Marine Bioresources

Prospects and Obstacles

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habitats decreases the ability of the ecosystem to support necessary functions like acting as a buffer against storms and acting as a carbon sink. Many coastal development activities require the conservation of ecosystems for possible future uses in sustainably supporting the marine ecosystems (Udeme et al., 2023; Ugoma et al., 2023).

10. Conclusion

Marine bioresources are meant to reveal the function of ecological processes and ecosystem goods and services, food supplies, and potentials for sustainable bioenergy sources. Marine habitats including coral reefs, mangrove forests, seagrass beds, and the deep sea support species and link global biogeochemical processes. However, all these ecosystems are in danger now due to overfishing pollution and climate change. Overfishing affects the structures of the ecosystems, pollution affects the quality of water and affects the organisms living within them, and climate change exacerbates all these challenges and leads to corals being bleached, loss of habitats for species and shift in species location. These impacts eventually undermine the occurrence of species and ecosystem conditions that are required to sustain life in the world. Conservation of our marine resources is important for the health efficiency of our oceans. Measures such as proper fishing techniques, curtailing pollution, and rehabilitating marine habitats and species' populations are critical measures that may be used to safeguard the oceans and seas, and MPAs offer species a secure environment in which to grow and rebuild. Another factor necessary for promoting conservation of the marine bioresources is increasing public awareness of the ecological and economic benefits of the bioresources. Integrating science, policy, and community support can facilitate scientific breakthroughs to sustain the economic, ecological, and social capital of coastal and marine systems through the management and mitigation of climate change impacts for present and future generations.

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Chapter 2

Application of marine greens in climate change mitigation

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1. Introduction

The phenomenon of environmental change, marked by a dramatic shift in climate patterns largely driven by the release of greenhouse gases (GHGs), stands as one of the most pressing crises facing the globe today. Central to this shift is the greenhouse effect, a process whereby gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) trap heat within Earth's atmosphere, thereby fueling the ongoing escalation of global temperatures. While these gases are emitted through both natural mechanisms such as volcanic activity, forest fires, and the release of gases from oceans and thawing permafrost (Aransiola, Oyewole, et al., 2024, p. 1–257), the overwhelming contribution comes from human activities, notably energy production, industrial operations, and significant alterations in land use.

To fully grasp the scope of the current climate crisis, it is essential to recognize the profound and different impacts environmental change has on both natural ecosystems and human societies. Recent findings from the United Nations Climate Change Secretariat (UNCCS) highlight several key climate indicators affected by these changes, such as increasing global temperatures, shifting precipitation patterns, rising sea levels, ocean acidification, and a marked increase in the frequency of extreme weather events. Particularly alarming are the climate-related hazards droughts, hurricanes, heatwaves, floods, and wildfires that have surged in recent years. For instance, the UNCCS reported a significant uptick in such disasters, and the Center for Research on the Epidemiology of Disasters (CRED) recorded 315 climate-related catastrophic events in 2018 alone, underscoring the pervasive threat environmental change poses to global ecosystems and human populations.

The global consciousness surrounding climate change began gaining serious traction in 1979, following the inaugural World Climate Conference held in Geneva. Organized by the World Meteorological Organization (WMO), this conference was a pivotal event that reviewed the scientific understanding of climate change and laid the groundwork for future global actions. This momentum continued with the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, established by the WMO and the United Nations Environment Program (UNEP), to provide governments with critical scientific insights necessary for shaping climate policy. The adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, which became legally binding in 1994, solidified the international community's commitment to combating climate change through coordinated efforts.

Nevertheless, despite significant strides, there remain concerns regarding the adequacy of current climate policies. A comprehensive analysis by Nieto et al. of the Paris Agreement's Intended Nationally Determined Contributions (INDCs) from 188 countries paints a rather disconcerting picture if additional measures are not adopted, global emissions could rise by 31.5% by 2030. Moreover, projections suggest that the current trajectory of emissions would likely lead to a global temperature rise of at least 3°C by 2050, with the possibility of a 4°C increase if emissions continue to grow unchecked.

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To meet the ambitious goals set forth by the Paris Agreement, a 45% reduction in anthropogenic GHG emissions by 2030 relative to 2010 levels is required to limit global warming to 1.5°C. For a 2°C cap, emissions must fall by approximately 25% by 2030, with the goal of reaching net-zero by 2070. However, current and projected mitigation efforts appear insufficient, necessitating further innovation and stringent policy actions (Gimba et al., 2024).

Mitigation strategies, which are indispensable in curbing climate change, center on reducing GHG emissions or enhancing carbon sinks. Schmitz defines mitigation as any human intervention aimed at diminishing the atmospheric concentration of GHGs. Given the global nature of the issue, international cooperation is often paramount for effective mitigation. Common strategies include decarbonization technologies such as renewable energy adoption, improvements in energy efficiency, and the deployment of carbon capture and storage (CCS) systems. Additionally, negative emissions techniques, such as bioenergy coupled with CCS, afforestation, and soil carbon sequestration, offer promising pathways to reduce atmospheric CO_2 levels.

Among these strategies, marine greens—particularly macroalgae and microalgae play a crucial role in climate mitigation by sequestering carbon. These organisms absorb carbon from their environment, which can then be utilized in energy production or converted into chemicals, thus serving as a natural counterbalance to rising CO_2 levels (Gimba et al., 2024). Incorporating marine-based carbon capture solutions into broader mitigation strategies may significantly bolster global efforts to mitigate climate change. The all-encompassing nature of climate change impacts ranging from the collapse of ecosystems and biodiversity loss to significant socio-economic disruptions demands urgent, comprehensive action. Reducing emissions while simultaneously enhancing resilience against climate shocks requires a multipronged approach that engages every sector of society. Only through concerted global efforts can we secure a sustainable future for humanity and the planet.

2. Marine greens

Marine greens, a diverse group of photosynthetic organisms thriving in marine ecosystems, either anchor themselves to substrates in benthic zones or float freely in the water column. These organisms, integral to the food web of tropical benthic ecosystems, include various algae species along with other marine photosynthesizers (Acosta-Calderón et al., 2016; Aransiola, Babaniyi, et al., 2024). Uniquely adapted to saltwater environments, marine green algae play an essential role in marine ecology, serving as a primary food source for numerous aquatic species and supplying critical nutrients to the broader oceanic food chain (Cardol et al., 2008). Often referred to as sea greens, these marine plants and algae are found in or near oceanic environments (Leslie, 2022), with their biochemical makeup typically consisting of lipids, proteins, nucleic acids, carbohydrates, and pigments like astaxanthin, fucoxanthin, and lutein (Chen & Xu, 2020). Notably, the specific composition of marine greens varies depending on the algae strain and cultivation practices.

Marine greens employ a relatively simple reproductive strategy and harness sunlight through photosynthesis, forming the foundation of their role as primary producers (Shanab et al., 2012). Their biomass exhibits remarkable structural and functional diversity, allowing them to thrive amid various environmental stressors such as salinity fluctuations, osmotic pressure, temperature extremes, nutrient shortages, and photo-oxidative stress (Shanab et al., 2012). As some of the oldest known photosynthetic organisms, with a lineage stretching back roughly 3.8 billion years (Stolz & Obermayer, 2005), marine greens encompass an estimated 280,000 species.

These organisms can be classified by their pigmentation and structure into different types. Brown algae, or Phaeophytes, are defined by their filamentous or thalloid forms and their characteristic brown hue, driven by the pigment fucoxanthin, which conceals other pigments (Ellamie et al., 2020). Species like *Laminaria, Saccharina,* and *Sargassum muticum* are examples of brown algae commonly found in temperate and arctic marine zones (Ko et al., 2014). Although these algae have holdfasts that resemble roots, they function merely to anchor the algae to surfaces in rocky coastal waters, as brown algae are strictly confined to saltwater habitats.

Another vital subgroup within marine greens is cyanobacteria, also known as blue–green algae. These prokaryotic organisms, capable of oxygenic photosynthesis, occupy various extreme habitats (Kauff & Budel, 2011; Dvorak et al., 2015). Cyanobacteria such as *Chroococcus subnudus* and *Planktothrix agardhii* have played a crucial role in the evolution of oxygenic photosynthesizers, significantly contributing to the development of Earth's oxygen-rich atmosphere (Bekker et al., 2004). Cyanobacteria are highly adaptable, engaging in nitrogen fixation and displaying cellular differentiation, with some genera even exhibiting eukaryotic-like characteristics (Nurnberg et al., 2014).

Marine greens are found across a broad spectrum of habitats, from coastal areas to the expansive open ocean. Coastal ecosystems, which account for just 7% of the world's oceanic area, nevertheless support high biodiversity, while open ocean environments span vast distances beyond the continental shelf (Charette & Smith, 2010a, 2010b). Phytoplankton, including marine greens, occupy the euphotic zone ranging from the ocean surface down to depths of 250 m where they contribute substantially to global primary production, generating over 5×10^{13} kg of biomass annually (Kumar & Singh, 2021). Their distribution and metabolic functions are influenced by key environmental factors such as nutrient availability, temperature, and light conditions (Upadhyay et al., 2019).

Marine macroalgae, often referred to as seaweeds, are macroscopic, multicellular photosynthetic organisms that are classified into three major groups based on pigmentation: green (Chlorophyta), red (Rhodophyta), and brown (Phaeophyta) (Gupta et al., 2017). Seaweeds are critical components of marine macrophyte ecosystems, coexisting alongside seagrasses and mangroves, and serve as essential links in the aquatic food web. Globally, approximately 20,000 species of seaweed have been identified, with 221 species being used commercially for diverse applications. Of these, 110 species are harvested for phycocolloid extraction, while 145 species are used as food sources. The burgeoning fields of biotechnology, genetic engineering, and omics technologies hold great promise for optimizing the utilization of marine greens, positioning them as pivotal tools in addressing various global challenges.

3. Contribution of marine greens to climate change mitigation

Since the advent of industrialization, human activity has dramatically escalated the atmospheric concentration of GHGs, with carbon dioxide (CO_2) making up an overwhelming 68% of these emissions (Even et al., 2022; Farghali et al., 2022; Zobeashia et al., 2018). The primary culprits fueling this surge are the combustion of fossil fuels, factory farming, industrial operations, mining, and waste production. This rampant release of CO_2 has significantly accelerated global warming, triggering profound and widespread effects on human health, ecosystems, soils, and aquatic systems. In response, the 2015 Paris Agreement underscored the urgent necessity for the development of eco-friendly, cost-efficient, and scalable solutions to curb CO_2 emissions and combat climate change (Troell et al., 2022). However, despite the multitude of strategies put forth to reverse these dangerous emission trends, tangible progress has been frustratingly elusive, underscoring the need for innovative approaches.

In this quest for novel solutions, ocean-based strategies have emerged as a particularly promising avenue, rivaling traditional land-based efforts. The ocean, a massive natural regulator of CO_2, plays a pivotal role in controlling atmospheric carbon levels through its vast carbon sequestration and storage capabilities . Since the dawn of industrialization, marine ecosystems have absorbed over 560 Pg (Pg) of CO_2, an astonishing figure that translates to the daily uptake of roughly 25 million tons of human-made CO_2 (Gao & Hader, 2020; Wu et al., 2022). In fact, the ocean is responsible for capturing about 30% of global CO_2 emissions, solidifying its status as the second-largest reservoir of organic carbon on the planet. This immense capacity for carbon storage highlights the ocean's indispensable role in climate change mitigation.

Complementing the ocean's natural carbon sequestration, biological solutions that leverage marine greens have emerged as a significant frontier in the battle against climate change. Marine greens comprising both macroalgae (such as kelp, wakame, and nori) and microalgae are proving to be powerful carbon sinks with unique advantages (Mehrotra & Pathak, 2020). Through photosynthesis, these organisms draw CO_2 from their surroundings, transforming it into organic carbon and thereby reducing atmospheric CO_2 levels. On a global scale, the cultivation of marine greens has demonstrated the potential to sequester considerable quantities of carbon, making a substantial contribution to climate mitigation efforts. This carbon-capturing process not only helps slow climate change but also provides an ecologically sustainable pathway to reduce GHG concentrations.

In essence, the integration of marine greens into climate change mitigation strategies presents a highly promising area for both research and practical application. By capitalizing on the natural carbon sequestration potential of marine ecosystems and scaling the use of algae biomass, substantial headway can be made in the global fight against climate change. Incorporating these ocean-based approaches into larger climate action frameworks could significantly enhance efforts to reduce CO_2 emissions, steering humanity toward a more sustainable future.

3.1 Carbon sequestration

Carbon sequestration, as outlined by the Intergovernmental Panel on Climate Change (IPCC), refers to the process by which the carbon content of a pool other than the atmosphere is increased. This mechanism is critical to the broader effort of mitigating climate change, a process the IPCC defines as "a human intervention aimed at reducing greenhouse gas emissions or enhancing their sinks." Of particular importance is carbon sequestration within soils, where atmospheric carbon is transferred into soil reservoirs, effectively converting them into carbon sinks. To properly evaluate the impact of environmental mitigation efforts, it is vital to measure the flux of GHGs before and after such interventions, particularly in relation to carbon sinks. However, it is essential to recognize that merely reducing emissions does not equate to achieving negative emissions; rather, it influences the behavior of carbon sinks. Furthermore, soil carbon sequestration might not always contribute to climate change mitigation, as the process can be impacted by historical sink capacities or past GHG emissions.

Beyond terrestrial ecosystems, carbon sequestration extends to the capture and long-term storage of carbon dioxide (CO_2) and other carbon forms, a critical strategy for mitigating the harmful effects of CO_2, a potent GHG responsible for exacerbating global warming. Within this framework, the cultivation of marine greens such as kelp, wakame, and nori has emerged as a highly effective strategy for reducing CO_2 levels. Studies reveal that marine greens can sequester up to 700 million tons of carbon annually across the global continental shelf (Mehrotra & Pathak, 2020). Among these, kelp stands out as a key player, responsible for more than 70% of the total carbon fixed by cultivated marine greens. Other species, including nori, wakame, and Gracilaria, also contribute significantly to the process, converting dissolved inorganic carbon and CO_2 into organic carbon.

In addition to their inherent carbon sequestration capacity, marine greens offer a broader range of environmental benefits. Banerjee et al. demonstrate that these organisms can effectively reduce CO_2 emissions by capturing carbon from stationary sources. This captured carbon can then be repurposed for the production of valuable chemicals or used to generate energy, thereby amplifying the ecological and economic benefits of marine greens. Furthermore, research conducted by Mashoreng et al. has highlighted the potential of various seaweed species including maricultured varieties like *Kappaphycus alvarezii* and strains of *Eucheuma spinosum*, as well as pond-cultured seaweeds such as *Gracilaria verrucosa* and *Caulerpa* racemose to act as effective carbon sequestrants. These findings underscore the significant role marine greens play in capturing atmospheric CO_2 and advancing global climate mitigation strategies.

3.2 Albedo effect

Albedo, defined as the fraction of solar radiation reflected from the land surface back to the atmosphere, plays a critical role in controlling the Earth's energy balance. It is essentially a measure of the planet's reflectance and determines how much sunlight the Earth absorbs. The concept of albedo is pivotal in understanding how various methods aimed at mitigating climate change, collectively referred to as climate intervention strategies, impact the environment. These approaches involve boosting the reflection or scattering of sunlight back into space, effectively cooling the Earth by manipulating its energy balance. Techniques to achieve this range from stratospheric aerosol injection, which disperses reflective particles high in the atmosphere, to marine cloud brightening, aimed at increasing cloud reflectivity, and enhancing surface albedo through reflective surfaces or materials. By artificially amplifying the planet's natural reflectivity, these interventions seek to offset the warming caused by rising GHG concentrations.

However, the application of albedo enhancement strategies is fraught with potential risks and challenges, particularly when considering large-scale deployments. For instance, the application of biochar to soil surfaces a method proposed for carbon sequestration raises significant concerns regarding its impact on albedo. Biochar, when applied at high rates (e.g., 30–60 tons per hectare), can lead to a decrease in surface reflectivity. This reduction in albedo can subsequently increase soil temperature, thereby potentially undermining the carbon sequestration benefits of biochar. This highlights a crucial balance that must be maintained: while biochar may offer benefits in terms of carbon storage, its effects on surface reflectivity and soil temperature must be carefully evaluated.

Additionally, there are broader risks associated with albedo enhancement techniques. One such risk is the issue of reversibility. Once certain albedo interventions are implemented, they may not be easily reversible, leading to potential long-term consequences that could be challenging to mitigate. Furthermore, effective monitoring, reporting, and verification of albedo interventions pose significant challenges. Accurate assessment of the impacts of these interventions is essential for ensuring that they achieve the intended effects without unintended side consequences.

3.3 Oxygen production

Marine green algae are vital pillars of marine ecosystems, playing an intricate and indispensable role in sustaining ecological balance while simultaneously aiding in the fight against climate change. These algae serve as the backbone of oceanic environments, providing critical nutrients, producing oxygen, and fostering biodiversity across a wide array of marine habitats. As foundational components of the aquatic food web, they support a diverse range of life, from fish, crustaceans, and invertebrates to larger marine mammals like manatees and sea otters (Edison et al., 2016). Through photosynthesis, marine algae not only generate substantial oxygen, maintaining the delicate oxygen balance in underwater ecosystems but also contribute to the overall vitality of marine habitats (Ghoneim et al., 2014). This oxygen production supports the respiration of marine organisms, making it essential for the health and functionality of these ecosystems. In addition to their oxygen-producing capabilities, marine algae are formidable players in carbon sequestration. By absorbing carbon dioxide during photosynthesis and storing it within their biomass, they effectively reduce atmospheric CO_2 levels, making them key agents in mitigating the impacts of climate change (Edison et al., 2016). Their role in reducing the greenhouse effect is pivotal, helping to curb the rising concentrations of CO_2 in the atmosphere and slow global warming.

Beyond carbon capture, marine greens like seagrasses and certain seaweed species are essential to nutrient cycling in marine environments. Seagrass roots release oxygen into the sediment, creating aerobic zones that facilitate nutrient uptake and enhance water quality. Similarly, the thallus of certain seaweeds can absorb nutrients directly from the water, thereby mitigating issues such as eutrophication and preventing harmful algal blooms from proliferating (Mantri et al., 2020). This nutrient absorption helps maintain ecological balance, preventing nutrient overload that could otherwise trigger detrimental algal blooms. Marine algae also play a crucial role in bioremediation, contributing to environmental cleanup efforts. By fixing carbon dioxide, releasing oxygen, and increasing biological oxygen demand, they help purify contaminated water (Babaniyi et al., 2023; Singhal et al., 2021). Their incredible adaptability allows them to thrive under varying conditions—whether autotrophic, heterotrophic, or mixotrophic—depending on the availability of light and substrates. Microalgae, in particular, are highly efficient at absorbing pollutants during photosynthesis, improving water quality and reducing the need for external aeration in biodegradation processes (Nithin et al., 2020). Moreover, when paired with heterotrophic microorganisms, microalgae can break down complex pesticides, demonstrating their versatility and effectiveness in environmental restoration (Chen & Wang, 2020).

3.4 Habitat preservation: Marine greens for habitat preservation

Marine algae hold a pivotal role in safeguarding marine ecosystems, significantly impacting both ecological stability and overall marine health. Their growth and metabolic processes are highly influenced by environmental variables such as pH, salinity, temperature, light, aeration, and water mixing. Among these, temperature plays a particularly crucial role in driving the biochemical mechanisms of marine algae. Typically, optimal growth conditions are achieved within the 20–35°C range, where photosynthesis and other metabolic functions operate most efficiently (Chowdhury et al., 2020; Okewu et al., 2024). Salinity, another key factor, affects species differently; while most marine algae thrive at salinity levels between 20 and 24 g/L, this is often lower than the salinity of their natural oceanic habitats (Perumal et al., 2012). Light, too, is fundamental, providing the energy required for photosynthesis a process by which marine algae convert light energy into chemical energy, using it to fix carbon dioxide and synthesize essential carbohydrates and proteins (Nigam et al., 2020; Ozkurt, 2009). Remarkably, certain marine greens like *Spirulina* demonstrate a remarkable ability to survive in highly alkaline environments, with pH ranges from 8.5 to 11.0. Despite this resilience, their optimal growth tends to occur within a narrower pH range of 8.2–8.7 (Blinová et al., 2015; Vo et al., 2015).

Marine habitats are classified into two main categories: coastal and open ocean environments, each supporting a distinct array of ecosystems. Coastal regions, which span from the shoreline to the edge of the continental shelf, are exceptionally biodiverse, despite comprising just 7% of the ocean's surface area. These nutrient-rich areas are hotspots for biological activity and sustain a wide range of species (Charette & Smith, 2010a, 2010b). In contrast, open ocean environments beyond the continental shelf tend to be less nutrient-dense, harboring species adapted to the deeper, more expansive areas of the ocean. Within the open ocean, the pelagic zone is further segmented by depth, light availability, and nutrient concentration. These subdivisions include the epipelagic, mesopelagic, bathypelagic, and abyssopelagic zones. Of these, the epipelagic zone also referred to as the photic or euphotic zone occupies the uppermost layer of the ocean, where sunlight penetrates sufficiently to sustain photosynthesis in phytoplankton. This zone is vital for primary production and supports the vast majority of marine life due to its high biological productivity. A comprehensive understanding of these habitat dynamics is essential for protecting marine algae and ensuring the long-term sustainability of marine ecosystems.

4. Technological applications

4.1 Biofuel production

Marine green microalgae are rapidly gaining recognition as a potent resource for biofuel production, thanks to their remarkable growth rates, rich lipid profiles, and carbon-capturing capabilities. Their unique attributes position them as an innovative solution for tackling rising CO_2 emissions, directly addressing the global climate crisis. Microalgal biomass, in its versatility, serves as an ideal feedstock for a range of bioproducts, particularly biofuels. These microorganisms thrive by absorbing key nutrients carbon, phosphates, and even heavy metals from wastewater, transforming pollutants into valuable biomass. This process not only supports bioenergy production but also contributes to CO_2 mitigation efforts.

Beyond their role in carbon sequestration, microalgae stand at the forefront of future energy strategies, playing a critical part in absorbing significant quantities of harmful emissions, including CO_2, nitrous oxide, and sulfur dioxide, especially from industrial sites like power plants (Aransiola et al., 2023). When it comes to biofuel generation, marine microalgae open up diverse possibilities, ranging from bioethanol and biodiesel to biogas. Their biomass, rich in sugars and capable of rapid multiplication, makes them especially attractive for bioethanol production. The high sugar content of marine green microalgae has sparked intense interest in their potential as a sustainable and renewable bioethanol feedstock. Similarly, their high oil content and environmental adaptability make them highly efficient for biodiesel production (Fig. 2.1). These algae offer a unique advantage in biofuel creation: their capacity to absorb CO_2 during growth renders the fuel carbon-neutral, as the CO_2 emitted upon biodiesel combustion is balanced by the CO_2 captured in the algae's life cycle.

In the framework of biogas production, marine green microalgae offer significant benefits due to their high concentrations of carbohydrates, proteins, and lipids key organic compounds that are readily converted by microorganisms during anaerobic digestion. This bioconversion process produces biogas, a renewable energy source that reduces dependence on fossil fuels while simultaneously addressing the environmental impact of excess algae biomass from aquaculture or industrial operations. The integration of microalgae into waste management systems for biogas production further enhances process efficiency and sustainability. Thus, marine microalgae not only represent a clean energy source but also provide a different approach to climate change mitigation and resource management.

4.2 Carbon capture and storage

Carbon capture and storage represents a cutting-edge technological approach aimed at dramatically curbing CO_2 emissions from industrial processes, particularly those associated with coal-fired electricity generation and various manufacturing sectors. This technology is capable of capturing an impressive 90% of CO_2 emissions, effectively preventing these GHGs from permeating the atmosphere and intensifying climate change (Fig. 2.1). The CCS framework consists of three essential phases: the initial capture of CO_2 from industrial operations, followed by the transportation of this gas to designated storage sites, and finally, its secure confinement within geological formations such as depleted oil and gas reservoirs or deep saline aquifers. Such a methodology is vital for diminishing the carbon footprint of high-emission industries and fits within a broader array of carbon abatement strategies that encompass nuclear power and renewable energy sources.

The underlying technology of CCS employs advanced processes engineered to ensnare carbon dioxide produced through the combustion of fossil fuels or other chemical and biological reactions, subsequently storing it in a manner that

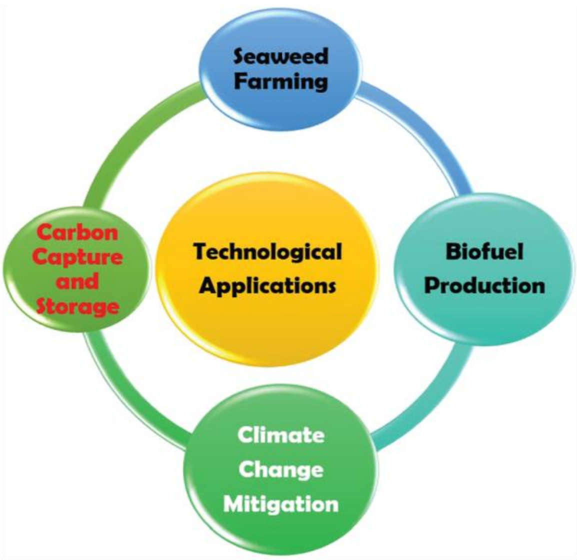

FIGURE 2.1 Technological applications of marine greens.

prevents its release into the atmosphere. The advancement and widespread application of CCS technologies are paramount for reaching global net-zero emissions targets, particularly as the pivotal year of 2050 draws near. Current forecasts indicate that achieving net-zero emissions is implausible without the effective and widespread adoption of CCS technologies. This assertion is bolstered by ongoing developments in related fields, including hydrogen, ammonia, and methanol emerging as promising contenders for zero-carbon emissions. The transition toward these alternative fuels is being propelled by collaboration among equipment manufacturers, engine builders, and energy companies, all striving to enhance technology, improve fuel flexibility, and develop the necessary infrastructure for renewable and sustainable hydrocarbon fuels.

A noteworthy instance of innovation within the carbon capture landscape is ARAMCO's introduction of mobile carbon capture units tailored for automobiles, trucks, and marine vessels. This initiative exemplifies a broader trend in the industry, emphasizing the reduction of GHG emissions and the integration of sustainable technologies across various sectors. In the maritime realm, the International Maritime Organization (IMO) has made substantial strides in enhancing fuel efficiency and curtailing marine exhaust emissions through the implementation of the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). These initiatives have already yielded significant reductions in both fuel consumption and emissions. Moreover, the establishment of Emission Control Areas (ECAs) has further catalyzed modifications in operational strategies and equipment, compelling the industry to pursue new technologies and alternative fuels.

The shift toward alternative fuels like hydrogen, ammonia, and methanol signifies a profound transformation in maritime fuel strategies. Hydrogen and ammonia are deemed zero-carbon fuels, emitting no CO_2 when combusted. However, their current production predominantly hinges on natural gas reforming, a process that generates GHGs unless paired with CCS technologies. To achieve genuinely green fuel production, it is essential to harness renewable energy sources such as hydropower, wind, or solar power to supplant traditional methods. This transition is crucial to ensuring that the entire lifecycle of fuel production minimizes GHG emissions. Methanol also stands as a viable alternative fuel, with potential production from renewable sources utilizing captured CO_2 and hydrogen generated via electrolysis, resulting in what is termed green methanol. Despite these encouraging developments, the large-scale production and GHG-friendly utilization of these fuels remain in the nascent stages of implementation.

In summary, CCS technology emerges as a cornerstone in the global effort to mitigate CO_2 emissions and realize climate objectives. Its integration with burgeoning alternative fuels and renewable energy sources will be instrumental in steering us toward a low-carbon future. Terminology such as carbon neutral, zero GHG emissions, net-zero emissions, and negative emissions technologies is becoming increasingly pivotal as industries, regulators, and governments collaborate to combat climate change and cultivate sustainable energy solutions.

4.3 Seaweed farming

Seaweed, a broad term encompassing a variety of marine algae, plays an indispensable role within marine ecosystems. Although these fascinating organisms can mimic the appearance of aquatic plants some reaching lengths of over 150 feet they do not belong to the plant kingdom; instead, they are classified within the Protista kingdom. This diverse assemblage includes brown algae (Phaeophyta), green algae (Chlorophyta), and red algae (Rhodophyta). Unlike true plants, seaweeds lack root systems, internal circulatory mechanisms, and the capability to produce seeds and flowers. Nevertheless, these remarkable organisms are crucial allies in the fight against climate change and global warming. They act as natural buffers for coastlines, dissipating wave energy in marine environments, thereby playing a vital role in curbing coastal erosion. For example, the kelp forests found in Norway, predominantly composed of *Laminaria hyperborea*, have been documented to reduce wave heights by approximately 60%. Moreover, macroalgae and various seaweeds are significant players in mitigating ocean acidification, a key contributor to climate change.

The potential of seaweeds for climate change mitigation can be distilled into four pivotal strategies. First, protecting and restoring wild seaweed forests can yield significant co-benefits for climate mitigation efforts. Second, the expansion of sustainable nearshore seaweed aquaculture offers promising avenues for enhancing climate resilience. Third, seaweed-derived products can be strategically employed to offset industrial CO_2 emissions, bolstering emission reduction initiatives. Finally, a method involving the sinking of seaweed into the deep sea serves as an innovative approach to carbon sequestration. Each of these strategies highlights the different contributions of seaweeds to tackling environmental challenges.

Effective management at the local level is paramount in minimizing the adverse effects of climate change on seaweed ecosystems. Coastal managers play a critical role in safeguarding seaweed forests against threats like overharvesting, pollution, and bottom trawling activities that can severely compromise these essential habitats. By addressing these stressors, it becomes feasible to bolster the resilience of seaweed forests in the face of climate change. Restoration initiatives can be further supported by various strategies. For instance, restoring artificial reefs can create new substrates for algal growth, while selectively harvesting grazers like sea urchins can alleviate pressures on vulnerable seaweed populations. Genetic modifications aimed at enhancing resilience to stressors, such as heat waves, also represent a promising avenue of research. However, one innovative management strategy for restoring kelp forests involves the application of "green gravel." In this method, small kelp are cultivated on gravel substrates and then released into the environment, a technique that has shown promise in promoting kelp forest restoration while enhancing the overall resilience of these vital ecosystems. Such forward-thinking techniques underscore the continuous research and development within the realm of seaweed farming and restoration, with the goal of unlocking the full potential of seaweeds in mitigating climate change.

5. Conclusion

As specter of climate change looms ever larger on the horizon, the role of marine ecosystems, particularly marine green technology, cannot be overstated. The root of this discourse lies in the relationship between marine environments and their potential to serve as formidable tools in the global resource against climate disruption. Marine green, encapsulated by entities such as seagrasses, algae, and mangroves, offers a panacea of sorts, embedding itself as a critical component in the broader narrative of ecological restoration and climate resilience. More so, at the heart of marine green's efficacy is its ability to act as a carbon sink. The ocean's vast expanse, coupled with its biological richness, makes it an unparalleled repository of carbon dioxide.

Through the processes of photosynthesis and carbon sequestration, marine plants not only absorb atmospheric CO_2 but also facilitate its storage in sediments, a function that terrestrial counterparts struggle to match in scale and efficiency. The sheer volume of carbon sequestered by marine flora stresses their indispensability in mitigating the anthropogenic footprint. However, this process is not devoid of complexities; the dynamics of oceanic carbon sequestration are influenced by many factors ranging from temperature fluctuations to ocean acidification each adding a layer of unpredictability to an already complicated system. Yet, marine green's contribution transcends mere carbon capture. The preservation and restoration of these marine ecosystems offer co-benefits that ripple through the broader environmental matrix. For instance, seagrass beds not only sequester carbon but also provide critical habitats for marine biodiversity, stabilize coastlines, and purify water bodies. Mangroves, with their dense root networks, serve as organic barriers against coastal erosion and storm surges, providing both ecological and socio-economic benefits to coastal communities. These different roles highlight the importance of an integrated approach to marine conservation, one that recognizes and leverages the interconnectedness of ecosystem services.

Nonetheless, the potential of marine green is not without its challenges. The degradation of marine ecosystems, driven influenced by elements like pollution, overfishing, and the climate change, poses a significant threat to their carbon sequestration capabilities. Ocean acidification, a byproduct of increased CO_2 levels, further complicates the picture by altering the chemistry of seawater, thereby impacting the growth and survival of marine plants. Moreover, the spatial variability of these ecosystems dictated by geographical, climatic, and anthropogenic factors necessitates tailored conservation strategies that are responsive to local environments. A one-size-fits-all approach is unlikely to yield the desired outcomes; instead, adaptive management practices that are informed by continuous monitoring and research are essential.

In light of these challenges, the integration of marine green technologies into climate policy frameworks emerges as a critical priority. Governments, international bodies, and environmental organizations must collaborate to foster the development and deployment of marine-based solutions. This includes not only the protection and restoration of existing marine ecosystems but also the exploration of innovative approaches such as ocean fertilization and the cultivation of seaweed farms, which hold promise for enhancing the ocean's capacity to serve as carbon sink. Furthermore, inclusion of marine green strategies in the Nationally Determined Contributions (NDCs) under the Paris Agreement could serve as a catalyst for their broader adoption, aligning global climate goals with the imperatives of marine conservation.

Yet, the efficacy of these measures hinges on a robust framework of governance and financing. The mobilization of financial resources both public and private is imperative to support large-scale marine restoration projects. Equally important is the establishment of regulatory mechanisms that ensure the sustainable use of marine resources, preventing exploitation that could undermine conservation efforts. International cooperation will be key in this regard, particularly in addressing transboundary issues such as marine pollution and the management of shared water bodies. In summary, leveraging marine greens in the battle against climate change marks a transformative shift in our approach to environmental stewardship. This strategy demands a comprehensive and integrated framework that marries ecological wisdom with socio-economic foresight and cutting-edge technological innovation. The vast potential of marine ecosystems to bolster climate resilience is undeniable, yet unlocking this potential hinges on collaborative action, bold creativity, and a steadfast commitment to sustainability's core values. As we navigate toward a more climate-resilient future, it is crucial to place the oceans the blue lungs of our planet at the heart of our fight against global warming. The moment to act is upon us, and the path ahead is unmistakable: embrace the power of marine greens and harness the ocean's immense capacity to pave the way for a sustainable tomorrow for all.

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Chapter 3

Marine bioresources in managing ocean microplastics pollution

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1. Introduction

The marine environment is an aquatic environment with high salinity, viable temperate, a zone that can be penetrated by light, and a deeper zone that sunlight cannot be reached, including subsystems like coral reefs and sea grasses, serving as a highly productive zone for numerous diversity of species and habitats (Aransiola, Oyewole, et al., 2024). This environment, comprising 71% of the Earth's surface, is an intricate and vital component of the planet's ecosystem that provides us with invaluable resources and services (Aransiola, Babaniyi, et al., 2024; Costanza et al., 1997). This complex and dynamic environment provides habitat for a wide variety of biodiversity ranging from primitive species like horseshoe to more complex organisms like whales and dolphins contributing to a stable and productive ocean ecosystem. These resources include marine biodiversity and natural compounds with pharmaceutical potential (Amobonye et al., 2023; Leal et al., 2016) that can be used for biotechnological applications and research. Marine resources include living organisms that live in or on the ocean such as, fish, seabirds, marine mammals, sponges, and seaweeds as well as nonliving resources like dissolved organic and inorganic materials, minerals, and oil reserves (Auta et al., 2022; Rogers et al., 2014). The marine environment provides critical services like carbon sequestration, nutrient cycling, and coastal protection and is also of great importance to humans in terms of climate regulation, food security, transportation, and other economic activity. However, this environment is increasingly threatened by anthropogenic activities leading to the pollution of microplastics creating a growing global concern (Thompson et al., 2004).

Large plastic debris breakdown either by biotic or abiotic means to form smaller fragments of plastic referred to as microplastics with size ranging from 1 to 5 mm and are widely distributed in aquatic and terrestrial environments (Musa et al., 2024). Due to their tiny size, they are easily and widely distributed, becoming more prevalent, particularly in the ocean, and have raised significant concerns in recent years. These significant threats not only affect marine life and environment but also human health having a significant ecological impact (Aransiola et al., 2023; Suzuki et al., 2024). Microplastics take various forms such as, fragments, pellets, fibers, foams, and microbeads. These tiny particles can be ingested by different marine organisms like fishes, low-nutrient organisms (Zooplankton e.g., Artemia), larvae of shellfish, and sea squirt (Yang et al., 2021) due to the fact that these microplastics are similar in size and density to planktonic organisms. Bioaccumulation of microplastics have been observed in suspensions and deposit-feeding organisms at the base of the food web with evidence showing that these ingested microplastics can be transported to higher trophic levels, that is, from planktons to whales (Harrison et al., 2011), thereby leading to accumulation of toxic substances within the food web, physical harm, and even death affecting species of different trophic levels (Wright et al., 2013). This by extension poses risk to other seafood consumers including humans. According to Yang et al. (2021), this has been demonstrated in an experimental exposure test that showed how persistent organic pollutants (POPs) could be accumulated in food webs from the ingestion of microplastics. The impact of toxic substances on marine fish that ingests

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TABLE 3.1 Ingestion of microplastics by various marine organisms.

Marine organism	Type of microplastic	Size range (mm)	Effect	References
Fish of various species	Fragments, fibers	<5	Gastrointestinal blockages, Liver inflammation, Oxidative stress	Rochman et al. (2013)
Seabirds	Pellets	1–10	Reduced feeding and digestive issues	Lavers and Bond (2016)
Zooplankton	Fragments, fibers	<1	Reduced feeding and impaired reproduction	Cole et al. (2013)
Oysters	Microbeads and fibers	<1	Damage tissue and oxidative stress	Sussarellu et al. (2016)
Crabs	Fragments, fibers	>5	Redarded growth and change in feeding behavior	Watts et al. (2014)

microplastics has been observed to develop liver inflammation, pathological effects, and oxidative stress (Rochman et al., 2013) (Table 3.1).

The physical properties of microplastics such as its size and density make it easier to be distributed and transported over long distances in both aquatic and terrestrial environments, making it more challenging to remediate and control. The use of traditional cleanup methods could be less effective, necessitating the integration of innovative techniques that could be more sustainable in addressing this environmental issue. This chapter helps provide a comprehensive overview of how this microplastics pollution can be managed and mitigated in marine environments by the use of marine bioresources. Through this exploration, this chapter highlights the use of marine bioresources as a more sustainable, effective, and environmentally friendly method of combating the pollution of microplastics in marine ecosystems and the world at large.

2. Microplastics pollution of the marine

2.1 Sources and types of microplastics

The significant primary sources of synthetic plastic wastes in marine environments includes coastal tourism, fishing activities, marine industries, and plastic product manufacturing of which directly impacts seas and oceans (Urbanek et al., 2018). These synthetic plastic fragments to smaller fragments of less than 5 mm in size are referred to as microplastics. These microplastics are classified into primary and secondary microplastics. Primary microplastics comprise synthetic materials directly manufactured into small size such as microbeads and microfibers used to manufacture personal care products and are usually found in municipal and domestic wastewater sludge (Sooriyakumar et al., 2022; Zhang et al., 2020). Instead of the traditional exfoliants (ground almonds and oatmeal), microplastics are utilized in the form of microbeads varying in shape, size, and composition depending on the product to be produced. This type of microplastics is used in the production of cosmetics products like shower gel, eye shadow, and facial cleanser and other products like toothpastes, sanitary products, and pharmaceuticals (Thushari & Senevirathna, 2020). This use of microbeads has subsequently resulted in the increase in demand for microplastics, which are utilized in large amounts for the manufacturing of cosmetic products, which eventually makes their way to the ocean through waste streams, rivers, and drainage systems by bypassing wastewater treatment procedures (Auta et al., 2017). Secondary microplastics, on the other hand, result from the fragmentation of larger plastics through processes like mechanical abrasion, photodegradation, and biological activities (biodegradation). Common sources are the breakdown of plastic bags, bottles, fishing gears due to wave action, UV radiation, and so on (Fig. 3.1), which subsequently degrade into microplastics. Synthetic textiles shed microfibers during washing and make their way to the ocean when discharged into waterways (Napper & Thompson, 2016).

A way to categorize ways microplastics make their way to the ocean is by classifying them into land-based and marine-based activities. Land-based activities like tourism and recreational activities are significant contributors to the accumulation of plastics in coastal areas and marine ecosystems (Thushari & Senevirathna, 2020). Other activities include residential and domestic activities, agriculture activities (microplastics from fertilizers), and various economic activities, which are important sources of microplastics that can be carried into the ocean through runoffs. Another significant contributor to microplastic pollution, that is, land-based sources, is textile fibers. Plastic fibers, like polyester, acrylic, and nylon, shed from clothing during washing and are tiny enough to bypass water treatment systems and enter water bodies,

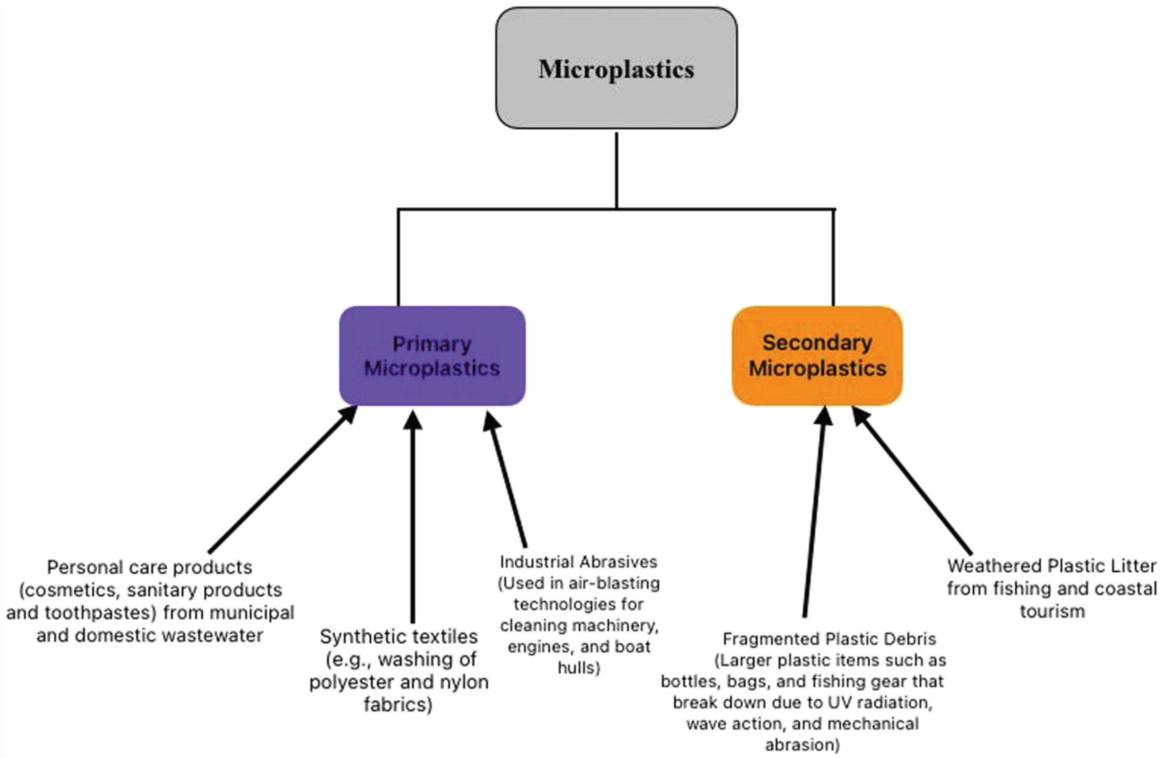

FIGURE 3.1 Source of microplastics in the ocean.

which eventually make their way into the ocean. The increased demand of synthetic textiles globally, the release of microfibers into the ocean, has increased drastically losing a threat to the marine ecosystem. Marine-based activities as a source of microplastics pollution in oceans on the other hand include commercial fishing, shipping, and other economic activities. The loss equipment like fishing gears, ropes, and so on degrade with time breaking down into smaller particles resulting in the release of microplastic in oceans.

2.2 Distribution and prevalence of microplastics in marine environments

Microplastics are widely distributed throughout marine environments, from surface water to the deep sea, and from coastal zones to remote oceanic regions. Their size and buoyancy make it easier for them to be transported over long distances by ocean current (Doughty & Eriksen, 2014). Microplastics have been found in various marine zones including seawater, biota, and sediments. Atmospheric deposition is also a pathway for microplastics to enter the ocean. Microplastics can be carried by the wind and deposited in the ocean by rain. This pathway shows how microplastics can be dispersed globally as airborne particles over long distances before settling in marine environments (Bergmann et al., 2017). Surface water has high concentrations of microplastics due to their buoyancy while coastal areas, especially those near urban centers and river entrances, also show increased levels of microplastics usually from offshore pollution sources (Jambeck et al., 2015).

A quite less obvious yet significant pathway for microplastics to enter the ocean is through the feces of zooplankton. In a study by Cole et al. (2016), zooplankton, particularly *Calanus helgolandicus* and *C. typicus*, were exposed to polystyrene microplastics. These organisms ingested the microplastics, which passed through their digestive system as they were not able to digest them and were then encapsulated in their feces. The fecal pellet with the microplastics could sink to the bottom of the exposure vessel and could be ingested by larger copepods. This study shows how fecal pellets could be a vector for microplastics dispersal and how these microplastics make their way to higher trophic organisms in the marine ecosystem.

The prevalence of microplastics in marine has grown significantly over the years. Tons of plastics are subsequently found in oceans all over the world and are estimated to increase in the future. Microplastics have been found in marine species such as plankton, fish, seabirds, and marine mammals indicating this nature of ubiquity (Cole et al., 2013). The density of plastics influences its accumulation in marine environments. It can gather within the water column, float on surface water, or sink to the ocean floor after being colonized by biotic and abiotic components. The way they spread in ocean environments is influenced by their density, where they originate from, and their movement through waves and currents of the ocean. The physical and chemical properties of microplastics contribute to their endurance and prevalence causing widespread pollution in the ecosystem facilitated by processes of water movement and forces of ocean current (Auta et al., 2017).

3. Mechanisms of plastisphere in the ocean environment in solving microplastics pollution

3.1 Plastic and microplastic pollution in aquatic environments

Plastics, being polymers, coupled with their ability to adsorb various substances (metals, POP's and additives) make a distinctive medium for microbial adhesion (Du et al., 2022). Owing to their relative novelty and being artificial media in marine systems, plastics may cause disruptions in the balance of the ecosystem and sever natural boundaries (Zhai et al., 2023), and because of their durability, plastics are not completely broken down in the environment; instead, they form smaller-sized particles, and when these particles become less than 5 mm in size, they are called microplastics (An et al., 2022). Microplastics are synthetic solid particles or polymeric matrix, that regular or amorphous in shape, ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water (Frias & Nash, 2019). In the marine ecosystem, microplastics are found in shelf, beaches, deep water sediments, subsurface, and surface waters (Hossain et al., 2023), and of all the various anthropogenic wastes in aquatic environments, plastics are becoming the material of most concern to environmentalists (Ding et al., 2022).

3.2 The plastisphere

The plastisphere is a term first coined and characterized by Zettler et al. (2013), and it describes the new community of microorganisms attached to plastic surfaces and distinct from the environment (aquatic or terrestrial) where the plastics are found. The attachment and colonization of a community of microorganisms on free-floating plastic surfaces are referred to as the plastisphere (Mishra et al., 2024). Biofilm-forming microorganisms colonize microplastics creating the plastisphere. This unique environment aids dispersion of microbes as well as affects the development, transportation, persistence, and ecology of microorganisms (Barros & Seena, 2021). Like other biofilms, the plastisphere is built by attachment of microbes, secretion of extracellular polymeric substances, and exponential growth of microbes (Zettler et al., 2013). Plastisphere formation is influenced by a complex interaction of various factors, primarily spatial and seasonal. Polymeric characteristics (type, shape, and surface features), however, also play a role (Singh et al., 2022). Environmental factors, water current, availability of nutrients, and type of microplastic surface control the relationships between microorganisms on the plastic surface, ultimately controlling biofilm (plastisphere) formation (Ghosh & Das, 2018).

3.3 Plastisphere-mediated microplastic degradation

Physical plastic degradation processes (e.g., waves breaking them down against ricks and sand) and chemical degradation processes (e.g., photo-oxidation) happening in the aquatic environment lead to the breakdown of aquatic plastic waste to microplastics, ultimately leading to the formation of the plastisphere (Tang, 2024). These processes convert plastics to microplastics, making them more susceptible to further degradation. Microbial (plastisphere) regulated degradation of microplastics enhances microplastic catabolism without causing any negative effects to the environment and the ease of adaptability by microbes to various environments ensures microplastic degradation (Du et al., 2022). The microbial biodegradation process involves carbon (from plastics) metabolism into biogas and biomass by the action of microbial communities (bacteria, actinomycetes, and fungi) that use plastics as a carbon source (Alshehrei, 2017).

Microplastic degradation carried out by microorganisms is simply the catabolism of plastic macromolecules into smaller, environmentally friendly metabolites like water (H_2O), carbon(iv)oxide (CO_2), and methane (CH_4) by the action of various enzymes secreted in biofilms (Yuan et al., 2020).

Plastic fragments and microplastics have the ability to serve as a source of carbon, supporting growth and colonization by microbes (Alshehrei, 2017). In the environment, microplastics are found in association with microorganisms, organic matter, and inorganic particles. These associations enhance the formation of biofilms (plastisphere) by various microorganisms on the surface of the plastics by aiding the adsorption of microbes to the surface of microplastics, which act as a substrate (Mishra et al., 2024).

The cleavage and breakdown of microplastic particles by microorganisms are heavily dependent on the growth of the mycelium, as physio-chemical structure of the plastic is disrupted by mycelium growth (Mishra et al., 2024). Enzymatic reactions by microorganisms cause structural damage to microplastics, which causes a loss of properties. However, before degradation by microorganisms, these plastics waste particles must first be broken down by physical processes; abrasion, hydrolysis, and UV light (Alshehrei, 2017). After this, enzymatic secretion by microorganisms mediates the hydrolysis or oxidative breakdown of plastic macromolecules, releasing molecules of lower molar masses. Simple compounds like water (H_2O) and carbon(iv)oxide (CO_2) are produced when the micro molecules released are used up by microorganisms (Dussud et al., 2018; Mohanan et al., 2020).

Biodeterioration involves the changing of the physical and chemical properties of a polymer by microorganisms. After this, the polymers are broken down to simpler ones by **bio-fragmentation**. This is followed by the "taking up" of these simple compounds by microorganisms by **assimilation** and the products of the organisms' metabolism (like CO_2, CH_4, and H_2O) undergo **mineralization** (Fig. 3.2) (Rashed et al., 2023; Sanniyasi et al., 2021).

Higher molecular weight polymers, however, are more difficult for microorganisms to assimilate due to their large fragments and resulting difficulty to break down. Intracellular and extracellular degradation are used by microorganisms to overcome this molecular weight barrier (Rashed et al., 2023). Intracellular degradation involves the aggregation on and colonization of the microplastic surface by microbes and the hydrolysis of the polymer into shorter chains. Extracellular degradation involves the use of hydrolase enzymes secreted by bacteria to degrade complex polymeric units to simpler ones, which can be more easily metabolized prompting the start of the mineralization process (Rashed et al., 2023).

The part played by the fungi *Fusarium oxysporum* and *F. solani* in breaking down plastic polymers (PET) has been shown by previous studies (Mayali, 2018) and Zhai et al. (2023) reported the successful degradation of polystyrene by *Exiguobacterium*, *Bacillus anthracis*, *Enterobacter* sp., and *Aspergillus* sp. Bacillus sp., *Rhodococcus* sp., *Pseudomonas aeruginosa*, and *Aspergillus clavatus* have been successfully investigated for their biodegradation potential (Amobonye et al., 2021; Tareen et al., 2022). Microplastic degradation is the result of the joint metabolism of multiple microorganisms in the plastisphere, which have the ability to turn complex plastic polymers into simpler products of metabolism like CO_2 and H_2O.

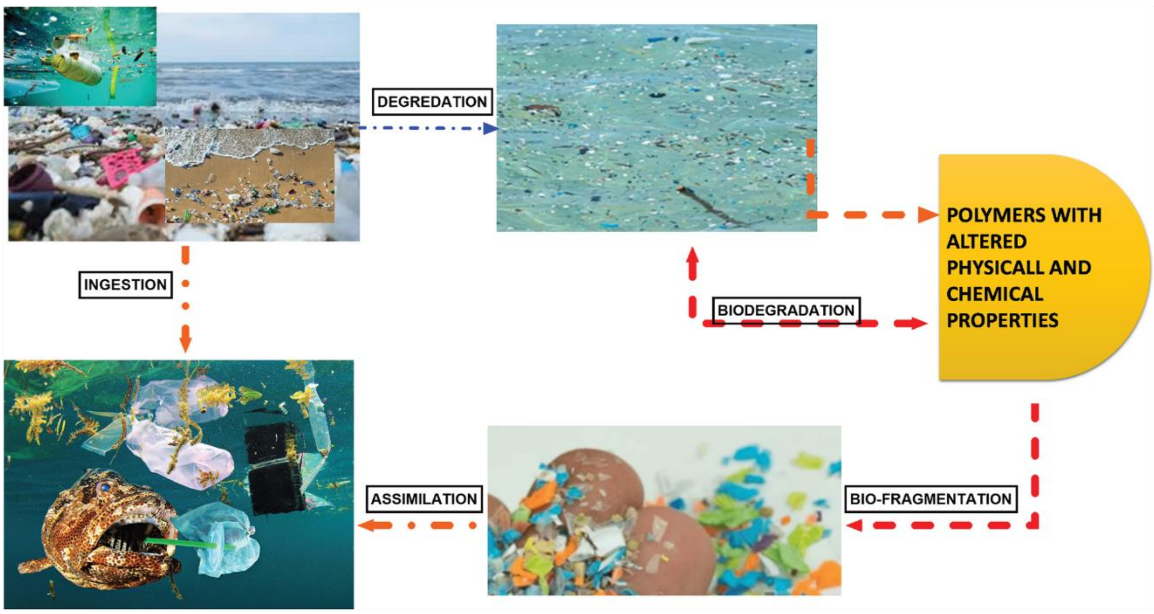

FIGURE 3.2 Consecutive steps in microplastics degradation.

4. Future guidelines in using marine bioresources to manage marine microplastics

4.1 AI in focus

New technologies are launching, often daily. These advancements are becoming popularly used in many different domain names as a way to handle problems worldwide. There are technologies that are used for manipulation of genes, and quantum mechanics, which are changing the way we work or think. Artificial intelligence along with machine learning (ML) is one of the most promising solutions to combat microplastic pollution among these emerging technologies. Machines can be created with the help of AI, and for analyzing data from the past, ML provides a method to predict or come up with consequences based on which they might work (Agarwala, 2021). With the help of ML and AI, ocean cleaning can play a vital role in protecting these ecosystems against pollution/degradation, as well as developing sustainable microplastic methods.

Recently, AI has been applied to the management of microplastics. Autonomous robots with AI are detecting and identifying microplastics (Koski, 2022; Taddia et al., 2021) as well as machine learning models that were used to analyze data providing meaningful information on the composition of microplastics (Michel et al., 2020; Zhu et al., 2020). Such developments have broadened the scope of research, utilization, and administration concerning microplastics. Some robots such as robotic fish, drones, and smart cars have been invented in order to take out microplastics from water bodies (Zhang et al., 2023; Zolich et al., 2022). It is highly resilient to environments and thus can be used a long time before replacement. Another is the creation of Gillbert, a peer-into-detail 3D-printed robotic fish, which was built with intentions of gathering microplastics from environments (Designboom, 2022). First up is Gillbert, an aquarium-roaming fish bot with a remote-control module and filtration. The robot's gills filters can block up to 2 mm wide microplastics from the water. The collected MP's are stored inside the cleaning robot in a container and can be disposed of safely or recycled. Gillbert, in its current form, is still too small to handle anything other than microplastic sampling. Future exploration efforts should focus on scaling up the machine so that it can rid waters of microplastics and plastics on a large scale (Guo et al., 2024).

Robotic systems serve for the digitalization of waste object sorting. The digital camera of the robots makes it possible to automate these sorting tasks by using an ML algorithm. These plastic weighs are photographed by the robot's digital camera and then examined using deep studying fashions. These models can be used to find, locate, and classify the plastic waste which in turn would help robots easily sort plastics using intelligent control (Guo et al., 2024). These robots and their cameras with machine learning algorithms can automate sorting tasks. Another study (Liu et al., 2021) constructed a robot equipped with an RGB-D camera and tasked this machine to search for and grasp plastic objects. The YOLACT model was trained with a dataset of 1500 images of plastic items dispersed against complex backgrounds (e.g., bottle caps drinking bottles; foam food containers) on tiles, sidewalks, and/or grassy roads. This instructed the model to be able to know object detection properly in practical use cases. The trained model was used to detect and locate plastic items present in the scenes of RGB images from depth cameras, thereby achieving real-time detection scenarios since it can perform target localization on video feeds. Point clouds were created using the depth data from the cameras and used for a simulation of plastic object surfaces to create an effective grasping strategy. The success rate of grasps was more than 90% (Liu et al., 2021).

Automatic identification, classification, and quantification of microplastics (MPs) using ML methods have been tasked with identifying MPs from images taken by digital cameras (Sundar, 2022) and microscopes (Wang et al., 2023). These models are trained using MPs annotated images, the "knowledge source" of these models to identify features like shape, size, color, or texture related to factorial cells (Guo et al., 2022). Trained models contain the identification (Guo et al., 2021) and inserting of bounding boxes around detected MPs in new, previously not-observed images which might either be photos or frames from video recordings (Liu et al., 2022).

5. Conclusion

The study of marine bioresources as a means to reduce microplastics pollution in the marine environment provides a promising solution through natural biodegradation processes. These bioresources include marine organisms associated with plastics known as plastisphere with plastic-degrading enzymes, capable of degrading microplastic. Understanding the plastisphere reveals that communities of microorganisms are able to degrade plastics through biochemical means. The microbial biodegradation process involves carbon from plastics metabolizing into biogas and biomass by the action of these microbial communities, plastisphere. They break down plastic macromolecules into smaller, environmentally friendly metabolites like water (H_2O), carbon(iv)oxide (CO_2), and methane (CH_4) by the action of various enzymes that they secrete. With the influence and use of AI, the identification and utilization of these agents of biodegradation increase the development of efficient and scalable bioremediation strategies. An integrative approach, involving partnership of marine biologists, environmental scientists, chemists, and AI specialists to maximize the potential of marine bioresources, is quite essential in other to provide an innovative and viable solution to mitigate microplastics pollution, thus addressing this environmental challenge and contributing to the long-term environmental-friendly marine environment.

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Chapter 4

Food for all: Exploring fulfilling SDG2 by sea

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1. Introduction

Let us start by defining hunger in simple terms: it occurs when a person cannot manage even half a stomach of food once a day, and this state continues for more than three consecutive days. While this definition may seem straightforward, a staggering number of people experience this daily. According to the 2023 edition of the "State of Food Security and Nutrition in the World" report, between 691 and 783 million people faced hunger in 2022, marking an increase of 122 million compared to 2019 (Sreehari et al., 2023). The rising cost of food compounds the problem. As reported by OECD (2021), the FAO Food Price Index—which tracks global price changes in a basket of food items like sugar, meat, cereals, dairy, and vegetable oil—rose from 95.1 points in 2019 to 143.7 points in 2022.

Rather than delving into the well-documented challenges of land-based agriculture—such as climate change, fertilizer shortages, limited space, and adverse geographical features like rivers and mountains—this discussion will focus on the potential of the sea to address hunger. Achieving zero hunger requires localized, adaptive, and participatory solutions that account for institutional capacities, agroecosystem diversification, ecological management, and improving local diets. Conceptual frameworks such as socio-ecological systems and sustainable diets provide integrated approaches to agricultural and food security challenges, informing policies that are more effective and holistic (Papargyropoulou et al., 2024, p. 102705).

The focus here will be on how marine resources can be utilized to combat hunger while addressing the challenges inherent in this approach. Unlike land, which must support population, infrastructure, and agriculture and is further strained by climatic extremes and soil degradation, the sea offers untapped opportunities. However, harnessing its potential is not without difficulties, and these will also be explored. The path to achieving Zero Hunger should focus on solutions that are tailored to specific locations, adaptable to changing conditions, and involve active participation from local communities. These solutions must address local institutional capacities, promote diverse agricultural ecosystems, support ecological management, and enhance the quality of local diets. Two key frameworks—socio-ecological systems and sustainable diets—provide integrated perspectives for analyzing agriculture and food security. These frameworks can guide the development of effective policies that are both practical and sustainable, ensuring long-term progress toward eradicating hunger (Aransiola, Akinsola, et al., 2024; Aransiola, Oyewole, et al., 2024).

The Earth's land-to-water ratio is approximately 1:2, meaning there is significantly more water than land available (Lehmköster & Maribus, 2011). This prompts an important question: what if we could utilize the sea as a space to grow food? This could include cultivating plants, farming animals, or even harvesting insects—essentially exploring all viable options for food production. While we already utilize some marine resources for food, the idea is to expand this usage to meet a greater share of nutritional needs, potentially filling up to 90% of the stomach, at least once a day if not twice. This perspective shifts the focus from land-based constraints to the vast, untapped potential of the ocean as a resource for food production.

Marine Bioresources. https://doi.org/10.1016/B978-0-443-36320-7.00013-2

2. How can sea be used?

Regenerative sea farms are an intriguing alternative to traditional land-based farming even though they are small in scale. One compelling approach is creating farming areas in the ocean to cultivate marine plants and animals. For instance, Bren Smith, founder of Thimble Island Ocean Farm and the Connecticut-based nonprofit GreenWave, has developed a 3D ocean farming system that functions as an underwater garden anchored by a network of light nets, vertical and horizontal lines, and cages that grow a mix of oysters, mussels, kelp, and other sea vegetables and shellfish (Meyer et al., 2019) (Fig. 4.1). This innovation has a little carbon footprint but massive outputs, revitalizing ocean ecosystems and creating a new ocean economy.

Marine aquaculture makes use of natural resources like seawater and sunlight as energy sources to grow sea-based food making the process remarkably sustainable and efficient (Orcutt et al., 2011). This approach has promising prospects as an environmental solution, providing nutrient-rich food, creating job opportunities, and reviving coastal ecosystems. Sea greens can also serve as bioplastics, biofuels, and cattle feed additives that minimize methane release from livestock (McCay & Sunidhi, 2024) (Fig. 4.2). Kelps in particular are significant for their ability to absorb and retain carbon and nitrogen which helps in combating global warming and climate change (Filbee-Dexter & Wernberg, 2020).

Shellfish add to the ecological benefits. Shellfish reefs enhance coastal resilience by reducing storm surge impacts, while bivalves naturally filter pollutants from the water as they feed. This includes removing excess nitrogen, often caused by fertilizer runoff from industrial farming (Coen et al., 2011). However, there are challenges, such as integrating sea vegetables and other marine products into the economy at a scale comparable to land-based agriculture. With careful planning, strategic leadership, and innovative approaches, these challenges are surmountable. Solutions include creative farm designs, targeted farmer training programs, and online support hubs for small-scale cooperative sea farmers. These efforts are rapidly building a nationwide network of kelp farmers who are implementing climate solutions, fortifying shorelines, and enhancing food security (Institute of Medicine, 1991). By embracing these practices, sea farming holds immense promise for both people and the planet. The vast array of ocean plants and animals offers immense potential for integration into our food systems, and in many ways, we have only scratched the surface of what is possible. However, this raises an important question "Is society ready to embrace nutrient-rich sea vegetables and shellfish as a larger part of our diets?"

The U.S. Census Bureau estimates the shore length at 12,000 miles, while the National Oceanic and Atmospheric Administration (NOAA) places the total coastline length at approximately 95,471 miles. This highlights the extensive reach of our coastal resources, which remain largely untapped for food production. "There is not a lot of water on Earth at all," remarked David Gallo, an oceanographer at the Woods Hole Oceanographic Institution in Massachusetts. Despite its abundance, the ocean covers the planet with a water layer spanning 15,000 miles (24,000 km) at an average depth of 3.2 km. This immense volume of water presents a compelling opportunity to expand our food sources by sustainably cultivating marine life, but it also underscores the challenges of managing and harnessing such vast resources effectively.

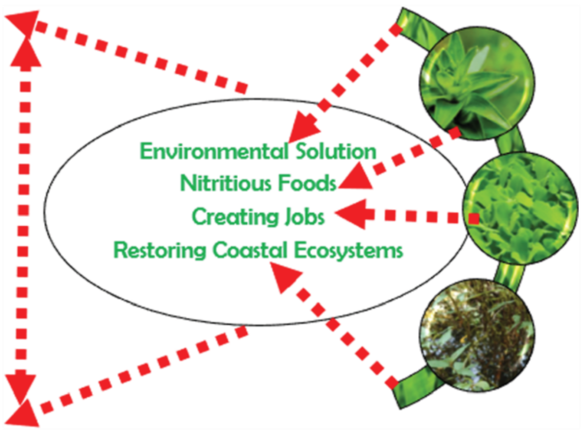

FIGURE 4.1 Benefits of 3D ocean farming system.

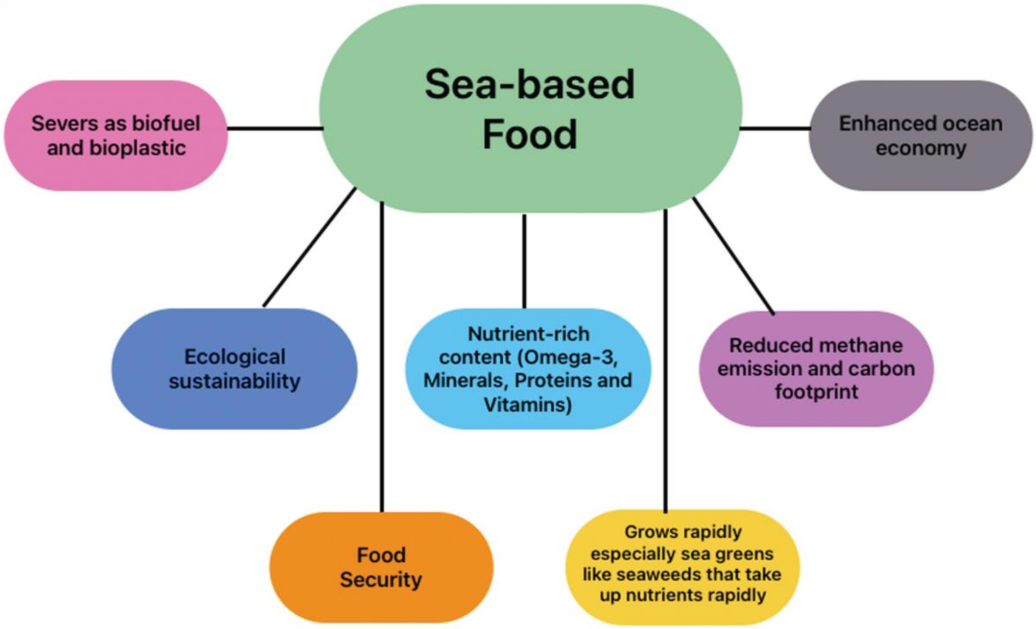

FIGURE 4.2 Sea-based food and potential benefits.

3. Tentative problems to use sea

The U.S. Census Bureau estimates the length of the shoreline at 12,000 miles, while the NOAA places the total coastline at approximately 95,471 miles (Gleick & Heather, 2021). However, utilizing the sea as a food source presents unique challenges, particularly due to the type of food we are accustomed to consuming. Staple grains like wheat, maize, and rice are rooted plants, making them unsuitable for cultivation in the ocean. On land, farming is better controlled, but in the sea, factors such as water currents, tides, and coastal dynamics make control far more difficult, even along shorelines.

With nearly half the world's population living within 65 miles of the ocean, coastal ecosystems are among Earth's most critical landscapes (Burkett et al., 2018). Yet, these areas are notoriously hard to map accurately. Until recently, there was no comprehensive high-resolution geospatial dataset of global shorelines. This gap has now been addressed by a new mapping and ecological inventory developed by Esri, the U.S. Geological Survey, and other partners (Sayre, Butler, et al., 2021).

While rooted crops like cereals and traditional vegetables cannot be grown in the ocean, marine resources such as sea plants, fish, shellfish, and even insects present viable alternatives for food production. Sea algae, in particular, has the potential to be a significant food source to combat hunger (Table 4.1). Addressing global hunger requires diversification of food sources, which calls for innovation and adaptability in utilizing the ocean's resources. However, the ocean poses unique challenges, particularly in monitoring and controlling the composition of marine food. On land, chemical analyses enable the regulation of toxins like heavy metals in crops, benefiting from extensive ecosystem studies. Meanwhile, these cannot be done in the ocean, as its vast realm and complexity make it difficult to carry out similar controls thereby posing a significant limitation. Meal preferences are deeply rooted in an individual's traditional background as they would prefer to continue with the food they have been used to, further complicating the adoption of sea-based foods into their diets. Staple foods like wheat, maize, and rice are core dietary components for many persons, and alternative foods may not provide the same sense of acceptance or satisfaction. This leads to both psychological and practical challenges in shifting toward sea-based diets. Also, while the ocean provides vast amounts of volume, it still poses issues that also involve critical issues of coastal erosion.

A worldwide challenge that has been of major concern is the need to balance the benefits derived from the ocean with its capacity to provide for future generations. To achieve sustainable management of the ocean and minimize environmental impact, overharvesting of capture fisheries and aquaculture facilities should be avoided. Failing to do so could reduce the marine ecosystem's ability to sustain food production and other societal benefits. Additionally, the social and

TABLE 4.1 Land-based food and their sea-based food equivalent with its potential benefits.

Land-based food	Sea-based food equivalent	Potential benefits	References
Wheat	Seaweeds, *Ulva*	Grows faster, occupies space more efficiently, and has a long chain of Omega-3 fatty acids, minerals and vitamins. A safer alternative to land-based wheat.	Hofmann et al. (2024).
Rice	Seagrasses (seed of *Zostera marina*)	More carbohydrates, iron, sodium, and calcium content. Higher vitamin B_{12} content. Used to make flour for bread and atoles production.	Pérez-Lloréns and Brun (2023)
Livestock	Bivalves (oysters, clams, mussels and scallops)	Filter feeders, high protein, minerals and healthy fat content, do not depend solely on feed input and have massive production capacity.	Costello et al. (2019)
Vegetables	Marine red algae	Contain protein, minerals, and polysaccharides and are used as food colorants.	Dumay et al. (2014)

economic goals of fisheries and aquaculture must adopt sustainable practices to protect and ensure long-term value. The gradual land loss along coastlines from natural processes like wave actions or human activities actually worsens these challenges. In some areas, natural erosion destroys property, interrupts economic activities, and even results in loss of life. Human actions—such as sand mining, land reformation, and building sea barriers, usually cause sediments to be transported along coasts. The changes in river catchments can also cause either an increase or decrease in the natural sediment flow to coastal areas. Global climate change compounds the gravity of these issues further, contributing to the change of wave patterns, rise in sea level, and recurring and severe storm incidents, all of which worsen coastal erosion and its repercussions. It is therefore critically important that the ocean's sustainability and coastal management strategies should be taken seriously to address these challenges.

Another significant aspect to consider is the dynamic nature of water, both in its quantity and its composition and how it interacts with its environment. Anthropogenic activities significantly affect coastal ecosystems causing global climate change, which is closely associated with rising sea levels (Jaagus, 2006; Johansson et al., 2004) and frequent storm events (Alexandersson et al., 1998; Lowe et al., 2001; Masselink & Russell, 2006; Meier et al., 2004; Morton et al., 2005; Suursaar et al., 2006; Tõnisson et al., 2011).

Coastal sedimentation and morphology are directly influenced by marine environments as well as regional landforms, their composition, and human activities such as agriculture, mining and urban development which alter the pattern of precipitation, runoff from both points (municipal and industrial discharge pipes) and nonpoint (agricultural runoff) sources, sea level changes, and storm behavior. These interactions influence the distribution and dynamics of sediments along coastal regions. Additionally, aeolian processes—such as wind-blown dust from deserts in Africa and Asia—can also impact some coastlines complicating further the delicate balance of these ecosystems. Such factors highlight the relationship between natural and human-induced changes in coastal and marine environments.

4. Some developments

Imagine a hypothetical underwater vessel where plants and animals coexist in a symbiotic system. In this system, aquatic plants and animals would live together and mutually benefit from each other. With a bottom layer of mud substrate or organic material, seeds are cultivated, and aquatic animals like fish are introduced into the environment. Plants provide oxygen and food for the animals, while the animals, in turn, provide organic nutrients that fertilize the plants. This concept reflects the principles seen in recirculating aquaculture systems (RAS), which efficiently produce significant amounts of food with minimal water use.

RAS technology is currently being explored to grow plants underwater within fish production systems, indicating initial potential. Integrating crop cultivation with aquatic species offers several benefits: plant roots absorb chemical organic compounds effectively, a large number of microorganisms maintain system health, and no chemicals or pesticides are required. However, scaling this method into a commercially viable model is challenging. Researchers are investigating ways to cultivate fish and plants together on a larger scale without disrupting existing fish production. Underwater farming, by its nature, eliminates the need for pesticides, as pests cannot access the units unless introduced. Each biosphere in such systems is equipped with seedbeds and a 10-m coiled tube. Irrigation water and fertilizers are stored in a tank at the base of the coil and delivered to plants using a pump. All functions are remotely operated from an above-water tower powered by solar panels. These solar panels also power a fan within each biosphere to regulate humidity for the plants. This system is highly water-efficient; seawater inside the units evaporates and condenses to provide fresh water for the plants, and only in the initial planting stage is an external water source needed.

With this approach rooted plants can be cultivated in the sea starting with experiments on crops such as spinach. As progress is made, staple crops such as rice, wheat, and possibly even genetically modified maize. Although it might seem challenging, this vision offers a pathway to combat hunger and sustain many lives. Challenges like ocean pollution, global warming, and other environmental factors could limit its success but it should be noted that it represents a bold step toward sustainable underwater agriculture which could significantly contribute to global food security (Gimba et al., 2024).

5. What can an individual do?

As individuals, we all have a responsibility to use resources wisely and sustainably avoiding wastage and mismanagement. This means that we consciously have to take only what we need and leave the rest for others and future generations. Transformation takes time, but small, deliberate and consistent practice can make a huge difference. Imagine if each person on Earth chose to eat just one spoonful less at every meal—collectively, this result would make a significant amount of food become available for those in need.

There must be a personal effort within, made every day with every meal. It's not about comparing ourselves to others; the fight is solely with our habits and choices. If we cannot actively contribute to cultivating food, the least we can do is prevent waste and conserve what we have. While it may take a while, this shared, mindful approach from individuals around the world has the ability to impact lasting change.

6. Conclusion

The ocean holds significant potential as an alternative food source to tackle the world hunger crisis, especially as the limitations in land-based food production cannot meet the needs of the growing population. The thought of using the ocean as a farming ground to minimize hunger might seem difficult to achieve but taking a step one at a time and being consistent with our actions brings us closer to achieving a sustainable future in marine fisheries and aquaculture. Sea-based foods can be used as an alternative to their land-based counterparts, seaweeds can be used in place of wheat and Fish/bivalves in place of livestock. However, these opportunities also have some challenges in terms of overfishing and overharvesting, ocean pollution, and coastal erosion which should be addressed, and sustainable strategies should be practiced so that we can have a future where everyone can afford or access modest food. SDG 2 is achieved. Still a long way to go, yet one can begin from somewhere.

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Chapter 5

Remote sensing and geographic information system (GIS) in marine bioresources innovations and monitoring

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1. Introduction

As tools for gathering, analyzing, and storing geographic data, geospatial technologies are particularly well-suited to tackle these issues in marine planning (AAAS, 2018). The aforementioned factors facilitate multilevel perception (MSP) and are in line with the goals of natural resource management, conservation, and ecosystem health (Kirkfeldt, 2019). These factors also allow for the identification, gathering, and evaluation of geographic data at various levels. Global positioning systems (GPS), remote sensing (RS), and geographic information systems (GIS) are a few examples of frequently used GTs. The term "remote sensing" describes the process of gathering data and pictures from a distance. This includes not just satellite photos but also scanning tools like sonars that are used to map the seafloor. GPS, a satellite-based geolocation system, allows the public to follow mobile human users and tag mobile marine animals. GIS can be used to make maps and charts and to create, organize, and present data in a way that is spatially referenced. GIS also helps with decision-making, raising awareness of issues connected to marine water quality and developing sustainability with a national focus. Most previous studies on geographical technology solutions have focused on RS (El Mahrad et al., 2020) or a single technology in connection to MSP uses (Lee et al., 2019). Although GTs have previously been employed for planning and particular MSP requirements (González et al., 2020), their use for MSP is where they are lacking. This work aims to show how the innovations of RS and GIS-derived data are useful in the marine ecosystem. The importance of this analysis resides in how GTs explicitly address the demands of ocean managers, planners, and MSP practitioners by highlighting important resources available to them and thereby enhancing scientifically informed ocean use planning. Egypt's Mediterranean coastline is one of the longest in North Africa, spanning over 1050 km from El-Salloum in the west to El-Arish in the east. Even though the Egyptian Mediterranean coast is commercially significant and has witnessed major investments in a number of industries, including marine fisheries, the average annual fish production of this large area was just 60,000 tons (GAFRD, 2000–20). Using specific environmental indicators (Chl-a, SST, and productivity data), satellite RS has been used worldwide to locate and monitor the PFZs, according to a body of literature (Ali et al., 2022).

2. The marine life, resources, and economic value

2.1 GIS and biodiversity/habitat conservation

Marine and coastal resources management needs geography; though often seen as belonging to the biophysical sciences, its management is culturally and politically driven. Part of the methods of used in marine resources management includes centralized approaches (limiting access to oceans through permit, zoning of oceans, and enforcement of limits to catching

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fishes), community-based approaches, and the newly embraced spatial approaches. The later emphasizes ocean space regulation (Levine et al., 2015).

2.2 Geospatial technique and mapping in the marine region

In other to understand spatial pattern of human use, GIS, and mapping cannot be over emphasized. While GIS is used in illustrating spatial patterns in the field, a unique set of challenges is being presented by the mapping of the marine spaces because of its dynamic nature. This map shows the species distribution, the various habitat types, their importance in accessing economic value, and their integration in proper recording and accounting systems (Galparsoro et al., 2014).

The inventory and catchment of wetland/marine resources when conservation and management is being considered is of great importance. This is achievable with the digital maps that help in the aspect of monitoring and quantifying changes over time scale and also in decision-making. Maps preparation procedures starts with the surveying of the ground. This presents topographical maps that show various classes of land use/land cover including the marine/wetlands. Documented important tool for decision-making analyzing, viewing, and characterizing water, land, and component of the atmosphere is RS (Nath et al., 2020). Table 5.1 explains the various platforms, data types, processing software, and the applications of the acquired marine data necessary for monitoring the marine ecosystem.

2.3 GIS in the marine ecosystem

Inclusive in the wetland/marine boundary should be all open water, aquatic vegetation such as submerged, emergent, and floating weeds with satellite images giving an unambiguous mark of the wetland/marine extent. Vegetation presence in this region offers important information on the condition of the tropic (Nath et al., 2020; Okewu et al., 2024).

A host to varieties of habitat is the marine environment and are categorized below

1. Those occurring at the seafloor known as benthic habitats are reinforced by different types of base for example seabed composed of muds and sands, or the ones with firm base seagrass meadows, coral reefs of cold water and sponge aggregation
2. Those associated with water column for example pelagic habitats in the open ocean.

TABLE 5.1 Marine data acquisition plat form, processing software, and uses.

Platform	Data type	Processing software	Application/uses
Satellite/Radiometer (active and passive sensors)	Imageries	Geographic information softwares, oceanography software, Hydrographic software Fishery management software, statistical analysis software	Ocean color monitoring, chlorophyll detection, study carbon cycle, biogeochemical modeling, oil spillage
AUV (autonomous underwater vehicle)	Imageries		Conducts biological and geophysical surveys
Ship MBES (multibeam echo sounder)	Multispectral image and bathymetric chart		High resolution creation of maps of seabed
Echo sounder	Bathymetric charts and maps of seabed		Measure depth of water and the topography of the seabed.
Side scan sonar	Images of the seafloor		Seafloor feature mapping and underwater object detection
Bathymetric LiDAR	High resolution models of the coastal elevation		Water depth measurement and topography of the coast
Global positioning system (GPS)	Surveyed georeferenced data		Provides positioning and location data
Acoustic Doppler current profilers	Data of the direction and velocity of the current		Measures current of the ocean and the level of water
Sediment corers	Samples of sediment		Collection of the samples of the sea floor sediment

Habitat can be shaped primarily by physical processes and geology (geophysical) or by formation caused by living organism (biogenic).

2.4 The economic, social, and environmental benefit

Oceanography includes physical and marine bio-geochemistry and covers about 70% of the surface of the earth, which support the continuous life existence on the planet earth. It serves as source of food, means of transportation, recreation, source of energy, and minerals (Table 5.2). Of great importance also is the ocean to the weather and climatic condition of the earth surface. Some countries of the world depend on marine resources such as fishes to sustain their economy (Okewu et al., 2024). The pelagic habitat gives support to fishes with great commercial importance and also helps in maintaining the ecosystem functions (photosynthesis from phytoplankton).

In 2020, according to BPS (2021), 2.8% gross domestic product of Indonesia was from fishes. A larger and important influence to livelihood, nutritional security, foods, and well-being of many families was from the oceans (Gibson et al., 2020). Its mangrove forest area is the largest worldwide with 18% of the world's total, marine wild-capture fish second largest producer (Tran et al., 2019) and supplies demand for global fishes with about 25% (BKPM, 2018). Indonesia has the only route that connects diverse tropics ocean basin, and its water also play a significant role in the climate and ocean system (Sprintall et al., 2014).

TABLE 5.2 Some countries across the continent with available marine resources.

Continent	Countries	Available marine resources
Asia	Indonesia	Coral reefs, fisheries, seaweed, oil, marine energy
	Philippines	Tuna, fisheries, pearls, marine energy
	Japan	Fish, invertebrates, seaweed and algae, marine energy
	China	Fish shrimp scallops, mussels, seaweed, oil
	India	Fish shrimp, oysters
	Thailand	Fish, invertebrates, seaweed and algae, marine energy
America	United State	Fish, invertebrates, oil, marine energy
	Canada	Fish, invertebrate, oil
	Mexico	Fish, invertebrates, seaweed and algae, marine energy
	Brazil	Fish, invertebrates, seaweed and algae, offshore oil, marine energy
	Chile	Fish, invertebrates, seaweed and algae
Europe	Norway	Fish, invertebrates, marine energy
	United Kingdom	Fish, invertebrates, oil, marine energy
	Spain	Fish, invertebrates, seaweed and algae
	France	Fish, invertebrates, seaweed and algae, marine energy
	Greece	Fish, invertebrates, seaweed and algae
	Denmark	Marine energy
	Netherlands	Marine energy
Africa	South Africa	Fish and invertebrates, marine energy
	Nigeria	Fish, invertebrates, seaweed and algae, oil
	Egypt	Fish, invertebrates, seaweed and algae, oil
	Morocco	Fish, invertebrates, seaweed, and algae
	Kenya	Fish, invertebrates, seaweed, and algae
	Libya	Oil
Australia	Australia	Fish, invertebrates, marine energy

Due to the presence of massive sulfide deposit rich in copper, gold, zinc, silver, and other metals at the seafloor, several attentions have been attracted to it (Hannington et al., 2010). Research has shown that hydrothermal activities on ridges could last longer and thereby leading to a great percentage of accumulation of sea floor sulfide mineralization, this approximates probably for 86% of the massive sulfide resources of the sea floor (Hannington et al., 2011).

As a result of the reduction in the on-land mineral resources, deposits of massive sulfide on the seafloor have the potential of becoming important for development, exploration, and mining as of those on land (Aransiola et al., 2024). Owing tom the difficulty involved in investigating the environment of the ocean and location of the massive seafloor sulfide deposit, it is therefore important to improve efficiency in prospecting by reduction of the exploration search space through mineral prospectivity mapping.

3. Application of remote sensing and geographical information system to marine environment

GIS and RS techniques have developed into sophisticated and indispensable tools for investigating and assessing marine environmental studies. They provide effective means of collecting, analyzing, and visualizing datasets over large areas, also, inaccessible areas where other techniques seem unattainable. RS technique can be classifies as one of the most reliable approach for data collection, particularly in the modern era where it looks impossible to obtain information immediately at real time owing to it complexity. Passive and active RS are the two broad categories into which RS systems can be classified. While most active RS systems (such as microwave systems) measure the reflected microwave signal from various objects on Earth at higher wavelengths when compared to passive systems. Passive RS systems record reflected electromagnetic signals in the visible, near-infrared (NIR), and shortwave infrared (SWIR) bands as well as emitted electromagnetic energy in the thermal infrared (TIR) bands (Amani et al., 2022). In the passive RS, it primarily records solar radiation reflected from the Earth's surface at visible wavelengths in the 400–700 nm, near infrared (NIR) 720–1300 nm, and shortwave infrared (SWIR) 1300–3000 nm portions of the electromagnetic spectrum. The main principle behind optical RS is that distinct objects at different spectral bands will reflect and absorb solar light in different ways. As a result, every object has a distinct spectral behavior, or "spectral reflectance signature," which makes it visible to identify features on the earth surface (Amani et al., 2020).

Active sensors are used in light detection and ranging (LIDAR), synthetic aperture radar (SAR), active radar (RS), and altimeters. These sensors often gather surface data in microwave domains, such as the Ku and C bands (altimetry). These radar-based technologies send microwave pulses to earthly features and capture the values in waveform echo. These waveforms can subsequently be used to detect topographic characteristics and other areas of interest (Abazu et al., 2018; Amani et al., 2022; Baba et al., 2023). LiDAR and satellite altimetry, as reported by LaRocque et al. (2020), are revolutionizing the use of active RS techniques. Particularly in the fields of mapping and other spatial analyses, these technologies make it possible to gather and comprehend subsurface potential and underground surface data in a thorough manner.

GIS are widely used in business, communications, healthcare, and almost every other aspect of life. GIS is now more valuable and dependable in all contexts due to its technology breakthroughs over time. The use of GIS data is growing as businesses realize the value of the information that GIS can offer. According to Srivas and Khot (2018), GIS is a tool for gathering, storing, verifying, and displaying environmental, geographic, and demographic data. This data can be used across range of industries to make well-informed decisions about their operations. GIS and RS technology combined will create a comprehensive tool for study and a problem-solving strategy directly related to the marine environment.

3.1 Ocean monitoring

When it comes to tracking ocean variables like sea surface temperature (SST), turbidity concentration, ocean color, and sea surface height (SSH), RS, and GIS are essential. Scientists can identify changes in marine habitats, thanks to real-time data on ocean conditions provided by modern RS satellites. However, GIS aids in the integration and analysis of these data, assisting in the tracking of pollution sources, sea level rise (SLR), and oceanic currents in addition to monitoring natural disasters such as hurricanes and tsunamis. For instance, sea surface height (SSH) data can be retrieved using the altimetry technique, which can be used to monitor the marine environment by modeling SLR as it affects the coastal ecosystem over time. GIS platforms allow the spatial analysis of the obtained data SSH to assess the impact level over time and recommend more effective mitigation strategies.

3.2 Bathymetric survey

Shipboard echo sounding has been the standard method used to chart bathymetry. While this technology can produce precise depth readings at specific locations or along transects, its limitations include high operational costs, inefficiency, and in applicability to shallow seas.

RS techniques, on the other hand, provide a more adaptable, successful, and economical way to map bathymetry over large areas (Saida et al., 2017). Bathymetric survey is use to estimate the topography map of the sea floor. Fig. 5.1 depicts typical optical satellite streaming pulse signal for ocean depth estimation.

To produce intricate maps of the seafloor, RS techniques like LiDAR and satellite-derived bathymetry are frequently integrated with GIS tools. The integration of high-resolution satellite imagery and LiDAR data with a GIS framework enables the creation of three-dimensional seafloor models, which are useful for predicting sediment transportation and ocean current behavior as well as facilitating safe navigation.

The depth estimation's accuracy depends on a few different variables. Starting with the data collection phase, the image dataset's resolution and the model used to process the data and also, the model used in processing in GIS platform.

3.3 Sea floor habitat

Seafloor habitats, such as coral reefs, seagrass beds, and mangrove ecosystems, can be mapped with the use of RS data collecting methods, high-resolution image data (hyperspectral and multispectral imaging), and GIS tools. GIS spatial analytic platform, acoustic tools like sonar and video surveillance offer full information on the kind, traits, distribution, and condition of these sea floor ecosystems. It provides adequate information about the structure and makeup of the reef. It also allows for the monitoring of the biophysical parameters of the seas and oceans where the reefs are found and facilitates the detection of changes in these parameters over time. RS is a highly useful tool for coral reef monitoring.

FIGURE 5.1 Optical remote sensing, light detection and ranging (LIDAR) and unmanned aerial vehicle (UAV) equipment use for depth data acquisition beneath the earth surface.

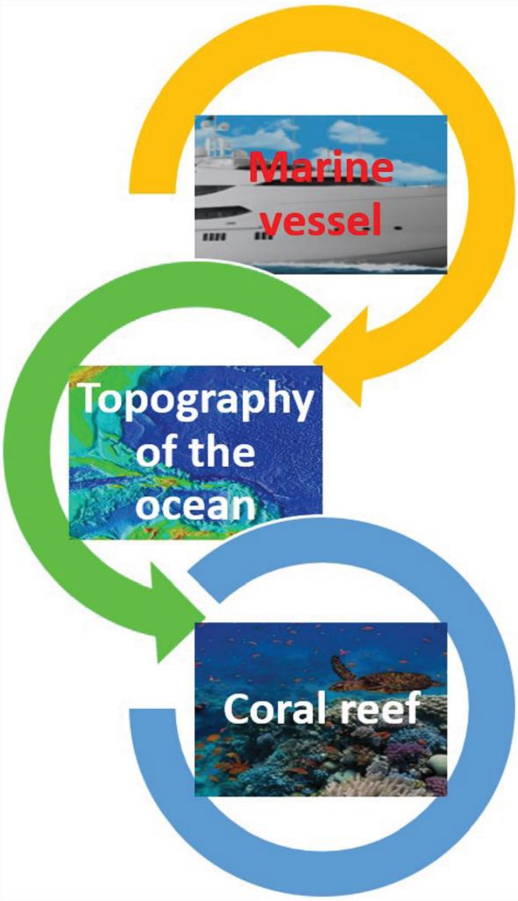

FIGURE 5.2 The use of remote sensing technique and onboard vessel in determining seafloor topography and coral reef and seagrass mapping using high resolution satellite data.

Along with other environmental data, this RS derived data are integrated into a GIS. In order to enable integrated coastal zone management (ICZM), the GIS is utilized to create an inventory of all available data as well as a tool for spatial analysis of that data (Goossens & Ghabour, 2005). Fig. 5.2 shows remotely sensed approach of streaming information about seafloor ecosystem.

Using sonar and high-resolution satellite image data in a GIS framework to assess coral reef area and damage as a result of climate change or human activity, protected marine areas are managed in part using these maps.

3.4 Fisheries management

RS and GIS are valuable for managing fisheries by tracking fish populations, monitoring their migration patterns, and assessing the health of aquatic ecosystems. RS technique can detect changes in water temperature, salinity, and phytoplankton concentrations and by extension the health condition of fish, which affect fish distribution and breeding cycles. According to Meaden and Corocci (2009), the problems facing fisheries and fish production in the world can best be viewed as state of instability in the spatial domain. However, the capacity to provide outputs from fisheries activities at an optimum level is dependent upon the variable factors controlling this output to be imbalance state. This has greatly influenced the output of its production. The used of hyperspectral image resolution data have made this task more visible and achievable. Wide fisheries at depth of about 20 m beneath water surface can be monitored efficiently from remotely areas (Tim et al., 2014). The use of GIS tools has giving more flexibility to the analyses of it ecosystem. The combination of both techniques will richly impact the fisheries production and effectively manage it ecosystem.

3.5 Climate change impact assessment

Understanding how climate change influenced the oceans depends heavily on RS and GIS. The entire globe is really concerned about climate change. The RS approach can be used to offer reliable data for tracking the effects of climate change in a global scale. Compared to other methods of gathering data, this method offers excellent precision coverage across a wide region. Satellite data from RS can be used to track climate change scenarios such rising sea levels, anomalies in temperature, and precipitation patterns. The spatial modeling of climatic scenarios and the display of their effects on human communities, coastal zones, and marine biodiversity are made possible by GIS. For instance, Remote satellite data on SLR and SST can be analyzed within a GIS framework helps develop model for monitoring coastal inundation and also predict future impacts on coastal infrastructure, biodiversity loss, and fisheries.

Using GIS and remotely sensed approaches together creates a platform that is valuable for controlling, charting, and monitoring marine habitats. By providing methods for preserving marine ecosystems, managing resources responsibly, and addressing the effects of climate change, these tools help scientists and decision-makers better understand the intricate and dynamic characteristics of the ocean.

4. Future perspectives and emerging technology of remote sensing in the marine environment

The marine environment, covering over 70% of the Earth's surface, is vital for regulating climate, supporting biodiversity, and sustaining human livelihoods. However, the pressing challenges of climate change, flooding, and overexploitation of marine resources require more accurate, timely, and comprehensive monitoring approach. RS technology has become a pivot in oceanographic research, where acquiring data about the Earth's surface and atmosphere can be achieve with high accuracy. Satellite-based sensors have advanced significantly over time, evolving from basic radiometers to sophisticated multispectral, hyperspectral, and radar sensors. Recently, emerging technologies such as artificial intelligence (AI), machine learning (ML) algorithm, and big data analytics are transforming the field, providing unprecedented and comprehensive capabilities for monitoring the marine environment.

4.1 Advances in remote sensing technologies

4.1.1 Synthetic aperture radar

SAR is another powerful technique in the active RS. SAR operates in the microwave spectrum, making it capable of collecting data regardless of the atmospheric condition of the study area. This is particularly important for marine applications, where cloud coverage is high, and monitoring must be continuous. SAR has proven highly effective in monitoring oil spills, sea level rise, and the dynamics characteristics of coastal zones. The European Space Agency's Sentinel-1 mission, equipped with SAR, is an example of the increasing reliance on radar data for marine applications. Fig. 5.3 depicts SAR satellite navigating at it orbit.

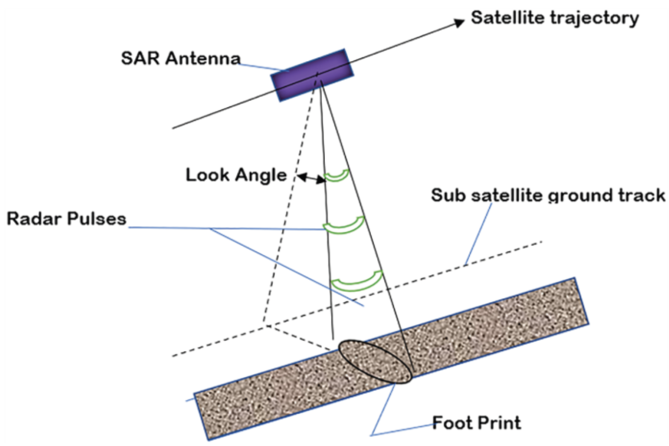

FIGURE 5.3 SAR satellite as it navigate in orbit, radar sends pulses signal to the target. The reflected signals returns to the radar where it is recorded as a function of time, range and, in the azimuth direction.

SAR's future advancements include higher-resolution imaging and polarimetric technology for enhanced surface feature capture. This technology could lead to better tracking of illegal anthropogenic activities such as fishing, mining, and more accurate monitoring of flooding activities and improved assessments of coastal erosion, all of which are vital for marine management and policy making.

4.1.2 High revolution image dataset

Hyperspectral imaging data are among the most advanced technological developments in RS. Unlike the conventional multispectral sensors that can only identify materials and processes with a limited level of detail since they only record data in a few wide spectral bands. Contrarily, hyperspectral sensors record information over hundreds of continuous spectral bands, enabling fine-scale distinction between various ocean characteristics with high level of clarity. Hyperspectral RS can be used to monitor coral reef and fish's health with high reliable result and also, detect changes in water quality and its characteristics in marine applications (Behrenfeld et al., 2020).

Additionally, oil spills and other contaminants can be detected with hyperspectral imaging, which provides vital information for environmental management. The high spectral resolution properties make it possible to monitor the biochemical characteristics of marine organisms, which could revolutionize the study of marine ecosystem health.

4.1.2.1 Miniaturized nanosatellite constellations

One of the most exciting developments in RS technology is the rise of small satellite constellations, particularly CubeSat. CubeSats are miniature satellites, typically less than 10 kg in weight that can be deployed in large numbers to provide frequent, high-resolution coverage of the Earth's surface. These satellites offer several advantages for marine RS, including lower costs of production, faster and less deployment times, and the ability to cover areas that are difficult to monitor with the conventional satellites (Sandau, 2010). One of the key advantages of CubeSats is their ability to provide high temporal resolution compared with the conventional satellites that require more time interval between successive satellite observations of the same location on earth. CubeSat constellations can offer near-continuous coverage, making them ideal for monitoring dynamic marine processes such as tides, ocean currents, and sea ice movements.

In the future, we can expect to see more specialized CubeSat missions focused on marine applications. These could include dedicated satellites for tracking illegal fishing, monitoring coral reef health, or assessing the impacts of ocean acidification. The combination of CubeSats with AI-driven analytics will enable near-real-time decision-making, offering unprecedented capabilities for managing the marine environment.

4.1.3 Enhancing data accuracy and resolution

Satellite-based RS offers a broad view of the marine environment; it often deficient in accuracy needed for certain applications. This is where in-situ sensors, deployed in the ocean itself, come into play. Autonomous underwater vehicles (AUVs), buoys, and drones equipped with sensors can provide high-resolution data on parameters such as temperature, salinity, and nutrient levels. By combining satellite data with in-situ measurements, researchers can achieve a more comprehensive and accurate understanding of marine processes.

4.2 Integration of artificial intelligence and machine learning

4.2.1 Automating data analysis

The vast amount of data generated by modern satellite missions requires advanced analytical tools for effective processing and interpretation. This is where AI and ML come into play. ML algorithms can process massive datasets, identifying patterns and anomalies that would be difficult or impossible for humans to detect (GoodFellow et al., 2016; Mitchell, 2017). In marine RS, ML is already being used to classify water quality, sea level, and track ocean wave pattern over time (Peng et al., 2018). The future perspectives in this area is the development of fully automated systems for real-time in monitoring marine environment. The algorithms are trained to automatically detect oil spills or sea level rise, triggering alerts to relevant authorities. This would drastically reduce response times and allow for more effective mitigation of environmental disasters. Additionally, AI can be used to enhance data simulation, combining information from multiple sources (e.g., satellites, drones, and in-situ sensors) to provide a more comprehensive situation of the marine environment and a better way of mitigation.

4.2.2 Predictive modeling and forecasting

Another exciting application of AI in marine RS is the development of predictive models. By analyzing historical satellite image to extract climate data, alongside real-time observations, ML algorithms can predict future ocean conditions. AI poses more advantage when compared to other parametric models for prediction. The training of the dataset gives the model an edge to comprehend the pattern of the features to be used. This is particularly useful for forecasting sea level rise, extreme weather events such as hurricanes, and changes in ocean currents that could impact global climate systems (Pauly & Christensen, 2020). These predictive models can be crucial for disaster preparedness and marine resource management, offering governments and organizations the ability to act proactively rather than reactively.

4.3 Big data and cloud computing in marine remote sensing

4.3.1 Data volume and storage challenges

Cloud computing platforms such as Google Earth Engine and Amazon Web Services (AWS) are increasingly being used to store, process, and analyze large-scale RS data. This is because it allows large data manipulations and facilitates flexible analyses. These platforms allow researchers and policymakers to access real-time data, perform complex analyses, and share results more efficiently. With the advent of high-resolution satellites and sensors, the volume of data being generated is growing geometrically. The conventional methods of storing and processing such are becoming obsolete and time consuming. The coverage of marine environment using satellite RS requires a large space for data collection and processing. Clouding computing approach has provided more improved ways of managing volume of data for the monitoring of marine environment.

4.3.2 Data sharing and collaboration

The future of marine RS lies in the collaboration between different players in marine industry. The stakeholders, include governments, research institutions, and private companies. Big data platforms allow for the sharing of satellite imagery and derived products across borders and disciplines. This data-shared will facilitate collaboration on a global scale, enabling coordinated efforts to tackle issues such as climate change, marine pollution, and oceanic ecosystem (Liu et al., 2019).

5. Conclusion

The future of RS in the marine environment is promising. With emerging technologies, it provides better and convenient ways on how to monitor and manage oceanic ecosystems. Hyperspectral imaging, SAR, AI and ML, big data, and CubeSats, are all set to play important roles in the next generation of marine RS systems. These technologies will enable more precise, real-time, and predictive monitoring of the marine environment, helping governments, organizations, and researchers tackle the pressing challenges of climate change related challenges and biodiversity. As these technologies continue to advance, they will provide the tools necessary for more sustainable and effective management of the world's oceans, ensuring their health for future generations.

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