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MINI REVIEW

The Interactions of Emergent Contaminants (ECs) with Soil Microbiome

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Abstract

Emerging contaminants (ECs) in the environment pose a substantial worldwide problem. The pollution owing to these pollutants requires rigorous research due to their harmful impact on soil microbes, flora, fauna, and human health. This category contains a varied array of substances, including medications, personal care items, industrial chemicals, and microplastics. Such pollutants pose severe hazards to ecosystem integrity and biodiversity. Emerging pollutants largely come from anthropogenic activity, including industrial operations, and their abundance dramatically alters soil ecosystems. Therefore, this review highlights the interactions of emerging contaminants with soil microbiome. Soil microbial communities are crucial to nutrient cycling and the preservation of soil health. The entry of new pollutants into soil ecosystems affects these microbial communities, altering their ecological activities and undermining overall soil health. These pollutants engage with soil microbes through multiple methods, resulting in modifications in the diversity of soil microbiota and eventually influencing plant survival and performance. The issue of contamination by emerging toxins is particularly acute in urban contexts, where industrial operations and inefficient waste management techniques lead to increased concentrations in the ecosystem. This pollution impacts the composition and quantity of soil microorganisms, alters their genetic traits, and affects their functional activities. The exposure to new pollutants disrupts ecological balance and poses significant health risks to humans. This analysis elucidates the interactions between developing pollutants and soil microorganisms, stressing the significance for soil ecosystem processes and offering options for mitigation to encourage a healthy environment.

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Graphical Abstract

Highlights

- ECs originate primarily from human activities, which include industrial operations.
- Soil microbial communities are significantly impacted by ECs.
- Increased contamination alters the composition and genetic traits of soil microbiota.
- Soil health disruption compromises the vital ecosystem services like nutrients cycling.
- The study of EC-microorganism interactions is crucial for environmental health.

Keywords Emerging contaminants · Soil microbes · Microplastics · Industrial chemicals · Pharmaceuticals

Introduction

Emerging contaminants are compounds that have lately been recognized as environmental pollutants, generally coming from industrial, agricultural, and pharmaceutical operations (Calvo-Flores et al. 2018; Chahal et al. 2023). This categorization comprises medications, personal care items, and several industrial chemicals that often remain beyond the reach of normal environmental surveillance (Patel et al. 2020). Additionally, they encompass micro/nanoplastics, polyfluoroalkyl substances (PFAS), heavy metals, and polychlorinated biphenyls (PCBs). (Chahal et al. 2023). The presence of these pollutants poses major threats to soil health and microbial communities, potentially leading to modifications in nutrient cycling, pathogen dynamics, and the general viability of ecosystems (Nwankwo et al. 2025).

The rising frequency of new pollutants in the environment causes considerable problems for soil integrity and the various microbial communities it supports (Maddela et al. 2022). The spread of these contaminants may disturb the population of soil bacteria, leading to detrimental effects for ecosystem processes and agricultural output. These pollutants interact with soil microbial communities by affecting both their composition and function (Nwankwo et al. 2025). Their presence can limit microbial development, diminish biodiversity, and interfere with critical biogeochemical processes, consequently compromising soil health and fertility (Ojija 2024). Furthermore, xenobiotic chemicals originating from pesticides, herbicides, antibiotics, and fertilizers contribute to soil deterioration and compromise agricultural sustainability. The pollution of soil due to these compounds adversely influences plant nutrition and the variety of beneficial microorganisms within the soil matrix (Chahal et al. 2023). Consequently, less nutrient cycling occurs, resulting in lower soil fertility and impaired interactions between plants and the soil environment.

It is vital to understand that polluted soil influences more than agricultural operations; it also impairs water supplies and heightens threats to both biodiversity and human health (Okeke et al. 2023; Puri et al. 2023). Contemporary pollutants are entering terrestrial and sedimentary settings, consequently worsening environmental concerns (Chahal et al. 2023). While nanomaterials like metal nanoparticles (AgNPs and Titanium Dioxide (TiO_2) nanoparticles) are commonly employed in environmental cleanup, their introduction into ecosystems poses considerable risks to microorganisms, perhaps leading to mortality or harm, alongside modifications to their genetic structures (Wang et al. 2024). The unique physicochemical properties that make nanoparticles valuable (their small size, high surface area, and reactivity) also enable them to penetrate biological barriers, accumulate in organisms, and cause toxicity through mechanisms distinct from their bulk counterparts. The massive manufacture of plastic items has resulted in the pervasive presence of microplastics throughout soils, aquatic systems, and several other habitats (Kane et al. 2020). Practices such as irrigation, fertilization, the application of sludge, and atmospheric deposition have made soil a significant store for pollutants (Ling et al. 2022). Research demonstrates that irrigation with treated wastewater substantially increases soil microplastic contamination and introduces heavy metals, personal care products, pharmaceuticals, and persistent organic pollutants into the soil. Microbial communities are crucial to biogeochemical cycles within the soil, and the introduction of new pollutants can dramatically affect the makeup of these communities, consequently altering many soil parameters (Du et al. 2022). Li et al. (2022) argue that the levels of soil enzymes and the nitrification process are mostly determined by the bacterial composition and abundance, whereas diversity is primarily shaped by the availability of nitrogen and phosphorus in the soil. This review attempts to study the connections between developing pollutants and soil microorganisms.

The significance and relevance of bacteria present in soil ecosystems

Soil conditions are prone to ongoing modification. Humus, which includes a number of vital nutrients and chemicals, plays a crucial function in promoting a broad array of microorganisms inside the soil (Fagunwa and Olanbiwoninu 2020). The rhizosphere is inhabited by several species of soil microorganisms, including archeae, bacteria, fungi, viruses, cyanobacteria and protozoa (Jabborova et al. 2021). These microorganisms engage in numerous roles, such as digesting contaminants, preserving soil health, and allowing nutrient transfer to plants. The rhizosphere refers to the soil layer proximal to plant roots, wherein the qualities of the soil are affected by root activity. The maintenance of different biological forms and ecosystems is substantially dependent on microbial diversity. The synergistic interactions between plants and microbes are vital for ecosystem functionality (Okeke et al. 2023). Roots anchor plants into the substrate, permitting the uptake of water and ions, while also functioning as reservoirs for nutrients; additionally, they engage with a wide variety of soil microbes (Fagunwa and Olanbiwoninu 2020). Certain soil bacteria create relationships with roots by dwelling within them or in their proximity, and these interactions can be helpful, neutral, or accidental (Jabborova et al. 2021). Symbiotic interactions are represented by the partnerships between diazotrophic bacteria and legumes, as well as with mycorrhizal fungi.

Soil microorganisms and root systems have a vital role in affecting plant development and metabolic activities (Okeke et al. 2023). In 1904, Lorenz Hiltner invented the word rhizosphere, defining it as the habitat of bacteriorhiza, which is crucial for plant nutrition (Khan et al., 2022). Hiltner's findings reveal a link between a powerful plant immune response and the structural properties of the rhizosphere microbiome. The rhizosphere is characterized by a larger density of bacterial populations, a greater diversity of bacterial species, and heightened microbial activity compared to the bulk soil (Jabborova et al. 2021). Root exudates, composed of various compounds, promote beneficial bacteria development and plant health. Plant species secrete these substances from their roots, modifying soil biochemistry and creating a conducive environment for the growth of beneficial bacteria that improve plant health. These substances include carbohydrates, amino acids, organic acids, and essential nutrients, supporting microbial populations in the rhizosphere (Fagunwa and Olanbiwoninu 2020; Okeke et al. 2023; Wang et al. 2024).

Scientific literature in the field of emerging contaminants in soil and on soil microbiome is shown in Fig. 1. Scholarly agreement shows that three basic passive mechanisms, which are diffusion, ion channel transport, and vesicular transport, are important to the production of chemicals by plant roots. Diffusion enhances the movement of tiny neutral and polar molecules through lipid membranes into the cells (Khan et al., 2022). The translocation of carbohydrates, amino acids, and carboxylate anions across the membrane is mediated by proteins, happening in response to the electrochemical gradient generated across the membranes of root cells. Various plant species, their genetic makeup, and the features of root exudates have a crucial role in regulating the growth of rhizospheric bacteria (Ling et al. 2022). Root exudates selectively promote certain rhizospheric microorganisms; for instance, citric acid exuded by cucumber roots attracts *Bacillus amyloliquefaciens*, whereas fumaric acid from banana roots attracts Bacillus subtilis, resulting in

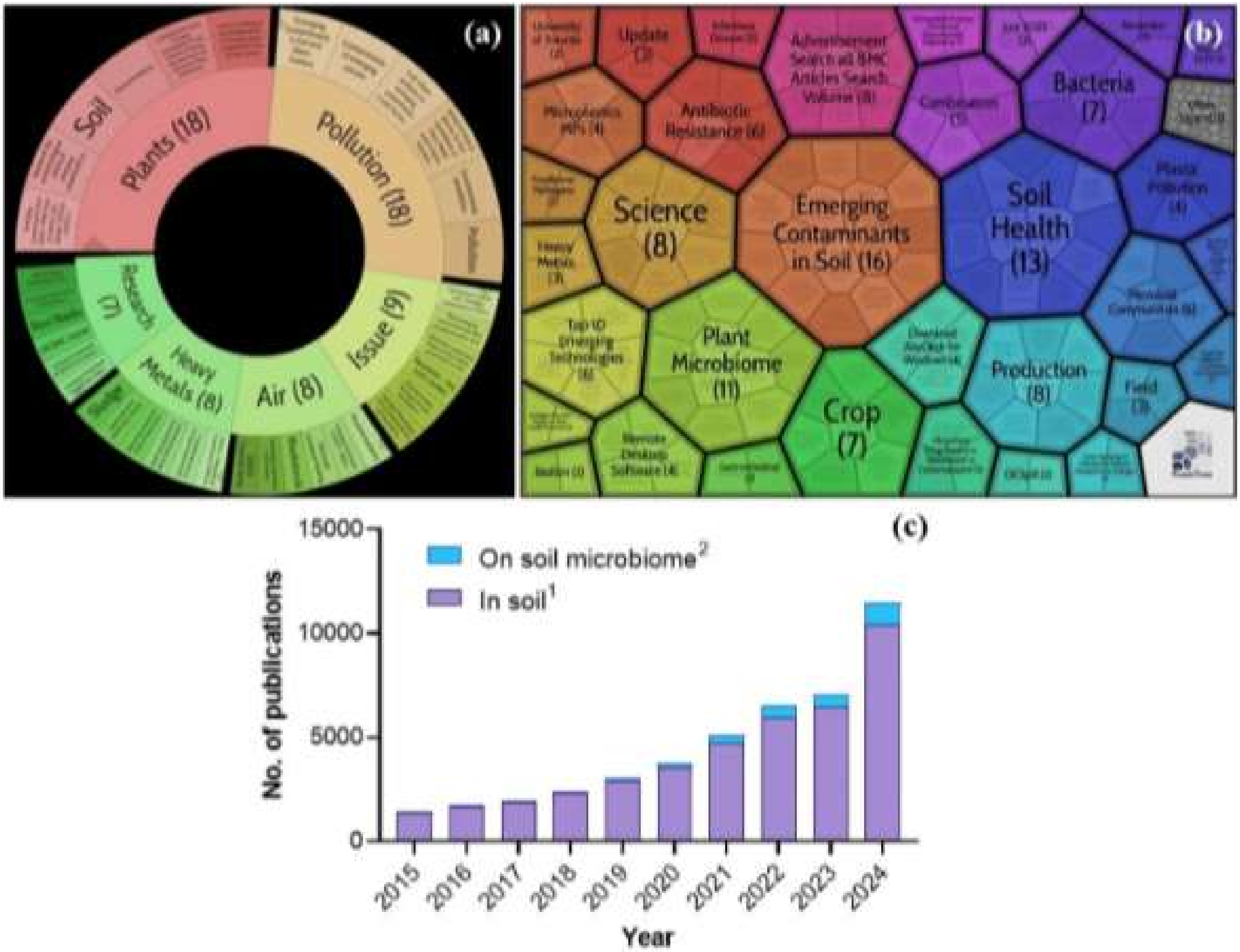

Fig. 1 Scientific literature in the field of emerging contaminants in soil and on soil microbiome. Web search results clustered using Carrot[2]'s Lingo algorithm clustered (https://search.carrot2.org/#/search/web) using key words (a) emerging contaminants in soil (pie-chart), (b) emerging contaminants soil microbiome (treemap); (c) Stacked bar diagram shows number of publications, data collected from ScienceDirect (https://www.sciencedirect.com/) using keywords: [1]Emerging contaminants in soil, [2]Emerging contaminants soil microbiome

biofilm formation on the roots (Jabborova et al. 2021). The possible benefits provided by endophytes and aboveground microbiota include greater crop resistance against pathogens, decreased stress, and improved growth performance. There is a rising trend toward harnessing beneficial bacteria in place of artificial fertilizers and synthetic pesticides for crop development. The administration of microbial inoculants to seeds, which create symbiotic interactions within the root system, constitutes a praiseworthy agricultural technique for disease mitigation (Ling et al. 2022). Furthermore, microorganisms can ameliorate nutrient shortage stress in plants by boosting antioxidant activity and decreasing the buildup of damaging reactive oxygen species (ROS) (Wang et al. 2024). Predominantly, soil bacteria play a vital role in relieving the harmful impacts of water shortage on plants by boosting nutrient availability, changing soil structure, creating protective chemicals, and encouraging disease resistance in plants (Wang et al. 2024).

Sources and kinds of emerging contaminants in the agricultural sector

Emerging pollutants occur from numerous sources connected with anthropogenic activities, industrial discharges, agricultural techniques, and urban runoff, resulting in the introduction of complicated chemical combinations into ecosystems. If improperly managed, these pollutants pose threats to soil microbiota, agricultural lands, soil integrity, and ultimately, human and environmental health (Okeke et al. 2023).

Pesticides, herbicides, and fungicides are important contributions to soil pollution (Aralappanavar et al. 2024a, b). Although vital for agricultural production, the persistence of pesticides in the environment leads to their accumulation in soil and water, potentially threatening species and changing ecological conditions (Fan et al. 2022). Improper fertilizer application may result in nutrient leaking into aquatic systems, producing eutrophication and rising nitrous oxide emissions, which negatively influence the environment as a greenhouse gas. Furthermore, many fertilizers include trace quantities of pollutants such as heavy metals, which can accumulate in soil, consequently affecting soil health and food safety (Jomova et al., 2025). The employment of treated wastewater and sewage sludge in agricultural operations allows the entrance of medicines, personal care items, and household chemicals into the environment (Fan et al. 2022). While nutrient and water conservation measures are useful for agriculture, they may accidentally increase the possibility of undesired biological agents in the soil, eventually disturbing the growth and stability of both microbial communities and surrounding plant life.

Moreover, industrial emissions from manufacturing and mining, along with numerous other activities, disperse heavy metals, polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (POPs) into the environment (Jomova et al., 2025). Additionally, the application of nanomaterials in agricultural techniques introduces nanoparticles that concentrate inside the soil, consequently altering soil properties and the activities of soil organisms (Rashid et al. 2023). The consequences of climate change contribute to pollution, since flood events transfer toxins into agricultural areas, while drought circumstances enhance their concentrations within the soil (Aralappanavar et al. 2024a, b). Rainfall runoff over urbanized surfaces further contaminates nearby land with metals, PAHs, and different chemical compounds (Aralappanavar et al. 2024a, b).

Microplastics, coming from irrigation techniques, agricultural inputs, and organic components, are more abundant in soils, compromising soil quality and structure while also allowing the transfer of additional pollutants (Fan et al. 2022). Global trade and different farming practices facilitate the transmission of contaminants over wide distances. Even when a pesticide is outlawed in one jurisdiction, it may still be applied in other places and then reintroduced into the previous area through imported commodities (Rashid et al. 2023). The transition of certain pollutants into metabolites during degradation might cause dangers that differ from, or at times surpass, those associated with the original chemicals (Aralappanavar et al. 2024a, b). This activity contributes to the formation of pollutants inside the soil.

Numerous studies have indicated that different pharmaceuticals can accumulate in soil and plants owing to the discharge of treated wastewater and sludge from waste management facilities (Okoye et al. 2022). A more immediate worry includes pesticides, which have the potential to travel up to 300 m from their application locations. A fundamental problem resides in the enormous gap between the discovery of pollutants and the complete evaluation of their environmental consequences. Currently, ecotoxicity studies play an increasingly essential role in determining the impacts of pollutants on soil biota. Recent studies indicate that 90% of soil samples and 54% of earthworm specimens evaluated contained different pesticides. In addition to polychlorinated biphenyls (PCBs), per- and polyfluoroalkyl substances (PFAS) comprise a group of industrial chemicals regularly identified in soil, with their prevalence ascribed to manufacturing discharges and the breakdown of legacy PFAS compounds. Research reveals that the breakdown of fluorotelomer-based polymers is connected with the worldwide degradation of PFAS. This highlights the widespread presence of new pollutants, indicating a need for the development of effective mitigation techniques. To identify the features of developing pollutants, they are often divided into medicines, agricultural chemicals, and industrial by-products (Khan et al., 2022). The origins of these environmental pollutants are depicted in Fig. 2.

Pharmaceuticals

A considerable proportion of agricultural soils is damaged by the presence of pharmaceuticals, including antibiotics and hormones, which permeate these settings through treated wastewater, biosolids, and animal dung. Rashid et al. (2023) found that biosolids applied in agricultural techniques included several medications, with triclocarban exhibiting the highest quantity reported at 23 μg/g. Certain medications survive in the soil long after others have undergone degradation; for instance, carbamazepine demonstrates high longevity in the soil matrix, whereas oxytetracycline ranks as the second most durable antibiotic (Okoye et al. 2022). The administration of antibiotics within pharmaceutical practices promotes modifications in the variety and functional capacity of soil microorganisms (Singh et al. 2023). This disturbance severely impacts essential processes, including nitrogen fixation, phosphorus solubilization, and the decomposition of organic materials. Notably, tetracycline is noted for its inhibitory effects on nitrogen-fixing bacteria, thereby lowering the nitrogen available to plants. Furthermore, the antibiotics sulfamethoxazole and tetracycline limit soil urease activity, hence slowing the breakdown and recycling of organic molecules.

Antibiotics applied in medicine generate variations in the variety and functioning of soil microbes, thereby altering processes such as nitrogen fixation, phosphorus availability, and the breakdown of organic matter (Shahane and Shivay 2021). The administration of tetracycline to soil microorganisms has been reported to limit the activity of

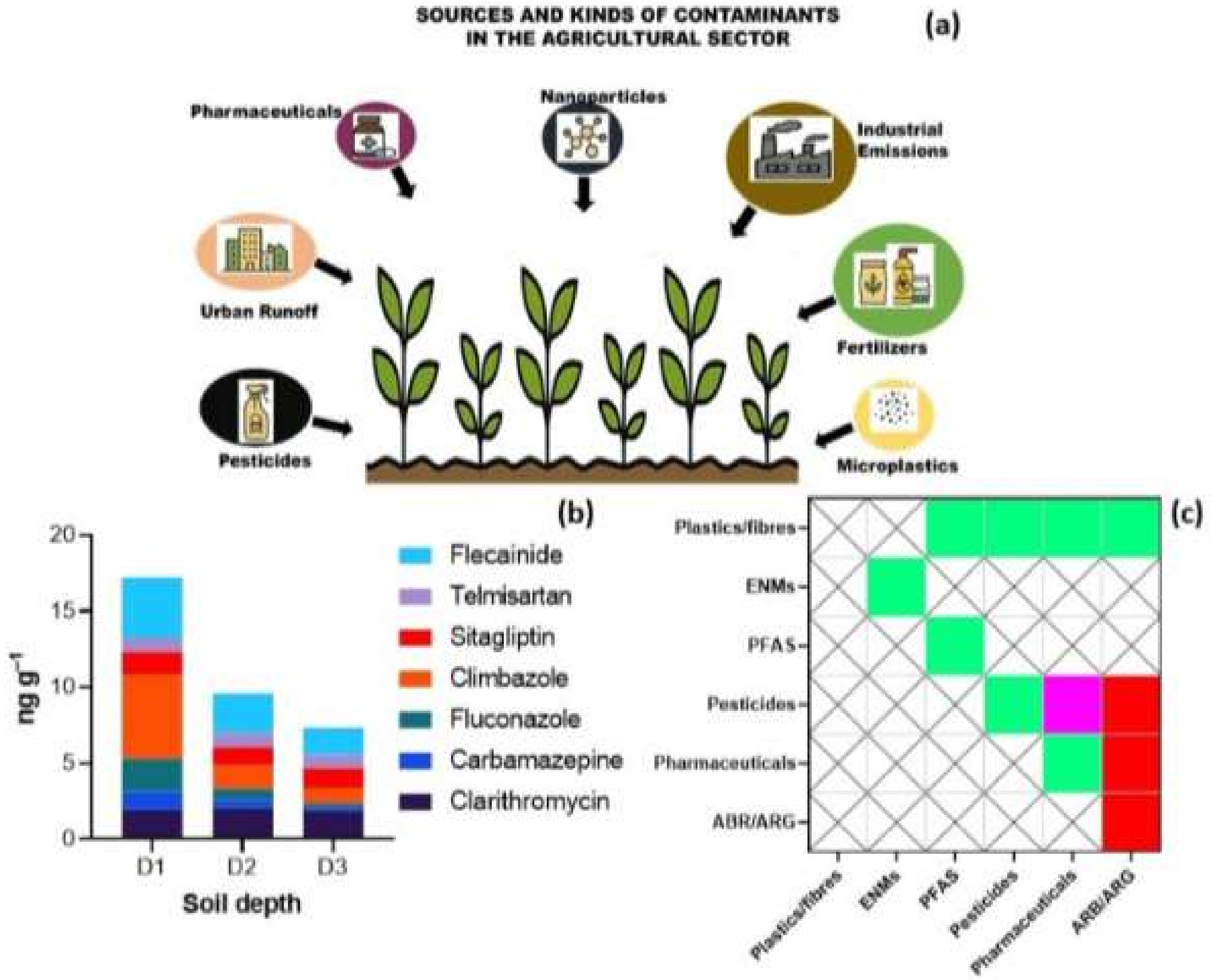

Fig. 2 Emerging contaminants in agricultural soils – (**a**) Sources of contaminants in the in agroecosystem, (**b**) Concentrations of different emerging contaminants in agricultural soils at different soil depths, such as D1, 0.0–0.30 m; D2, 0.30–0.60 m and D 3, 0.60–0.90 m (data from Gatta et al. 2025), and (**c**) Existing evidence of co-contaminant interactions - Green: limited data to support potential for contaminant interactions, Pink: existing data demonstrates contaminant interactions in the environment, and Red: existing data demonstrates contaminant interactions and implications for human health (data from Carter et al. 2025)

nitrogen-fixing bacteria, potentially leading to a lower availability of nitrogen for plant uptake. Furthermore, studies show that antibiotics such as sulfamethoxazole and tetracycline decrease the enzymatic activity of urease, hence lowering the rate of organic matter breakdown within the soil matrix. Pharmaceuticals can also change the chemical characteristics of soil. Research indicated that the administration of carbamazepine, diclofenac, fluoxetine, orlistat to earthworms (*Eisenia fetida*) resulted in modifications in both soil pH and the pH within the earthworms, which might have ramifications for other soil-dwelling creatures.

Additionally, some substances ingested by plants may translocate to other aerial components, including stems, leaves, and flowers, potentially leading to bioaccumulation along the food chain. Various studies imply that leafy vegetables, such as lettuce and spinach, may absorb pharmaceutical residues. In experiments using radish (*Raphanus sativus*) and ryegrass (*Lolium perenne*), researchers found five medicines inside plant tissues, with carbamazepine having the highest quantities of 52 µg/g in radish and 33 µg/g in ryegrass. Nonetheless, the level of absorption is dependent upon both the plant species and the exact chemical contents of the medications. The research also found that sulfamethazine concentrations remained below the detection limit of <0.01 µg/g (Earl et al. 2024).

The presence of medicines in agricultural soil creates considerable concerns for health and food security (Okoye et al. 2022). Specifically, the extended detection of substances such as carbamazepine and oxytetracycline shows chronic contamination. These compounds impair critical soil processes by reducing beneficial bacterial populations responsible for nitrogen fixation and by lowering enzyme activity, hence underlining their harmful influence on soil fertility. The potential for bioaccumulation in crops poses concerns to human health upon ingestion. Moreover, the impacts of fertilizers on soil pH and the survival of earthworm populations show that these agents may affect the larger ecosystem. Given the increasing usage of biosolids and wastewater in agricultural techniques, it is vital to investigate the consequences of medicines on soil health.

Pesticides

While pesticides, which include herbicides, fungicides, and insecticides, play an important role in contemporary agriculture, excessive application can adversely influence soil health and alter the connections among plants, microorganisms, and soil. Reports from the European Union reveal that around 83% of topsoil samples include pesticide residues, with over half exhibiting residues of various pesticide kinds. This ubiquitous soil pollution poses dangers to non-target creatures. For instance, organophosphate pesticides can kill earthworms, which are necessary for the breakdown of organic matter and soil aeration, consequently reducing soil vitality and lowering the chances for plant development (Mishra et al., 2022). Among the different pesticide combinations observed in EU soils, glyphosate and its metabolite AMPA were the most widespread, identified in 25% of the samples, demonstrating their prolonged persistence in the environment (EEA, 2023).

Studies have indicated that pesticide levels on organic farms are much lower than those seen on conventional farms (EEA, 2023). Moreover, pesticides can affect the chemical composition of root exudates, which are critical for nutrient uptake and microbial interactions. Glyphosate, in particular, impairs plants' potential to recruit mycorrhizal fungi and rhizobacteria by reducing root exudate production (Bueno de Mesquita et al., 2023). Residual pesticide residues have also been identified in bees, nectar, and pollen, potentially altering the symbiotic interactions between plants and soil microbes. Furthermore, pesticides demonstrate a tendency to stay in the soil, adding to persistent pollution. Ethoprophos was discovered in the topsoil at 16 of the 20 locations tested in dry areas, which were present in all 15 subsurface samples, demonstrating its lengthy retention within the soil matrix (Faraj et al. 2024).

Residues from pesticides can impede plant development by interrupting important cellular activities and restricting nutrient absorption, which may particularly damage delicate species. Moreover, the transport of pesticides into groundwater or their incorporation into deeper soil layers through precipitation and irrigation greatly heightens the danger of groundwater pollution (Faraj et al. 2024). Pesticides offer multiple difficulties to soil health and the long-term profitability of agricultural systems. The finding of pesticide residues in 83% of topsoil samples across Europe, as reported by EU study, shows the vast contamination of agricultural land by these compounds. Furthermore, 25% of soil samples suggested that these pollutants have severe long-term consequences on soil ecosystems (Froger et al. 2023). Pesticides can accidentally alter soil biota, including earthworms and numerous mycorrhizal fungi, which are vital for stimulating plant development. Consequently, this disturbance can lead to lower root exudation, poor nutrient absorption, and consequently reduced crop yields.

Additionally, non-target species, such as bees, and floral components, including nectar and pollen, typically display pesticide residues, underlining the substantial ecological repercussions and implications for pollination processes. The transfer of pesticides into groundwater poses serious environmental and public health problems (Earl et al. 2024). As the demand for agricultural production and livestock management rises in a quest to promote population sustainability and environmental stewardship, it is vital to seek alternate pest management options that eschew chemical treatments. The major focus should be on establishing integrated pest management, biological control techniques, and applying less persistent pesticides that are beneficial to soil health, ecological integrity, and the sustainability of future agricultural production (Earl et al. 2024).

Industrial contaminants

Industrial operations and amendments, such as sewage sludge application, have resulted in considerable accumulations of heavy metals, microplastics, and per- and polyfluoroalkyl substances (PFAS) in soils, predominantly through runoff and deposition processes (Mondol et al. 2024). These pollutants drastically influence soil quality and plant development viability. Microplastics injected into agricultural soils by irrigation and fertilizer application modify critical soil qualities, including porosity, water retention capacity, and bulk density. Their presence can restrict water penetration, inhibit gas exchange, and clog soil pores crucial for plant health (Mondol et al. 2024).

Research suggests that agricultural soils in the UK contain between 320 and 12,560 microplastic particles per kilogram. Observations suggest a large temporal increase, with 2022 levels indicating a 1.6-fold spike compared to 1966. Elevated microplastic concentrations, linked to organic and inorganic fertilizer applications, underline the importance of these inputs in microplastic buildup (Cusworth et al. 2024).

Studies have shown that higher microplastic content corresponds with lower bulk density and enhanced soil porosity by 7–15%. These alterations contribute to reduced water retention, crucial for supporting plants during droughts. Furthermore, another study indicated that microplastics negatively impacted fungal populations in well-watered soils due to hazardous compounds, whereas inadequate water management enhanced fungal growth in dry soils linked with microplastic entrapment (Mondol et al. 2024).

The PFAS, recognized for their environmental persistence, are commonly identified in agricultural soils due to biosolid application and the use of polluted water sources. Perfluorooctanesulfonic acid (PFOS) is the major PFAS component, accounting for around 36% to 50% of observed values, with concentrations ranging from 0.6 to 3.0 ng/g dry weight in waste-treated wetlands in Uganda. Similarly, soils in South Korea contain PFAS coming from irrigation with textile wastewater effluent, with values between 0.12 and 13.9 ng/g dry weight. Research has proven a connection between PFAS exposure and deleterious effects on plant development, including decreased seed germination, restricted root growth, and altered nutrient absorption (Li et al. 2022). Additionally, PFAS penetration into agricultural products offers significant dangers for human consumption. These findings emphasize two key concerns: lower agricultural yields and the danger of bioaccumulation in the food chain, affecting human health (Eze et al. 2024).

Industrial pollutants such as microplastics and PFAS create substantial and chronic threats to agricultural soils and crop yield. The rising abundance of microplastics has drastically affected crucial factors for healthy plant growth, bulk density, porosity, and water retention, thereby altering agricultural operations, especially in water-scarce countries. PFAS pollution appears in lower agricultural yields and probable bioaccumulation in food systems (Earl et al. 2024). Given their longevity in crops, these chemicals pose long-term hazards to sustainable agriculture and public health. In view of continued industrial development, tackling these difficulties needs improved industrial waste management, increased water treatment technology, and targeted remediation tactics. Future research should focus on clarifying pollutant-soil-ecosystem interactions and creating creative techniques to decrease threats to agricultural production and food safety.

Mechanisms of interaction

Understanding the mechanism of interaction between emerging contaminants and soil microbiota is crucial for evaluating their ecological implications and developing effective remediation strategies. The mechanisms of interactions involve adsorption and desorption, biodegradation as well as bioaccumulation.

Adsorption and desorption

The processes of adsorption and desorption are crucial to understanding the interactions between developing toxins and soil microbiota, regulating their bioavailability and ecological consequences (Ren et al. 2018). Adsorption refers to the attachment of pollutants to soil particles, a process impacted by parameters such as soil composition, pH, and organic matter concentration (Chen et al. 2020). This mechanism determines the retention of pollutants within the soil matrix and greatly impacts their availability to microbial populations. Conversely, desorption includes the release of pollutants from soil particles back into the environment, affected by soil composition, moisture, and the chemical characteristics of the contaminants (Sarkar et al. 2021). This dynamic equilibrium influences not only pollutant bioavailability to soil microorganisms but also their breakdown and transformation in the environment.

Emerging pollutants such as plastics are pervasive in environmental matrices (Barbosa et al. 2020). The interaction of plastic trash with soil organic matter and their extensive persistence, often lasting for centuries, contribute to the production of micro- and nanoplastics (Bläsing and Amelung 2018). Recent research employing model soils has shown interactions between micro- and nanoplastics with polychlorinated biphenyls (PCBs) and heavy metals (Velzeboer et al. 2014; Davranche et al. 2019). These particles display harmful effects on soil biota, including disturbance of the gut microbiota of *Enchytraeus crypticus* and deleterious effects on soil enzyme functional diversity (Maddela et al. 2022). Additionally, microplastics have been demonstrated to diminish α-diversity in microbial communities (Li et al. 2020). Thus, soils serve as final sinks for plastic trash and locations for micro- and nanoplastic formation, posing major threats to soil biota and trophic transmission.

Most emerging contaminants (ECs) display substantial retention within the soil matrix, even after extended water washing, due to their high affinity for soil components compared to other pollutants (Biel-Maeso et al. 2021). Column miscible displacement tests by Teijón et al. (2014) demonstrated that naproxen, a nonsteroidal anti-inflammatory medication, exhibits minimal sorption to aquifer matrices but greater affinity for solid particles. The complexation of ECs emerges from numerous interaction processes within soil matrices, considerably impacting their behavior and toxicity in terrestrial ecosystems. For example, the adsorption rate and equilibrium capacity of triclosan (TCS) on polyethylene (PE) were measured as 29.3 mg μg^{-1} h^{-1} and 1248 μg g^{-1}, respectively, but TCS adsorption rates on polystyrene

(PS) and soil particles were much lower (0.27 and 0.60 mg μg^{-1} h^{-1}, respectively). Understanding these interactions is crucial for forecasting environmental destiny and directing remediation and soil health management.

Furthermore, adsorption and desorption activities promote pollutant retention while boosting microbial breakdown pathways, thereby lowering bioavailability and toxicity (Ren et al. 2018). The balance between these mechanisms is critical for clarifying contaminant-soil microbiota interactions and their effect on microbial community structure and function.

Biodegradation

Biodegradation is a crucial method *via* which soil bacteria attenuate the consequences of developing contaminants by turning complex pollutants into simpler, less hazardous molecules (Bala et al. 2022). This technique detoxifies polluted soils and increases ecosystem health. Diverse microbial taxa, including bacteria and fungi, play crucial roles in pollutant breakdown, ultimately improving soil quality and boosting plant development. Biodegradation includes complicated interactions between pollutants and microbial populations, changing dangerous compounds into less toxic ones (Maglione et al. 2024). This knowledge assists in isolating microbial strains with strong degradation capacity, boosting remediation efficacy.

Soil microbes demonstrate extraordinary metabolic plasticity, enabling them to break down or change a wide spectrum of new pollutants by using them as carbon or energy sources. Biodegradation acts as a significant natural attenuation process; nevertheless, its performance depends on parameters such as pollutant availability, microbial community makeup, and environmental circumstances (Zhang et al. 2024). A detailed study of microbial metabolic pathways might inspire bioaugmentation procedures, wherein successful strains are introduced into polluted locations to speed pollutant breakdown. This technique also permits identification of important enzymes involved in degradation, increasing remediation outcomes and boosting soil health and ecological stability.

Bioaccumulation

Bioaccumulation refers to the steady accumulation of chemicals, including new toxins, inside the tissues of organisms over time, dramatically affecting microbiota and their ecological activities (Yu et al. 2024). This process can detrimentally influence microbial diversity and metabolic activity, consequently affecting soil health, since certain pollutants may limit microbial activities or stimulate the growth of pathogenic species. Additionally, bioaccumulation in soil microbes can impair crucial nutrient cycling mechanisms required for plant development and soil fertility. Co-occurring contaminants, such as heavy metals and antibiotics, can exhibit combined toxic effects, confounding microbial responses. These interactions may exacerbate toxicity or promote microbial resistance mechanisms, altering gene expression and ecosystem functioning (You et al. 2022).

Conversely, soil health can be enhanced with the introduction of microorganisms that promote nutrient availability and attenuate or neutralize hazardous xenobiotics (Rebelo et al. 2023). Emerging pollutants alter soil microbiota composition and function via multiple processes (Wang et al. 2024). Microorganisms may utilize pollutants as carbon and energy sources or co-metabolize them in the presence of adequate substrates (Bala et al. 2022). Plant–microbe interactions in the rhizosphere, especially those linked to pollution degradation or removal, have gained substantial interest for their potential in bioremediation (Chaudhry et al. 2005). Plants can change their rhizosphere microbiome by actively shedding substrates, which differ among species (Santoyo 2022). These exudates are crucial in bioremediation, since they considerably impact the pace and efficiency of microbial pollutant breakdown (Ling et al. 2022).

Understanding bioaccumulation mechanisms and related interactions is vital to clarify contaminant routes into the food chain and their consequences on higher trophic levels. This understanding is vital for creating ways to reduce emerging contaminants' detrimental impacts on soil ecosystems. Furthermore, monitoring microbial reactions to these contaminants might serve as significant markers of ecosystem health.

Impact of emerging contaminants on soil ecosystem

Evidence from various studies indicates that soil pollution with emerging contaminants can disrupt the interrelationships within the soil-plant system (Fig. 2). Certain chemicals persist in the soil, whereas others may decompose into harmful by-products. Emerging contaminants influence the physicochemical properties of soil, impacting characteristics such as texture, porosity, pH, and mineral content (Singh et al. 2023). The presence of these contaminants in soil can modify microbial communities and faunal diversity, thereby influencing plant survival and overall performance (Khan et al., 2022).

Direct toxicological effects of contaminant-microbiome interactions

Emerging contaminants exert direct toxicological impacts on soil microorganisms through various mechanisms. Heavy metals and nanoparticles inflict cellular damage by inducing oxidative stress, disrupting membrane integrity, and causing DNA damage. Similarly, per- and polyfluoroalkyl substances (PFAS) elicit oxidative stress while also compromising membrane stability and cellular metabolism. These direct toxic effects frequently lead to diminished microbial biomass, decreased enzymatic activities, and alterations in community composition that favor more resilient species (Ameen et al. 2021; Khan and Sikder 2024; Campillo-Cora et al. 2025). The observed effects encompass a spectrum of mechanisms, including the induction of oxidative stress, membrane damage, protein denaturation, DNA disruption, and enzymatic inhibition, which collectively undermine microbial viability and compromise ecosystem functionality.

Oxidative stress and generation of reactive oxygen species

Oxidative stress constitutes the principal mechanism by which emerging contaminants inflict direct toxicity upon soil microorganisms. The introduction of heavy metals, nanoparticles, and diverse organic pollutants instigates the production of reactive oxygen species (ROS), which include hydroxyl radicals (HO-), superoxide anions (O_2-), hydrogen peroxide (H_2O_2), and hydroperoxyl radicals (ROO-). These highly reactive entities surpass the capacity of cellular antioxidant defense systems, resulting in extensive damage across microbial cellular structures (Sule et al. 2022; Silva et al. 2023).

Heavy metals, including copper, iron, and chromium, engage in Fenton and Haber-Weiss reactions, thereby catalyzing the synthesis of hydroxyl radicals from hydrogen peroxide. Per- and polyfluoroalkyl substances (PFAS) similarly elicit oxidative stress by perturbing cellular redox equilibrium and disrupting mitochondrial electron transport chains (Juárez-Maldonado et al. 2021).

Herbicides and pharmaceutical agents play a substantial role in the generation of reactive oxygen species (ROS) within soil bacterial populations. Investigations involving *Stenotrophomonas* sp. subjected to herbicides revealed increased concentrations of malondialdehyde and peroxide, signifying pronounced oxidative stress. The herbicide mesotrione was found to exacerbate oxidative stress and elevate hydrogen peroxide production in *Pantoea ananatis*, whereas 2,4-dichlorophenoxyacetic acid resulted in heightened peroxide levels in *Pseudomonas* sp. (Silva et al. 2023; Bakaeva et al. 2024).

Membrane damage

Bacterial cells subjected to emerging contaminants demonstrate marked elevations in lipid peroxidation byproducts, including malondialdehyde (MDA), diene conjugates, and triene conjugates. Investigations involving *Comamonas testosteroni* exposed to hexachlorobenzene revealed heightened concentrations of these peroxidation byproducts, signifying considerable membrane impairment (Dimova et al. 2022; Silva et al. 2023).

Organic pollutants exhibit a pronounced efficacy in penetrating cytoplasmic membranes, leading to membrane swelling and enhanced fluidity (Murínová and Dercová 2014). Deterioration of membrane integrity results in modified permeability, disrupted ionic gradients, and the forfeiture of selective transport mechanisms crucial for cellular homeostasis. The infiltration of organic solvents into membranes induces an unregulated efflux of protons and potassium ions, consequently diminishing the proton-motive force and compromising energy conservation (Zheng et al. 2024).

Protein denaturation and enzymatic disruption

Heavy metals exert direct toxicological effects by binding to sulfhydryl groups in proteins, which induce conformational alterations and enzymatic inactivation. Metals such as cadmium, mercury, and lead exhibit a pronounced affinity for cysteine residues, thereby disrupting the disulfide bonds essential for maintaining the tertiary structure of proteins (Mishra et al. 2017; Iimaa et al. 2025). Empirical studies indicate that soil subjected to heavy metal contamination displays markedly lower protein concentrations in comparison to uncontaminated controls, with protein levels proving to be more sensitive indicators of contamination than conventional enzymatic assays (Hang et al. 2013; Iimaa et al. 2025).

DNA damage and genetic disruption

Emerging pollutants are known to induce DNA damage through both direct interactions and reactive oxygen species (ROS)-mediated pathways. Heavy metals exhibit a propensity to bind directly to DNA bases, notably guanine, resulting in structural modifications and compromised replication fidelity. Nanoparticles, particularly those composed of transition metals, facilitate the synthesis of 8-hydroxydeoxyguanosine and other oxidative DNA lesions, which can lead to mutagenic base pairing during the replication process (Rim et al. 2013). Organophosphate pesticides, including chlorpyrifos, methyl parathion, and malathion, trigger apoptosis and the formation of DNA interstrand crosslinks in bacterial organisms. (Sule et al. 2022).

The toxicity of nanoparticles is notably influenced by their size, as evidenced in investigations of DNA damage. Smaller nanoparticles possess an enhanced genotoxic capacity attributed to their superior cellular uptake and increased surface reactivity. Research indicates that silver nanoparticles (AgNPs) cause substantial DNA strand breaks and chromosomal anomalies in soil bacteria, with these effects being amplified under lower pH conditions that facilitate nanoparticle dissolution and the release of silver ions (Mishra and Yang 2025).

Protein denaturation

Heavy metals exert direct toxicological effects by binding to sulfhydryl groups in proteins, which leads to conformational alterations and subsequent enzymatic inactivation. Cadmium, mercury, and lead exhibit a particularly strong affinity for cysteine residues, thereby disrupting the disulfide bonds that are essential for maintaining protein tertiary structure, leading to cellular dysfunction (Mishra et al. 2017; Cui et al. 2018). The principal resistance mechanism employed by bacteria involves the adsorption of metal ions to reactive groups within cellular components, thereby facilitating their sequestration within the cell protoplast. Nevertheless, when the buffering capacity is surpassed, metalloregulatory systems become ineffective, leading to conformational changes in protein channels and transporters that impair cellular function (Zhang et al., 2013; Iimaa et al. 2025).

Enzymatic inhibition by emerging contaminants

Soil enzymes are integral to biogeochemical cycles, and their inhibition constitutes a significant toxicological impact of emerging contaminants. Per- and polyfluoroalkyl substances (PFAS), particularly long-chain variants such as perfluorooctanesulfonic acid (PFOS), markedly inhibit critical enzymes, including sucrase and urease, which are vital for carbon and nitrogen cycling, respectively. Such inhibitory effects arise from various mechanisms, including competitive binding to active sites, allosteric alterations, and oxidative damage to enzyme structures (Shittu et al. 2023).

Microplastics similarly interfere with enzymatic functions, with research indicating reductions in activities of β-glucosidase (32%), urease (40%), and dehydrogenase (50%) within contaminated soils (Aralappanavar et al. 2024a, b). Investigations involving bacterial strains revealed that exposure to Sulfonylurea herbicides, such as metsulfuron-methyl, led to a substantial reduction in acetolactate synthase (ALS) activity (50–73% inhibition), the enzyme responsible for the biosynthesis of branched-chain amino acids (Bakaeva et al. 2024). Exposure to pesticides consistently diminishes the activities of catalase (CAT), superoxide dismutase (SOD), and glutathione peroxidase (GPx) in soil bacteria. Notably, the herbicides acetochlor and metolachlor specifically influence antioxidant enzyme activities, with catalase exhibiting heightened sensitivity to oxidative stress conditions (Sule et al. 2022; Silva et al. 2023).

Impacts on gene expression

Emerging contaminants markedly influence microbial gene expression profiles, with repercussions that transcend mere DNA damage. Exposure to heavy metals induces the upregulation of stress response genes, encompassing those that encode heat shock proteins, DNA repair enzymes, and efflux pumps. Nonetheless, extreme levels of contamination may surpass these protective mechanisms, culminating in extensive transcriptional disruption (Iimaa et al. 2025). Gene expression analyses conducted on *Stenotrophomonas maltophilia* subjected to elevated concentrations of hydrogen peroxide indicated that the enzymes KatA2 and alkyl hydroperoxidase are pivotal for bacterial survival in oxidative stress environments. This emphasizes the critical role of antioxidant gene expression in the adaptation of bacteria to the stress induced by emerging contaminants (Silva et al. 2023).

Per- and polyfluoroalkyl substances (PFAS) have been demonstrated to influence the expression of genes associated with membrane transport, energy metabolism, and the biosynthesis of secondary metabolites. Prolonged exposure to PFAS can lead to irreversible genetic changes that modify microbial community composition and functional capabilities (Shittu et al. 2023).

Impact on antibiotic resistance and gene transfer

A critical concern associated with emerging contaminants is their contribution to the enhancement of antibiotic resistance in environmental bacteria. Soil functions as a principal reservoir for antibiotic-resistance genes (ARGs), with the extensive application of antibiotics accelerating their dissemination. The soil resistome encompasses resistance genes that can be transferred among bacterial communities, thereby impacting human health *via* horizontal gene transfer mechanisms (Wang et al. 2021; Han et al. 2022). The prevalence and diversity of ARGs in soil are modulated by several factors, including the structure of bacterial communities, physicochemical soil properties, and the presence of mobile genetic elements. Research has indicated significant positive correlations between ARGs and transposase and integrase genes, highlighting the role of mobile genetic elements in the dissemination of resistance genes (Han et al. 2022).

Horizontal gene transfer (HGT) constitutes a fundamental mechanism for the dissemination of antibiotic resistance genes among soil bacteria. The primary HGT mechanisms; conjugation, transformation, and transduction, function within soil environments, with transformation being particularly vital for the uptake of extracellular DNA from lysed bacterial cells. Recent investigations have shown that even minimal concentrations of extracellular antibiotic resistance genes (eARGs) in soil can catalyze rapid evolutionary changes in antibiotic resistance via natural transformation (Tao et al. 2022). Environmental factors considerably affect the efficiency of HGT, with intermediate soil moisture levels (5–20%) creating optimal conditions for transformation occurrences. Additionally, the presence of selective pressure from antibiotics, even at low concentrations, facilitates rare transformation events to proliferate within bacterial populations, thereby posing substantial risks to human health (Kittredge et al. 2021).

Impact on soil microbiome

Soil microbes play a key role in sustaining healthy soil ecosystems by aiding the biodegradation of organic matter, recycling important nutrients, strengthening soil structure, minimizing pollution, and stimulating nutrient absorption by plants (Singh et al. 2023). Various studies indicate that substances such as antibiotics (Vasilchenko et al. 2023), fungicides (Vasilchenko et al. 2023), perfluoroalkyl compounds (Yin et al. 2023), and textile dyes exhibit toxic effects on soil bacteria, reducing microbial abundance and altering soil microbiota distribution. Emerging pollutants can influence microbial makeup, changing genetic features, population density, and overall microbial activities (Aralappanavar et al. 2024a, b). Recent research shows that microplastics—including polyethylene, polystyrene, and polyvinyl chloride—influence the soil microbiome by increasing the relative abundance of Actinobacteria, Proteobacteria, and Ascomycota, while decreasing Basidiomycota, Acidobacteria, and Chytridiomycota populations (Fan et al. 2022).

Compounds such as phthalates and polyvinyl chloride have boosted fungal species including *Fonsecaea*, *Rhinocladiella*, *Capronia*, and *Cladophialophora*. The presence of microplastics and other emerging contaminants (ECs) changes populations of Gemmatimonadota, Actinobacteria, Acidobacteria, Chloroflexi, Basidiomycota, Planctomycetota, and Ascomycota. These microbial alterations may explain differences in nutrient cycle and metal regulatory activities. Disruption of microbial biodiversity by ECs occurs through direct toxicity or indirectly by changes in ambient circumstances, nutrition availability, and microbial genetics. Multiple studies demonstrate that ECs such as antibiotics and textile dyes negatively influence soil organisms (Wang et al. 2024). Exposure to harmful ECs promotes tolerant species, enabling resistance microbial growth. Antibiotics in pharmaceutical waste block critical enzyme systems involved in carbon transformation, affecting microbial survival and modifying metabolic activities. Additionally, compounds generated from eggs can change microbial environments, benefit certain species while disadvantage others. Similarly, microplastics may foster certain microbial communities at soil–plastic interfaces, thereby altering total diversity (Nath et al. 2023).

Certain ECs can modify soil pH, impacting enzyme activity, cellular energy generation, and nutrient availability, consequently endangering soil microbial survival. Some microorganisms exploit ECs as alternate energy sources, increasing their development (Bloor et al. 2021). Nanomaterials and antibiotics can harm microbial cells or induce genetic alterations, changing community structure. Nanomaterials disturb cell integrity or induce mutations, while antibiotics apply selection pressure, encouraging resistance genes that may co-select for other functional genes regulating soil biogeochemical processes (You et al. 2022). Antibiotics may affect microbial genetics or boost development of resistant species, enhancing their competitive advantage. Application of sewage sludge, animal dung, or avermectin corresponds with increased antibiotic resistance genes (ARGs) in soils (Niu et al. 2022). Only resistant bacteria survive, affecting soil microbiome makeup and abundance. Kumar et al. (2022) revealed that exposure to dibenzofuran/dibenzo-p-dioxin enabled survival only of microorganisms possessing dioxygenase genes. Similarly, Triclosan exposure induced considerable alterations in fungal and bacterial soil populations. ARG presence in agricultural soils allows resistant populations via horizontal gene transfer, with changes enhanced in soils polluted with ARGs, PFAS, and micro- and nanoplastics.

Microplastics impact microbial diversity by offering habitats for novel microbial species. Changes in diversity impact soil enzyme activity and nutrient cycling. Soil pollution with phthalate derivatives and microcystin lowers nitrogen-processing bacterial numbers and capacities. Exposure to carbendazim, red-S3B dye, and chlorothalonil lowers soil enzyme activity (Chauhan et al. 2023).

Emerging pollutants also affect soil microbiota around plant roots, reducing nutrient absorption. For example, albendazole affects arbuscular mycorrhizal processes of *Rhizophagus irregularis* in *Lotus japonicus* roots, altering phosphorus absorption (Geetha Thanuja et al., 2022). Soil contamination by silver nanoparticles damages ectomycorrhizal fungi, lowering their viability and restricting nutrient uptake and development of forest plants. Overall, alterations in soil microbial diversity have far-reaching ecological implications. Altered microbial populations can interrupt nutrient cycle, limiting soil fertility and plant development. Long-term changes in soil ecosystem services may affect agricultural output and ecological stability (Wang et al. 2024). Understanding interactions between soil components and bacteria is vital to assess and minimize detrimental impacts on terrestrial habitats. Figure 3 depicts the consequences of developing pollutants on soil health.

Impact on the soil fauna

The existence of soil fauna is vital for sustaining soil health, as it helps the breakdown of organic matter, boosts the quantity and variety of soil microbes, and improves the physical and chemical features of the soil (Ahmed and Al-Mutairi, 2022). Recent data suggests that emerging contaminants (ECs), including pesticides, micro-nano plastics (MNPs), and trace amounts of medicinal chemicals, severely damage soil fauna, hence lessening their vital role in preserving a clean and fruitful soil ecosystem (Astaykina et al. 2022). Research has shown that earthworms exposed to MNPs, organophosphate insecticides, dibenzofuran, and polychlorinated dibenzodioxins in polluted soils developed gastrointestinal damage, which reduced their nutrition absorption capacity and overall longevity. Furthermore, modifications in the microbial communities within earthworms were identified following exposure to modest quantities of pesticides. The application of ECs such as antibiotics, nanoparticles, and bisphenol A (BPA) has been proven to disrupt reproductive systems and increase death rates in earthworms, enchytraeids, and collembolans. These findings also indicated considerable modifications in the DNA and enzymatic profiles of soil fauna living in polluted habitats. The attempts of soil organisms to avoid contaminated places, along with higher infertility and mortality rates, may hasten changes in diverse soil-dwelling animal populations, which might have severe impacts on the larger ecosystem. The effects of developing pollutants on soil fauna are depicted in Fig. 4.

Effects of plants

The presence of plants in soil supports the residence and functioning of microbes and diverse tiny animals (Hakim et al. 2021). Consequently, any impairment in plant health dramatically undermines the symbiotic soil-plant interaction. Extensive scientific inquiries have proven that environmental contaminants (ECs) or their metabolites significantly influence seed germination, root and shoot development, and the overall growth and survival of plants. Numerous detrimental effects have been documented following the exposure of plants to soils contaminated with microplastic nanoparticles (MNPs), including mutations in *Vicia faba* L. (fava bean), inhibited cell division, prolonged seed germination periods, alterations in photosynthetic processes in *Lepidium sativum* L. (garden cress), and stunted growth in *Arabidopsis thaliana* (thale cress). Furthermore, the roots of *Vicia faba*, *Oryza sativa*, and *Lactuca sativa* may meet physiological dysfunctions when microplastics stick to their surfaces. Beyond tris (2-chloroethyl) phosphate (TCPP),

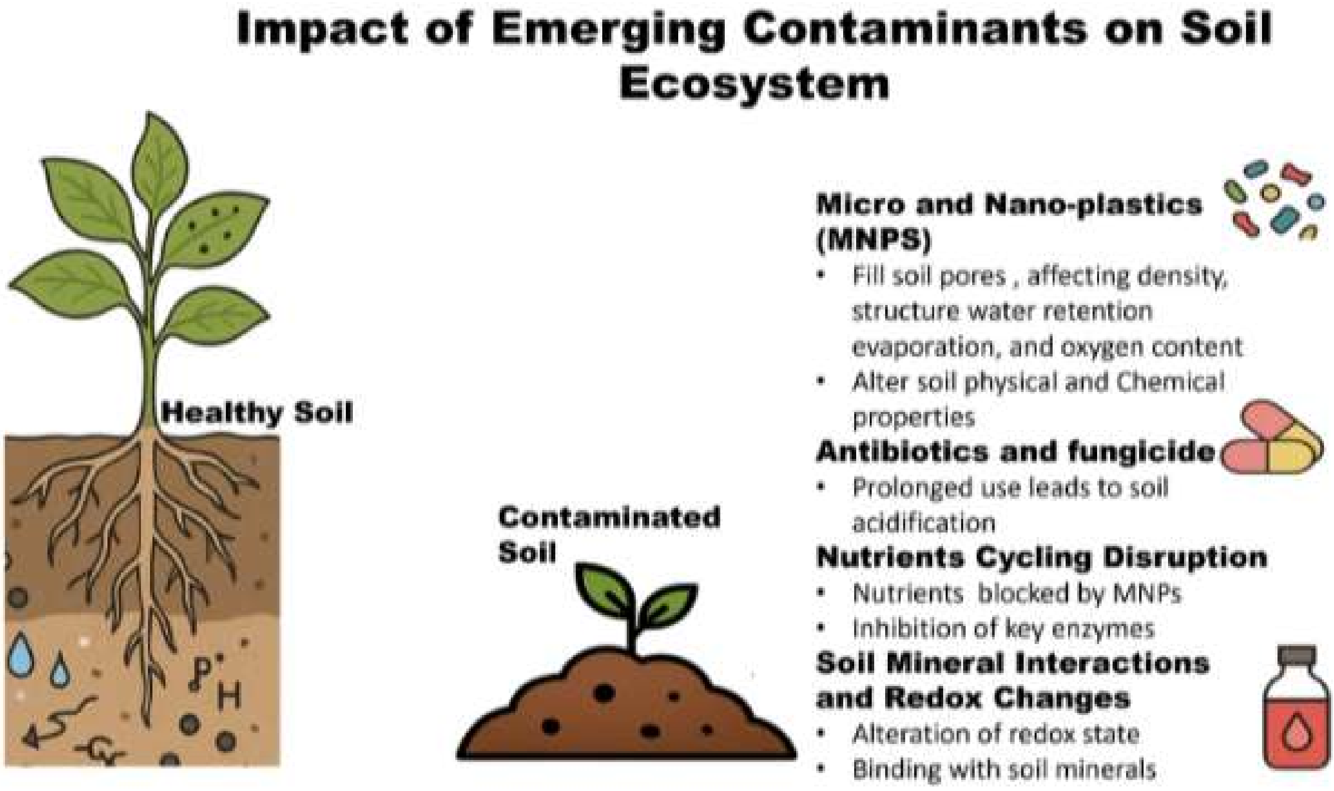

Fig. 3 Impact of Emerging Contaminants on Soil Ecosystem

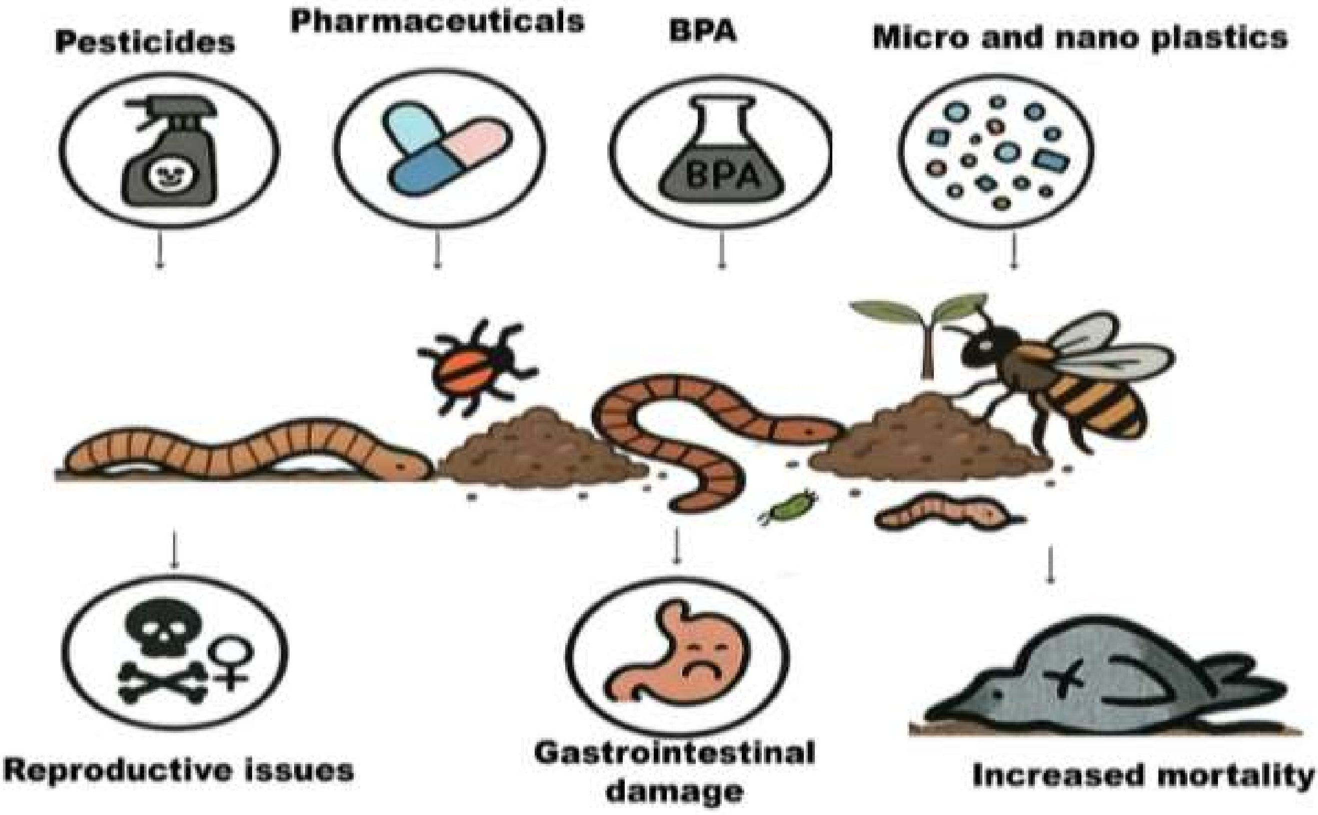

Fig. 4 Impacts of Emerging Contaminants on the soil fauna

chemicals such as triclosan, antibiotics, nanoparticles, textile residues, and pesticides are known to severely affect plant health upon contact.

Exposure to these agents can cause reduced seed germination rates, shorter root lengths, lower biomass, changes in root and shoot characteristics, difficulties with fruiting, changes in plant metabolism, lower antioxidant levels, variations in nutrient composition, changes in root exudate profiles, and an increase in necrotic and chlorotic leaf conditions (Huet et al. 2023). Numerous studies have demonstrated that plants prefer to store ECs inside their cellular structures, which exacerbates the direct negative impacts of these pollutants on nearby flora. Optimal plant growth is dependent upon adequate interactions between soil and plants; it is obvious that ECs in agricultural soils hold the ability to disrupt several elements of both soil and plant systems (Ingraffia et al. 2022). These disturbances cumulatively contribute to lower yields in crops.

Effects on humans

Human civilization is firmly based on agriculture, which maintains life and supplies important food resources internationally (Wijerathna-Yapa and Pathirana 2022). However, the expansion of pollutants in the food supply, owing to contemporary agricultural techniques, offers a huge concern (Earl et al. 2024). Various substances, including pesticides, herbicides, fertilizers, antibiotics, microplastics, brominated flame retardants, hormones, and chemical additives, represent major hazards to worldwide food safety. Water is crucial for both agricultural production and the workers engaged in maintaining the continuity of our food supply. The excessive use of agricultural pesticides leads to water contamination, severely harming ecosystems, agricultural productivity, and public health (Rad et al. 2022). Emerging pollutants can permeate water sources, providing substantial health concerns to people, even at small doses (Bayabil et al. 2022). The discharge of pollutants from agricultural activities greatly jeopardizes sensitive aquatic ecosystems in wetlands, lakes, rivers, and other water bodies (Rad et al. 2022).

The introduction of additional toxins through irrigation further exacerbates the problem, as these compounds may persist on consumables (Al-Hazmi et al. 2023). Aquatic species are at risk of acquiring antibiotic resistance due to the indiscriminate application and absorption of such substances into water, which disturbs normal nutrient cycling and endangers human populations by exposing them to antibiotic-resistant bacteria (Okeke et al. 2023). The systematic use of antibiotics in animals in agricultural production raises concerns over the possibility of antibiotic resistance among consumers, agricultural workers, and the larger community, consequently straining healthcare resources (Okeke et al. 2023; Kavusi et al. 2023).

Effect of on the soil physiochemical properties

The fundamental variables forming the physiochemical characteristics of soil are important to the creation of a strong soil ecosystem. Optimal soil density neither too compacted nor extremely loose, permits appropriate air circulation, which helps the organisms live inside the soil matrix. This state further helps plant roots to efficiently absorb essential water via nearby root hairs (Zhou et al. 2021). Soil pH substantially regulates nutrient availability and the makeup of diverse microbial communities within the soil ecosystem (Ferrarez et al., 2022). Additionally, it plays a significant function in influencing the concentration of dissolved organic carbon present in the soil.

The deployment of manmade nanoparticles (MNPs) in agricultural contexts can modify several physical and chemical characteristics of the soil through multiple processes. MNPs interact with soil, changing fundamental features and impacting physical and chemical processes. They occupy soil pore spaces, consequently altering soil density, structural stability, and the interstitial spaces between particles. Consequently, this modification affects the rates of water evaporation from the soil, its water retention capacity, and its oxygenation levels (Singh et al. 2023). The presence of MNPs may also promote preferred channels for water transport, leading to diverse hydrological behaviors within the soil. Moreover, the action of MNPs generates alterations in soil aggregation through both natural and human mechanisms. They hinder the cohesion of soil particles, hence disturbing the development of aggregates. Research reveals that MNPs can diminish populations of Actinobacteria, organisms necessary for soil aggregation, consequently affecting the overall composition of the soil (Zhou et al. 2021).

The adjustment of pH values in soil owing to antibiotics and fungicides arises from their chemical interactions within the soil matrix. Prolonged administration of antibiotics and zoxamide in agricultural situations is connected with soil acidification. This fall in soil pH is likely owing to the release of protons or to the disturbance of microbial communities that regulate soil pH levels (Liu et al. 2023). Emerging contaminants (ECs) can profoundly impact nutrient dynamics and their cycles within the soil ecosystem. For instance, micro-nano plastics (MNPs) might limit the availability of vital nutrients for plants and other creatures. Furthermore, they inhibit essential enzymes such as chitinase and leucine aminopeptidase, which play critical roles in nutrition cycling, as revealed by Zhou et al. (2021). This inhibition may occur through direct impacts on enzyme activity or by affecting the nature of microbial communities responsible for enzyme synthesis.

Additionally, certain ECs can interact with soil minerals, therefore changing their characteristics and reactivity, potentially reducing the soil's capacity to retain nutrients and cations. The presence of ECs may also influence the soil's redox state, thereby impacting nutrient accessibility and microbial activity (Maddela et al. 2022). Alterations in the physicochemical characteristics of soil produced by ECs can have important ramifications for soil health, plant development, and the overall operation of the ecosystem. Emerging pollutants, such as microplastics, affect the physical and chemical features of soil, altering aspects like the organic carbon content and the soil's structural integrity. These adjustments subsequently impact microbial biomass, diversity, and the stability of microbial networks by modifying habitat conditions and the availability of nutrients (Han et al. 2024). Understanding these processes is critical for creating measures to reduce the consequences of ECs on soil quality.

Economic impacts of emerging contaminants

Emerging pollutants offer enormous obstacles to international commerce and exert influence on the economic sector, in addition to their adverse consequences on environmental and human health. Given the global movement of food goods, a contamination originating in one place might have effects on food safety globally. Consequently, it is vital for governments to collaborate in monitoring and addressing these concerns (Lee et al. 2023). The implementation of global food safety laws is dependent upon the work of organizations such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), which need coordinated involvement among nations (Schonrock et al., 2023).

Adaptation Mechanisms and Microbial Resilience

Soil microorganisms utilize a range of adaptive strategies to manage the stress induced by emerging contaminants. Immediate adaptation encompasses epigenetic alterations, activation of stress response pathways, and metabolic reconfiguration, which may confer rapid yet potentially reversible tolerance. In contrast, long-term adaptation is characterized by genomic alterations and permanent physiological modifications that improve survival and fitness in contaminated environments (Tan et al. 2022). Furthermore, cross-protection mechanisms enable microorganisms that have adapted to one type of stressor to concurrently acquire tolerance to various other environmental pressures. This phenomenon is especially pertinent in contaminated soils, where multiple stressors frequently coexist, thereby exerting selective pressure that favors the proliferation of broadly tolerant microbial strains (Tan et al. 2022).

Network Complexity and Microbial Interactions

Microbial co-occurrence networks in contaminated soils frequently demonstrate modified complexity and connectivity patterns in contrast to unaltered environments. Minimal contamination levels can enhance network connectivity, as microorganisms establish more collaborative relationships to mitigate stress. Conversely, elevated contamination levels generally result in network fragmentation and diminished functional diversity, with only the most resilient species persisting (Wang et al. 2025). These alterations in network structure have significant implications for ecosystem stability and resilience, as simplified microbial communities may exhibit reduced capacity to sustain vital ecosystem functions when faced with further \environmental stressors.

Mobile genetic elements as mediators of contaminant interactions

Soil ecosystems are increasingly exposed to a diverse array of emergent contaminants **(ECs)**, including pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), microplastics, and other persistent organic pollutants. These contaminants interact with soil microorganisms through complex mechanisms that fundamentally reshape microbial community structure and function. The mobilome, the collective pool of mobile genetic elements (MGEs) including plasmids, transposons, integrons, bacteriophages, and integrative conjugative elements, serves as a critical mediator in these interactions, enabling rapid bacterial adaptation to contaminated environments while simultaneously facilitating the dissemination of both beneficial and detrimental traits (Bhat et al. 2023; Zhang et al. 2024).

Plasmids serve as crucial vehicles for the horizontal transfer of genes encoding contaminant degradation pathways and resistance mechanisms. Conjugative plasmids carrying catabolic genes can rapidly disseminate throughout soil bacterial communities, enabling community-wide adaptation to novel contaminants. Studies have demonstrated that plasmid-mediated bioaugmentation can effectively enhance the degradation of various organic contaminants by promoting gene transfer to indigenous bacterial populations (Garbisu et al. 2017). Class 1 integrons represent particularly important MGEs in contaminated soils, functioning as platforms for the capture, integration, and expression of adaptive gene cassettes. These elements are found in 2–5% of soil bacteria and become highly active under stress conditions through SOS response activation. Integrons can rapidly acquire novel gene cassettes encoding resistance to antibiotics, heavy metals, and other contaminants, enabling swift adaptation to changing environmental conditions (Al-Ubaidy and Alsultan 2023; Bhat et al. 2023).

Transposable elements facilitate genetic rearrangements that can lead to novel metabolic capabilities. In contaminated soils, transposons play important roles in mobilizing resistance genes and catabolic pathways between different genetic contexts. Studies have revealed remarkable conservation of transposon structures in soil bacteria, suggesting their fundamental importance in bacterial adaptation (Shintani et al. 2023). Integrative and Conjugative Elements (ICEs) represent large mobile DNA molecules that integrate into host chromosomes and transfer through conjugation. These elements often carry multiple adaptive functions, including aromatic compound degradation pathways, making them particularly relevant for environmental remediation applications (Hirose 2023).

Resistance dissemination through mobile elements

The use of antibiotics, especially in veterinary medicine to treat diseases and promote animal growth, consumes approximately 70% of global antibiotics, leading to the proliferation of antibiotic resistance genes and posing a significant global health threat (Osti et al. 2025). Soil environments serve as major reservoirs for antibiotic resistance genes, with mobile genetic elements (MGEs) facilitating their dissemination across bacterial communities (Mendonça et al. 2025). The plastisphere has been identified as a particular hotspot for resistance gene accumulation and transfer. Class 1 integrons are especially important, being found in higher abundances in contaminated versus pristine soils (Al-Ubaidy and Alsultan 2023; Bhat et al. 2023).

Heavy metal contamination selects for MGE populations that are enriched in multiple genes conferring resistance to heavy metals. These elements carry genes encoding various resistance mechanisms, including efflux pumps, metallothioneins, and detoxification enzymes. The horizontal transfer of metal resistance genes can occur rapidly following contamination events (Mahbub et al. 2023; Wei et al. 2025). The co-occurrence of multiple resistance genes on single MGEs creates opportunities for cross-resistance development, where exposure to one contaminant selects for resistance to others. This phenomenon is particularly problematic in agricultural soils that receive multiple inputs, including antibiotics, heavy metals, and pesticides (Wei et al. 2025).

Mitigation strategies for emerging contaminants

Mitigation strategies aimed at reducing the impact of emerging contaminants on soil microbiome are essential for maintaining ecosystem health and functionality. The remediation approaches regarded as safe and efficient are bioremediation techniques and soil management practices. Other mitigation strategies are summarized in Table 1.

Bioremediation

Microbes play a significant part in environmental cleanup through bioremediation, where they lower contaminant concentrations to harmless levels via biological processes (Maglione et al. 2024). Despite the difficulties presented by emerging contaminants, soil microorganisms exhibit significant potential for bioremediation applications. Indigenous soil bacteria harbor cytochrome P450 genes, which facilitate the degradation of persistent organic pollutants, including pesticides and other xenobiotic compounds. Notably, *Pseudomonas fluorescens* and *Bacillus polymyxa* have demonstrated particularly high degradation efficacy against chlorinated hydrocarbon pesticides (Doolotkeldieva et al. 2018).

The efficiency of bioremediation is significantly influenced by the accessibility of contaminants and the metabolic capacity of soil microorganisms as well as the optimization of environmental parameters such as temperature, pH, moisture content, and nutrient availability. Biostimulation techniques that augment indigenous microbial activity through nutrient supplementation have shown promise in expediting the degradation of contaminants (Doolotkeldieva et al. 2018; Kakde and Sharma 2024). Bioaugmentation strategies, which involve the introduction of specialized degradative microorganisms, can enhance the efficiency of bioremediation, particularly when integrated with biostimulation methods. The combination of bioaugmentation and phytoremediation has revealed particular potential, as plant roots create conducive environments for the newly introduced microorganisms while simultaneously aiding in contaminant uptake and transformation (Kakde and Sharma 2024). Advanced molecular methodologies are facilitating the creation of engineered microbial systems with enhanced capabilities for the degradation of specific contaminants. Such approaches represent promising pathways for effectively addressing the challenges posed by emerging contaminants in soil ecosystems.

Understanding the interactions between pollutants and soil elements affecting bioavailability is essential for developing effective bioremediation strategies. the rhizosphere, the region of soil that is touched by plant roots, is a hotspot for microbial activity and has a large potential for the breakdown of toxic organic compounds (Pathan et al. 2020). The rhizosphere, enriched with microbial activity due to plant root interactions, is crucial for degrading toxic organic compounds (Saravanan et al., 2022). Rhizoremediation, which integrates plants and their rhizosphere microbes, is a cost-effective and efficient in-situ phytoremediation approach (Segura and Ramos 2013; Saravanan et al., 2022). Key ecological concepts are vital for successful rhizosphere bioremediation, offering a viable alternative to conventional physicochemical remediation methods. Environmental factors such as aerobic conditions, temperature, and pH impact microbial activity and the effectiveness of bioremediation processes.

Bioremediation of emerging contaminants and research direction

The bioremediation of emerging contaminants represents one of the most pressing environmental challenges of the 21st century, requiring novel approaches that transcend traditional microbial treatment methods. Innovative strategies, including synthetic microbial consortia, microbiome engineering, nanobioremediation, and the integration of omics technologies with machine learning, are revolutionizing our ability to predict, monitor, and enhance the degradation of complex pollutants (Adamu et al. 2023; Lea-Smith et al. 2025). These cutting-edge approaches leverage advances in synthetic biology, nanotechnology, artificial intelligence, and systems biology to create more efficient, targeted, and adaptable remediation systems.

Synthetic microbial consortia (SMC) represent a paradigm shift from traditional monoculture-based approaches to multi-species engineered systems that exploit synergistic interactions for enhanced pollutant degradation. These consortia are deliberately assembled to exhibit functional redundancy, metabolic versatility, and ecological resilience through carefully orchestrated division of labor and cross-feeding relationships (Adamu et al. 2023).

Recent advancements in SMC have achieved significant success in addressing emerging contaminants. Heavy metal bioremediation has reached 85% efficiency using *Bacillus subtilis* and *Pseudomonas aeruginosa* through bioaccumulation and exopolysaccharide (EPS) production. For plastic degradation, *Ideonella sakaiensis* and *Bacillus coagulans* effectively degraded polyethylene terephthalate (PET), presenting sustainable alternatives to chemical recycling (Adamu et al. 2023). In pharmaceutical degradation, engineered consortia enhanced catabolic pathways for both aliphatic and aromatic compounds, with *Pseudomonas putida* and *Acinetobacter baylyi* demonstrating synergistic degradation of polycyclic aromatic hydrocarbons PAHs. Synthetic consortia also showed potential in breaking down

Table 1 Mitigation strategies for some emergent contaminants

Mitigation Strategy	Case study	References	Advantages	Limitations
Bioremediation	*P. aeruginosa* HJ4 in PFAS removal for 48 h. *P. plecoglossicida* resulted in 75% degradation efficiency in 6 days. *Thermobifida halotolerans resulted in 70–82% lindane degradation in 30 days. Saccharomyces cerevisiae and Cunninghamella elegans for heavy metals (mercury, nickel, and lead) remediation. Pleurotus tuber-regium* effectively removed petroleum hydrocarbons and heavy metals when combined with sawdust and poultry manure substrates.	LaFond et al. (2023); Chetverikov et al. (2017); Usmani et al. (2021); Duc et al. (2021); Adewole et al. (2017).	Cost-effective, specific strain selection, natural process, minimal equipment, enzyme production, and resistant to harsh conditions	Generally slow process, limited PFAS degradation, strain-specific, Scale-up challenges, longer treatment times, optimal conditions
Phytoremediation	Hemp: 14.3 µg/plant *Melilotus officinalis* successfully remediated copper and petroleum hydrocarbon-contaminated soil, while Salix species showed promise for PFAS removal	Wu (2021), Huff et al. (2020) Priya et al. (2023); Dutta et al. (2025).	Very low cost, sustainable, public acceptance, habitat restoration	Very slow, limited depth, seasonal variations, uptake limits
Synthetic Microbial Consortia	PET degradation by *Ideonella-Bacillus* co-culture; 85% heavy metal removal efficiency (various synthetic biology studies)	Synthetic biology and consortia engineering studies (2020–2025)	Engineered efficiency, controlled performance, synergistic effects	High complexity, containment issues, regulatory uncertainty
Nanobioremediation	Silica NPs + *Pseudomonas* for PAH removal; Bacterial NPs for Cd/Cr removal > 90% efficiency.	Chauhan et al. (2020)	Enhanced reactivity, targeted delivery, novel mechanisms	Nanoparticle toxicity, high costs, scale-up challenges
Advanced Oxidation (Fenton)	Nitrophenols: 50–100% mineralization; Combined with biodegradation, more effective (Goi 2005)	Goi (2005), Advanced oxidation processes studies. Gallego-Ramirez et al. 2024	Low-cost reagents, rapid treatment, proven technology	Iron requirements, pH sensitivity, and sludge generation
Advanced Oxidation (Ozonation)	Diesel contaminated soil remediation; Enhanced biodegradability and toxicity reduction (Goi 2005)	Goi (2005), Ozonation soil treatment studies	No waste generation, enhances biodegradability, versatile	High ozone costs, competing organic matter, and equipment needs
Electrokinetic Remediation	Chromium removal from contaminated soil; pH conditioning improved extraction (Jameel et al. 2024)	Priya et al. (2023), Jameel et al. (2024), Electrokinetic remediation reviews	Suitable for low-permeability soils, doesn't require excavation	Long treatment times, pH changes, and electrode maintenance

complex pollutants, including pharmaceuticals and industrial solvents (Renganathan et al. 2025).

Microbiome engineering modifies microbial communities to enhance pollutant degradation, recognizing that community structure impacts efficiency and degradation products, thus favoring optimization over natural assemblages (Xu and Jiang 2024). Bioaugmentation has shown significant success, with treated microbiomes exhibiting a high percentage of key degrading enzymes sourced from inoculated bacteria (Ruan et al. 2024). Engineered rhizosphere microbiomes provide diverse functions such as organic pollutant degradation and plant growth promotion, decreasing the need for chemical inputs (Xu and Jiang 2024). The combination of microbiome engineering with phytoremediation fosters synergies by improving environments for engineered microbes and enhancing plant contaminant tolerance and degradation efficiency (Kakde and Sharma 2024).

Nanobioremediation (NBR) combines nanotechnology with biological processes, leveraging biogenic nanoparticles from plants or microorganisms to improve contaminant removal efficiency. This approach overcomes traditional bioremediation limitations while ensuring environmental safety (Das et al. 2025). Mechanisms such as biosorption, bioaccumulation, biomineralization, and enzymatic reduction occur through plant-microorganism interactions, converting toxic substances into less harmful forms. Nanoparticles possess unique attributes such as high surface-to-volume ratios, enhanced reactivity, and targeted delivery, which enhance their effectiveness in environmental remediation (Pandey 2018).

Nanobioremediation has demonstrated success across diverse contaminant types. Silica nanoparticles combined with *Pseudomonas aeruginosa* and graphene oxide remove polycyclic aromatic hydrocarbons (PAHs). Magnetic nanoparticles immobilized with *Halomonas* species effectively degrade palladium metal contamination. Recent studies show that nano-biosorbents and nano-catalysts significantly enhance remediation efficiency compared to conventional approaches. The integration of nanobioremediation with other strategies, such as phytoremediation and chemical techniques, can enhance contaminant removal efficiency and manage complex pollution scenarios more effectively (Das et al. 2025).

Metagenomic analysis has emerged as a powerful tool for predicting degradation potential and optimizing bioremediation strategies. System-wide metagenomic approaches can predict microbial degradation by profiling community metabolic potential, including genes involved in pollutant degradation and key soil functions (Jeffries et al. 2018). Metagenome mining paired with bioinformatic predictions, structural modeling, and functional assays provides a powerful approach for discovering novel enzymes for soil remediation. Three novel enzymes (two dioxygenases and one peroxidase) identified through metagenomic approaches demonstrated efficiency in degrading naphthalene and phenanthrene, with enhanced capabilities for anthracene and pyrene degradation when combined with inorganic oxidants (Nagy et al. 2024).

Metaproteomics provides crucial insights into the functional and phylogenetic processes involved in biodegradation, enabling real-time assessment of microbial community responses to contamination. The study of proteins induced by contamination allows tracking of anthropogenically influenced processes at contaminated sites. Metabolomics combined with bioinformatics tools enables better understanding of microbial communities, their catabolic pathways, and genes responsible for encoding catabolic enzymes. Targeted and untargeted metabolomics using LC/MS/MS systems investigate reprogrammed metabolism underlying biofilm formation and pollutant degradation processes (Chandran et al. 2020).

Artificial intelligence and machine learning algorithms are revolutionizing bioremediation through enhanced prediction and optimization capabilities. AI analyzes vast datasets including genomic data, environmental parameters, and historical bioremediation outcomes to identify patterns and relationships that may elude traditional methods (Blessing & Olateru, 2025). AI-driven monitoring systems continuously collect data from contaminated sites, analyzing variables like microbial activity, pollutant concentrations, and environmental parameters to optimize remediation strategies in real-time. These systems enable dynamic bioremediation through reinforcement learning that adjusts treatment parameters based on real-time data (Singh et al. 2025). Biosensors integrated with IoT and AI provide rapid, on-site monitoring capabilities essential for preventing contamination spread and optimizing treatment efficiency. Smart biosensor systems enable real-time pollutant detection and detoxification, offering continuous monitoring crucial for large-scale applications (Huang et al. 2023). Nano-scale biosensors enable real-time monitoring of molecules with enhanced sensitivity and specificity. These devices can detect tiny molecules like drugs and environmental contaminants in real-time, offering significant improvements over conventional monitoring approaches (Thanigaivel et al. 2025). Smart biosensor systems integrate multiple sensing modalities with AI algorithms to provide comprehensive environmental monitoring capabilities. These systems offer rapid, on-site, and real-time monitoring essential for preventing contamination spread and optimizing remediation strategies (Huang et al. 2023).

Bioaugmentation

The growth of different pollutants continues to severely damage agroecosystems and jeopardizes the interactions between soil and plants. This issue is compounded by the presence of xenobiotic and non-degradable chemicals, which impose severe stress on plant life (Aguilar-Romero et al. 2022). The introduction of bioaugmentation offers a potential technique to alleviate adverse stresses within the soil ecosystem, hence minimizing the deleterious impacts on plants and strengthening the interactions between soil and vegetation, ultimately resulting in enhanced agricultural yields. Current research focuses on the acclimatization of microbial populations to certain toxins through laboratory trials, which aims to boost their efficacy upon introduction into aquatic systems (Aguilar-Romero et al. 2022). Findings suggest that ibuprofen was efficiently removed by 99% within a 21-day timeframe. The most notable microbes found using this in-situ remediation approach were *Flavobacterium* and *Fluviicola* from the Bacteroidetes phylum, *Thermomicrobia* from Chloroflexi, and *Nonomuraea* from Actinobacteria. While this technology exhibits substantial efficacy, it has obstacles in discovering uncommon microbes capable of digesting particular substances. Nonetheless, a novel iteration of the process involving aqueous extracts from specifically prepared bio-mixtures has solved this problem.

Soil management practices

Soil management procedures and soil management practices are crucial to reducing the consequences of developing pollutants on microbial diversity and functionality within the soil ecosystem. Enhancements in agricultural production and environmental protection can be realized by appropriate control of the rhizosphere microbiome (Lee et al. 2023). Despite its complexity, the interactions within the rhizosphere are crucial for maximizing plant development and production (Lee et al. 2023). Microbial communities contribute to crop improvement by boosting nutrient availability, providing defense against diseases, and promoting response to varied stresses. The usage of extremophilic microorganisms, which are capable of safely digesting harmful compounds in the soil, provides a promising technique for encouraging increased productivity in plant-soil systems.

Kumawat et al. (2022) underline the need-to-know microbiological processes to properly control these interactions and accomplish desired outcomes. Although the presence of pollutants in soil offers substantial obstacles, these issues may be handled by rigorous soil management procedures and practices. Recent breakthroughs in molecular methods have permitted better insights into the functioning of the rhizosphere microbiome and its control. The application of rhizosphere engineering permits the production of microbiomes that may digest certain contaminants, improve effective plant-soil communication, and boost agricultural productivity in Asia (Lu et al. 2023). Arbuscular mycorrhizal (AM) fungi, which display endurance under harsh environmental circumstances, have emerged as a sustainable method for enhancing agricultural yields. The regulation of nitrogen levels in soil and the prevention of root diseases, alongside improved plant yield through AM colonization, can largely be attributed to the enhancement of soil health, nutrient availability, increased phosphate solubilization, and the remediation of soil contaminants (Murali et al. 2021). A short treatment with *Fluopyram* significantly altered the rhizosphere of pepper plants, increasing the growth of several *Bacillus* and *Rhizobium* species linked with nutrient management and corresponding with increased growth of pepper. Additionally, recent research into microbial communities in sugarcane has revealed their substantial significance in the health and production of this crop (Aguilar-Romero et al. 2022).

Biofertilizers

Experts apply information regarding root-associated microorganisms and put plant growth-promoting rhizobacteria (PGPR) into fertilizers to promote the symbiotic connections between plants and soil, hence enhancing crop yields. Biofertilizers contain diverse PGPR, including blue-green algae, fungal mycorrhizae, *Azotobacter*, *Azospirillum*, *Pseudomonas* spp., *Bacillus* spp., and *Rhizobium*. These biofertilizers, often referred to as bioinoculants, impact soil dynamics through different methods, such as relieving stress, enhancing soil nutrients, controlling pathogenic bacteria, and altering phytohormonal activity. Overall, biological nitrogen fixation and the conversion of complex molecules into simpler nutrients considerably boost nutritional availability. The involvement of fertilization in this environment is crucial, since beneficial organisms like *Clostridium* and Arbuscular Mycorrhizal Fungi (AMR) contribute to these processes (Asadu et al. 2024).

Typically, biofertilizers are delivered as inocula and may be obtained from solid or liquid substrates. Recent breakthroughs in microbiology have brought glycerol and starch as protective agents for successful biofertilizer packaging before distribution. Empirical research reveals that biofertilizers can greatly improve soil nutrient profiles, particularly with trace elements that may be insufficient (Asadu et al. 2024). For example, silicon, which enhances plant stress resilience, is released from silicates through biodegradation facilitated by biofertilizers. Despite their efficacy, the adoption of biofertilizers remains limited due to challenges in selecting appropriate bacterial strains, the transient nature of live bacterial efficacy, and difficulties in assessing their suitability across varying environmental parameters such as temperature, pH, and salinity. High tolerated concentrations of different contaminants by soil enzymes in bioremediation is shown in Fig. 5. Additionally, concerns regarding the possible dangers linked with pathogenic or mutagenic microbes

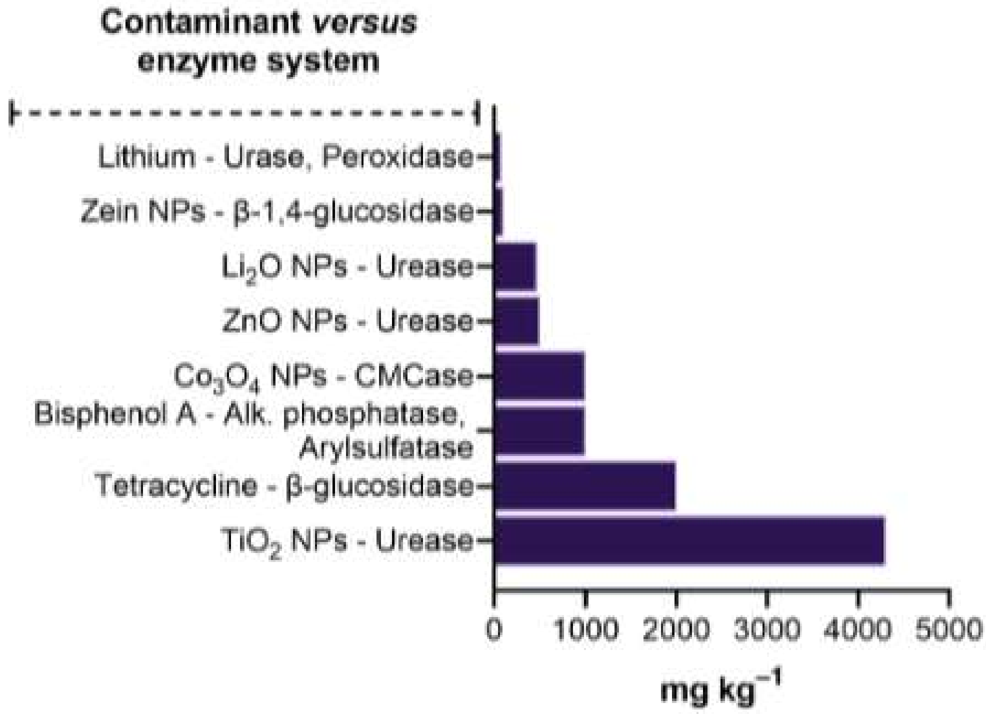

Fig. 5 High tolerated concentrations of different contaminants by soil enzymes in bioremediation. (NPs, nanoparticles; CMCase, Carboxy methyl cellulase) (Data from Ndikuryayo et al. 2025)

must be considered. Conversely, hybrid systems, including nano-biofertilizers, have emerged as viable answers to some of these difficulties (Mahapatra et al. 2022).

Knowledge Gaps and Future Perspectives

Despite progress in identifying many emerging contaminants (ECs), several pollutants remain poorly understood, notably regarding their prevalence, destination, and impacts in soils (Maddela et al. 2022). Novel medications, transformation products, and complex mixes of microplastics and nanomaterials are particularly understudied in terrestrial ecosystems (Chen et al. 2025). This gap hampers appropriate ecological risk assessment. Moreover, ECs seldom occur alone; soils generally include complex chemical combinations that may interact synergistically or antagonistically, affecting toxicity to soil microorganisms (Ramakrishnan et al. 2011). For example, simultaneous exposure to medicines and heavy metals might boost selection for antimicrobial resistance genes, whereas mixes of plasticizers and pesticides may adversely affect microbial metabolism. Future research should emphasize describing these lesser-known ECs and their combined effects, utilizing improved analytical and ecotoxicological tools to untangle these interactions. Understanding such synergistic impacts is vital for proper risk appraisal and appropriate remediation.

A fundamental difficulty in soil microbial ecology is demonstrating causal linkages between changes in microbial community composition and implications for soil ecosystem processes. Soil microbiota varies and is functionally redundant; therefore, alterations in taxonomic abundance may not necessarily translate into functional changes (Peddle et al. 2025). Additionally, microbial communities adjust dynamically to stressors like EC exposure through functional compensation and metabolic alterations, confounding estimates of impacts on nutrient cycling, organic matter breakdown, and pollutant degradation (Sarkar et al. 2021). Most investigations depend on correlative data from sequencing and enzyme tests, which do not completely disclose molecular pathways. Integrative techniques incorporating multi-omics (metagenomics, metatranscriptomics, metabolomics), stable isotope probing, and functional assays are needed to discover active bacteria and processes engaged in ecosystem functioning under contamination stress (Shah et al. 2024). Coupling microbiological data with soil physicochemical and plant response measurements will give a holistic knowledge of ecosystem-level consequences.

Traditional environmental risk assessment (ERA) frameworks rely on chemical concentrations and toxicity data from model species, sometimes disregarding the crucial functions of soil microbiota (Elsharkawy and Sharkawy 2025). Given the vital activities of microbial communities in soil health and ecosystem services, incorporating microbial ecological endpoints within ERA is imperative. This integration should incorporate microbial diversity, functional gene abundance, enzyme activity, and resistance gene prevalence as indicators of soil quality and pollutant effect. These microbial measurements can act as early warning signs of ecological alteration not detected by chemical analysis alone. Incorporating microbial data into prediction models can increase risk assessment accuracy by accounting for biodegradation potential and microbial adaptability. Achieving this need multidisciplinary collaboration among microbiologists, ecotoxicologists, chemists, and politicians to produce uniform microbial evaluation techniques and regulatory standards. Ultimately, this integration will boost environmental management, educate sustainable land-use plans, and safeguard soil ecosystems from rising contamination risks.

Conclusion

Emerging pollutants pose significant risks to soil health and disturb the symbiotic interactions between plants and soil, ultimately affecting global food security. These contaminants undermine soil fertility and adversely impact important microorganisms, resulting in a decrease in agricultural yield. Implementing strategies that focus on microbial control and the administration of low fertilizer levels may alleviate the harmful consequences of agricultural practices. Such solutions boost the resistance of plants against contamination while improving resource consumption. Nevertheless, there exists a scarcity of understanding addressing the implications of new pollutants within agricultural environments. Therefore, a coordinated strategy is vital to allow joint research activities that integrate policy breakthroughs with practical tactics for farmers to harness these improvements to their advantage.

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Declarations

Conflict of interests The authors declare no competing interests.

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