillum ferrooxidans* and *Acidithiobacillus ferrooxidans* oxidize metal sulfides, releasing metals into solution.

18.4.3 Industrial sludge

Industrial sludge is a byproduct of various industrial activities, including paper and pulp manufacturing, metal processing, and chemical production. These sludges often contain heavy metals such as chromium, zinc, copper, nickel, and lead. Many of these metals are considered pollutants but are also valuable resources. Microorganisms can extract and accumulate these metals, turning industrial waste into a potential resource (Islam et al., 2017).

Example: The use of fungi like *Aspergillusniger* has been explored for bioaccumulation of heavy metals from industrial sludge.

18.4.4 Municipal solid waste

Municipal solid waste (MSW), often referred to as garbage or trash, consists of everyday items discarded by households, industries, and businesses. Some components of MSW contain metals like aluminum, copper, or precious metals that can be recovered using biomining processes. Certain components of MSW, particularly those containing E-waste or metal-rich materials, can be treated with microorganisms to recover metals. Waste materials like used batteries, discarded electronics, and even textiles can provide valuable metal recovery opportunities (Sharma et al., 2025).

Example: Microorganisms like *Bacillus* species are known to bioaccumulate metals from municipal waste containing electronic components.

18.4.5 Agricultural waste

Agricultural waste refers to the organic material left over from farming activities, such as crop residues, animal manure, and contaminated soils. Some agricultural waste can contain elevated levels

of heavy metals due to the use of fertilizers and pesticides. In some instances, agricultural waste may contain valuable metals such as zinc or copper, especially when contaminated by industrial or urban pollution. Certain plants and microorganisms can be employed to recover these metals (Oluseun Adejumo & Adebukola Adebisi, 2021).

Example: Phytomining using hyperaccumulator plants or the bioleaching process through fungi can be employed to recover metals from polluted agricultural soil.

18.5 Mechanisms of biomining by marine microbes

Biomining, in the context of marine microbes, is an emerging field of study that utilizes the natural metabolic capabilities of marine microorganisms to extract valuable metals from ores and waste materials in marine environments. Marine environments, including oceans, coastal sediments, and deep-sea ecosystems, harbor a unique set of microorganisms that have adapted to extreme conditions, making them promising candidates for various biotechnological applications, including biomining (Imhoff et al., 2011).

18.5.1 Marine microbial mechanisms in biomining

Marine microbes can contribute to biomining processes in several ways, predominantly through bioleaching, bioaccumulation, and bioremediation. These processes enable the extraction of valuable metals, including copper, gold, silver, and REEs, from ores, sediments, and waste materials in marine environments (Cozma et al., 2024).

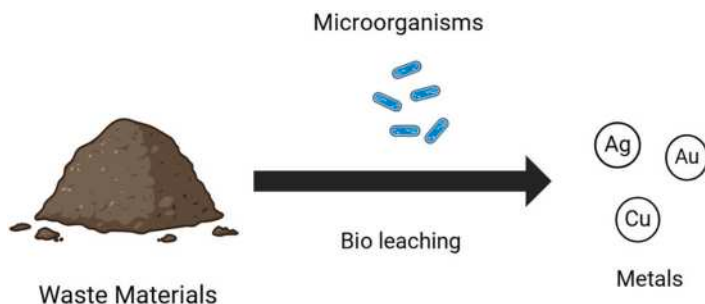
18.5.1.1 Bioleaching by marine microorganisms

Bioleaching is the process by which microorganisms, particularly acidophilic bacteria, oxidize metal ores to solubilize valuable metals from their solid forms into the aqueous phase. It can also be described as a process that uses microorganisms for the extraction of metals from ores and secondary sources (Fig. 18.1). Bioleaching acts as an alternative to traditional extraction methods. Marine microorganisms involved in bioleaching typically live in environments with high salinity and varying pH levels, and their metabolic processes help recover metals from minerals that are otherwise difficult to process through conventional means (Jones & Santini, 2023).

Marine acidophilic bacteria: These bacteria thrive in acidic environments (pH 1–3), which are common in marine habitats such as hydrothermal vents, acidic sediments, and coastal environments with high levels of sulfide minerals. These bacteria have evolved mechanisms to oxidize metal sulfides and release metals into solution.

Thiobacillus and *Leptospirillum* are well-known examples of acidophilic bacteria used in bioleaching, but their marine counterparts, like *Acidithiobacillus ferrooxidans* and *Ferroplasma acidarmanus*, also play an important role.

The process involves the oxidation of metal sulfides (e.g., copper, gold, and zinc sulfides) to produce metal ions, which can then be further processed or recovered (Newman & Cragg, 2020).

**FIGURE 18.1**

Bioleaching.

18.5.1.1.1 Marine fungi and yeasts

Marine fungi and yeasts are also known to participate in bioleaching processes. For instance, *Aspergillusniger* and *Penicillium* species, commonly found in marine environments, are capable of leaching metals such as copper, manganese, and cobalt from contaminated marine sediments. Fungi typically release organic acids like citric and oxalic acids, which help dissolve metal ions and make them bioavailable for uptake (Imhoff et al., 2011).

18.5.1.2 Bioaccumulation by marine microorganisms

Bioaccumulation refers to the process by which microorganisms take up metals from the environment and store them within their cells. Marine microorganisms, particularly marine bacteria, algae, and fungi, are capable of accumulating high concentrations of metals, making them valuable for biomining applications.

18.5.1.2.1 Marine bacteria

Certain marine bacteria, such as *Pseudomonas*, *Bacillus*, and *Vibrio* species, have been shown to accumulate metals such as mercury, cadmium, copper, and zinc from contaminated marine environments. These bacteria often concentrate the metals within their cell walls or in intracellular compartments, which can later be extracted (Singh et al., 2021).

Vibrio harveyi, a marine bacterium, is known for accumulating copper, while *Pseudomonas aeruginosa* has been reported to bioaccumulate heavy metals from polluted marine environments.

18.5.1.2.2 Marine algae

Marine algae, such as *Chaetomorpha* and *Ulva*, can accumulate and concentrate metals, including copper, nickel, and cadmium, from seawater. Algae typically accumulate metals on their cell surfaces through adsorption or in their cells through internalization mechanisms(Singh et al., 2021).

18.5.1.2.3 Marine fungi

Marine fungi, like *Trichoderma* and *Aspergillus* species, can also accumulate metals, particularly in marine sedimentary environments. These fungi accumulate metals in their hyphal structures and can serve as natural “biomineralizers.”

18.5.1.3 Bioremediation in marine environments

Bioremediation is the process by which microorganisms break down or transform toxic pollutants, including metals, into less harmful forms. In marine environments, bioremediation by microorganisms can play an important role in detoxifying contaminated sediments, wastewater, and marine ecosystems that are polluted by heavy metals from industrial waste, mining activities, and marine shipping (Shin et al., 2013).

Marine microorganisms for bioremediation: Marine bacteria, fungi, and algae can be used in bioremediation processes to reduce the concentrations of heavy metals such as mercury, arsenic, and cadmium in contaminated marine environments.

Desulfovibrio and *Shewanella* species are known to reduce toxic metals like uranium and chromium to less soluble forms, effectively immobilizing them in sediment.

Pseudomonas putida has shown potential in reducing the bioavailability of toxic metals in marine environments through biotransformation.

18.5.2 Unique marine microorganisms in biomining

Marine microorganisms involved in biomining differ from their terrestrial counterparts in that they are often adapted to extreme conditions, such as high salinity, extreme temperatures, and high pressures, that are not commonly found in land-based environments. Their unique biochemical pathways and mechanisms make them particularly suited for biomining in marine ecosystems (Newman & Cragg, 2020).

18.5.2.1 Marine sulfate-reducing bacteria

SRBs play a crucial role in the biogeochemical cycling of sulfur and can also aid in the extraction of metals from sulfide minerals. These bacteria reduce sulfate to hydrogen sulfide (H_2S), which reacts with metal ions to form insoluble metal sulfides, which can be recovered through bioleaching or bioaccumulation (Alabssawy & Hashem, 2024).

Examples:

Desulfovibrio species are well-known SRB that can be found in marine sediments and are involved in the reduction of metal ions like copper, zinc, and nickel to their insoluble forms.

18.5.2.2 Hydrothermal vent microorganisms

Hydrothermal vents, located deep in the ocean, release hot, mineral-rich fluids that are home to a variety of unique microorganisms capable of living in extreme temperatures and pressures. These microorganisms play a critical role in bioleaching processes and metal cycling in these extreme environments (Alabssawy & Hashem, 2024).

18.5.2.2.1 Thermophilic bacteria

Some thermophilic (heat-loving) bacteria that inhabit hydrothermal vents, such as *Thermoplasma* species, can metabolize metal sulfides at high temperatures, facilitating the extraction of metals such as copper, zinc, and gold.

18.5.2.2.2 Chemosynthetic microorganisms

Many hydrothermal vent microorganisms are chemotrophs, meaning they derive energy from the oxidation of inorganic compounds, such as hydrogen sulfide, which is abundant in hydrothermal fluids. These organisms can catalyze the oxidation of metals like iron and copper, making them useful in biomining applications (Singh et al., 2021).

18.5.2.3 Marine cyanobacteria and algae

Cyanobacteria and marine algae can also play an important role in metal accumulation, especially in coastal waters. Their ability to absorb and concentrate metals such as copper, cadmium, and zinc from seawater can be utilized for the extraction of valuable resources.

Examples:

Synechococcus, a genus of marine cyanobacteria, has been studied for its ability to accumulate metals like copper and nickel from seawater.

Marine algae, such as *Ulva* and *Chaetomorpha*, have been demonstrated to accumulate metals like copper and cadmium.

18.6 Advantages of marine microbial biomining

Marine microbial biomining is an innovative approach to extracting valuable metals from ores, waste materials, and contaminated environments in marine ecosystems. This technique offers several distinct advantages over conventional mining and metal extraction methods, particularly in terms of environmental sustainability, cost-effectiveness, and resource recovery. Marine microorganisms are uniquely adapted to extreme conditions such as high salinity, high pressure, and varying pH levels, which makes them excellent candidates for use in biomining processes in marine environments (Vivoda, 2024).

18.6.1 Environmental sustainability

One of the primary benefits of marine microbial biomining is its environmentally friendly nature. Traditional mining and metal extraction methods, such as cyanide heap leaching and smelting, are associated with severe environmental impacts, including deforestation, habitat destruction, and the release of toxic chemicals into the environment. Marine microbial biomining, on the other hand, offers a sustainable solution with fewer harmful environmental consequences (Singh et al., 2021).

Nontoxic processes: Microbial biomining uses natural biochemical processes, such as bioleaching and bioaccumulation, to extract metals without the need for toxic chemicals like cyanide or mercury, which are commonly used in conventional mining. This reduces the risk of water contamination, soil degradation, and air pollution associated with traditional mining methods (Singh et al., 2021).

Bioremediation of contaminated marine environments: Marine microorganisms can be used to clean up polluted ocean waters and sediments that contain heavy metals. By recovering metals from contaminated waste or sediments, marine microbial biomining helps restore marine ecosystems affected by industrial or mining activities (Singh et al., 2021).

Reduction of carbon footprint: The biomining process typically consumes less energy compared to traditional extraction methods, which often require large amounts of electricity, fuel, and water. Therefore, it contributes to a lower carbon footprint and mitigates the effects of climate change (Vivoda, 2024).

18.6.2 Cost-effectiveness

Marine microbial biomining can be a more cost-effective alternative to traditional mining techniques. The costs associated with conventional metal extraction can be high due to the need for large-scale infrastructure, chemicals, and labor. In contrast, biomining processes, which rely on microorganisms to extract metals, typically require less energy, fewer chemicals, and lower operational costs (Singh et al., 2021).

Lower energy consumption: Microbial processes generally require lower temperatures and pressures compared to traditional mining methods. This makes them less energy-intensive and more cost-effective. Additionally, microorganisms are capable of functioning in natural marine conditions, which reduces the need for specialized equipment or large-scale energy consumption (Shin et al., 2013).

Minimal infrastructure: Marine microbial biomining often requires fewer physical resources such as mining machinery and complex processing plants, which can result in lower upfront costs and maintenance expenditures (Shin et al., 2013).

Recovery from low-grade ore and waste: Marine microorganisms can be used to extract metals from low-grade ores, mining tailings, or industrial waste, which are typically not profitable to process through conventional methods. This ability to recover metals from secondary sources (e.g., E-waste, sludge, or marine sediments) adds economic value to materials that would otherwise be discarded (Singh et al., 2021).

18.6.3 Versatility in extreme environments

Marine microorganisms are specially adapted to survive and thrive in extreme environmental conditions such as high salinity, deep-sea pressures, and varying temperatures. These unique adaptations make them well suited for biomining in diverse marine environments, including hydrothermal vents, deep-sea sediments, and coastal regions with high concentrations of metal-rich waste or ores (Alabssawy & Hashem, 2024).

Adaptation to high salinity: Many marine microorganisms can tolerate high salt concentrations in seawater, enabling them to extract metals from saline ores and seawater in coastal and deep-sea environments. This ability to thrive in saline conditions gives marine microbial biomining a distinct advantage over terrestrial biomining (Vivoda, 2024).

Thermophilic microorganisms: Thermophilic microorganisms, which can survive at extremely high temperatures, are found near hydrothermal vents in the deep ocean. These organisms can be employed for bioleaching metals from ores at elevated temperatures, making them valuable for extraction in hot, mineral-rich marine environments (Vivoda, 2024).

Pressure resistance: Deep-sea environments with high pressure can be challenging for most organisms. However, marine microorganisms, such as those found near hydrothermal vents, are

adapted to high-pressure conditions, making them capable of functioning in these extreme environments and enabling biomining in deep-sea settings (Alabssawy & Hashem, 2024).

18.6.4 Selective metal recovery

Marine microorganisms can be highly selective in the metals they accumulate or leach, making them a powerful tool for extracting specific metals from complex waste streams or ores. This selectivity allows for targeted recovery of valuable metals, reducing the need for multiple chemical separation steps (Alabssawy & Hashem, 2024).

Selective leaching: Certain marine bacteria, fungi, and algae have a natural ability to selectively leach specific metals from ores or waste materials. For example, marine bacteria can be used to selectively leach copper, gold, or silver from low-grade ores, reducing the need for extensive processing to separate these metals (Vivoda, 2024).

Efficient metal separation: Marine microorganisms are capable of binding heavy metals to their cell surfaces or accumulating them intracellularly. This bioaccumulation process can be fine-tuned to selectively capture valuable metals such as copper, zinc, cadmium, or mercury, making marine microbial biomining a viable option for recovering metals from complex mixtures (Vivoda, 2024).

18.6.5 Potential for waste recycling and resource Recovery

Marine microbial biomining allows for the recovery of valuable metals from waste materials such as E-waste, mining tailings, and industrial sludge. This recycling process helps in reducing the environmental burden of waste disposal while recovering precious metals that can be reused in industries such as electronics, construction, and renewable energy (Sánchez-Castro et al., 2023).

E-waste recycling: With the growing amount of E-waste generated globally, marine microbial biomining can provide a sustainable solution to recover valuable metals, such as gold, silver, and copper, from discarded electronics, batteries, and circuit boards. This reduces the environmental impact of E-waste disposal and contributes to a circular economy (Singh et al., 2021).

Recovery from mining tailings: Mining operations often leave behind waste materials (tailings) that contain residual metals, such as copper and gold, which can be difficult to extract through traditional methods. Marine microbial biomining offers a cost-effective and sustainable alternative for recovering these metals from tailings, transforming waste into valuable resources (Singh et al., 2021).

18.6.6 Minimizing land use and environmental disturbance

Marine microbial biomining minimizes the need for large-scale excavation and land disruption, which are often associated with traditional mining methods. By extracting metals directly from marine environments, this process reduces the environmental footprint of mining activities (Vivoda, 2024).

Minimal land disturbance: Unlike traditional open-pit or underground mining, marine microbial biomining does not require extensive land clearing, which can lead to habitat destruction and soil erosion. Instead, it focuses on marine environments, making it a more ecologically sensitive approach (Shin et al., 2013).

Use of existing marine resources: By utilizing marine microorganisms that thrive in natural oceanic conditions, biomining operations do not require the construction of large, resource-intensive facilities. Instead, they can be integrated into existing marine infrastructure or implemented on a small scale in coastal areas ([Shin et al., 2013](#)).

18.7 Challenges in using marine microbes for biomining

While marine microbial biomining presents significant advantages, there are also several challenges that need to be addressed to optimize its application on a larger scale. These challenges range from the difficulties associated with marine microbial growth in extreme conditions to issues related to the scalability, economic viability, and efficiency of the biomining processes. Below, we discuss the major challenges in detail, along with references to relevant literature ([Singh et al., 2021](#)).

18.7.1 Low metal concentration in marine ores and waste

A primary challenge in marine microbial biomining is the typically low concentration of metals in marine ores, sediments, and waste materials. Compared to terrestrial ores, marine deposits often contain lower concentrations of metals, which makes the extraction process less economically feasible without significant advances in biomining technology.

Low recovery efficiency: Marine microorganisms may struggle to effectively extract metals from low-concentration ores. This is particularly problematic in cases where metals like copper, gold, or REEs are present in minute amounts in marine ores, which require specialized, efficient, and prolonged biomining processes.

Resource dilution: The vast volume of water in marine environments leads to dilution, which decreases the metal concentrations available for microbial extraction. This can necessitate the use of large amounts of biomass or extended operational timeframes for metal recovery ([Singh et al., 2021](#)).

18.7.2 Adaptation to extreme marine environments

Marine environments often exhibit extreme conditions, such as high salinity, high pressure, and fluctuating temperatures, which can make it difficult for microorganisms to survive and function optimally. While marine microbes have evolved to thrive in such environments, some biomining processes are still hindered by the following challenges ([Alabssawy & Hashem, 2024](#)):

Salinity stress: Many marine microbes, particularly those that are involved in bioleaching, must tolerate high salt concentrations. High salinity can limit the growth and metabolic activity of certain microorganisms, reducing the overall efficiency of metal extraction processes.

Temperature extremes: While thermophilic marine bacteria can be useful in bioleaching at high temperatures (e.g., hydrothermal vent environments), their growth rate may be slow, and the costs associated with maintaining high-temperature conditions can be prohibitive.

Pressure: Deep-sea environments, where some of the most valuable mineral deposits are found, can experience extreme pressures that limit the growth and activity of certain microbial species.

Research on deep-sea microorganisms capable of bioleaching under high-pressure conditions is still in early stages (Alabssawy & Hashem, 2024).

18.7.3 Slow growth and metabolic activity of marine microbes

Marine microbes involved in biomining processes, especially those in deep-sea or extreme environments, often exhibit slow growth rates. This can result in long operational periods for metal extraction, making the process inefficient and costly (Sánchez-Castro et al., 2023).

Long processing time: Slow microbial growth and metal extraction can significantly extend the time required for bioleaching or bioaccumulation, reducing the economic feasibility of large-scale operations.

Low efficiency in metal recovery: Due to the slow metabolism of certain marine microorganisms, the recovery of valuable metals from ores or sediments may be inefficient, requiring the use of large quantities of microorganisms or repeated cycles of extraction to achieve optimal metal yields (Sánchez-Castro et al., 2023).

18.7.4 Scalability of biomining processes

The transition of marine microbial biomining from laboratory research to industrial-scale operations is a major hurdle. While laboratory-scale studies show promising results, scaling these processes to the large-scale extraction of metals presents several obstacles (Shin et al., 2013).

18.7.5 Microbial contamination and control

Microbial contamination poses a significant challenge in marine microbial biomining. Unwanted or competitive microorganisms, including pathogens, may interfere with the desired biomining processes, reducing the efficiency and selectivity of metal extraction (Alabssawy & Hashem, 2024).

Competition with nontarget organisms: Marine environments contain a wide variety of microbial species, and some may outcompete or inhibit the growth of the desired biomining microorganisms. This can hinder the efficiency of bioleaching or bioaccumulation, requiring additional measures to control microbial populations.

Unintended consequences: The introduction of certain microorganisms into marine environments could have unintended ecological consequences. Nonnative species may become invasive, leading to negative impacts on marine ecosystems (Alabssawy & Hashem, 2024).

18.7.6 Limited understanding of microbial mechanisms

The mechanisms by which marine microbes extract and accumulate metals are still not fully understood. This knowledge gap presents a challenge in optimizing the microbial processes for efficient biomining (Dev et al., 2020).

Lack of specificity in metal recovery: Understanding how marine microorganisms interact with specific metals at the molecular and biochemical level is essential to developing highly selective

biomining processes. Without this knowledge, it is difficult to engineer microorganisms for more efficient metal extraction.

Complex biochemical pathways: The biochemical pathways involved in metal extraction are complex and not fully elucidated for many marine microorganisms. Further research is required to identify the enzymes and metabolic pathways involved in bioleaching and bioaccumulation, which could help optimize the processes (Vivoda, 2024).

18.7.7 Economic feasibility and market viability

Despite the environmental and technical advantages of marine microbial biomining, its economic feasibility remains a major challenge. Biomining is often slower and less efficient compared to conventional mining techniques, making it less economically competitive at present (Sánchez-Castro et al., 2023).

High operational costs: The costs associated with cultivating and maintaining marine microorganisms, as well as ensuring optimal conditions for metal extraction, can be high. The energy and resources required to scale up microbial biomining may not be economically viable when compared to traditional mining techniques.

Profitability: The recovery of metals from marine environments is still in its early stages, and the market for biomined metals remains limited. Until the costs of microbial biomining decrease and the efficiency of recovery improves, it will struggle to compete with traditional mining methods (Sánchez-Castro et al., 2023).

18.8 Future trends and innovations in biomining using marine microbial products

The application of marine microorganisms in biomining represents a promising frontier in sustainable mineral extraction, particularly as industries move toward greener and more resource-efficient practices. Biomining through marine microbial products not only promises environmental benefits but also provides new avenues for improving the efficiency, selectivity, and cost-effectiveness of metal recovery. The future of marine microbial biomining is shaped by advancements in biotechnology, genetic engineering, and system integration, which aim to overcome existing challenges and unlock new possibilities (Chen et al., 2024).

18.8.1 Advances in synthetic biology and genetic engineering

The application of synthetic biology and genetic engineering in marine microorganisms holds the potential to significantly enhance the efficiency of biomining processes. By altering the genetic makeup of marine microbes, scientists can develop strains that are more effective at bioleaching or bioaccumulating valuable metals (Sánchez-Castro et al., 2023).

Tailored microbial strains for metal recovery: Through genetic modifications, microbes can be engineered to exhibit higher tolerance to extreme environmental conditions (e.g., high salinity, temperature, and pressure) and enhance their ability to recover specific metals. For instance,

bioengineering microorganisms to produce more efficient biosurfactants or metal-binding proteins can accelerate the metal leaching process (Sánchez-Castro et al., 2023).

Metabolic pathway optimization: By modifying the microbial metabolic pathways involved in bioleaching or bioaccumulation, researchers aim to increase metal uptake and improve recovery yields. This could involve enhancing the efficiency of specific enzymes like metalloproteins, which play a critical role in the dissolution of metal ores (Sánchez-Castro et al., 2023).

Reduced toxicity: Genetic engineering can also minimize or eliminate the production of toxic byproducts that could be harmful to the environment during biomining. Microbial strains can be optimized to extract metals while minimizing the impact on the surrounding ecosystem (Sánchez-Castro et al., 2023).

18.8.2 Enhanced use of marine enzymes and metabolites

Marine microorganisms are known to produce a wide range of enzymes and metabolites with unique properties that can be harnessed for more efficient metal extraction. The use of marine-derived enzymes, such as laccases, lipases, and oxidoreductases, can provide more effective and selective methods for metal leaching (Vivoda, 2024).

Marine enzyme development: Marine microorganisms produce specialized enzymes that are optimized for extreme environments. For example, enzymes from extremophiles can function in saline or high-pressure environments, making them ideal candidates for bioleaching in marine ecosystems (Singh et al., 2021).

Exopolysaccharides and biofilm formation: Marine microbes often produce exopolysaccharides that form biofilms, which can enhance metal bioleaching efficiency. Biofilms create a protective environment for microbial cells, help in the adsorption of metal ions, and improve the stability of the biomining process. Researchers are exploring the potential of these natural products to improve metal extraction from ores and contaminated waste (Singh et al., 2021).

Metabolic byproducts for bioremediation: Marine microbial byproducts, such as organic acids and siderophores, can aid in both the bioleaching of metals and the cleanup of contaminated marine environments. The ability of these products to selectively bind to specific metals could be further developed for the sustainable extraction of rare and precious metals from marine sources (Vivoda, 2024).

18.8.3 Integration with circular economy and waste recycling

As industries increasingly move toward circular economy models, marine microbial biomining can play an essential role in recycling waste materials and recovering valuable metals from them. Innovations in this area focus on the integration of biomining with waste recycling processes, including the recovery of metals from E-waste, mining tailings, and industrial effluents (Sánchez-Castro et al., 2023).

E-waste biomining: The growing challenge of E-waste disposal presents an opportunity for marine microbial biomining. Marine microorganisms capable of bioleaching or bioaccumulating metals from E-waste materials like circuit boards, batteries, and cables are being explored for sustainable recovery of precious metals, such as gold, silver, and copper (Sánchez-Castro et al., 2023).

Recovery from mining tailings: Mining operations often produce large amounts of waste known as tailings, which contain residual metals. Marine microbial biomining offers a sustainable solution for recovering metals from these tailings. This is especially valuable in marine mining operations, where leftover materials may be deposited in the ocean (Sánchez-Castro et al., 2023).

Recycling of contaminated marine sediments: Marine microbial biomining can also help recover metals from contaminated sediments, which are typically rich in heavy metals like mercury, lead, and cadmium. By combining microbial processes with other waste recycling strategies, biomining could become a key component of sustainable marine resource management (Sánchez-Castro et al., 2023).

18.8.4 Advances in bioreactor design and automation

The design and optimization of bioreactors are crucial for scaling up marine microbial biomining. Innovations in bioreactor systems, coupled with automation and monitoring technologies, will enable more efficient and controlled biomining processes in marine environments.

Microbial fuel cells: Microbial fuel cells that harness the metabolic energy of marine microorganisms could be used in biomining processes to generate electricity while extracting metals. The coupling of biomining with energy generation could enhance the sustainability and economic viability of the process (Alabssawy & Hashem, 2024).

Automated monitoring systems: Automation in the form of sensors and control systems will play a vital role in maintaining optimal conditions for microbial growth and metal recovery. Innovations in real-time monitoring of parameters such as pH, salinity, temperature, and metal concentrations will improve the efficiency and scalability of biomining operations (Chandran et al., 2023).

Customized bioreactors for marine conditions: Bioreactors designed for marine environments will need to be adapted to the unique challenges posed by high salinity, pressure, and temperature fluctuations. Research is focused on designing bioreactors that can function effectively under these conditions, while maximizing metal recovery rates and minimizing operational costs (Chandran et al., 2023).

18.8.5 Expansion of offshore and deep-sea mining applications

As offshore and deep-sea mining for valuable minerals and metals becomes more widespread, marine microbial biomining is expected to play an increasing role in recovering metals from these challenging environments. Innovations in this field will focus on improving microbial activity under high-pressure, low-light, and extreme-temperature conditions found in deep-sea habitats (Alabssawy & Hashem, 2024).

Hydrothermal vents and deep-sea mining: Hydrothermal vent ecosystems are rich in metals like copper, gold, and silver. Marine microorganisms adapted to these environments are being explored for their potential to extract these metals from the vent systems. Research into deep-sea microbial processes could lead to new approaches in biomining of metals from oceanic hydrothermal deposits (Vivoda, 2024).

Microbial applications in deep-sea sediment mining: Sediments from deep-sea ecosystems are rich in valuable minerals. Marine microbial biomining could be used to extract metals from these

sediments in an environmentally sustainable way, reducing the need for destructive mining techniques that impact marine biodiversity ([Vivoda, 2024](#)).

18.8.6 Multifunctional marine microbial products

Future trends in marine microbial biomining may involve the development of multifunctional microbial products that combine metal recovery with other applications such as bioremediation, biofuels production, or wastewater treatment. These versatile products could enable more integrated and cost-effective approaches to marine resource management ([Sánchez-Castro et al., 2023](#)).

Biofuels and bioremediation synergy: Marine microorganisms could be used not only for metal extraction but also for the production of biofuels, thus providing an integrated solution to resource recovery in marine environments. The development of multifunctional systems that combine these processes could lower costs and improve overall sustainability ([Alabssawy & Hashem, 2024](#)).

Marine microbial bioremediation: In addition to metal recovery, marine microbial biomining systems can be designed to clean up pollutants from marine environments, such as oil spills or plastic waste. Integrating biomining with bioremediation could make marine microbial systems a powerful tool for both resource extraction and environmental restoration([Alabssawy & Hashem, 2024](#)).

18.9 Case studies and success stories in marine microbial biomining

Marine microbial biomining has gained attention in recent years due to its potential to offer environmentally friendly and sustainable methods of metal extraction from marine ores, sediments, and industrial waste. While this field is still emerging, several case studies have highlighted the success and promise of using marine microorganisms for biomining and bioleaching. These success stories demonstrate the potential of marine microbes in recovering valuable metals and contributing to sustainable resource management. Below are detailed case studies and success stories in marine microbial biomining, along with references.

18.9.1 Bioleaching of copper from marine sediments using marine sulfate-reducing bacteria

Background: SRB are a group of microorganisms found in marine and freshwater environments that have the ability to reduce sulfate to sulfide. These bacteria play an essential role in the biogeochemical cycling of metals. SRBs have been studied for their potential to aid in the extraction of metals like copper from marine sediments.

Case study: A study conducted by researchers in the 2010s explored the use of SRB for bioleaching copper from marine sediments. The researchers isolated SRB strains from coastal sediments and tested their ability to mobilize copper from sediment samples collected from the Mediterranean Sea. The results showed that SRBs could significantly increase the concentration of dissolved copper in the sediment leachates by producing hydrogen sulfide, which reacts with copper to form soluble copper sulfides.

Outcome: This study demonstrated the potential of marine SRBs to facilitate the bioleaching of copper from low-concentration marine sediments. The process proved to be both effective and environmentally friendly, as it avoided the use of toxic chemicals typically required in traditional copper mining methods (Wang et al., 2020).

18.9.2 Biomining of gold from marine ores using *Acidithiobacillus ferrooxidans*

Background: Gold is one of the most sought-after precious metals, and traditional mining methods can have significant environmental impacts. Marine microbial biomining offers an alternative, more sustainable approach for gold extraction. *Acidithiobacillus ferrooxidans*, a well-known acidophilic bacterium, has been studied for its ability to bioleach gold from low-grade ores.

Case study: A case study involving the use of *Acidithiobacillus ferrooxidans* for gold biomining was conducted in a coastal mining operation in Australia. The researchers isolated *Acidithiobacillus ferrooxidans* from marine environments near hydrothermal vent systems. They tested the bacterium's ability to oxidize gold-bearing pyrite (fool's gold) to release gold in a bioleaching setup.

Outcome: The study showed that *Acidithiobacillus ferrooxidans* was effective at oxidizing gold in the form of pyrite, resulting in the mobilization of gold into the solution. The process was successful at extracting gold from ores at lower concentrations than traditional methods, and it generated minimal environmental pollution, making it a promising alternative for gold recovery in marine environments (Shin et al., 2013).

18.9.3 E-waste recovery using marine microbes in Portugal

Background: E-waste is a growing environmental challenge globally. It contains valuable metals such as gold, silver, and copper, but traditional recycling methods are often inefficient or harmful to the environment. Marine microbes, particularly marine bacteria, have been investigated for their ability to bioleach metals from E-waste materials in a more sustainable way (Ankit et al., 2021).

Case study: In Portugal, a research group conducted an experiment where marine bacteria isolated from the Atlantic Ocean were tested for their ability to recover precious metals from E-waste. The researchers used marine bacterial strains, including *Pseudomonas* and *Bacillus* species, to bioleach gold, copper, and silver from circuit boards and other E-waste components.

Outcome: The results of the study showed that marine microorganisms were effective at leaching metals from E-waste in an environmentally friendly manner. The use of these marine bacteria reduced the need for toxic chemicals and cyanide-based leaching agents, which are commonly used in traditional E-waste recycling methods. This success story highlights the potential for marine microbial biomining to play a significant role in E-waste recycling (Jaiswal & Srivastava, 2024).

18.9.4 Marine microbial bioleaching for rare earth elements recovery

Background: REE) are crucial for modern technologies, but their extraction is often associated with high environmental costs. Marine microbial biomining offers a potential solution to recover REEs from marine resources, including sediments, ores, and waste materials.

Case study: A team of researchers from the United States and China explored the potential of marine microbes for bioleaching REEs from marine sediments. They isolated several strains of *Acidithiobacillus* and *Leptospirillum* species from deep-sea hydrothermal vent environments and tested their ability to extract REEs from mineral samples collected from the Pacific Ocean.

Outcome: The study found that the selected marine bacteria were capable of leaching significant amounts of REEs, including lanthanum, cerium, and neodymium, from low-grade ores. The researchers demonstrated that bioleaching by these marine microbes could be a more sustainable and environmentally friendly method for REE recovery, with the potential to replace traditional mining methods that generate toxic waste and have a high carbon footprint (Dev et al., 2020).

18.9.5 Bioremediation and metal recovery in the deep-sea hydrothermal vents

Background: Deep-sea hydrothermal vent systems are known to host diverse microbial communities that thrive under extreme conditions such as high temperature, high pressure, and high concentrations of metals. These systems have been studied for their potential in bioleaching and bioremediation applications.

Case study: A successful biomining project took place at a deep-sea hydrothermal vent near the Juan de Fuca Ridge, off the coast of the Pacific Ocean. Researchers identified marine thermophilic bacteria, such as *Thermoproteus* species, capable of bioleaching metals like copper, gold, and zinc from the mineral-rich vent sediments. The project explored how these microbes could be utilized to extract metals from hydrothermal vent resources without causing significant ecological disruption.

Outcome: The results were promising, demonstrating that the microbial communities around hydrothermal vents could effectively bioleach metals from complex mineral deposits. This case study is a significant example of how natural microbial processes can be harnessed for resource extraction in extreme marine environments, offering a potential model for sustainable deep-sea mining (Adetunji & Erasmus, 2024).

18.10 Conclusion and recommendations on marine microbial biomining

18.10.1 Conclusion

Marine microbial biomining represents a promising and sustainable alternative to traditional mining practices for metal recovery. The use of marine microorganisms, including SRB, acidophilic microbes, and thermophilic species, for bioleaching and bioremediation of metals offers several environmental and economic benefits. These microorganisms possess unique capabilities to extract valuable metals from a variety of sources, including marine sediments, E-waste, hydrothermal vents, and low-grade ores.

Through the case studies presented, it is clear that marine microbial biomining can be effective in recovering metals like copper, gold, silver, REEs, and even valuable metals from E-waste. The natural processes used by marine microbes, such as bioleaching and biosorption, often result in less environmental impact compared to traditional chemical-based mining methods, which are often harmful to ecosystems.

However, despite the considerable progress, marine microbial biomining still faces several challenges. These include optimizing the efficiency of metal extraction, scaling up laboratory results to industrial levels, managing operational costs, and addressing the regulatory and environmental concerns associated with the use of marine resources. Nevertheless, advances in biotechnology, synthetic biology, bioreactor design, and automation provide a clear path forward for overcoming these challenges.

18.10.2 Key recommendations for the future of marine microbial biomining

While marine microorganisms have shown promise in metal recovery, there is significant potential to enhance their capabilities through genetic engineering. By modifying microbial strains to increase their tolerance to extreme conditions, improve their bioleaching efficiency, and increase metal specificity, the effectiveness of biomining could be further amplified. Recommendation: Focus on genetic modifications of marine microbes to enhance their performance in metal recovery, including increased resistance to environmental stress and higher metal accumulation rates. The integration of marine microbial biomining with the principles of the circular economy presents significant opportunities, especially for E-waste recovery. Developing biotechnologies that can extract valuable metals from discarded electronic materials and mining tailings could reduce the environmental footprint of resource extraction. Recommendation: Encourage further research into the use of marine microbes for recycling valuable metals from E-waste, mining tailings, and other industrial waste materials.

While laboratory-scale studies have shown that marine microbial biomining can be effective, translating these results to large-scale industrial operations remains a challenge. Developing efficient bioreactor systems capable of operating under marine conditions (high salinity, pressure, temperature) and scaling them up for commercial use is crucial for the widespread adoption of microbial biomining. Recommendation: Invest in the development of specialized bioreactors, automated control systems, and monitoring technologies to optimize large-scale marine microbial biomining processes.

Although marine microbial biomining has the potential to reduce environmental impact compared to traditional methods, it is critical to ensure that biomining activities do not inadvertently harm marine ecosystems. Therefore, a comprehensive environmental monitoring system and regulatory framework need to be developed. Recommendation: Implement robust environmental impact assessments, continuous monitoring of microbial activity, and the establishment of regulatory guidelines to ensure the sustainability of marine microbial biomining operations. The future of marine microbial biomining will depend on interdisciplinary collaboration among academic researchers, industry stakeholders, and government regulators. Such collaborations can facilitate knowledge sharing, technological innovation, and the development of policies that support the growth of the field. Recommendation: Foster collaboration between academia, industry, and government to facilitate research and the commercialization of marine microbial biomining technologies.

Public perception of marine microbial biomining is still in its infancy, and there is a need for education on the environmental benefits and the economic potential of this technology. Public engagement will be critical for the acceptance of marine microbial biomining practices, especially as they begin to be implemented in coastal and marine areas. Recommendation: Develop outreach programs and educational materials to raise awareness of the benefits and potential applications of marine microbial biomining, emphasizing its sustainability and environmental advantages. The potential for marine microbial biomining in deep-sea ecosystems is immense, especially for REEs and other valuable metals.

Research into the unique microbial communities that thrive in deep-sea environments could reveal novel biomining techniques. Recommendation: Investigate the use of marine microbes for deep-sea mining applications, particularly in the recovery of REEs from oceanic deposits.

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The potential of marine microbial products in Alzheimer's disease management

Abraham Olufemi Asuku^{1,2}, Peace Ayo Olaoluwa², Oluremi Racheal Adeyemo³ and Wael Mohamed⁴

¹*Bioresources Development Centre, National Biotechnology Research and Development Agency, Ogbomoso, Oyo State, Nigeria,*

²*Department of Physiology, Faculty of Basic Medical Sciences, College of Health Sciences, University of Ilorin, Ilorin, Kwara State, Nigeria,*

³*Department of Automated Clinical Biochemistry, University Hospital Southampton, NHS Foundation Trust, Southampton, United Kingdom,*

⁴*Basic Medical Science Department, Kulliyyah of Medicine, International Islamic University Malaysia (IIUM), Kuantan, Pahang, Malaysia*

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19.1 Introduction

The cognitive condition known as Alzheimer's disease (AD) results in a progressive decline in cognition, intellect, comprehension, and organizational skills. Alzheimer's symptoms worsen with time, and it gradually decreases an individual's ability to achieve simple daily chores. This disease's onrush may start 10 years or more before the first indications appear, according to researchers. People over 65 are predominantly afflicted by AD (Amin et al., 2024; Asuku et al., 2022a).

The gradual damage of the neuronal structure and function is a cardinal sign of AD, which has been linked to aging (Asuku et al., 2022; Yan et al., 2020). The prevalence of AD rises with population growth and life expectancy (Colín-Martínez & Arias, 2024). The capacity to carry out purposefully complex chores, aphasia, and increasing memory loss are the major signs of AD. AD patients also have diminished visuospatial ability, poor abstract thinking and numeracy, personality and behavioral changes, and trouble using some senses to discern previously recognized objects.

As the symptoms worsen over time, they may become lethal. The frontal, temporal, parietal, motor, sensory, and subcortical regions precede the pathogenic sequence of AD, which starts with the center temporal lobe, which is crucial for cognition. AD has a complicated and not well-known neuropathology. Three stages of AD were distinguished by the 2011 National Institute on Aging and Alzheimer's Association (NIA-AA) recommendations: preclinical AD, MCI (symptomatic predementia), and dementia. One characteristic of preclinical AD, which is the initial stage before AD dementia develops, is that daily functioning and employment remain mostly unaffected, and the ability to live independently is comparatively full (Kudo et al., 2024).

Memory loss (e.g., inability to communicate new messages, trouble recalling previously learned information, or challenges with semantic memory) is the most prominent drawback. Certain delicate motor abilities can lead to problems with coordination and planning. Even on regular routes, individuals could get lost. The MCI stage, which lasts for about two years, is characterized by patients who are unable to live freely and are in danger of dying as a result of many mishaps and complications (Hu et al., 2023).

The patient starts to lose recognition for their family and other close friends at this time, and their behavior changes more drastically. Urinary incontinence, which is linked to loss of muscle mass, inactivity, and bedridden status, is a concern for about 30% of patients. The capacity to send and receive emotional cues is still present, though. Patients' actions steadily worsen, and they lose all self-care abilities in the disease late stages; most of them die within a year or two due to complications (Hu et al., 2023).

Though the exact cause and progression of AD are still unknown, the neuropathological indicators of the disease include amyloid- β ($A\beta$) buildup in the brain parenchyma and cerebral vasculature, intraneuronal neurofibrillary tangles, and gradual degeneration of synapses (Asuku et al., 2024a; Long & Holtzman, 2019). Even though AD has been recognized for more than a century, little is known about the complex molecular mechanisms underlying its pathogenesis. Numerous multifaceted pathways afflicted by the disease are currently believed to be important contributors to its onset and/or progression, including vascular abnormalities, mitochondrial harmful changes, oxidative stress, decreased brain glucose utilization, and neuroinflammation (Lane et al., 2017).

The study by Back et al. concentrated on the neocortex, a brain part that is affected in the AD early stages. The study provided fresh perspectives on the processes behind $A\beta$ -induced modifications to synaptic function and neocortical neurons' reliance on NMDA receptors, which are known to be critical for spatial memory and learning and memory (Back et al., 2021). Researchers have never

stopped searching for new treatments because the number of people with AD is increasing. Over the past few years, numerous studies have discovered that the aquatic habitat has a wide variety of distinct and varied compositions, including sterol, alkaloids, polysaccharides, carotenoids, and polyphenols, all of which have pharmacological and biological characteristics (Hafez Ghoran & Kijjoa, 2021). About 50% of all species on Earth is located in aquatic ecosystems, which make about 70% of the planet's surface (Hosseini et al., 2020).

Because of this, more and more individuals are searching these resources for drugs that can cure human illnesses (Khotimchenko et al., 2022). The pharmacological potentials of marine microbial products (MMP) have been discovered to have the ability to cure AD as regards to AD's therapeutic targets is fully discussed in this chapter, along with a brief explanation of the associated pathology of AD. The intent of this chapter is to highlight the immense prospects of marine natural products while also directing the creation of new therapy drugs for AD.

Although estimates of microbial diversity are mostly unknown, the seas are home to a great variety, with over 250,000 species known to exist and up to 8.5 million still undiscovered (Corinaldesi, 2015). Numerous previously undiscovered habitats with challenging conditions have been found as a result of maritime exploration in recent decades. Numerous species that are well suited to the conditions and generate a broad variety of active biomolecules can be found in such habitats. Over the past 50 years, more than 25,000 new physiologically functional compounds have been discovered, with a 5% yearly rise and 1378 new molecules discovered in 2014 alone (Blunt et al., 2016).

Microorganisms like bacteria, fungi, and fungi-like protists (such as thraustochytrids) have drawn a lot of attention as possible important chemical producers among marine species. The bioactive compounds found in marine microorganisms are still mostly unexplored and untapped. Therefore, there is a great deal of potential for new discoveries in the search for molecules and compounds originating from marine microbes for biotechnological and industrial uses.

19.2 Marine microbial products

The biological activity of marine natural products can be ten times higher than that of terrestrial species, which has aroused scientific interest (Bălașa et al., 2020). The biomedical field has continuously shown the potentials of the biological activities of marine natural products, including their antithrombotic, anticoagulant, antiinflammatory, antihypertensive, antidiabetic, heart-protective, neuroprotective (Aransiola et al., 2024a; Karthikeyan et al., 2022), anticancer, antimicrobial, and antiviral effects (Asuku, 2024). The chemical compounds present in marine natural products, including polyphenols, polysaccharides, sterol, marine toxins, carotenoids, alkaloid compounds, amino sulfonate, diterpenoids, and macrolide-type compounds, are significant, and a plethora of studies indicated that they may be able to prevent AD (Asuku, 2024; Bălașa et al., 2020).

The adaptations these species need to survive in this “primordial soup” have brought about the use of these bioactive chemicals as secondary metabolites in defensive and offensive processes. Nowadays, microorganisms like bacteria, protozoa, fungi, and microalgae constitute the source of marine compounds with pharmacological activity (Asuku, 2024; Barzkar et al., 2019) as shown in Table 19.1. About 20% come from marine sponges and corals; little research has been done on the Porifera phylum, which includes echinoderms, mollusks, fish, coelenterates, and macroalgae.

Table 19.1 Pharmacologically active compounds of marine natural products and their mechanisms of actions for Alzheimer's.

Compound	Origin	Family	Mechanism of action
Sponges			
Gracilins	Marine sponges (<i>Spongionella gracilis</i>)	Diterpenoid compounds	Reduction of the b-secretase or BACE-1 enzyme; antioxidant and anti-inflammatory qualities. Reduction of tau protein hyperphosphorylation.
Manzamines	Marine sponges (<i>Haliclona sp.</i>)	beta carboline-structured alkaloids.	GSK3beta and CDK inhibition
Macroalgae and microalgae			
Fucoidans	Brown seaweeds	Polysaccharide sulfates	Inhibits the caspase-3 and caspase-9 enzymes.
Phlorotannins	Brown seaweeds (<i>Ecklonia stolonifera</i> , <i>Ecklonia cava</i>)	Polyphenols	Acetylcholinesterase and butyrylcholinesterase enzyme inhibition
Homotaurine	Red seaweeds	Amino-sulfonate	Preventing a harmful soluble amyloid oligomer from forming.
Spirolides	<i>Alexandrium ostensfeldii</i> <i>peruvianum</i> <i>dinolagellates</i>	Cyclic imines	Reduced ERK and GSK-3 β in the cortical neurons of 3xTg mice. Preventing glutamate-induced neurotoxicity in both 3xTg and control neurons.
Bacteria			
Caniferoles	The Actinobacteria phylum	Polyol macrolides	Antioxidant and antiinflammatory properties. BACE-1 enzyme blockade
Crustaceans, Tunicates, and marine invertebrates			
Bryostatins	Brown bryozoa (<i>Bugula neritina</i>)	Macrolide lactones	Improves cognitive function, spatial learning, and memory; Restores neurotrophic activity, reduces amyloid beta peptide;
Chitosan	Crustaceans	Polysaccharides	And alters neural synapses under synaptic dysfunctions. Acetylcholinesterase enzyme inhibition.

19.2.1 Bacterioplankton

Bacteria are found in all types of environments, including the harshest ones, and were the first living things on Earth (Arora & Panosyan, 2019). Marine bacteria, which are unicellular prokaryotes with a size range of 0.5–1 μm and a variety of shapes and configurations, are the smallest known autonomous sea organisms (Zubkov, 2014). They can form parasitic or symbiotic relationships with more sophisticated creatures like as corals, sponges, or macroalgae, or they can live freely. It is believed that the oceans contain 10,000,000 different types of microorganisms (Wilkins et al., 2019).

Given that 50% of known antibiotics are generated from bioactive compounds, an area that is currently thought to be declining, their terrestrial counterparts have been thoroughly studied. Because they are thought to be a great source of novel, untested treatments with unique uses, bacterioplankton constitute a new area of research and are frequently referred to as “chemical gold” (Siddharth & Vittal, 2018). Because their mass production is more cost-effective, ecologically beneficial, and sustainable through large-scale manufacturing and fermentation processes, marine bacterial flora also presents opportunities in terms of biotechnology when compared to more complex organisms (Raimundo et al., 2018). Its production and industrialization are fairly advanced because to its quick growth and usage of economical carbon sources.

19.2.2 Marine microalgae

Marine microalgae primarily contributed to the development of ecosystems. According to Tesson et al. (2016), they can coexist freely in sediments or the water column or as photo-symbionts with more sophisticated species as mollusks, sponges, and corals. Phytoplankton can use light and inorganic materials to form complex macromolecules including proteins, polysaccharides, lipids, and pigments. It is roughly calculated that in the three families Chlorophyta (green algae), Chrysophyta (yellow, brown, and diatom algae), and Pyrrophyta (dinoflagellates), there are over 50,000 various phytoplankton species with sizes and forms varying from 2 to 200 μm (Kiuru et al., 2014).

Many microalgal species have short reproductive cycles, therefore under carefully regulated circumstances; remarkable quantity can be produced in photobioreactors closed system (Otero et al., 2017). Changes in temperature, light, salinity, pH, and the availability of nutrients all affect the biosynthesis of significant amounts of vital metabolites. In order to adapt and live, a person's metabolism is altered in response to a stressor. Accordingly, modifications to the microalgae's culturing circumstances result in a change in their biochemical makeup, which may improve the synthesis of desired target molecules (de Moraes et al., 2015).

Consequently, photobioreactors offer themselves as the best building systems for enhancing and refining cultivation techniques and control conditions, which in turn promote the synthesis of novel bioactive compounds of interest (Venkata Mohan et al., 2015).

19.2.3 Marine macroalgae

Tropical and intertidal zones are a habitat to the eukaryotic, multicellular photosynthetic organisms known as marine macroalgae, or seaweeds. According to their pigment content, they are classified as green algae (Chlorophyceae), brown algae (Phaeophyceae), and red algae (Rhodophyceae) (Motuhi et al., 2016). Although their use in healthcare has been linked to traditional medicine, marine

macroalgae are most recognized for their usage in the food industry, particularly in Asian nations. Due to the wide range of bioactivities and uses of macroalgae, over 32,000 new compounds have been identified to date (Aransiola et al., 2024; Patra et al., 2016). In recent years, new environmentally friendly methods for extracting these chemicals have become more popular.

Because these techniques use fewer and fewer solvents, extract compounds more quickly, perform well at low temperatures, are selective for the desired compound, and prevent undesirable reactions and byproducts during the extraction process, they have become more popular than traditional extraction techniques. Additionally, the chemical make-up of bioactive compounds varies by species and is impacted by a number of variables, such as organism size and age, tissue type, predation pressure, and abiotic factors. To stop overexploitation and stress on wild populations, effective culture techniques must be developed (Otero et al., 2018).

19.2.4 Marine sponges

Marine sponges are invertebrates that are members of the Porifera phylum. They may live in a variety of environments with varying salinities, temperatures, and pressures. The spicule skeleton, which is made up of calcium carbonate, silica, and a protein called spongin, is housed in the soft body of these organisms, as their name suggests. As stationary filter feeders, sponges may consume the microbes and materials in the water that passes through their body because of their straightforward channel layout.

They must, however, evolve robust chemical defense mechanisms to deal with the external risks posed by this specific situation, which also makes them vulnerable to potentially dangerous particles, infectious agents, and predators. Numerous substances, such as cyclic peptides, alkaloids, terpenes, sterols, and nucleosides, have been found to be synthesized by sponges (Sagar et al., 2010). However, as sponges are symbionts that harbor a microbial flora that offers its host a chemical defense through the creation of secondary metabolites, they cannot be solely credited with creating the novel chemicals. As a result, the majority of sponge findings pertaining to this issue originate from their symbionts. This isn't disheartening because the environment for raising and caring for these organisms are difficult and require refinement, and using natural specimens for this kind of study isn't environmentally sustainable.

19.2.5 Marine tunicates

Tunicates, is a member of Urochordate subphylum and are identified by their adult sessile invertebrate stage, which contrasts with their vertebrate-like larval free stage. Tunicates are the only animals recognized to produce cellulose. There are currently about 3000 species described. They can have a range of morphologies and reproduce both sexually and asexually. Ascidians drug development commenced in the year 1960s with the discovery of the anticancer and antiviral geranyl hydroquinone, which was produced from the species *Trididemnum* (Dou & Dong, 2019).

Since then, this subphylum has yielded 1200 natural chemicals. As previously stated, when fully grown, tunicates are sessile and have been shown to harbor a wide variety of microorganisms. Accordingly, some of the new biotechnologically significant chemicals that were initially discovered in tunicates were later found to have come from the symbiotic flora that coexists with them (Schmidt, 2014).

19.2.6 Marine arthropods

Crustaceans are a substantial subphylum of arthropods, with approximately 52,000 species. They are the earliest arthropods from which insects are descended, distinguished by their exoskeleton which is chitinous (Ghafor, 2020). Crustaceans are a cheap source of nutrients for the fisheries and aquaculture sectors nowadays (Gonçalves & de Oliveira, 2016). Utilizing food waste has prompted recent research into this subphylum's beneficial compounds. One of the first techniques was the 2013 purification of a peptide (CMCC-1) with antibacterial function. Chitin, the main component of these arthropods' exoskeletons, was the focus of many studies that mostly followed similar pattern because of its safety, abundance in food industry residues, structural stability, and bioavailability (Elieh-Ali-Komi & Hamblin, 2016).

Abbreviations: dual-specificity tyrosine phosphorylation-regulated kinase 1 A (DYRK1A); cyclin-dependent kinase 5 (CDK5); beta-secretase enzyme (BACE); glycogen synthase kinase 3 beta (GSK-3 β); extracellular signal-regulated kinase (ERK); cell division cycle 2-like kinase 1 (CLK1).

19.2.7 Gracilins

Gracilins are gotten from marine sponges. Gracilins restore the potential of the mitochondrial membrane, protecting primary neurons and avoiding alterations caused by the typical uncoupler of mitochondrial oxidative phosphorylation, carbonylcyanide-p-trifluoromethoxyphenylhydrazone (Leirós et al., 2015). They can also boost the nuclear factor erythroid 2-related factor 2 (Nrf2) expressions, which is associated with the stimulation of the antioxidant pathway.

According to Choi and Choi (2014), gracilins' antioxidant properties enhance their mechanisms of action on Nrf2 levels in the nucleus by forcing them to bind preferentially to proteins implicated in the Nrf2-Keap1-ARE signaling cascade or apoptosis. Furthermore, because gracilins can inhibit the phospholipase A2 (PLA2) enzyme, they have a strong antiinflammatory impact by decreasing the generation of ROS caused by amyloid β (Gegunde et al., 2019).

19.2.8 Manzamines

Manzamines are alkaloids composed of a pentacyclic diamine ring with 8- and 13-membered rings on a pyrrolo [2,3-i] isoquinoline framework coupled to a β -carboline structure. When it was found that an increase in ATP concentration did not alter its inhibitory action, in vitro experiments subsequently revealed its ability to inhibit the GSK3 β enzyme noncompetitively. As of right now, over 100 analogs have been described, and there probably are a lot more that need to be evaluated in medicinal chemistry research (Karan et al., 2020).

19.2.9 Fucoidan

Fucoidan, a type of sulfated polysaccharide, is gotten from brown seaweeds. According to reports, fucoidan influences the inflammatory process at various stages. It induces apoptosis, inhibits several enzymes, and hinders lymphocyte adhesion and invasion (Apostolova et al., 2020). Given that the enzymes caspase-9 and caspase-3 are essential for apoptosis processes, fucoidan's ability to suppress

their activation suggests that it predominantly stops neuronal death via inhibiting apoptosis. It has been discovered that fucoidan therapy can reduce amyloid-beta's inhibitory effect on protein kinase C (PKC).

Fucoidan can help neurons survive and prevent amyloid-beta neurotoxicity. Inactivation of GSK-3 β by protein kinase C causes cytoplasmic beta-catenin to accumulate in the nucleus, triggering transcriptional activation of growth and differentiation-related genes necessary to enhance neuron viability in a TCF/LEF-1-dependent manner.

Fucoidan has recently been proven to be neuroprotective in a mouse model of AD. The compound demonstrated neuroprotective benefits against apoptosis caused by D-Gal and A β in PC12 cells, as well as memory and learning decline caused by D-Gal in mice model of AD. [Wei et al. \(2017\)](#) described the linked mechanisms as cholinergic system control, oxidative stress reduction, and suppression of the caspase and mitochondrial death pathways.

19.2.10 Phlorotannins

The brown algae species *Eisenia bicyclis*, *Ecklonia cava*, and *Ecklonia stolonifera* contain polyphenols known as phenoltannins ([Karan et al., 2020](#)). Phlorotannins such as phlorogucinol, eckol, dieckol, phloroeckol, and phlorofurofucoeckol boost acetylcholine, the brain's most important central neurotransmitter, by blocking acetylcholinesterase and butyrylcholinesterase activities.

Because the majority of the drugs now used to treat AD operate by inhibiting the acetylcholinesterase enzyme, the finding that phlorotannin blocks the BACE-1 enzyme may lead to improved medications and treatment for AD patients. Phlorotannin dieckol regulates the PI3K/Akt/GSK-3 β signaling pathway, affecting APP proteolytic processing and A β production ([Yoon et al., 2021](#)).

19.2.11 Homotaurine

Homotaurine (3-aminopropanesulfonate) is a small natural amino sulfonate molecule that was first identified from diverse marine red algae species. It was then chemically developed and used in medicine as tramiprosate. The molecule was given the name homotaurine because it closely resembles taurine (2-aminoethanesulfonate), a vital amino acid for numerous human metabolic activities.

Three phase II and three phase III clinical trials investigated homotaurine's therapeutic efficacy in AD. Its affinity for the γ -aminobutyric acid type A receptor and ability to inhibit A β have a significant neuroprotective impact ([Jakaria et al., 2019](#)). Because of its affinity for GABA receptors, this drug acts as an excitatory neurotransmission modulator.

19.2.12 Spirolides

The dinolagellates *Alexandrium ostenfeldii* and *Alexandrium peruvianaunum* produce spirolides, a new class of lipophilic marine toxins that belong to the cyclic imine family ([Otero et al., 2009](#)). N-acetyl aspartate (NAA) levels increased, which positively impacted AD markers. In vivo studies in the hippocampus of 3xTg-AD patients demonstrated a reduction in intracellular amyloid-beta levels and an increase in synaptophysin levels. 13-Desmethylspirolide C possesses anti-AD effects and can cross the blood-brain barrier.

19.2.13 Caniferolide A

Streptomyces caniferus is from the Actinobacteria phylum. Its extracts yielded Caniferolide A, a macrolide-like compound (Aldholmi et al., 2019). According to studies, this drug reduces the specific symptoms of AD. Caniferolide A lowers neuro-inflammatory markers in BV2 glial cells stimulated with lipopolysaccharide (LPS), prevents FFKB-p65 translocation to the nucleus, and activates the Nrf2 pathway (Alvariño et al., 2019).

It has also been shown to impede the effects of iNOS, JNK, and p38, as well as limit reactive oxygen species (ROS), pro-inflammatory markers and nitric oxide (NO) release. Furthermore, by drastically decreasing reactive oxygen species levels, the drug suppresses BACE-1 enzyme activity and microglial amyloid-beta activation.

19.2.14 Bryostatins

Bryostatins are a type of macrolide identified by a strongly oxygenated structure and eleven chiral centers. Although bryostatin-1 is the most extensively researched analog, at least 21 bryostatins have been found and isolated thus far. Bryostatins tightly regulate protein kinase C (PKC). In spite of its hydrophilic nature, bryostatins serve as potent phorbol ester and bind to PKC strongly (Russo et al., 2015). Bryostatin-1 rapidly activates and phosphorylates PKCs, resulting in PKC membrane translocation and downregulation. In clinical studies, bryostatins were examined as therapies for AD, AIDS/HIV, and cancer. As a result, various research organizations have identified these compounds as pharmaceutically promising in recent years.

19.2.15 Chitosan

Chitosan, a polymer originating from marine organisms, is formed when chitin is partially deacetylated. It is usually found in the exoskeletons of insects and crustaceans, as well as the cell walls of some fungi (Elieh-Ali-Komi & Hamblin, 2016). Chitosan is not particularly soluble. Chitosan is transformed into chitosan oligosaccharides, which are water-soluble molecules, to increase its utility in biomedical applications. Chitosan and chitosan oligosaccharides have antiinflammatory, immunomodulatory, antibacterial, anti-HIV, and antioxidant properties (Tsvetkov et al., 2020). By regulating amyloid-beta levels through its production and activity of the BACE-1 enzyme, chitosan prevents AD. In addition to being employed as acetylcholinesterase inhibitors, chito-oligosaccharides have been demonstrated to be effective in preventing AD (Asuku et al., 2024b). Neuroprotective characteristics of chitosan and its derivatives include suppression of amyloid- β production, antiinflammatory activity, AChEI activity, and prevention of apoptosis. So far, most of the neuroprotective benefits of chitosan and its derivatives have been seen in vitro.

19.3 Current research on marine microbial products and Alzheimer's

AD International estimates that 50 million people worldwide suffered from dementia in 2018. Two-thirds of individuals impacted reside in middle- and low-income countries, and that number is

expected to treble by 2050 (Weidner & Barbarino, 2019). Alzheimer's has become a big worldwide concern. The kinds of medications used to treat Alzheimer's have not really increased in number, despite the fact that the number of persons with the disease is rising quickly.

The lengthy clinical cycle of medications is one factor contributing to the sluggish renewal of therapeutic pharmaceuticals. For example, GV-971 phase III trial lasted five years (NCT04520412), while Aducanumab's phase 3 trial lasted three years (NCT05310071). The second factor is the high setback rate of clinical trials. Although, a number of pharmaceutical behemoths, like Pfizer, Roche, and others, have reported that AD medications have a significant clinical failure rate (Cacabelos, 2019).

The majority of clinical therapeutic trials focus on tau and A β ; however, recent clinical failures suggest that there are additional pathogenic mechanisms at play. This led scientists to concentrate on creating medications that target several targets (Reich & Hölscher, 2020). The strategy of multitarget targeted ligands (MTDLs) has been developed and proposed numerous times. In order to create hybrid molecules, the MTDL design approach entails combining many drug pharmacophores into a single structure.

The establishment of MTDLs also offers chances for the creation of medications that use marine chemicals as their major ingredients. Compared to synthetic pharmaceuticals, the time-consuming process of producing medications is removed because one molecule can act on several targets. Second, because they come from edible naturally occurring organisms—many of which are edible compounds and have been extensively utilized in the food, cosmetics, and other industries—the use of marine compounds is assured (Anisha et al., 2022). The biggest barrier to marine compounds becoming medicinal medications is currently the absence of clinical trials.

Animal testing is currently ongoing for most discovered marine compounds that could be utilized to treat AD. The Centers for Disease Control and Prevention (CDC) may be the first to develop a technique and recruit medical experts to speed up clinical research of marine medications, in addition to chemical, biological, and marine researchers. The stability and extraction of marine chemicals present another difficulty for marine medications. For instance, marine indole alkaloids have a number of biological applications and can be utilized to treat AD because of their neuroprotective qualities. However, assessing bioactivity has proven difficult due to a scarcity of isolated and purified molecules (Hu et al., 2021).

As a result, it is evident that aquatic resources provide us with a wide range of possible research medications. Potential components for the creation of medication options to treat AD can be found in marine natural substances. We must outline the health consequences of the new medications for the treatment of AD in order to guarantee that drug development has a promising research advancement and offer good opportunities and application prospects in the biomedical sector. This entails the advancement of in vitro and in vivo research as well as additional study of the molecular mechanisms, toxicity, and adverse effects of active substances (da Silva, 2021).

19.4 Opportunities and limitations in utilizing marine molecules to treat AD

With high prevalence and incidence rates that will only rise as the population ages, AD is among the major health and social issues of the twenty-first century (Lyketsos, 2020). Therefore, it is a difficult but crucial scientific task to identify strong and promising lead candidates for pharmacological

development to control AD. Numerous research institutions are actively considering the neuroprotective advantages that marine bioactive compounds produce.

Because of the enormous costs linked to bringing a novel pharmaceutical to market, from discovery to clinical phase to licensure, converting these materials into effective medications is the most challenging task. Moreover, important stages of the drug development process include the isolation, characterization, and extraction of compounds from marine sources. The industry must invest in all of these technological methods while recognizing that they do not guarantee profitability. Even with advances in separation techniques, extracting natural chemicals from sponges, microalgae, and marine microorganisms remains a tough task. Extracting and purifying the rarer novel small secondary metabolites has become challenging (Ahmad Dar et al., 2020).

19.5 Conclusion and recommendations for future research

This chapter briefly looks at the pathophysiology of AD and firmly introduces a number of MMP that may be used to treat the condition. MMP have a high potential for use in biomedicine and are an economical and environmentally benign resource. The therapeutic value of MMP is further evidenced by the effective clinical use of sodium oligomannate capsules (GV-971), an acidic oligosaccharide material derived from the extract of marine brown algae. However, academics or tiny technological labs are mostly responsible for developing viable medications. Therefore, to move marine substances from laboratory to clinical trials more quickly, researchers from various fields must work together and cooperate, government agencies must actively advocate, and patients and physicians must trust and cooperate (Hu et al., 2023).

More biotechnology investment is also required to better understand the potential health benefits of the traits of different marine organisms and their constituent parts, as well as to identify anti-AD medications of marine origin with substantial neuroprotective efficacy. This will help ensure that these marine resources are developed and used in a more sustainable manner in the future (Hu et al., 2023).

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Emerging marine microbial products and future directions of research

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Joshua O. Akhigbe¹, Sarah Chioma Nwakanma¹, Aisha Eniola Adegbite¹, Amina Yahaya¹, Adejoke Blessing Aransiola², Sesan Abiodun Aransiola^{1,3} and Naga Raju Maddela⁴

¹*Department of Microbiology, Faculty of Science, University of Abuja, Abuja, Nigeria,*

²*Department of Surveying and Geoinformatics, Faculty of Environmental Science, University of Abuja, Abuja, Nigeria,*

³*Centre for Artificial Intelligence & Multidisciplinary Innovation Studies, College of Accounting Sciences, University of South Africa, Pretoria, South Africa,*

⁴*Departamento de Ciencias Biológicas, Facultad la Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador*

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20.1 Introduction

The marine environment is the largest and most diverse ecosystem on earth, with high biodiversity, habitats, and environmental conditions (Aransiola et al., 2025; Corinaldesi et al., 2017). These characteristics contribute to making it a habitat for a variety of microorganism species that have great potentials of producing useful bioactive compounds which are not commonly found in terrestrial environments (Aransiola, Oyewole, et al., 2024; Mohamed et al., 2021). Marine microbial species including bacteria, fungi, viruses, and microalgae have tremendous ability to adapt and thrive in environments with extreme temperatures, high pressure, high carbon dioxide (CO₂), high salinity, extreme acidity, and low nutrient availability and as they respond to these harsh conditions, they develop the ability to produce useful bioactive compounds like marine-based nutraceuticals, antioxidants, antibacterials, anticancer, apoptotic, and antiviral agents (Aransiola, Bamisaye, et al., 2024; Ghosh et al., 2022) for diverse industrial usage or purposes like pharmaceutical applications,

agricultural practices, food safety, and ecological stability. Marine microbes use their unique metabolic pathways to synthesize secondary metabolites known as marine microbial products (MMPs). These MMPs have gained enormous popularity because of how special their biochemical structures and immense variety of biological activities are significantly distinct from those produced by terrestrial microbial species (Barzkar et al., 2024). This uniqueness of bioactive product structures could be the strategy these microbes use for their successful adaptation and survival in different habitats even in environments with harsh conditions (Santos et al., 2020). MMPs are harnessed for their antimicrobial, anticancer, antiinflammatory effects in pharmaceutical companies, cosmetic production industries (Ding et al., 2022), as well as medical facilities. They are also useful in enzyme production by various industries (Maldonado-Ruiz et al., 2024) and for the production of biopesticides for agricultural purposes. They also serve as antibiotic, anticancer agents and can as well serve as biofuels for a sustainable energy in the environment.

Although only a few percent of marine microbial species are explored currently, the fact still remains that there is huge potential for the development of more novel compounds that could transform a lot of industries and their products. MMPs have been studied to be a significant source of various therapeutic agents with over 17 approved drugs and other kinds of useful products (Gaudêncio et al., 2023). This can be seen in *Hormosquilla* sp. which produces “Anaehes” that exhibit both antibacterial and antifungal properties inhibiting the growth of microbial cells (Ng et al., 2020).

Marine bacteria and fungi offer new strategies to fight against drug-resistant pathogens. *Marinomonas mediterranea*, a bacterium isolated from the Mediterranean Sea along the Murcia coast, has effects against *Pseudomonas* sp. and *S. aureus* which are resistant to ceftazidime and methicillin antibiotics, respectively. Similarly, janthinopolyenemycin A and B polyketides from *Janthinobacterium* strains ZZ145 and ZZ148 were identified to inhibit the growth of *Candida albicans* (Rani et al., 2021).

A promising dimension of MMPs is its potential to contribute to global food security, this is because as the population grows conventional agricultural and livestock production methods face a lot of challenges due to scarcity of land resources, changes in climate and urbanization, resulting in the need for an alternative approach for natural nutrient and helpful bioactive compound production. MMPs have shown great ability in tackling these issues (Boziaris, 2014). The significance of marine-derived products in the context of improving overall wellbeing, gut health, and nutrient uptake, and reducing disease risk has since been recognized as marine microorganisms are seen as a source of structurally and physiologically distinct chemicals with various biotechnological producing rare compounds like, dichloroimine, isonitrile, isocyanate, and halogenated compounds as well as marine-derived probiotics and prebiotics contributing to improved food utilization (Ghosh et al., 2022).

Incorporating artificial intelligence (AI) and computational modeling have reshaped the discovery and application of MMPs. AI-driven approaches, including machine learning (ML), deep learning, and bioinformatics, are facilitating the identification of novel molecular structures and properties, optimizing bioactive compounds production, and predicting biological activities of bioactive compounds. This chapter highlights the role of MMPs as a solution to food hunger. It explains the products of marine-sedimented microbes and their new applications. It also explores the benefits of AI application and modeling in marine microorganisms and how they can improve the discovery and application of MMP. Furthermore, the chapter discusses future predictions for MMP detection, application, and control and how combining biotechnological advancements with sustainable management strategies in marine microbial biotechnology can revolutionize industries, create a more environmentally friendly future while still maintaining a major focus on food security, nutraceuticals, pharmaceuticals, and industrial applications.

20.2 MMP as a solution to future hunger

Population growth worldwide is creating an unmatched need for food, with estimates projecting that global food production will need to increase by at least 70% before 2050 (Canton, 2021). The current agricultural systems face numerous limits such as scarcity of resources, climate change, as well as environmental degradation which prevents them from delivering enough food for forthcoming demands. The term MMP refers to food products from marine microorganisms, that include microalgae, cyanobacteria, and marine fungi, according to Dewapriya and Kim (2014). Marine microorganisms have high nutrients, fast regeneration time, and are environmentally friendly, which makes them ideal candidates for combating malnutrition and food scarcity (Augusto et al., 2024).

Food security appears promising because of marine-based solutions, as Augusto et al. (2024) have indicated. Marine-based resources enable the food industry to expand its ingredient diversity which in turn reduces its reliance on conventional agriculture and improving climate resilience. These resources contribute significantly to food waste reduction, thus supporting the principles of a circular economy. An example is the extraction of valuable compounds from the waste materials of seafood, including fish skins and shells, which offers a productive resource management which protects the environment (Augusto et al., 2024).

The microorganisms found in marine ecosystems contain high amounts of nutrients, particularly within microalgae species. The microorganisms *Spirulina* and *Chlorella* possess a protein content reaching 70% by dry weight, which contains all essential amino acids needed for human health (Dewapriya & Kim, 2014). These microorganisms contain omega-3 fatty acids, vitamins B12, A, and E, along with trace minerals like iodine and iron, giving them a capacity to deal with malnutrition. These essential nutrients support heart functions and brain health while research shows they help decrease the chances of developing cardiovascular diseases (CVD) (Larsen et al., 2011). The microalgae species, *Nannochloropsis* possess nutritional benefits as alternative protein sources instead of traditional meat or soy, which need large amounts of land and water resources. The replacement of traditional plant species plays an important role in areas where agricultural land equals scarce resources (Aransiola, Oyewole, et al., 2024; Mosibo et al., 2024).

Throughout human history marine-derived foods have kept their important dietary position as they feed billions of people with substantial amounts of animal protein. Due to their nutritional benefits, marine-derived foods serve as essential solutions for both malnutrition treatment and food security maintenance (Larsen et al., 2011). Additionally, the disease-preventing compounds in these plants enhance immunity while protecting individuals from lifestyle diseases, including heart-related problems (Ameen et al., 2021). MMPs also promote innovation in biotechnology, alongside aquaculture, and sustainable industries. MMPs also support economic growth in developing regions through their affordable production methods (Larsen et al., 2011).

Like all novel technologies, MMPs face challenges, especially in applications and scaling up. The mass production of MMP demands complex cultivation systems, which require bioreactors and high energy consumption. These technologies remain too costly and inaccessible in substandard regions where hunger is a serious concern (Ameen et al., 2021). Additionally, consumers and mainstream audiences may resist the integration of marine-based products into their diets because of their unfamiliarity, having different or specific taste preferences, as well as cultural biases. The hesitation of many consumers to accept food products derived from algae or bacteria stands high according to Dewapriya and Kim (2014). Also, regulatory frameworks for new food products are often difficult

and time-consuming. Due to mandatory extensive testing requirements, the entry delay of MMP into the commercial market becomes longer (Diogo Cruz & Vasconcelos, 2023).

Public-private investment in research and development creates opportunities for lowering production costs in cultivating marine microbes. Photo-bioreactors utilizing low-energy technology together with renewable power integration systems can operate to reduce financial costs in production (Ameen et al., 2021). Production technologies for developing regions will benefit from public-private partnerships which create better technology access. Promoting consumer awareness through educational campaigns emphasizing the nutritional and environmental benefits of MMP can increase acceptance. For example, highlighting the success of *Spirulina* in combating malnutrition can inspire confidence in marine-derived foods (Pal & Bose, 2022). Including MMP into existing food products, like snacks and beverages, can also help to ease the transition for consumers. Also, government bodies and international organizations need to create specific standardized assessment protocols for MMPs so they can easily pass evaluation tests. The global food market entry of MMP will become faster through simplified approval procedures coupled with financial support for innovative activities (Diogo Cruz & Vasconcelos, 2023). These are some solutions to the challenges faced by MMPs.

MMPs are also very environmentally sustainable. They efficiently use resources in food production. Marine microorganisms grow in saltwater environments, which reduce the demand for freshwater and farmland. While traditional crops may take months to mature, some marine microbes can double in size within a few hours, allowing for continuous and flexible food production (Ameen et al., 2021; Fenical, 2020). Growing marine microbes is also eco-friendlier than traditional farming, since they produce fewer greenhouse gases and prevent water pollution from nutrient runoff, making them a sustainable food source (Ameen et al., 2021; Augusto et al., 2024).

20.3 Products of marine-sedimented microbes and their new applications

Marine-sedimented microbes are a group of diverse microorganisms that can be found in ocean sediments and they produce a wide range of bioactive compounds which is significant to the environment and industries (Maldonado-Ruiz et al., 2024). These bioactive compounds or products can be either enzymes, antimicrobial agents, or biopolymers. These products are highly recognized for their use in biotechnology, pharmaceuticals, and environmental bioremediations (Ding et al., 2022) (Table 20.1).

Marine microorganisms are known to produce different industrial enzymes such as amylases, protease, and lipases (Maldonado-Ruiz et al., 2024). These enzymes are obtained and applied in pharmaceutical, food, and textile industries. Example of microbes in this aspect are *Bacillus* sp., *Pseudomonas* sp., *Penicillium* sp., and many others (Table 20.2) (Ding et al., 2022; Maldonado-Ruiz et al., 2024).

Another marine-sedimented microbial products are antimicrobial compounds. These antimicrobial compounds are considered bacteriocins which are peptides produced from a certain bacterium that showcase antibacterial properties (Haripriya & Suthindhiran, 2024). This antimicrobial compound has such an advantageous use that it can be used in anticancer treatment, cosmetic industries, and food industries.

Table 20.1 MMPs: Key features and solutions.

Feature	Description	Challenge	Solution
High nutritional value	Rich in proteins, vitamins, and omega-3s (<i>Spirulina</i> , <i>Chlorella</i>)	Consumer skepticism	Educate consumers and integrate into mainstream products.
Rapid growth	Rapid biomass increase, enabling year-round production.	High production costs	Investment in cost-effective low-energy cultivation technologies
Low resource input	Thrives in saline water, requiring no arable land or freshwater.	Limited access to technology	Promotion of public-private partnerships in developing regions.
Sustainability	Minimal environmental impact compared to conventional agriculture.	Regulatory challenges	Development of clear and standardized regulatory frameworks

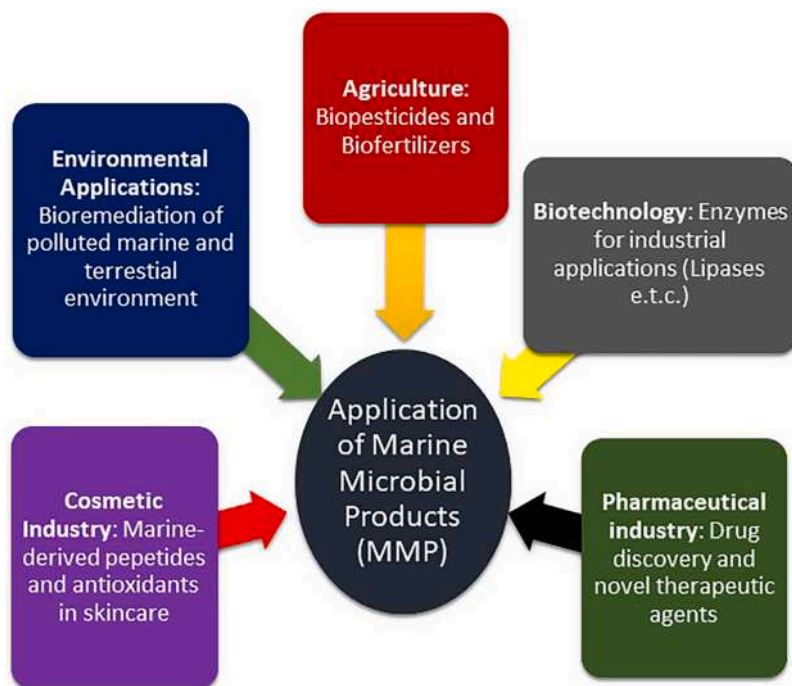
Table 20.2 Marine-sedimented microbial products and applications.

Product	Source Microbe	Application
Salinosporamide A	<i>Salinispora tropica</i>	Cancer therapy
Extremophilic enzymes	Various sediment microbes	Industrial processes
Biosurfactants	Bacillus species	Oil spill bioremediation
Polyhydroxyalkanoates (PHA)	Halophilic bacteria	Bioplastic production
Biofertilizers	Nitrogen-fixing microbes	Sustainable agriculture

These compounds have applications in these industries because they have chemotherapeutic ability, antioxidant and antiinflammatory effects, and they can inhibit the growth of spoilage and pathogenic microorganisms (Chbel et al., 2021; Tong et al., 2021). For instance, Salinosporamide A obtained from *Salinispora tropica* which has a strong anticancer property (Table 20.2) (Lee & Jeong, 2020).

In Table 20.2, marine microorganisms also produce biopolymers such as polyhydroxyalkanoates (PHAs) and extracellular polysaccharides (EPS). PHAs are biodegradable plastics that can be utilized in various applications, such as packaging and biomedical devices (Birolli et al., 2019; Dell'Anno et al., 2023). On the other hand, EPS play a crucial role in environmental processes, such as carbon fluxes in marine ecosystems, and it has potential applications in bioengineering and agriculture (Dell'Anno et al., 2023; Zhang, Chen, et al., 2021).

MMPs can be applied in biopharmaceuticals. The bioactive compounds gotten from marine microorganism can lead to the discovery of new antibiotics, enzymes, and polymers (Aliko et al., 2022; Dionisi et al., 2012). In addition to pharmaceutical applications, marine-sedimented microbes

**FIGURE 20.1**

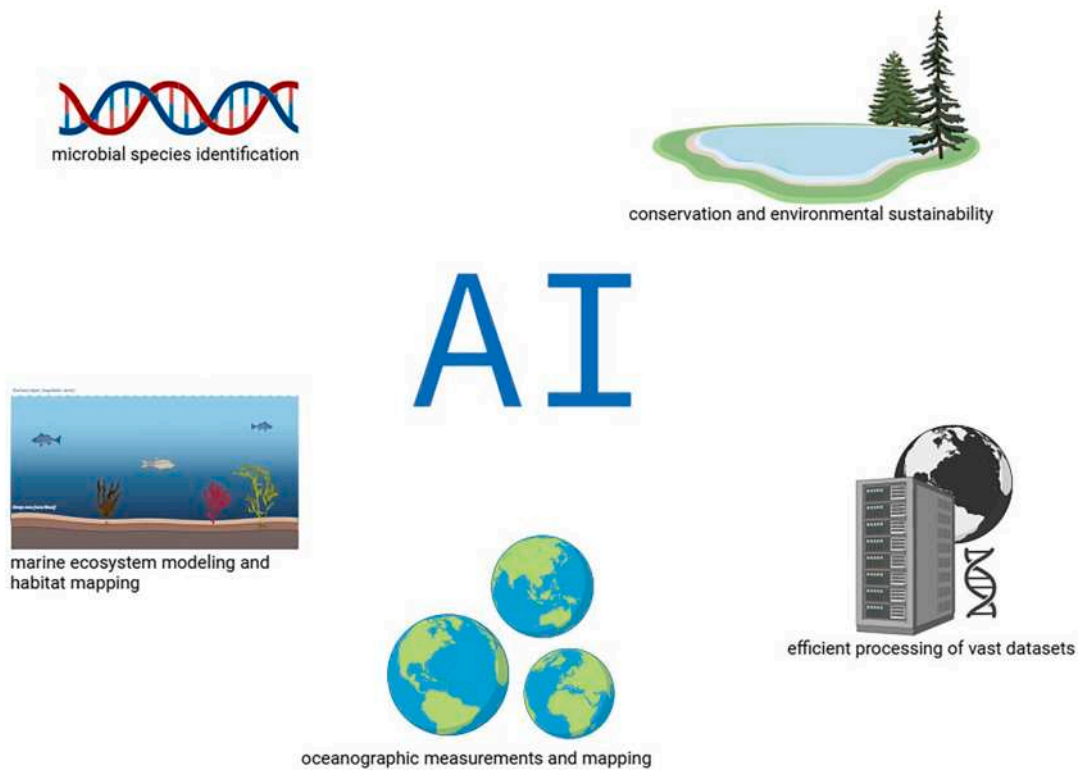
New applications of MMPs.

can be isolated and used in environmental biotechnology (Fig. 20.1). They can be used in bioremediation of contaminated water and soil or oil spillages (Fig. 20.1) (Gupta et al., 2020). This aspect is essential because of the increasing anthropogenic activities in the environment which disrupt the balance in the ecosystem (Dell'Anno et al., 2021). Marine microbes can also be used in the production of biofuels, which serve as an alternative to traditional energy sources (Kwofie et al., 2024) (Fig. 20.2).

Although marine sediment microbes and their products are very useful, how they are obtained can be hindered by various factors such as logistical, technical, economical, and ethical challenges (He et al., 2020). Sampling process of the deep sea is not only costly but it also requires technical expertise, which must be very advanced (He et al., 2023). Moreover, some of these marine microbes cannot be cultured due to their demanding growth conditions, which can limit their ability to produce more marine sediment products (Liu, Chen, et al., 2022).

20.4 AI application and modeling in MMPs

The integration of AI in microbiology is pushing the field into a transformative era. AI is on track to revolutionize it with the use of technologies like ML, computer vision, and object detection. AI has

**FIGURE 20.2**

Applications of AI in managing marine products.

also proven its invaluable application in the extraction of significant information from vast datasets. These potentials have attracted attention from marine scientists (Logares et al., 2021). The applications of AI in the field of microbiology are diverse and cover a wide berth of high-performance computing demanding tasks like forecasting disease outbreaks, observing and studying microbe interactions, predicting drug targets and candidates for vaccine testing, classifying microbial drug resistance, identifying infectious-disease causing organisms, maintaining industry hygiene standards, and ensuring quality control (Peña-Guerrero et al., 2021; Russo et al., 2020). The combination of AI with traditional marine study models has been proven to improve marine safety (Khayyam et al., 2020).

AI algorithms are trained on mathematical models with highly specific structures using massive volumes of statistical data to facilitate the development of filters that compute and understand the statistical patterns imbibed in the training data. These algorithms are very effective in coming up with solutions to problems of optimization and they have shown incredible success in diverse fields of science like self-driving vehicles (Khan et al., 2021), medical imaging (Hickman et al., 2022), geophysics (Yu & Ma, 2021), and nanoscience (Jiang & Li, Jia, et al., 2022). There has been an

incredible reemergence of interest in ML across various fields of research over the last half-decade. This reemergence is caused by the coming together of three major technological advancements, the first being the increased accessibility of affordable computing power and data storage. Second, there are devices capable of gathering vast amounts of digital data at incredible speeds, and lastly, technology for the seamless transfer of data globally by the development of a network of interconnected computer systems (Dogan et al., 2024).

The ways in which complex oceanic data is analyzed and interpreted have been transformed by AI and ML, effectively revolutionizing marine science. This has led to a more in-depth understanding of marine ecosystems and the dynamics that operate within them. AI and ML have aided the efficient processing of large sets of data, including images from satellites, oceanographic measurements, and underwater sensory data. This helps in the identification of patterns, connections, and abnormalities in datasets, paving the way for the prediction and possible control of marine phenomena like algal blooms and oceanic currents. In addition to these, the technologies of AI and ML play key roles in species identification, mapping of marine habitats and ecosystem modeling, which go hand-in-hand with sustainability and environmental conservation efforts. Computer vision, a fundamental application of AI in marine science uses image and video processing technologies to extract valuable information from underwater data. This aids in the study of marine flora and fauna, the monitoring of habitats and assessment of changes in the environment, ultimately playing a key role in the advancement of oceanic research and guiding conservation strategies. AI algorithm technology also addresses challenges of data processing in areas like marine pollution (Agarwala, 2021) and energy (wind and wave) research (Gu & Li, 2022). The application of these technologies makes way for marine scientists to further expand the understanding of oceanic systems, reduce the knowledge gap, and make data-driven decisions, effectively contributing to the preservation and protection of marine environments (Dogan et al., 2024).

AI is being used in the development of self-regulating systems for identification and classification of species in the marine environment. Computer vision algorithms have the ability to analyze image and video data of marine organisms like fish, planktons, and coral, providing accurate and swift identification compared to traditional identification techniques. These algorithms are trained using deep learning techniques like convolutional neural networks (CNNs) and can identify and separate specific species or objects of interest within the visual data in marine environments. These models enable efficient data gathering and processing by recognizing and identifying patterns and distinct features that differentiate different species for assessment of marine populations and ecological studies (Dogan et al., 2024). Advancements in robotics and AI integration are providing specialized systems and devices for marine environments (Molina-Molina et al., 2021). For instance, AI-powered robots possess the potential to become very important assistants to researchers during dives, or even replace human divers entirely (Christensen et al., 2022). This reduces the probability of human error, while reducing risks to the lives of scientists.

AI also has applications in genome mining for detecting and analyzing secondary metabolic compounds, as well as existing and new biosynthetic gene clusters (BGCs) which are found in the microbes. ML algorithms have the ability to predict BGC assembly lines and can be applied in the development of novel BGCs of marine microorganisms for future applications and in the expression/manifestation of these biosynthetic genes (Sahayasheela et al., 2022). Small Molecule Accurate Recognition Technology (SMART) is a tool that was developed recently to speed up the discovery and classification of new natural products (NP's) (Gaudêncio et al., 2023). Algorithms such as

antiSMASH and DeepBGC, that are AI based have shown incredible capability in the identification of hidden biosynthetic pathways possibly unnoticed by traditional detection techniques (Blin et al., 2021). AI models can introduce tweaks to improve overall effectiveness and significantly reduce toxicity levels which has invaluable applications in drug discovery. This ability becomes of utmost importance when viewed against the backdrop of the incredible complexity and vastness of marine microbial genomes, which may contain thousands of BGC's responsible for the synthesis of NPs (Zhou et al., 2020).

20.4.1 Challenges facing AI application and modeling in MMPs

The monitoring of marine life powered by AI makes use of advanced algorithms to gather and compute data from various sources like underwater images, videos, recordings, and environmental sensors (Souza et al., 2023). AI possesses the ability to classify and identify species, track, and predict movement and behaviors, ultimately providing insights into population dynamics and habitat changes. By successfully automating the processes of data collection and analysis, AI technologies support a deeper understanding of marine environments and significantly contribute to the conservation and preservation of these environments, which support the management of ocean resources and sustainability (Ditria et al., 2022). However, the field of underwater robotics presents numerous challenges and unresolved questions.

Marine environments create specific challenges, unique to that environment that, naturally, require thoughtful deliberation and ingenious solution. For instance, in a murky water body with low visibility, how will a robot operate and create its path? How can it adapt to disruptions caused by waves, movement of marine vessels or bigger aquatic fauna? Addressing such issues requires the development of responsive and practical technologies. While progress in this field remains gradual, the potential of AI-enabled marine robotics is immense. These technologies could unlock new ways to explore and understand the ocean, offering insights that were once thought impossible (Dogan et al., 2024). Jiang and Zhu (2022) defined some applications of AI in marine scientific research as:

- Monitoring marine biodiversity
- Modeling of deep-sea resources
- Prediction of ocean parameters.

Mariculture, the cultivation of marine organisms in controlled environments, stands to gain significantly from the integration of AI technologies (Phillips, 2009). Marine aquaculture, specifically mariculture, has been proposed as a promising solution to address food insecurity and malnutrition. This is based on projections highlighting its potential to compensate for stagnating fisheries catches (Golden et al., 2016) and its ability to serve as a healthier and more environmentally sustainable alternative to certain forms of terrestrial animal agriculture (Gephart et al., 2021; Sellars & Franks, 2024). AI can enhance mariculture practices through processes like, monitoring and optimization, feed optimization, water quality management, stockmanagemt and inventory control, and decision support systems.

AI applications and modeling are transforming MMP research by enhancing discovery, optimization, and sustainability. ML accelerates bioprospecting, predicts bioactivity, and streamlines bioprocessing. Integrating AI with omics data unlocks novel compounds for pharmaceuticals, biotechnology, and industry. Advancing these technologies will drive innovation and maximize

marine microbial potential and although progress and interest have grown, the ability to jointly analyze these chemical compounds and their genome involved in microbial metabolic interaction analysis is still developing (Moran et al., 2022). AI models face difficulties in handling the complexity of microbial interactions in marine ecosystems and relies on continuous upgrading of existing data and computational tools. Different software tools are used for processes such as assembly, gene prediction, and function annotation with their respective advantages (Zhang, Das, et al., 2021). AI technologies will help to ensure ethical, legal, and sustainable marine bioprospecting through digital regulatory frameworks. Likewise, it will help reduce environmental hazard enabling strategic and targeted bioprospecting by identifying rich microbial areas. Synthetic biology will also aid sustainability measures by reviving beneficial microorganisms endangered by climate change.

20.5 Future predictions of MMP detection, application, and control

Innovative technologies, particularly genomic and metagenomic sequencing, are leading to the discovery of new genes and metabolic pathways in marine microorganisms (Duarte et al., 2020). The use of CRISPR technology allows for targeted genetic alterations, which enhances both production efficiency and the customization of products (Duran-Vinet et al., 2023). Interdisciplinary collaboration among the fields of microbiology, chemistry, and bioinformatics is crucial for accelerating the application of scientific discoveries into practical uses (Pan, 2021). Marine microorganisms have gained a lot of attention for their noteworthy ability in producing bioactive compounds that can be used in different sectors such as pharmaceuticals, agriculture, and in industries for the production of novel drugs, biopesticides, or nutraceuticals. In MMP discovery and detection, the advancement of innovative biotechnological methods aids the discovery of next-generation antimicrobial agents. The application of MMPs in human foods, agriculture, medicine and an increased market demand motivates the research and development of new products and antibiotics. Also, the use of AI, and synthetic biology can develop reliable targeted antimicrobial agents that shows very little toxic effect, higher selectivity, and sustainable degradation processes. As the population of marine microbial diversity grows, the use of AI, genomics, and synthetic biology is important in harnessing the biotechnological potential of finding new bioactive compounds that has therapeutic effects against life-threatening diseases therefore improving human wellbeing (Rani et al., 2021). Marine microbes are estimated in the future to produce more than 23,000 bioactive compounds, continuously making it a significant source of bioactive natural products (Wei et al., 2023). Advances in technologies like genomics, metagenomics, proteomics, synthetic biology, and AI are potentially explored to revolutionize the detection and discovery of MMPs, enhancing the efficiency and effectiveness of finding novel bioactive compounds from marine microbes.

Genomics/metagenomics is a technique that has revolutionized our understanding of marine microbial communities. It is used to study the genome of marine microbial species by sequencing DNA directly from a specific environment in order to know the genetic makeup of species that have not been cultivated, providing an avenue for the discovery of new MMPs (Zhang, Chen, et al., 2021). This approach is of advantage as most marine microorganisms are difficult to cultivate under controlled conditions increasing the chance of detecting new metabolites.

Proteomics is the study of proteins that are produced by an organism by interpreting the functional expression of genes for its molecular and structural identification and also detecting the gene responsible for the production of proteins (Hosseini et al., 2022). In MMP detection, this can analyze enzymes involved in biological processes, facilitating the characterization of new biosynthetic compounds and their source. The use of proteomics technique would provide accurate, reliable, and complete gene assemblage therefore facilitating the development of novel BGC's.

Synthetic biology allows the formation of organic and engineered biosynthetic mechanisms in host microbes using several genetic tools like multiple automated genome engineering (MAGE), hierarchical conjugated assembly genome engineering (CAGE), and synthetic RNA/protein scaffolds for controlled expression (Mohamed et al., 2021).

AI and ML are anticipated to transform MMP detection by enhancing data analysis and secondary metabolites discovery enhancing computational predictions. They have been implored by many researchers to carry out several tasks like the identification of novel bioactive compounds and biological activity prediction. Matrix-assisted Laser Desorption/Ionization Time-of-flight (MALDI-TOF) is a powerful tool used because of its high throughput capacity and when implored together with ML tools can allow fast identification of biochemical processes of microorganisms (Sahayasheela et al., 2022). MALDI-TOF MS technique was considered to offer far higher resolution than 16S rRNA gene analysis and can more effectively differentiate bacteria having 16S rRNA similarity of about >99.2% facilitating fast and thorough characterization of natural products. (Gaudêncio et al., 2023). This can be integrated in MMP detection.

Metagenomic high-throughput can analyze large marine microbial secondary metabolites using robotic automation and AI-based image recognition, which detect novel microorganisms' species and biosynthetic gene clusters without culturing conventionally, thus allowing to the discovery of new antibiotics, enzymes, and bioactive compounds (Liu, Wang, et al., 2022). Marine microorganisms will be valuable sources of pharmaceuticals as AI-guided drug discovery will incorporate genomic and metagenomic databases to predict MMP-based therapeutic agents for antibiotic-resistant infections, cancer, and life-threatening diseases. Targeted drug approaches will make use of MMPs for patient-specific treatments based on individual microbiome profiling. Synthetic biology will enable large-scale production of MMP-derived food additives, proteins, and probiotics, enhancing food preservation and nutritional quality thereby increasing food quality and production.

Although progress has been made and interest has grown the ability to jointly analyze these chemical compounds and their genome involved in microbial metabolic interaction analysis is still developing. (Moran et al., 2022). AI models face difficulties in handling the complexity of microbial interactions in marine ecosystems and relies on continuous upgrading of existing data and computational tools. Different software tools are used for processes such as assembly, gene prediction, and function annotation with their respective advantages (Zhang, Chen, et al., 2021). AI technologies will help to ensure ethical, legal, and sustainable marine bioprospecting through digital regulatory frameworks. Likewise, it will help reduce environmental hazard enabling strategic and targeted bioprospecting by identifying rich microbial areas. Synthetic biology will also aid sustainability measures by reviving beneficial microorganisms endangered by climate change.

20.6 Conclusion

The study of marine sediment microbial products has uncovered various opportunities that has solved or mitigate global challenges like food security, pharmaceuticals, energy generations, improving the ecosystems. New bioactive compounds discovered by researchers are being used to enhance medical treatment and alleviate food shortages. Moreover, AI is being used to further advance the discovery and analysis of MMPs to make them readily available on a larger scale. Although, there are some challenges faced when obtaining MMPs, such as ethical, economical, and technical challenges. MMPs researches are now focused on improving exploration of marine habitats, detection methods, and new strain cultivation technology. This ensures that, while integrating the new technological methods in the research of MMPs, MMPs can contribute to ecosystem development and environmental conservation. As exploration of marine habitats continues, MMP will stand out in the near future as the key to global issues while preserving the veracity of the ecosystem.

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Marine fungi as evolving bio-cosmeceuticals

21

**Abraham Bravo-Pinargote¹, Jhon Cantos H.¹, Adriana Carolina Rincón Alarcón²,
Maria C.B.S.M Montenegro³, Luis Angel Zambrano-Intriago⁴ and Joan Manuel Rodríguez-Díaz^{5,6}**

¹*Carrera de Bioquímica y Farmacia, Facultad de Ciencias de la Salud, Universidad Técnica de Manabí,
Portoviejo, Manabí, Ecuador,*

²*Departamento de Ciencias Médicas, Facultad de Ciencias de la Salud, Universidad Técnica de Manabí,
Portoviejo, Manabí, Ecuador,*

³*LAQV@REQUIMTE, Department of Chemical Sciences, Faculty of Pharmacy, University of Porto,
Porto, Portugal,*

⁴*Departamento de Ciencias Biológicas, Facultad de Ciencias de La Salud, Universidad Técnica de Manabí,
Portoviejo, Manabí, Ecuador,*

⁵*Departamento de Procesos Químicos, Biotecnología y Alimentos, Facultad de Ingenierías y Ciencias Aplicadas,
Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador,*

⁶*Laboratorio de Análisis Químicos y Biotecnológicos, Dirección de Investigación, Universidad Técnica de Manabí,
Portoviejo, Manabí, Ecuador*

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21.1 Introduction

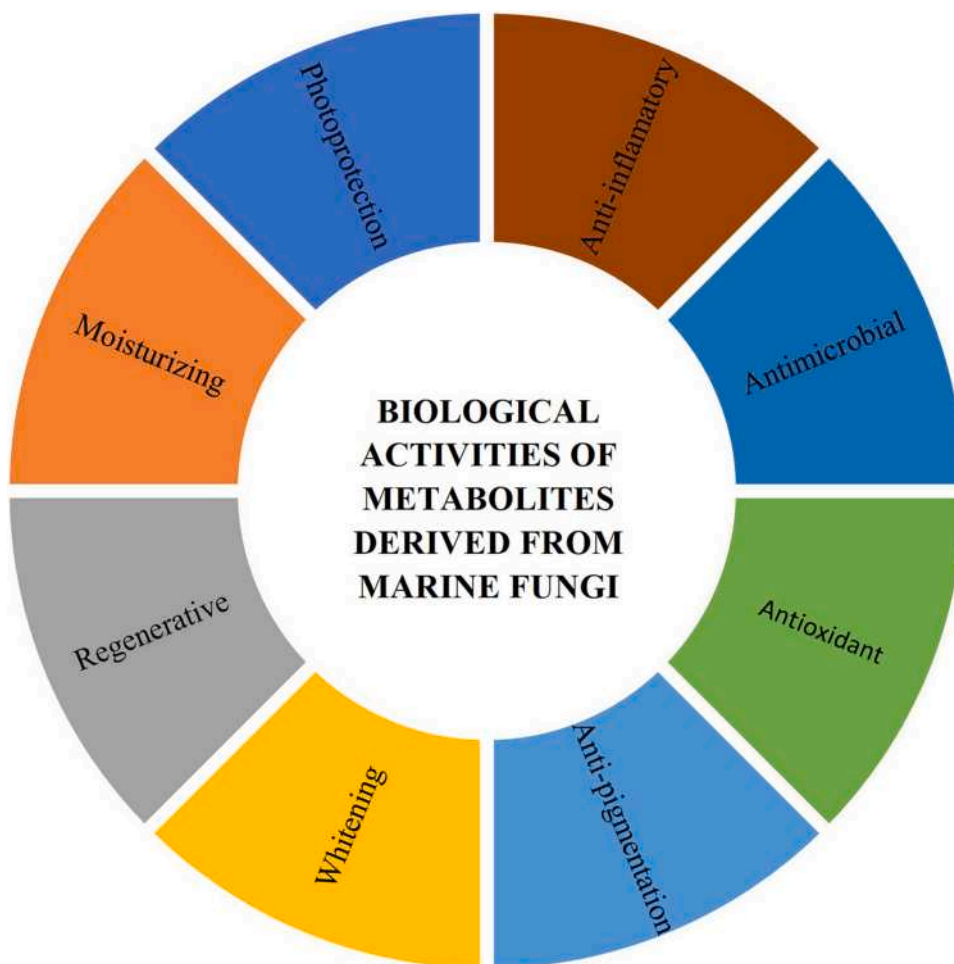
Increased interest in cosmeceuticals, products that merge esthetic and therapeutic benefits, has revolutionized the cosmetic industry in recent decades. This change is attributed in part to the recognition of the restrictions of synthetic components, such as their effects on the environment and possible negative consequences, and to the growth of natural compounds that guarantee biocompatibility, safety, and sustainability (Alves et al., 2020). The exploration of options not only addresses ecological trends but also increasing consumer demands for less intrusive products. This perspective has made it possible to find uncommon and valuable resources in understudied natural settings. Because of the chemical and biological characteristics that set them apart from their terrestrial counterparts, marine fungus have become an as-yet-understudied but interesting source of bioactive chemicals (Fig. 21.1) (Agrawal et al., 2018).

Marine fungi generate secondary metabolites with distinct chemical structures and a variety of biological roles because they thrive in harsh conditions as high salinity and pressure waters. Their ability to adjust to difficult environments has resulted in the generation of molecules that function as natural protective mechanisms against environmental stress. These include, for example, mycosporin-like amino acids, which function as natural UV protectors, and exopolysaccharide polysaccharides, which are recognized for their antioxidant and antiinflammatory characteristics (Badalyan et al., 2022; Corinaldesi et al., 2017). In addition, metabolites such as kojic acid, known for its tyrosinase inhibiting properties and ability to lighten the skin, have found useful uses in the cosmetic sector (Obaid et al., 2021). The variety of metabolites also includes alkaloids, terpenes, and lipids, many of which are still in the early stages of study, highlighting the unknown potential of these organisms (Mukherjee et al., 2024).

The marine environment offers its own benefits to the elaboration of cosmetic components. In contrast to plants and other terrestrial resources, whose exploitation faces obstacles such as deforestation and seasonal variability in production, marine fungi can be cultivated in a regulated and sustainable manner. This enables the continuous and scalable manufacture of bioactive metabolites without endangering natural ecosystems (Mukherjee et al., 2024).

The cosmetics industry has responded to the growing consumer preference for natural and ethical products by including marine fungus metabolites. Modern customers want products that are not just efficient but also less harmful to the environment. For instance, substances like β -glucans, which come from species like *Ganoderma lucidum* and *Lentinus edodes*, have demonstrated exceptional antiinflammatory and antioxidant properties, which makes them useful for formulations that address issues like skin deterioration and aging (Badalyan et al., 2022; Wu et al., 2016). It has also been demonstrated that substances like carotenoids and polyunsaturated fatty acids (PUFAs) can improve the moisture and flexibility of the skin, making them excellent additions to antiaging and regenerative products (Corinaldesi et al., 2017).

However, the use of marine fungi in the cosmetic sector presents challenges. The diversity in the generation of metabolites and the problems to reproduce their natural conditions in the laboratory are technical barriers that limit their commercial use (Fonseca et al., 2023). These obstacles are intensified in less researched species, whose description demands specialized techniques such as genomics and

**FIGURE 21.1**

Biological activities of metabolites derived from marine fungi with potential cosmeceutical applications.

metabolomics to recognize unique biosynthetic pathways. However, recent advances in genomics and biotechnology have facilitated overcoming these constraints, generating new opportunities for research and development of innovative compounds (Mukherjee et al., 2024).

In this chapter, the potential of marine fungal metabolites in the cosmetic sector will be analyzed, highlighting their bioactive characteristics and their potential contribution to the development of novel and sustainable products that meet the trends and requirements of the contemporary market.

21.2 Potential of marine fungi in cosmeceuticals

Because of their effectiveness, cosmetics meet increased consumer demand and are now one of the personal care sectors with the greatest rate of growth (Balboa et al., 2015). Most cosmeceuticals use active ingredients of synthetic origin to fulfill their function; however, synthetic components have been attributed with undesirable adverse effects for the consumer. An example of this claim is the use of sunscreens that often use compounds such as ethylhexyl methoxycinnamate (EHMC), butyl methoxydibenzoylmethane (BM-DBM), benzophenone 4 (BP-4), and octocrylene (OCR). Despite their widespread use in industry, these compounds can have undesirable effects such as endocrine disruption or contact dermatitis. It's also important to note that these substances have been discovered in surface and river waters, harming a range of species and having an impact on the ecosystem (Baghel et al., 2023). They are more prevalent in industrial and urbanized areas and are diluted in nearby areas (Sasounian et al., 2024).

Research highlights that cosmeceuticals made from natural products are safe for both the consumer and the environment (Baghel et al., 2023). With increasing consciousness of the side effects of chemicals and the benefits of natural products, a culture of requesting “greener” products has been generated, especially among the younger generation, which is an attraction for the industries (Mago et al., 2023).

The ability of the marine environment to develop distinct compounds with strong biological and selective activity makes it richer in biological and chemical variety, notwithstanding the growing popularity of derivatives from terrestrial animals (Balboa et al., 2015). In addition, plant-derived ingredients have certain limitations, due to their slow growth and chemical composition changes according to the time of the year, in contrast, marine fauna as can be quickly and economically cultivated in large quantities, such as algae (Agrawal et al., 2018).

However, research shows that marine fungi can be found in a variety of environments, including organic and inorganic substrates, mangrove plants, macro- and microalgae, seagrasses, coral reefs, ice, marine debris, deep water, hydrothermal vents, and oxygen-deficient environments (Gonçalves et al., 2022). Due to their exposure to extreme environmental conditions, some fungi have developed specific metabolic pathways not found in terrestrial fungi, making them an inventive source of new bioactive compounds (Agrawal et al., 2018).

It is estimated that the number of fungi species varies from 1.5 to 5.1 million species, being marine fungi only 1% of known species, it has been estimated that it varies from 10,000 to 12,000 species, being a great door to the research of new active compounds in view of the demand to create new safe, ecological and sustainable natural products (Gonçalves et al., 2022). There are two groups of marine fungi, obligate and facultative marine fungi, obligate marine fungi are those who grow and sporulate solely and exclusively in marine or estuarine habitat, on the other hand, facultative marine fungi generally develop in terrestrial environment and has adapted in marine environment (Agrawal et al., 2018).

There are limitations when investigating marine fungi, the main one being the restricted access to places where they grow, for example, in deep waters. The metabolites of marine fungi have been partially evaluated so far, to increase success in their cosmetic applications a better understanding of the physiology of the fungi and effective extraction methods are needed (Agrawal et al., 2018).

21.3 Cosmeceuticals and their role in the esthetics industry

The word “cosmetic” is usually associated with makeup, perfume, or other products oriented to the female public; however, the definition of cosmetic refers to any product intended to be in contact with the external part of the human body or with the teeth and mucous membranes of the oral cavity. Its main purpose is to clean, perfume, protect, or improve the esthetic appearance, without affecting the structure and function of the body (Balboa et al., 2015).

In contrast, cosmeceuticals is a combination of cosmetic products with pharmaceutical products, improving the appearance with biologically active substances, in other words, they are products that are applied topically, which possess certain substances (vitamins, phytochemicals, enzymes, antioxidants, essential oils, etc.) with the aim of improving the external appearance from the benefits of its components. They differ from medicines as they are not intended to treat pathologies, despite possessing active compounds (Balboa et al., 2015). Among cosmeceuticals, one can find lotions, creams, facial masks, etc. Due to their dual function of improving, esthetics and the advantage of improving skin health with fewer side effects than a drug (Fig. 21.2) (Mago et al., 2023).

A number of rules and regulations are implemented in the market for these products, including a list of components that are limited or prohibited based on the nation, in order to prevent adverse effects on cosmetics consumers. To make it easier for the products to enter other markets, all cosmetics, including cosmeceuticals, must adhere to the INCI nomenclature (International Nomenclature of Cosmetic Ingredients) when it comes to ingredient labeling (Balboa et al., 2015) (Fig. 21.3).

For active ingredients in cosmeceuticals of natural origin to be deemed optimal, a number of factors need to be considered, such as sustainable environmental production, ingredient performance, comprehension of the mechanism of action, quality assurance, global market regulations, and supply adequacy to meet demand (Balboa et al., 2015).

Ten thousand marine natural products, including fungus, have been isolated from marine species in the past 10years (Agrawal et al., 2018). The cosmeceutical market has been on the rise in recent

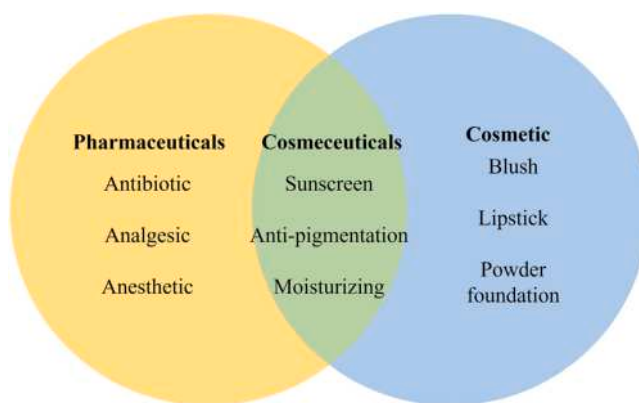


FIGURE 21.2

Intermediate position of cosmeceuticals in relation to cosmetics and pharmaceuticals.

Compound type	Metabolite	Aplication
MAAs Phenols Pyrone Fatty acids Carotenoids Alkaloids Peptides	Mycosporin-glutaminol-glucoside 5-O-methylsulochine 6-n-Pentyl-a-pyrone DHA, EPA, DPA β-carotene Dihydroxyisoechinulin A RHM1	Photoprotective Antioxidant Tyrosinase inhibitory Moisturizing Antioxidant Photoprotective Antimicrobial

FIGURE 21.3
Different classes of metabolites derived from marine fungi with potential use in the cosmeceutical industry.

years, becoming the fastest-growing segment in the personal care industry. Annual growth rates for the cosmeceutical industry of 425% from 2002 to 2007 and 410% from 2007 to 2012 have been recorded. For marine products, 15% of the cosmetic industry products were considered (Balboa et al., 2015).

21.4 Composition of marine fungi cosmeceuticals

There are multiple compounds derived from marine fungi with potential use in the cosmeceutical industry (Table 21.1), having different functions that are key targets in this industry.

Among the bioactive compounds that marine fungi possess are carotenoids, which have antioxidant and antiinflammatory effects, making them compounds with a photoprotective potential, thus, they can reduce the effects of the sun’s UV radiation (Agrawal et al., 2018). An alternative to traditional UV protection ingredients are mycosporin-derived amino acids (MAAs), which are substances containing an amino-cyclohexenimine ring joined to an amino group, an aminoalcohol, or an amino acid (Oren & Gunde-Cimerman, 2007), these molecules are found in the cytoplasm of fungal cells, algae, and other organisms, they are soluble and low molecular weight compounds containing chromophores, for sunscreen ingredients (Ding et al., 2022). For skin lightening, a notable ingredient is kojic acid, a product derived from rice fermentation, a product most commonly used as a depigmenting agent because it is a tyrosinase inhibitor and has few side effects in use (Borges et al., 2022). Nevertheless, kojic acid or its derivatives are also found in multiple species of fungi dispersed in the marine world.

Polysaccharides are compounds consisting of more than 10 monosaccharides (simple sugar forms) (Pacheco-Gómez et al., 2021). The most commonly utilized bioactive ingredients in cosmeceuticals are polysaccharides derived from microorganisms, particularly exopolysaccharides (EPS). High molecular weight carbohydrate polymers called EPS are found in nature and play a role in a number of processes, including competition, communication, and adhesion within and across species. In addition to bacteria, other microbes including fungus and microalgae also create these substances (Corinaldesi et al., 2017).

Table 21.1 Characteristics and functions of potential active compounds from marine fungi in cosmeceuticals.

Compound type	Metabolite	Function	Fungi	Refs.
MAA	Mycosporin-glutaminol-glucoside Mycosporin-glutamicol-glucoside	These metabolites are capable of absorbing radiation in the 310–320 nm range, providing a photoprotective effect.	<i>Phaeotheca triangularis</i> <i>Trimmatostroma salinum</i> <i>Hortaea werneckii</i> <i>Aureobasidium pullulans</i> <i>Cryptococcus liquefaciens</i> <i>Cladosporium sphaerospermum</i> (only glutamicol) <i>C. cladosporioides</i> (only glutamicol)	Borges et al. (2022) , Ding et al. (2022)
	MAA not determined	In small quantities absorbing UV radiation exceeding 320 nm	<i>P. crustosum</i> <i>S. cerevisiae</i> <i>E. amstelodami</i> <i>P. guilliermondii</i>	Kogej et al. (2006)
Chitin	Chitin derivative: Chitosan	Found in the cell wall of many marine fungi, with remarkable antimicrobial properties.	<i>Zygomycetes</i> , <i>Ascomycetes</i> <i>Basidiomycetes</i>	Corinaldesi et al. (2017)
Alkaloids	Dihydroxyisoechinulin A Diketopiperazine Golmaenone Neoequinulin A	These alkaloids possess considerable photoprotective activity.	<i>Aspergillus</i> sp.	Li, Li, Kang, et al. (2004) , Li, Li, Kim, et al. (2004)
	Benzodiazepine alkaloids: Circumtadin I, C, G Squalene	It showed high activity against UVA protection, more effective than oxybenzone. It plays a role in skin lubrication and cellular protection.	<i>Exophilia</i> sp. (family: <i>Herpotrichiellaceae</i>) <i>Thraustochytriales</i>	Zhang et al. (2008) Kaya et al. (2011)

(Continued)

Table 21.1 Characteristics and functions of potential active compounds from marine fungi in cosmeceuticals. Continued

Compound type	Metabolite	Function	Fungi	Refs.
Benzamide derivative	Methyl 4-(3,4-dihydroxybenzamido) butanoate	All these compounds have a variable antioxidant activity among them	<i>Aspergillus wentii</i> En-48	Li et al. (2014)
Phenols	5- <i>O</i> -Methylsulochine			
	Methyl 2-(2,6-dimethoxy-4-methylbenzoyl)-3,5-dihydroxybenzoate			
	Methyl-2-(2,6-dihydroxyl-4-methylbenzoyl)-3-hydroxy-5-methoxybenzoate			
	Physcion			
	4-(3,4-Dihydroxybenzamido) butanoic acid			
	Acrylamine			
3-Amino-5-ethenylcyclopentenones	Myrothenones A and B	Myrotenone A is a tyrosinase inhibitor, becoming more active than kojic acid, an ingredient noted for its use in skin whitening.	<i>Myrothecium</i> sp.	Li et al. (2005)
Pyrone	6-n-Pentyl- α -pyrone	Tyrosinase inhibitory activity with myrotenone A-like activity.	<i>Myrothecium</i> sp.	Li et al. (2005)
	6-[(<i>E</i>)-Hept-1-enyl]- α -pyrone	Possesses higher tyrosinase inhibitory activity than kojic acid.	<i>Botrytis</i> sp.	Zhang et al. (2007)
	Kojic acid dimethyl ether	Despite being its derivative, only kojic acid has bleaching activity	<i>Alternaria</i> spp.	Li et al. (2003)
	Kojic acid monomethyl ether			
	Phomaligol A	Inhibits the enzyme from binding to a copper tyrosinase active site	<i>Trichoderma viride</i> Strain H1-7	Tsuchiya et al. (2008)
	Homothallin II			
	Chrysophanol	Unique US patent, used as a bleaching agent	<i>Microsporum</i> sp.	Corinaldesi et al. (2017)

Fatty acids	R-3-Hydroxyundecanoic acid methylester-3-O- α -l-rhamnopyranoside	Shows antimicrobial activity against <i>Staphylococcus aureus</i> and methicillin-resistant <i>S. aureus</i> .	<i>Scyphiphora hydrophyllacea</i> <i>Paecilomyces variotii</i>	Zeng et al. (2012) Wang et al. (2016) Paecilonic acids A and B These compounds have demonstrated moderate antimicrobial activity. Mourshid et al. (2016) Fatty acid esters: penicilloitins A and B Aasen et al. (2016)
	PUFA: omega-3 fatty acid docosahexaenoic (DHA)	These fatty acids are essential for the maintenance of the skin barrier, promoting deep hydration and reducing inflammation.	<i>Penicillium</i> sp.	
	PUFA: eicosapentaenoic acid (EPA) PUFA: docosapentaenoic acid (DPA)		<i>Schizochytrium</i> , <i>Aurantiochytrium</i> , and <i>Ulkenia</i> (family: <i>Thraustochytriaceae</i>) <i>Thraustochytrid</i>	
Carotenoids	β -carotene Astaxanthin	Carotenoids are known for their ability to neutralize free radicals generated by exposure to UV radiation, preventing premature aging.		<i>Thraustochytriidae</i> sp. ONC-T18, CHN-1 <i>Ulkenia</i> sp. AS4-A1 <i>Aurantiochytrium</i> sp. KH105 Jin et al. (2018)
	Canthaxanthin Zeaxanthin Astaxanthin	Antioxidant and antiinflammatory properties that benefit skin photoprotection.	<i>Rhodotorula</i> <i>Phaffia</i> <i>Xanthophyllomyces</i>	

(Continued)

Table 21.1 Characteristics and functions of potential active compounds from marine fungi in cosmeceuticals. Continued

Compound type	Metabolite	Function	Fungi	Refs.
Terpenoids	Brasilianoids A-F	Stimulates filaggrin and caspase-14 are essential for maintaining skin hydration and resilience, helping to prevent transepidermal water loss and protecting against sun damage.	<i>Penicillium brasilianum</i> WZXY-m122-9	Zhang et al. (2018)
Sesquiterpene	1 β ,5 α ,6 α ,14-Tetraacetoxy-9 α -benzoyloxy-7 β H-eudesman-2 β ,11-diol, and 4 α ,5 α -Diacetoxy-9 α -benzoyloxy-7 β H-eudesman-1 β ,2 β ,11,14-tetraol	Possesses tyrosinase inhibitory activity, comparable to kojic acid.	<i>Pestalotiopsis</i> sp. Z233	Wu et al. (2013)
Peptides	RHM1	This peptide offers specific antimicrobial properties against <i>S. epidermidis</i> (acne-causing agent)	<i>Acremonium</i> sp.	Boot et al. (2006)
Pyridones	Trichodin A	Shows biological activity against <i>Staphylococcus epidermidis</i> , <i>Staphylococcus aureus</i> , and the yeast <i>Candida albicans</i> .	<i>Trichoderma</i> sp. MF 106	Wu et al. (2014)
	Trichodin B	Does not show the same activity with the previously mentioned strains.		
Vitamin B6 Phosphate	Pyridoxatin	It exhibits antimicrobial efficacy against <i>Trichophyton rubrum</i> , <i>B. subtilis</i> , <i>S. epidermidis</i> , <i>MRSA</i> , and <i>C. albicans</i>		
Lincosamides	Cylindromicin	It shows tyrosinase inhibiting activity, which provides a skin lightening effect.	<i>Tolypocladium</i> sp. SCSIO 40433	Khan et al. (2021)
Polyoxygenated decalin derivative	Dehydroxychlorofusarielin B	Mild antibacterial activity against <i>Staphylococcus aureus</i> , methicillin-resistant <i>S. aureus</i> and multidrug-resistant <i>S. aureus</i>	<i>Aspergillus</i> sp.	Nguyen et al. (2007)

Isobenzofuranone derivative	4,5,6-Trihydroxy-7-methylphthalide	DPPH is a free radical, so this compound, by neutralizing it, protects the skin from significant oxidative stress.	<i>Epicoccum</i> sp.	Abdel-Lateff et al. (2003)
Polysaccharides	Exopolysaccharide: EPS2	This exopolysaccharide demonstrated a strong superoxide radical scavenging capacity.	<i>Keissleriella</i> sp. YS 4108	Sun et al. (2004)
Pyrazine derivative	1-(1,3-Benzodioxol-5-yl)-1,2-propanediol and the 3-benzylidene-2-methylhexahydropyrrolo [1,2- α] pyrazine-1,4-dione	UVB absorption capability	<i>Annulohypoxylon stygium</i> (family: <i>Xylariaceae</i>)	Maciel et al. (2018)

Skin homeostasis depends on polyunsaturated fatty acids (PUFAs), such as the omega-3 fatty acids docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), and docosapentaenoic acid (DPA), which are present in some marine fungi (Corinaldesi et al., 2017). A lack of these fatty acids can impair the function of the skin barrier. By decreasing the synthesis of proinflammatory chemicals and blocking the mechanisms that produce prostaglandins, PUFAs in formulations aid in the fight against photoaging (Sasounian et al., 2024).

21.5 Physicochemical properties and biological functions of marine fungi

Although there is typically little biological activity research on marine fungi, it is undeniable that they have intriguing physicochemical properties for the industry, particularly the chitin-derived compounds that are present in the majority of fungi, including marine zygomycetes, chytridiomycetes, ascomycetes, and basidiomycetes (Chen & Heh, 2000; Kim & Bak, 2011), are candidates as absorption promoters and moisturizing agents, antimicrobial and antioxidant agents, delivery systems, and stabilizers (Corinaldesi et al., 2017). This could be due to its good emulsifying characteristics, due to its good polymeric matrices in the release of bioactive compounds, especially hydrophilic compounds. High molecular weight chitosan provides moisturizing characteristics for the skin and is a good release system in cosmetic preparations in cosmeceutical products, in addition to having hydrating and antimicrobial capacity.

In order to facilitate penetration into the skin, chitin neurofibrils can also form associations with other substances like collagen, vitamins, and carotenoids. The chitosan derivative carboxymethylchitosan (CMCS), which comprises active hydroxyl, carboxyl, and amine groups, is water soluble at neutral pH and possesses high viscosity, large hydrodynamic volumes, cation binding properties, high osmotic pressures, gel-forming abilities, and anionic activity (Geng et al., 2023).

21.6 Cosmeceutical application of marine fungi compounds

21.6.1 Cosmeceutical application of marine fungi compounds on the skin

Cosmeceuticals seek to integrate new compounds from natural sources for skin care because it is important to maintain skin health, beauty, and well being by improving appearance, strengthening the skin barrier, preventing premature aging, and protecting the skin from external factors. The skin, with a surface area of approximately 1.8 m^2 , is the first defense barrier forming an interconnection between the human body and the environment (Chambers & Vukmanovic-Stejić, 2020). Skin aging, traversed by every living organism, is a biological degradative mechanism of the dermis that is determined by genetic factors (intrinsic aging), is affected by external influences (extrinsic aging), and leads to a decrease in its physiological functions and structural integrity (Farage et al., 2008). As a result, this process manifests visible signs and changes in physical properties by reducing the thickness, elasticity, and curling of elastic fibers and also includes dryness, laxity, dilated pores,

vascular prominences, increased transparency, expression lines, and wrinkles (Farage et al., 2008; McCullough & Kelly, 2006).

Overexposure to solar radiation is one of the main causes of photoaging or dermatoheliosis causing abnormal skin reactions such as uncontrolled pigmentation, wrinkles and even skin cancer (melanoma) because it alters the composition of the extracellular matrix (ECM) by interacting with free radicals that cause oxidative stress, as UV rays reach the layers of the epidermis and dermis, UVB (320–290 nm) and UVA (400–320 nm), respectively (Alves et al., 2020). Likewise, excess UV radiation triggers a disorder in the production of enzymes such as tyrosinase which regulates melanin production, matrix metalloproteinase (MMPs), collagenase and elastase which are involved in skin firmness, repair, and elasticity, and hyaluronidase focused on moisture retention, each involved in the biological functions of the skin while playing a role in both regeneration and degradation processes in pigmentation, skin hydration, and connective tissue structure (Calado et al., 2021). The regularization of the activities of these enzymes is important for healthy skin, delaying the effects of premature aging and sun damage.

Nevertheless, several fungi with potential cosmeceutical molecules have been explored in the diversity of the seas, because under the extreme environmental conditions in which they are found, they have been able to develop secondary metabolites as a defense mechanism with unique chemical and structural characteristics such as fatty acids, terpenoids, alkaloids, phenols, carotenoids, peptides, and polysaccharides, essential for selective biological actions.

21.6.2 Photoprotection

Secondary metabolites produced by a variety of marine fungi may be photoprotectants with cosmeceutical UV filtering capabilities. For example, *Aureobasidium pullulans*, *Cryptococcus liquifaciens*, *Hortaea werneckii*, *Phaeotheca triangularis*, and *Trimmatostroma salinum*, all produce two different forms of mycosporins: mycosporin-glutaminol-glucoside and mycosporin-glutamicol-glucoside. While *E. amstelodami*, *P. crustosum*, *P. guilliermondii*, and *S. cerevisiae* contain trace levels of three substances, most likely MAAs, that absorb UV light beyond 320 nm, these mycosporins absorb UV rays in the 310–320 nm range (Kogej et al., 2006). Likewise, in *Cladosporium sphaerospermum* and *C. cladosporioides*, mycosporin-glutamicol-glucoside was detected as the predominant mycosporin (Oren & Gunde-Cimerman, 2007).

Similar findings were made in Korea, where benzodiazepine alkaloids, circumdatins I, C, and G, and marine fungi belonging to the family *Herpotrichiellaceae* of the genus *Exophiala* sp. were isolated from the surface of the marine sponge *Halichondria panicea*. These fungi demonstrated protective activity against UVA radiation with ED₅₀ values of 98, 101, and 105 µM, respectively, higher than oxybenzone (ED₅₀ of 350 µM), which is frequently found in sunscreens (Zhang et al., 2008). *Aspergillus* sp. associated with the red seaweed *Lomentaria catenata* exhibited the alkaloid dihydroxyisoechinulin A (ED₅₀ of 130 µM) and an alkaloid diketopiperazine golmaenone (ED₅₀ of 90 µM) along with the related neoequinulin A (ED₅₀ of 170 µM) (Li, Li, Kang, et al., 2004; Li, Li, Kim, et al., 2004).

Marine fungi from the genera *Rhodotorula*, *Phaffia*, and *Xanthophyllomyces* grow faster, are less difficult to cultivate, and are a promising source of carotenoids like astaxanthin, which has antioxidant and antiinflammatory qualities that are beneficial for skin photoprotection, even though they produce

fewer metabolites than other organisms like algae. Furthermore, increased production rates are made possible by their genetic alteration (Carlos; Jin et al., 2018; Mata-Gómez et al., 2014).

On the other hand, carotenoids like astaxanthin, β -carotene, canthaxanthin, echinenone, phenoxanthin, and zeaxanthin are found in *Thraustochytrid* species, such as strains of *Thraustochytriidae* sp. ONC-T18, CHN-1, *Ulkenia* sp. AS4-A1, and *Aurantiochytrium* sp. KH105. These carotenoids assist in preventing UV light-induced harmful activities (Aasen et al., 2016).

In São Paulo, Brazil, 3-benzylidene-2-methylhexahydropyrrolo [1,2- α] pyrazine-1,4-dione and the 1-(1,3-Benzodioxol-5-yl)-1,2-propanediol, from the endophytic fungus *Annulohypoxylon stygium* of the family Xylariaceae that was associated with the alga *Bostrychia radicans*, both compounds were shown to be photostable and nonphototoxic, with an absorption capability in the UVB range (Maciel et al., 2018).

21.6.3 Moisturizing and regenerative

It has been demonstrated that fatty acids obtained from marine fungi are useful for skin care and soft tissue regeneration, promoting the synthesis of collagen and having antiinflammatory and restorative properties (Ziboh, Miller, & Cho, 2000). Squalene, isolated from marine microorganisms such as *Thraustochytriales* protists, is a lipid naturally produced by sebaceous glands that can act in skin lubrication and cell protection, and owing to its moisturizing properties, it is a valuable ingredient because it is nontoxic, nonirritating, nonsensitive and keeps the skin moisturized due to its antistatic and emollient properties (Kaya et al., 2011).

Furthermore, because of their high biomass production, fungus-like protists called Atlantic Canadian *Thraustochytrids* have been the subject of much research about their ability to produce polyunsaturated fatty acids (PUFAs) including DHA, EPA, and DPA (Burja et al., 2006). From the marine fungus *Paecilomyces variotii* associated with the jellyfish *Nemopilema nomurai*, paecilonic acids A and B, two novel bicyclic fatty acids, were isolated (Wang et al., 2016). Moreover, six meroterpenoids were isolated from *Penicillium brasilianum* WZXY-m122-9 called brasilianoids A-F, associated with marine sponges collected from Weizhou Island in the South China Sea (Zhang et al., 2018).

21.6.4 Whitening and antipigmentation

Melanin, the main protective pigment against UV rays, can suffer alterations in its expression due to excessive sun exposure and modifies the production of its two types: eumelanin, a dark, insoluble polymer with photoprotective properties, and pheomelanin, a sulfur-containing polymer with red to yellow tones that is photosensitive and phototoxic (Lee, 2021).

Various marine fungi generate metabolites with depigmenting and whitening effects. In this context, they act as inhibitors of the enzyme tyrosinase, an oxidase enzyme with multifunctional activity for melanin synthesis in the melanosomes of melanocytes where it converts tyrosine to DOPA and then to dopaquinone, the intermediate of eumelanin and pheomelanin synthesis, thus setting the pace of melanogenesis (Lee, 2021).

In Baegunpo, Busan, myrotenone A and 6-n-pentyl- α -pyrone, were extracted from the marine algal fungus genus *Myrothecium* sp. that was associated with the green alga *Enteromorpha compressa*, demonstrated significantly higher antityrosinase activity than kojic acid, with IC₅₀ values of 6.6 and 0.8 μ M, respectively, versus 7.7 μ M for kojic acid (Li et al., 2005). On the other hand, the marine fungus *Botrytis* sp. of the *Sclerotiniaceae* family, which was isolated from the surface of the red alga *Hyalosiphonia caespitosa* in Dadaepo, Busan, produced the compound 6-[(*E*)-hept-1-enyl]- α -pyrone (IC₅₀ of 4.5 μ M), which demonstrated strong tyrosinase inhibition in comparison to kojic acid (IC₅₀ of 15.5 μ M) (Zhang et al., 2007).

Other fungi, such as *Trichoderma viride* H1-7 from marine sediments, generated homothalin II, which acts as a competitive inhibitor of tyrosinase by binding to the copper active site of the enzyme (Tsuchiya et al., 2008).

However, by using CuCl₂ to induce abiotic stress in *Pestalotiopsis* sp. Z233, which was isolated from the alga *Sargassum horneri*, two unpublished sesquiterpenes were obtained: 1 β , 5 α , 6 α , 6 β , 14-tetraacetoxy-9 α -benzoyloxy-7 β H-eudesman-2 β , 11-diol, and 4 α , 5 α -diacetoxy-9 α -benzoyloxy-7 β H-eudesman-1 β , 2 β , 11, 14-tetraol. With IC₅₀ values of 14.8, and 22.3 μ M, respectively, compared to 21.2 μ M for kojic acid, these sesquiterpenes showed comparable inhibition to that of kojic acid (Wu et al., 2013).

Finally, despite the fact that few marine fungal metabolites have reached the cosmetic market, a depigmenting agent named chrysophanol, which was extracted from the algal fungus *Microsporium* sp. (MFS-YL), was patented in the United States and registered in US patent 20140056834A1 as a skin whitening ingredient, demonstrating the potential of marine fungi in novel cosmetic applications (Corinaldesi et al., 2017).

21.6.5 Antioxidant

Sun exposure can generate high levels of reactive oxygen species (ROS) that in contact with skin cells generate oxidative stress, stimulating skin aging, decreasing collagen synthesis, increasing enzymatic degradation of proteins in the cellular matrix and even DNA damage (Calado et al., 2021), therefore, products with antioxidant activity are necessary to reduce oxidative stress damage. This activity is quite remarkable in marine fungi, which may have a potential use in cosmeceuticals. Many fungi have a great potential in this aspect, for example, exopolysaccharides such as EPS2, which possesses the fungus *Keissleriella* sp. YS 4108, which can inhibit superoxide radicals associated with carcinogenesis and mutagenesis in the skin (Sun et al., 2004).

Aspergillus chevalieri, *Penicillium* sect. *Exilicaulis*, and *Acremonium* sp. are more instances. Sponge, mangrove, and saltwater all include the genus *Acremonium*, which has demonstrated the capacity to generate hydroquinone derivatives with strong antioxidant activity that outperform synthetic hydroquinone derivatives like butylated hydroxytoluene (BHT) (Calado et al., 2021). In comparison to fungi *Stemphylium gracilariae*, *Penicillium sizovae* possess moderate activity and those possessing lower activity are *Nigrospora oryzae*, *Diaporthe* sp, *Fusarium incarnatum-equiseti* complex and *Arthrinium arundinis*, whose antioxidant activity is limited compared to the above fungi (Zhang et al., 2008). Similarly, certain metabolites of *Aspergillus wentii* have strong antioxidant activity (Li et al., 2014).

21.6.6 Antimicrobial

An objective in the cosmeceutical industry is to find new antimicrobial compounds that can be effective against skin disorders caused by commensal organisms, especially *Cutibacterium acnes*, *Staphylococcus epidermidis*, and *Malassezia* species, the first two of which play a key role in protecting the skin against pathogens, but are implicated in the appearance of acne following an increase in sebum associated with hormonal changes, producing an overcolonization of these bacteria in the pilosebaceous units. The increase in sebum production would also lead to an increase in *Malassezia*, causing pathologies such as pityriasis versicolor, seborrheic dermatitis and even psoriasis (Calado et al., 2021).

A remarkable compound found in the cell wall of many species of both marine and terrestrial fungi is chitosan, derived from chitin, found in zygomycetes, ascomycetes, and basidiomycetes (Corinaldesi et al., 2017). Chitosan has high antimicrobial activity, whether for viruses, bacteria or fungi, useful in cosmeceuticals because of its broad spectrum and low toxicity.

Extracts of *Aspergillus chevalieri* inhibit the growth of *Cutibacterium acnes*, although they show less efficacy against *Staphylococcus epidermidis* and *Malassezia furfur*. *Stemphylium gracilariae* also shows activity against both *C. acnes* and *M. furfur*. In addition, *Arthrimum arundinis* shows potent antifungal activity against *M. furfur*. Other fungi, such as *Nigrospora oryzae*, *Diaporthe* sp., *Penicillium sizovae*, *Penicillium* sect. *Exilicaulis*, and *Fusarium* show weaker or more specific inhibitory effects: some slightly affected the growth of *S. epidermidis* or *M. furfur* (Calado et al., 2021).

On the other hand, a new fatty acid glycoside called methyl-3-*O*- α -l-ramnopyranoside R-3-hydroxyuodecanoate was discovered in China's Hainan Province in an unnamed marine fungus connected to the mangrove species *Scyphiphora hydrophyllacea*. It demonstrated a moderate inhibitory effect against methicillin-resistant *S. aureus* and *Staphylococcus aureus* (Zeng et al., 2012). Similarly, the marine fungus *Paecilomyces variotii*, which was isolated from the jellyfish *Nemopilema nomurai*, yielded two new bicyclic fatty acids, paecilonic acids A and B (Wang et al., 2016). Likewise, the marine fungus *Penicillium* sp. was isolated from an ascidian, *Didemnum* sp., in a mangrove swamp at Sharm El-Sheikh on the Red Sea coast of Egypt to produce two novel antimicrobial fatty acid esters, penicilloitins A and B. Both compounds demonstrated moderate antimicrobial activity (Mourshid et al., 2016). Furthermore, it has been observed that marine yeasts, such as *Rhodotorula mucilaginosa* AMCQ8A, produce higher biomass and lipid contents; however, further research is necessary to fully explore their potential in the cosmeceutical sector (Jin et al., 2018). According to Boot et al. (2006), the RHM1 peptide has targeted antibacterial activity against *S. epidermidis*, making it perfect for acne.

21.6.7 Antiinflammatory

Regarding antiinflammatory activity, extracts of several fungi showed the ability to reduce nitric oxide (NO) production indicating antiinflammatory potential. Specifically, *Penicillium* sect. *Exilicaulis*, *Diaporthe* sp., *Nigrospora oryzae*, *Arthrimum arundinis*, and *Stemphylium gracilariae* can significantly reduce NO production under inflammatory conditions; in contrast, extracts of *Nigrospora oryzae* and *Arthrimum arundinis* can reduce NO levels to basal values, demonstrating a particularly prominent antiinflammatory activity (Calado et al., 2021).

21.6.8 Cosmeceutical application of marine fungi compounds on hair

The cosmeceutical industry is paying more attention to compounds derived from marine fungi because of their potential to enhance the appearance and health of hair.

Chitin and chitosan derivatives, such as glyceryl chitosan, stand out for their ability to foam and act as emulsifying agents, making them ideal for incorporation in shampoos (McClements & Gumus, 2016). Likewise, carotenoids, such as astaxanthin, have the potential to protect against damage caused by sun exposure and chemicals, prolonging its vitality and resistance (Jin et al., 2018). On the other hand, exopolysaccharides (EPS), including those produced by fungi, possess thickening and gelling properties, making them versatile ingredients in hair care products (Flores-Maciél et al., 2024).

These characteristics open up new opportunities to formulate innovative treatments that not only beautify the hair, but also protect it from adverse external factors.

21.7 Sustainability and ethics in marine fungi breeding

The ability of marine fungi to produce unique secondary metabolites with biological antioxidant, antiinflammatory, antimicrobial, depigmenting, antiwrinkle, and UV protective properties highly valued in advanced cosmetic formulations has made them a valuable source of rare and unusual bioactive compounds with potential cosmeceutical use, despite their status as an unexplored field (Fonseca et al., 2023).

However, the demand for these molecules poses challenges in terms of sustainability and ethics in their procurement, as indiscriminate harvesting of marine fungi can alter their natural ecosystems and put their biodiversity at risk; therefore, it is imperative to promote controlled cultivation practices, harvesting, ethical bioprospecting, and biotechnological techniques that minimize environmental impact and ensure that the cosmeceutical benefits of marine fungi do not compromise the health of the marine ecosystem. In other words, sustainable harvesting of marine fungi contributes to the protection of their biodiversity and ensures their future availability for research and bioactive applications without compromising their role in marine ecological cycles.

In this context, culture studies and molecular functional analyses have shown that marine fungi play multiple ecological roles similar to those observed in terrestrial ecosystems, many of these fungi act as saprophytes, degrading macromolecular materials and establishing themselves as the base of the microbial food chain (Scheu, 2002).

On the other hand, the lignocellulolytic enzymes of saprophytic fungi soften fibrous tissues, optimizing the availability of essential nutrients for detritivorous organisms, thus fungi are fundamental in the chemical cycling of carbon and nitrogen in marine sediments (Karthikeyan et al., 2014). In particular, the fungi found at depth contribute considerably to the formation of aggregates and to the supply of carbon (Raghukumar et al., 2004). Likewise, interactions between fungi and macroorganisms include mutualistic or symbiotic associations, saprophytic activity in damaged host tissues, and even certain degrees of pathogenicity (Richards et al., 2012).

The cultivation of marine fungi represents a significant renewable source for cosmeceuticals, due to their ability to produce bioactive compounds using advanced biotechnological techniques (Imhoff, 2016). The physiology of these fungi and the composition of the culture medium are critical factors in their production, and the availability of carbon and nitrogen sources is important for the success of the

culture, a phenomenon widely documented in terrestrial fungi and confirmed for marine fungi. The latter have been successfully cultivated in lab settings thanks to the use of complex substrates like starch, casein, pectin, malt extract, wheat bran, olive oil, xylan, and sugarcane bagasse. Additionally, the ideal growth conditions for marine fungi, including temperature and pH, typically fall between 20°C and 70°C and 3 and 9, respectively (Kjer et al., 2010). However, their adaptation to the marine saline environment implies a specific need for salt in the culture medium, not only sodium chloride, but also sulfates and trace elements present in seawater, such as heavy metals in minimal concentrations, so artificial seawater is often used to emulate the natural conditions necessary for the development of these organisms (Chen et al., 2011; D'Souza-Ticlo, Sharma, & Raghukumar, 2009).

Despite the high genetic diversity of marine fungi, most studies have concentrated on genera such as *Penicillium*, *Aspergillus*, *Fusarium* and *Cladosporium*, due to the relative ease of their isolation and cultivation; however, molecular studies have revealed the existence of a significant diversity of marine fungi that have not yet been successfully cultured in the laboratory, possibly owing to their dependence on symbiotic interactions or competition with terrestrial fungi in environmental samples, yet marine fungi of common genera show unique biosynthetic pathways for secondary metabolites not found in their terrestrial counterparts, opening up new opportunities for the development of innovative and sustainable cosmeceuticals (Imhoff, 2016).

Preserving microbial strains in culture collections is necessary for the best and most sustainable use of marine fungal resources because they enable the preservation of live cells through techniques that lower their metabolism, like cryopreservation, which guards against genetic and phenotypic changes that could result from repeated subculturing and maintains the integrity of microbial resources for long-term exploitation (Daniel & Prasad, 2010). Culture collections, in addition to preserving authentic biological material, are sources of reference strains for research.

Finally, it should be noted that the availability of marine fungi in publicly accessible collections is limited, which restricts access to reference sequences necessary for accurate sequence-based identification. Given the vast number of as yet undescribed species and strains, the importance of expanding these collections, as well as developing specialized software systems that properly manage the diverse data associated with each cultured taxon, is highlighted (Peña et al., 2012). Despite the existence of several specialized collections of marine fungi, their range is still too small to adequately capture marine biodiversity.

21.8 Future prospects for cosmeceuticals from marine fungi

A key to optimize the development of these cosmeceuticals lies in the integration of biotechnology because it allows to improve the cultivation and production of marine fungi, and omics sciences facilitate an exhaustive characterization of the bioactive compounds that these organisms can produce, this multidisciplinary approach enables not only the identification of new compounds but also the adjustment of cultivation and production conditions to maximize their performance. Thus, development of bioreactors that emulate the marine environment is showing promise for large-scale production and biotechnological process optimization. Other potential solutions include controlled miniaturization to boost screening yields, targeted strain stimulation to increase chemodiversity, and strain characterization using “omics” techniques (Sarkar et al., 2010).

Molecular and genomic tools will open the way to genetically manipulate marine fungi, facilitating the production of specific bioactive derivatives and maximizing their cosmeceutical potential. For example, astaxanthin production has been successfully increased by up to ninefold in *Aurantiochytrium* sp. SK4 through metabolic engineering (Suen et al., 2014). Moreover, progress in the use of genetic engineering tools, such as CRISPR, presents opportunities to optimize carotenoid production in fungi and other marine microbes in thraustochytrids.

These advances, combined with biotechnology and omics sciences, will boost the sustainability and efficiency of marine fungi as renewable resources, with potential for growth and diversification of their cosmeceutical applications.

21.9 Conclusions

Marine fungi emerge as a promising source of bioactive compounds with great potential in cosmetics, standing out for their sustainability and low environmental impact. Their unique metabolites offer antioxidant, antimicrobial, antiinflammatory, photoprotective, and depigmenting properties, positioning them as ideal candidates for developing innovative products that balance efficacy, safety and eco-friendliness.

Despite inherent challenges, such as the difficulty of accessing deep habitats and recreating their natural conditions, advances in biotechnology, cultivation, and omics tools have paved the way for their exploitation. Technologies such as genetic engineering, bioreactors that mimic marine ecosystems and the miniaturization of processes have optimized their production in a sustainable manner.

The increasing interest in natural and ethical products in cosmetics reinforces the importance of these organisms. Their responsible cultivation and sustainable bioprospecting methods ensure the conservation of marine biodiversity and their future availability, promoting a balance between innovation and ecological preservation.

Thus, marine fungi not only open up new possibilities for sustainable cosmetics, but also mark an evolution toward more responsible practices aligned with current scientific and ethical demands. Their incorporation into the sector represents an important advance in the natural products industry and in the development of cosmetic science.

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MARINE MICROBIAL PRODUCTS

APPLICATIONS AND OPPORTUNITIES

Edited by

Sesan Abiodun Aransiola, Mariam Iyabo Adeoba and Naga Raju Maddela

Marine Microbial Products: Applications and Opportunities explores the extensive and highly diverse world of marine microbes, an assemblage of organisms that contain a broad array of bioactive chemicals. Often unique due to the extreme environmental conditions in which they are synthesized, these chemicals present opportunities for innovations in human health, environmental sustainability, and technological progress. Readers will gain valuable insights into the biodiversity of marine microbes, characterization of their bioactive chemicals, and opportunities for innovation and sustainable development across multiple sectors. Written and edited by a diverse team of environmental microbiologists, this book is systematically structured to provide readers with a foundational understanding of marine microbial taxa, the products that may be synthesized from these organisms, technological innovations, and future directions of research.

Key Features

- Describes the diversity and characterization of marine microbial products
- Identifies interdisciplinary applications of marine microbial products in food, health, and renewable energy sciences
- Discusses technological innovations, shortcomings, and future research directions of the field

Dr. Sesan Abiodun Aransiola is a lecturer at the Department of Microbiology, University of Abuja, Nigeria. He obtained his BTech, MTech, and PhD in microbiology from the Federal University of Technology, Minna, Nigeria. His area of interest is environmental microbiology with a focus on biosorption and bioremediation. He is a member of both the Nigerian Society for Microbiology and the American Society for Microbiology and has coedited several books on the topic.

Dr. Mariam Iyabo Adeoba is a research fellow at the University of South Africa's Department of Mechanical Bioresources and Biomedical Engineering. She obtained her MSc from the University of Agriculture, Nigeria, and her PhD in zoology from the University of Johannesburg, South Africa.

Dr. Naga Raju Maddela is a professor of microbiology at the Technical University of Manabi, Ecuador. He obtained his PhD in microbiology from Sri Krishnadevaraya University, India, and has conducted postdoctoral research at Universidad Estatal Amazónica (Ecuador) and Sun Yat-sen University (P.R. China). He is a member of the Microbial Society, England, and the International Biodegradation & Bioremediation Society, Great Britain.



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