applied sciences

MDPI

Review

Harnessing Biotechnology for the Remediation of Organic Pollutants in Coastal Marine Ecosystems

Adenike A. Akinsemolu [1,2] and Helen N. Onyeaka [1,*]

[1] School of Chemical Engineering, University of Birmingham, Birmingham B15 2TT, UK; a.akinsemolu@bham.ac.uk
[2] The Green Institute, Ondo 351101, Nigeria
* Correspondence: h.onyeaka@bham.ac.uk

Abstract: The natural and biological processes of organisms offer significant potential for the removal and remediation of environmental contaminants including organic pollutants such as persistent organic pollutants (POPs) like polychlorinated biphenyls (PCBs), pesticides, herbicides, industrial chemicals, and pharmaceuticals. Biotechnology provides various approaches to detoxify or remove these pollutants from ecosystems through the use of microorganisms and plants. This review explores the application of biotechnology for the remediation of organic pollutants in coastal marine ecosystems. A thorough analysis of the existing literature highlights bioremediation methods, such as biostimulation, bioaugmentation, and bioattenuation, and phytoremediation methods, like phytoextraction, phytostabilization, phytovolatilization, phytodegradaton, and phytofiltration. as the most widely used techniques in biotechnology. While bioremediation has advanced substantially in fields such as electrochemistry, genetic engineering, and nanotechnology, there is still limited research on the compatibility and application of these technologies in phytoremediation. This paper therefore aims to examine biotechnological methods for tackling organic pollutants in coastal marine environments with an emphasis on the need for further research on enhancing phytoremediation through microbial inoculation and nanomaterial-assisted uptake.

Keywords: biotechnology; microorganisms; bioremediation; technology; marine ecosystems

check for updates

Academic Editor: Gyungsoon Park

Received: 22 May 2025
Revised: 7 June 2025
Accepted: 18 June 2025
Published: 19 June 2025

Citation: Akinsemolu, A.A.; Onyeaka, H.N. Harnessing Biotechnology for the Remediation of Organic Pollutants in Coastal Marine Ecosystems. *Appl. Sci.* **2025**, *15*, 6921. https://doi.org/10.3390/app15126921

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The coastal marine environment is a combination of vast and diverse ecosystems that are defined by their proximity and interaction with both the land and the ocean [1]. These environments include beaches, mangrove forests, coral reefs, wetlands, estuaries, and shallow coastal waters, which are all influenced by tides, currents, waves, and storms [2]. They serve as habitats for a variety of marine plants, animals and microorganisms that support essential ecosystem services such as climate regulation, food production and water purification [2]. Coastal ecosystems play an important role in climate regulation; many are classified as blue carbon ecosystems which include mangroves, seagrass meadows, and salt marshes that capture and store atmospheric carbon at rates significantly higher than terrestrial forests [1,3]. They help reduce the accumulation of greenhouse gases that contribute to global warming by sequestering carbon [4]. Additionally, these ecosystems support food security by providing accessible sources of protein, with over 10% of the global population depending on marine resources for sustenance [5,6].

However, these ecosystems are increasingly threatened by organic pollution which disrupts ecological balance and poses health risks to marine life and humans. Some studies

describe organic pollutants as biodegradable toxic molecular compounds broken down by microbial oxidation [7,8], while others define them as synthetic, non-biodegradable compounds that persist in the environment [9]. This conflict in definition is rooted in differing scientific perspectives on toxicity, biodegradability, and environmental persistence which can influence the selection of remediation strategies. For instance, pollutants classified as persistent may necessitate multi-stage bioremediation processes, whereas those considered readily biodegradable might be addressed through simpler microbial or enzymatic pathways. Despite this conflict in definition, most studies cite similar examples of organic pollutants that include herbicides, pesticides, petroleum hydrocarbons, industrial chemicals, pharmaceutical waste, and microplastic-associated contaminants [8]. The scientific interest in organic pollution has grown over recent decades with a focus on the identification, classification, environmental impact and remediation strategies of pollutants [10]. Bakiu et al. [11] categorized marine pollutants as either organic or inorganic and identified compounds such as antibiotics, hexachlorocyclohexane and polycyclic aromatic hydrocarbons (PAHs) as common organic pollutants in coastal ecosystems either in free form or bound to microplastics.

Traditional remediation methods are limited by high costs and ecological disruptions, and in order to address this, researchers are increasingly turning to biotechnology as a sustainable alternative. Biotechnology offers biologically driven solutions through mechanisms like biostimulation, biosurfactant production and bioaugmentation, which use and enhance microbial activity to degrade pollutants [12,13]. Aliko et al. [14] highlighted how microbial processes such as bioaccumulation, bioconcentration, and biomagnification are central to many biotechnological approaches used in coastal environments. Biotechnology also leverages natural biological processes that include enzymatic and metabolic pathways in microorganisms and plants for pollutant breakdown [15]. In addition, other biotechnology methods like phytoremediation and mycoremediation have emerged to offer complementary tools for pollutant removal. Phytoremediation employs microalgae and cyanobacteria, which can absorb and transform organic pollutants through biosorption, enzymatic degradation, and photosynthetic uptake. Their adaptability to saline conditions and high surface-area-to-volume ratios make them particularly effective in marine environments [16]. Mycoremediation, on the other hand, uses fungi and marine yeast strains such as *Yarrowia lipolytica* and *Candida tropicalis*, which produce extracellular enzymes like laccases and peroxidases capable of breaking down complex organic compounds in harsh environments [17].

Decades of innovation have led to the development of environmental biotechnology tools such as genetic engineering, cell manipulation and hydrogel-based delivery systems, which improve the efficiency and specificity of pollutant removal in saline and dynamic coastal conditions [15,18]. These tools enable the transformation of organic contaminants into less toxic or inert compounds, often with minimal disruption to the surrounding habitat.

Given the biodegradable nature of most organic pollutants, biotechnological methods, particularly those relying on microbial metabolism, have emerged as cost-effective, eco-friendly and adaptable alternatives to traditional remediation techniques [19]. This article reviews key categories of organic pollutants in coastal marine ecosystems and examines biotechnological advances like bioremediation and phytoremediation, highlighting their potential, limitations and opportunities.

2. Methodology

This review was conducted using a literature search to identify relevant studies on the biotechnological remediation of organic pollutants in coastal marine ecosystems. The

literature search was performed across multiple scientific databases, including Scopus, Web of Science, PubMed, Google Scholar and ScienceDirect. Keywords used include combinations of terms such as "bioremediation", "phytoremediation", "marine pollution", "organic pollutants", "coastal ecosystems", "microbial degradation", and "biotechnology for environmental remediation".

Inclusion criteria were as follows:

- Peer-reviewed articles published in English.
- Studies focusing on organic pollutants (e.g., hydrocarbons, pesticides, pharmaceuticals, microplastics) in coastal or marine environments.
- Articles discussing biotechnological approaches, such as bioremediation and phytoremediation.
- Publications from the last 15 years (2010–2025) were prioritized to ensure recent and relevant findings, although seminal works predating this period were also included when foundational to the topic.
- Reference lists of key publications were manually reviewed to identify additional sources.
- Data synthesis was thematic, emphasizing pollutant categories, microbial and phytoremediation mechanisms, limitations, and recent technological advancements.

3. Organic Pollution in Coastal Marine Ecosystems

The coastal marine ecosystem faces an ever-increasing threat from diverse organic pollutants that have both direct and indirect impacts on marine biodiversity and ecosystem health [11]. The organic pollutants present in coastal areas include numerous compounds such as persistent organic pollutants (POPs) like polychlorinated biphenyls (PCBs), pesticides, herbicides, industrial chemicals, pharmaceuticals, and polycyclic aromatic hydrocarbons (PAHs). These are dispersed in different sources, flowing into the marine ecosystem with surface runoff, sewage effluents, industrial effluents, urban stormwater runoff, or atmospheric deposition [20]. For instance, agricultural runoffs add enormous amounts of pesticides, herbicides, and fertilizers to the coastal aquatic environment, while industrial activities release higher amounts of PAHs and PCBs. Improper waste management and urbanization further worsen this by introducing untreated sewage and other organic contaminants into these ecosystems. Oil spills and sea activities also add hydrocarbons, which persist for longer durations in marine waters [21].

Organic pollutants have major ecological and biological impacts in marine environments and are harmful to individual organisms and the broader ecosystem. POP contaminants have high persistence and lipophilicity, so they accumulate in the fatty tissues of marine organisms, causing various toxic effects such as endocrine disruption, reproductive impairments, immunosuppression, and tumorigenic outcomes [22]. For instance, studies have associated the presence of PAHs with developmental abnormalities in fish larvae and an increase in the mortality rates of shellfish [23].

Biomagnification amplifies this impact because the contaminants are at higher trophic levels, which causes significant risk to apex predators and human populations relying on them for food [24]. Organic pollutants also create large-scale disturbances in an ecosystem, such as eutrophication, which is caused by excessive nutrient load via agricultural runoff and sewage effluents. Consequently, this leads to harmful algal blooms that reduce the amount of dissolved oxygen in the water and give rise to hypoxic or even anoxic conditions commonly referred to as "dead zones". Dynamic Equilibrium Theory suggests that ecosystems naturally attempt to balance such disturbances, but when pollutant influx surpasses the system's capacity for self-purification, equilibrium is lost, leading to ecosystem collapse. These conditions result in a great loss of biodiversity, shifted species compositions, and the collapse of essential ecosystem services [25].

However, many pollution sources are diffuse and non-point, making it very difficult to mitigate organic pollution from coastal ecosystems. For instance, agricultural runoff has numerous entry points into waterways, thus making it difficult to control. Another persistent problem is bioaccumulation. Organic pollutants easily accumulate and remain in marine ecosystems, posing threats for a long period of time after their introduction (Figure 1). Microbial succession plays a crucial role in natural remediation, where initial microbial colonizers degrade simple compounds while later successional species handle more complex organic contaminants. However, the efficiency of these microbial communities is often hindered by environmental fluctuations and pollutant toxicity.

Additionally, external factors such as climate change contribute to organic pollution dynamics. Changes in precipitation patterns and increased occurrences of erratic weather events affect the carrying and redistribution of pollutants into coastal waters. Dynamic Equilibrium Theory applies here as increased rainfall and flooding events introduce more contaminants into marine systems, surpassing natural self-regulation mechanisms and leading to ecological instability. This occurs when heavier rainfall events induced by climate change result in deeper surface runoff, increasing the influx of organic contaminants into marine systems [26].

The specific groups of organic pollutants in coastal marine ecosystems include the following sections.

3.1. Persistent Organic Pollutants (POPs)

POPs are a class of highly resistant chemical compounds that degrade slowly, hence bioaccumulating in marine organisms and biomagnifying through trophic levels [27]. They pose long-term ecological and human health risks. These pollutants are particularly concerning due to their global transport via ocean currents and atmospheric circulation. The main categories of POPs include polychlorinated biphenyls (PCBs) that are historically used as dielectric fluids in transformers, capacitors, and industrial lubricants. PCBs persist in sediments and accumulate in fatty tissues of marine species, leading to reproductive disorders, immune system suppression, and developmental abnormalities. Dioxins and furans are byproducts of industrial combustion and waste incineration; these toxic chemicals cause endocrine disruption, neurological damage, and carcinogenic effects in marine organisms [28]. Organochlorine pesticides (OCPs) like DDT, aldrin and dieldrin, which were once widely used in agriculture, still persist in marine environments despite bans, affecting predatory fish and marine mammals through biomagnification [29].

Polycyclic aromatic hydrocarbons (PAHs) are a major subclass of POPs. They are a group of complex organic compounds formed by the incomplete combustion of fossil fuels, biomass burning, and petrochemical spills [30,31]. They are among the most prevalent organic contaminants in coastal ecosystems due to their presence in crude oil, coal and tar; they are mutagenic and carcinogenic, hence posing serious threats to mankind [31]. PAHs can be classified into two categories: low-molecular-weight (LMW) PAHs (e.g., naphthalene, anthracene), which consist of 2- and 3-ring aromatic structures and are more water-soluble and acutely toxic to marine invertebrates and plankton, and high-molecular-weight (HMW) PAHs (e.g., benzo[a]pyrene, chrysene), consisting of 4- to 6-ring aromatic structures; they are more hydrophobic, persistent and prone to bioaccumulation, and they cause long-term carcinogenic and mutagenic effects in marine species [32].

PAHs are particularly dangerous in sediment-rich coastal environments where they bind to organic matter and affect benthic organisms [33]. Microbial Succession Theory plays a role in PAH degradation, as certain microbial communities with bacteria such as *Pseudomonas*, *Alcanivorax* and *Mycobacterium* species evolve over time to enhance their ability to metabolize these toxic compounds through dioxygenase-mediated pathways,

converting them into catechols and ultimately mineralizing them through central metabolic routes like the β-ketoadipate and TCA cycle.

3.2. Pharmaceutical and Personal Care Products (PPCPs)

PPCPs are an emerging class of organic contaminants originating from wastewater effluents, hospital discharge, and improper disposal of medications [34]. These pollutants include antibiotics (e.g., tetracyclines, fluoroquinolones) that disrupt microbial populations, leading to antibiotic resistance in marine microbiomes [35]; analgesics and anti-inflammatory drugs (e.g., ibuprofen, diclofenac) that accumulate in aquatic organisms and affect physiological functions [36]; and endocrine disruptors (e.g., synthetic estrogens, parabens), which alter hormonal balances in fish and invertebrates and leads to reproductive failure, feminization of male fish, and population decline [37].

3.3. Pesticides and Herbicides

Agricultural runoff and urban landscaping introduce various pesticides and herbicides into coastal marine ecosystems, where they persist in sediments and accumulate in marine organisms. The most concerning groups are organochlorine pesticides (OCPs); though banned in many countries, residues of DDT, chlordane, and heptachlor continue to be detected in marine sediments [38], disrupting endocrine functions in fish and birds.

Organophosphates (e.g., chlorpyrifos, malathion) can enter water bodies, particularly surface water, through various pathways, including irrigation effluents, industrial discharges, agricultural runoff, uncontrolled application, transport during rainfall, unintended spills, and waste from agricultural activities [39–41]. Widely used in modern agriculture, these neurotoxic compounds inhibit acetylcholinesterase in marine invertebrates and fish, leading to nervous system disorders [39]. Glyphosate and atrazine are common herbicides that disrupt photosynthesis in marine phytoplankton and seagrasses, altering primary production and food web dynamics [42].

Pesticides and herbicides contribute to large-scale disruptions such as eutrophication, harmful algal blooms, hypoxia, and biodiversity loss [43], ultimately influencing Microbial Succession Theory as affected microbial populations shift to favor pollutant-resistant species, often at the expense of ecological balance.

3.4. Microplastics and Synthetic Polymers

While not traditionally categorized as organic pollutants, microplastics and their associated chemical additives contribute significantly to marine pollution. These pollutants originate from primary microplastics that are manufactured as small particles (e.g., microbeads in personal care products, synthetic fibers from textiles), and secondary microplastics result from the breakdown of larger plastic debris due to UV radiation, wave action, and mechanical degradation [44].

Microplastics act as carriers for hydrophobic organic pollutants, such as PAHs and PCBs [45]; this facilitates their ingestion by marine organisms [46]. Examples are chemical additives such as bisphenol A (BPA), a known endocrine disruptor that leaches from polycarbonate plastics and affects reproductive health in marine species [47]. Additionally, environmental monitoring studies on BPA residues have shown that its presence in various natural aquatic systems can lead to harmful environmental impacts and contribute to metabolic syndrome [48]. However, BPA has been incorrectly evaluated in past risk assessments, often due to outdated toxicity thresholds or incomplete data on environmental persistence and bioaccumulation potential. Phthalates are used as plasticizers and these compounds disrupt hormone regulation and impair larval development in fish and crustaceans [49].

Microplastics further disrupt microbial community structure by serving as artificial substrates for biofilm formation [50], altering Community Assembly Theory in marine ecosystems, where pollutant-resistant bacteria thrive while sensitive species decline.

Table 1 summarizes major organic pollutants in coastal marine ecosystems and their impacts.

Figure 1 presents categorized data from the study by Vagi et al. [51], indicating that most studies focus on pharmaceuticals (28%), followed by pesticides and agrochemicals (24%), PAHs (21%), microplastics and plastic-derived chemicals (17%), and PCBs (10%).

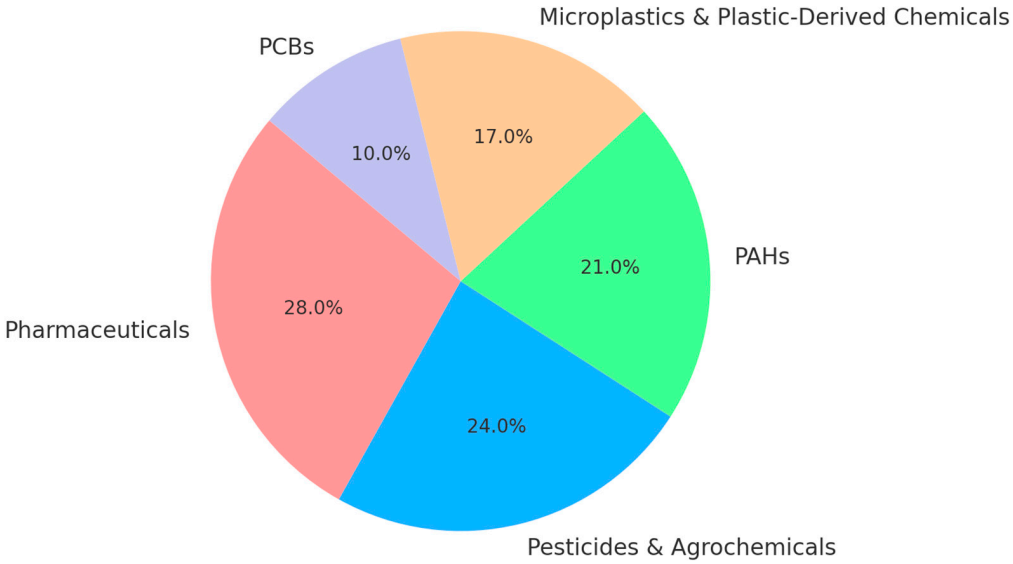


Figure 1. Distribution of research focuses on organic pollutants in coastal marine ecosystems based on the study by Vagi et al. [51].

Table 1. Major organic pollutants in coastal marine ecosystems and their impacts.

Category	Sources	Effects on Marine Ecosystems	References
Persistent Organic Pollutants (POPs)	Industrial chemicals (PCBs), combustion byproducts (dioxins, furans), pesticides (OCPs—DDT, aldrin, dieldrin). Incomplete combustion of fossil fuels, petrochemical spills, biomass burning.	Bioaccumulate and biomagnify, causing reproductive disorders, immune suppression, endocrine disruption. Mutagenic and carcinogenic; accumulate in sediments; affect benthic organisms; microbial degradation by *Pseudomonas* and *Alcanivorax*.	[22–33]
Pharmaceutical and Personal Care Products (PPCPs)	Wastewater effluents, hospital discharge, improper medication disposal.	Cause antibiotic resistance, physiological dysfunction in aquatic organisms, endocrine disruption leading to reproductive failure.	[34–37]
Pesticides and Herbicides	Agricultural runoff, urban landscaping, industrial discharge.	Endocrine disruption in fish and birds, nervous system disorders, disruption of photosynthesis in phytoplankton, leading to hypoxia and biodiversity loss.	[38–43]
Microplastics and Synthetic Polymers	Breakdown of plastic waste, microbeads in personal care products, synthetic fibers from textiles.	Act as carriers for pollutants like PAHs and PCBs; disrupt hormone regulation (e.g., BPA and phthalates); alter microbial community structures.	[44–50]

4. Biotechnological Methods for Remediation

Remediation refers to the set of procedures that remove, reduce or neutralize contaminants in the environment, bringing the affected ecosystems closer to their natural or near-natural state. In the case of coastal marine ecosystems, remediation has become important because it addresses the impacts that organic pollutants have on biodiversity by degrading ecological balance and utilizing ecosystem services. Traditional remediation techniques, including chemical and physical, can often be expensive and potentially contribute to secondary pollution; they are also poorly suited to their application in sensitive marine environments [52].

Biotechnology gives sustainable and eco-friendly alternatives in the remediation of organic pollutants. Biotechnological remediation takes advantage of biological systems such as microbes, plants, and enzymes to utilize organisms through natural processes of breaking down, transforming, or removing pollutants from the environment. This approach minimizes its impact on the environment and contributes towards making the entire remediation process much more effective. It is based on the use of biological processes to ameliorate environmental contamination, offering sustainable and eco-friendly alternatives to other remedial strategies. These methods comprise degradation, transformation, and removal of organic pollutants with efficiency, cost-effectiveness, and the least possible ecological disturbance. The major types of biotechnological remediation, such as bioremediation and phytoremediation, utilize the natural abilities of organisms to regenerate environments polluted in coastal marine ecosystems.

4.1. Bioremediation

Bioremediation, also referred to as microbial remediation, is the application of microbes such as bacteria, fungi and archaea to reduce organic pollutants into less harmful compounds. These microorganisms possess enzymatic systems that metabolize contaminants and often utilize them as carbon or energy sources [18]. Bioremediation is generally divided into approaches which are in situ or ex situ; in situ denotes remediation at the location of the contaminant, while ex situ transfers contaminants to other places for remediation. Considering the cost of transport, bioremediation of contaminants is preferentially conducted in situ [53]. Bioremediation is further divided into biostimulation, bioaugmentation, and bioattenuation.

Biostimulation involves the addition of nutrients such as nitrogen and phosphorus or the adjustment of environmental conditions like pH and oxygen levels to enhance the metabolic activity of indigenous microorganisms, thereby optimizing degradation processes [54]. For example, nitrogen-rich fertilizers are often applied during oil spill incidents to stimulate hydrocarbon-consuming bacteria. On the other hand, bioaugmentation involves introducing specific strains of microorganisms with superior pollutant-degrading abilities to contaminated sites [55]. This approach is particularly relevant when the indigenous microbial populations are insufficient or ineffective in degrading certain contaminants. In some cases, genetically engineered microbes are developed to target persistent organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), leading to their degradation [56].

The bioremediation of antibiotics is primarily facilitated by bacteria such as *Pseudomonas* spp., *Bacillus* spp., *Acinetobacter* spp. and *Streptomyces* spp. [57]. These microorganisms utilize peripheral metabolic pathways, including hydrolysis, oxidation and deamination, to break down antibiotic structures, making them more accessible for degradation. Once modified, central metabolic pathways, particularly the tricarboxylic acid (TCA) cycle, facilitate the complete mineralization of antibiotic derivatives, ensuring their removal from the environment.

Similarly, PCBs, which are persistent organic pollutants, are degraded by microorganisms such as *Burkholderia xenovorans*, *Pseudomonas putida*, and *Rhodococcus* spp. [58]. The primary peripheral pathway involved in PCB degradation is the biphenyl degradation pathway, where dioxygenase enzymes oxidize PCBs into chlorobenzoates [59]. These intermediates are subsequently processed through central metabolic pathways, including the β-ketoadipate pathway, which channels them into the TCA cycle for further breakdown. This mechanism is crucial for reducing the toxic effects of PCBs and preventing their accumulation in ecosystems.

In the case of PAHs, microbial degradation is primarily driven by microbes like *Mycobacterium vanbaalenii*, *Sphingomonas* spp., *Stenotrophomonas*, *Brevibacterium*, *Arthrobacter*, *Rhodococcus*, and *Pseudomonas aeruginosa* [60–62]. These bacteria initiate the degradation process through peripheral pathways involving dioxygenase enzymes, which convert PAHs into catechols and quinones [62]. These intermediates are then funneled into central pathways, such as the β-ketoadipate pathway or the TCA cycle, allowing for their complete mineralization. Since PAHs are highly hydrophobic and resistant to degradation [63], microbial bioremediation offers an effective strategy for their removal from contaminated environments.

Table 2 presents representative microorganisms involved in the bioremediation of various pollutants. It highlights the peripheral metabolic pathways used to break down contaminants.

Table 2. Representative microorganisms and metabolic pathways involved in bioremediation.

Pollutant	Representative Microorganisms	Peripheral Metabolic Pathways	Central Metabolic Pathways	References
Antibiotics	*Pseudomonas* spp., *Bacillus* spp., *Acinetobacter* spp., *Streptomyces* spp.	Hydrolysis, oxidation, deamination	Tricarboxylic acid (TCA) cycle	[57]
Polychlorinated Biphenyls (PCBs)	*Burkholderia xenovorans*, *Pseudomonas putida*, *Rhodococcus* spp.	Biphenyl degradation pathway (dioxygenase-mediated oxidation to chlorobenzoates)	β-ketoadipate pathway, TCA cycle	[58,59]
Polycyclic Aromatic Hydrocarbons (PAHs)	*Mycobacterium vanbaalenii*, *Sphingomonas* spp., *Pseudomonas aeruginosa*	Dioxygenase-mediated oxidation to catechols and quinones	β-ketoadipate pathway, TCA cycle	[60–62]

4.2. Phytoremediation Approaches

Phytoremediation refers to a mitigation technique in which plants, along with their associated soil microorganisms, carry out remediation of pollutant substances in order to reduce the toxic effects or concentration of the pollutants in the environment [63]. This technique utilizes plants to remediate contaminated media, including soil and water. It is favorable to the economy and environment as it utilizes green plants to absorb, accumulate, degrade, suppress, detoxify, or transform pollutants from contaminated soil and water [64,65]. Phytoremediation is a promising soil remediation technique as it has gained significant attention from various sectors due to how cost-effective, efficient and eco-friendly it is [66]. This method fits well into coastal ecosystems, where multifunctional vegetation, such as mangroves, seagrasses, and algae, play an important role [63]. The mechanisms underlying phytoremediation include the following:

a. Phytoextraction

Phytoextraction involves the absorption and accumulation of pollutants through the roots and their translocation to harvestable above-ground parts of the plants like the

leaves, stems and fruits [66,67]. This process is generally effective for removing both heavy metals and certain organic compounds from water and sediments. Aquatic plants such as water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna valdiviana* and *Spirodela polyrhiza*) and water lettuce (*Pistia stratiotes*) are known for their high biomass and ability to accumulate heavy metals and degrade organic pollutants in eutrophic and contaminated coastal waters [68–70]. The plants involved in phytoextraction can be used for other purposes like biofuel production or livestock feed, provided the toxins accumulated are safe [71].

b. Phytodegradation (Phytotransformation)

Phytodegradation refers to the breakdown of contaminants within plant tissues through metabolic processes or by rhizospheric microbial communities [65]. Plant release enzymes such as peroxidases dehalogenases and laccases play a critical role in converting toxic substances into less harmful metabolites. Degradation of contaminants in the rhizosphere is known as rhizodegradation [72]. Pesticides are one type of organic pollutants that can be remediated through degradation or transformation by various plant parts. Plant parts can play a crucial role directly or indirectly in the phytodegradation process: in the direct process, plants absorb the contaminants, break them down into less harmful compounds, and distribute them within plant tissue [72]. This process is particularly beneficial for treating xenobiotic compounds like pesticides, polycyclic aromatic hydrocarbons (PAHs), and trichloroethylene. Mangrove species like *Avicennia marina* and terrestrial plants such as *Vetiveria zizanioides* (vetiver grass) have been shown to degrade hydrocarbons, pesticides and phenolic compounds in coastal zones through this mechanism [73], while plants such as *Tegetes patula*, *Ipomea balsamina*, and *Mirabilis jalapa* have been widely used for their ability to degrade chlorinated solvents and hydrocarbons, transforming them into non-toxic chemicals in groundwater and soil environments [72]. The presence of rhizospheric microbes further enhances degradation through synergistic interactions.

c. Phytostabilization

Phytostabilization involves the immobilization of contaminants, especially heavy metals within the soil matrix or plant root systems. This mechanism is crucial in preventing the spread of contaminants in sediments [74]. This process operates through mechanisms such as adsorption, precipitation and complexation within the rhizosphere [72,75]. For instance, plants like *Arabidopsis arenosa*, *Deschampsia cespitosa*, *Silene vulgaris*, *Zea mays*, and *Brassica napus* [76,77] have demonstrated efficacy in reducing the bioavailability of heavy metals like lead (Pb), zinc (Zn), and cadmium (Cd) by forming stable complexes in the root zone [67]. Enhancement of phytostabilization can be achieved through soil amendments, including organic matter, biochar, and microbial inoculants [78]. These amendments improve soil structure, pH, and microbial activity, which further help in immobilizing contaminants. For example, the addition of spent mushroom compost and attapulgite has been shown to improve soil pH and fertility [79,80], enhancing the phytostabilization capacity of plants like *Koelreuteria paniculata,* which also modulates the rhizospheric microbial community to favor beneficial fungi [81].

d. Phytovolatilization

Phytovolatilization involves the uptake of contaminants by plants, their transformation into volatile forms, and subsequent release into the atmosphere. This mechanism involves various steps: the plants first absorb the contaminants from the soil, transform the volatile or semi-volatile chemicals into more volatile forms, and then release the contaminants to the atmosphere through plant transpiration via the leaves [67,72]. This method is particularly applicable to elements like selenium (Se), mercury (Hg) and arsenic (As) [81]. Plants such as

Brassica juncea and *Brassica oleracea* have been used for the volatilization of selenium [82,83], while *Polypogon monspeliensis* has been employed for arsenic [72].

Phytovolatilization can occur through direct pathways, where contaminants are absorbed and volatilized via transpiration, or indirect pathways, where root activity enhances the volatilization of subsurface contaminants [79]. Factors influencing this process include plant species, contaminant properties, and environmental conditions. For example, poplar trees (*Populus* spp.) have been used to volatilize trichloroethylene (TCE), a common groundwater contaminant, by absorbing it through roots and releasing it as a less toxic vapor [84].

e. Phytofiltration

Phytofiltration is the use of plant roots (rhizofiltration), shoots (caulofiltration), or seedlings (blastofiltration) to remove contaminants from aqueous environments [67]. In rhizofiltration, plants absorb, adsorb, and precipitate pollutants like heavy metals from water through their root systems [72,85]. Aquatic plants such as *Eichhornia crassipes* (water hyacinth), *Typha angustifolia* (narrowleaf cattail) and *Salvinia natans* have shown significant potential in removing metals like cadmium (Cd), lead (Pb) and mercury (Hg) from contaminated water bodies [86,87]. Terrestrial plants such as *B. Juncea* and *H. Annus* are also popularly used for rhizofiltration due to their longer and hairy root systems. After these plants are saturated with the pollutants, they are harvested and disposed of [67].

The efficiency of rhizofiltration is influenced by factors such as root surface area, plant growth rate, and the presence of root exudates that can alter the pH and redox conditions of the rhizosphere, facilitating metal precipitation and immobilization [88]. For instance, *Typha angustifolia* has demonstrated the capacity to accumulate substantial amounts of Cd and Zn, making it an effective candidate for treating industrial wastewater [86].

4.3. Limitations and Challenges of Bioremediation and Phytoremediation in Marine Environments

a. Environmental Constraints

Marine environments are highly dynamic and often present extreme conditions that can hinder the process of biological remediation. The outcomes of the bioremediation can be dependent on physical variables at the site which include pH, temperature, oxygen and availability of nutrients [89]. High salinity levels can inhibit microbial metabolic activity, especially for non-halotolerant species, hence reducing the efficiency of biodegradation [90]. Likewise, changes in temperature and pH can affect the enzymatic activity of both microorganisms and plants, which in turn disrupts key metabolic pathways [91]. Furthermore, reduced oxygen levels, especially in eutrophic or hypoxic zones, create hypoxic or anoxic conditions and impact the composition and activity of microbes, limiting aerobic degradation processes, which compels the use of anaerobic or facultative microbial strains [92] that may be less efficient or slower-acting.

b. Limited Bioavailability of Pollutants

Chemical factors like the quantity and type of contaminants, the presence of surfactants, and the accessibility of sources of carbon and nitrogen influence bioremediation [93]. Many organic pollutants, especially hydrophobic compounds like PAHs and PCBs, bind tightly to sediment particles due to their low water solubility and hydrophobic nature; pollutants like PAHs tightly adhere to sediments, which leads to accumulation in coastal and deep sediments [33], or are sequestered in microenvironments where microbial and plant access is restricted. This limited bioavailability severely reduces the rate and extent of degradation, even in the presence of highly capable degrading organisms. Innovative delivery systems or surfactants may be required to improve pollutant solubility and accessibility, but these additions may alter the ecosystem or require further remediation themselves.

c. Potential Formation of Toxic Intermediates

One of the under-explored risks of biological remediation is the in complete degradation of complex pollutants, which leads to the formation of toxic intermediates [94]. For example, during the microbial breakdown of PAHs or PCBs, partially oxidized products (e.g., chlorobenzoates, quinones) may exhibit greater toxicity or persistence than the parent compounds. If these intermediates accumulate due to metabolic bottlenecks or unfavorable environmental conditions, they may pose additional risks to marine organisms and human health.

d. Compatibility with Native Species and Ecological Balance

The introduction of non-native microbial strains or engineered organisms through bioaugmentation or genetic modification raises concerns about potential ecological disruptions, such as the outcompeting of native microbial communities or horizontal gene transfer [95]. Similarly, the use of fast-growing plants in phytoremediation, especially invasive species like *Eichhornia crassipes* (water hyacinth), may alter the natural balance of coastal vegetation and disrupt local biodiversity [96]. While these plants can effectively remove pollutants, they can also displace native vegetation, alter water flow, and negatively impact wildlife due to their rapid growth and spread.

e. Economic and Regulatory Constraints

Deploying biotechnological solutions in marine environments often involves significant upfront costs, especially when incorporating advanced technologies such as bioelectrochemical systems, genetically engineered microbes, or nanomaterials. Moreover, infrastructure limitations, especially in low- and middle-income coastal nations, impede long-term implementation and environmental monitoring. The regulatory frameworks for releasing GMOs or engineered systems into open marine settings remain unclear or restrictive in many regions; this poses challenges for the research and development of marine genetic engineering, limiting practical adoption despite scientific feasibility [97].

5. Current Advances in Biotechnological Remediation

Specific biotechnological techniques for the remediation of organic pollutants in coastal marine ecosystems have been extensively explored and documented in the literature. These approaches have increasingly benefited from advances in related fields such as genetic engineering, synthetic biology, nanotechnology, and environmental genomics, which have significantly improved remediation efficiency and adaptability to marine environments [15,18,98]. One of the most well-studied techniques is bioremediation, which uses microbial systems to break down or transform organic pollutants into less harmful compounds. This process may involve complete mineralization, partial degradation, or immobilization of the contaminants.

Effective bioremediation depends on several factors: (a) the characterization and proliferation of microbial communities; (b) contact between microbes and pollutants; (c) adequate microbial biomass; and (d) optimal environmental conditions such as nutrient availability, oxygen, salinity, and temperature [11]. Mechanisms such as biosorption, bioaccumulation, precipitation, and enzymatic conversion (e.g., via dioxygenases, hydrolases, dehalogenases) are commonly employed by microbial consortia. These systems are valued for their precision, low ecological impact, and compatibility with environmentally sensitive marine zones [13,98,99].

5.1. Advances in Bioremediation

a. Genetic and Metabolic Engineering: Techniques such as CRISPR-Cas9 and recombinant DNA technology have been used to engineer strains of *Pseudomonas*, *Burkholderia*

and *Alcanivorax* with enhanced degradation efficiency and stress tolerance [100,101]. These engineered microbes can degrade persistent compounds like PAHs and PCBs even under harsh marine conditions.

b. Synthetic Biology: Engineered microbial consortia now include synthetic operons, quorum-sensing circuits and pollutant-responsive promoters, which enable coordinated and pollutant-triggered degradation [102,103]. Moreover, biosensors developed from synthetic biology tools can monitor contaminant levels and remediation performance in situ [103].

c. Nanotechnology: Nanoparticles such as iron oxides, carbon nanotubes and silver nanoparticles are used to improve adsorption and delivery of microbial inocula. These are often embedded in hydrogel matrices made from marine-compatible polymers like alginate and chitosan, which protect microbes from environmental stress while enhancing pollutant interaction [104,105].

d. Bioelectrochemical Systems (BESs): BES technologies such as microbial fuel cells (MFCs) combine microbial activity with electron flow mechanisms to enhance the oxidation and reduction of organic pollutants. These systems are especially effective for degrading petroleum hydrocarbons by boosting electron transfer between microbes and electrodes, hence improving reaction rates and system control [106,107].

e. Metagenomics and Bioinformatics: High-throughput metagenomic sequencing and bioinformatic analyses allow for the discovery of novel pollutant-degrading genes, the design of custom microbial consortia and the monitoring of microbial succession and pollutant breakdown in real time [99].

These microbial innovations support precise and scalable remediation strategies with reduced ecological risk. Table 3 summarizes several key studies documenting the application of these technologies.

5.2. Advances in Phytoremediation

a. Microbial Inoculation: Bioaugmentation of plant roots with beneficial microbes such as *Bacillus* and *Rhizobium* enhances degradation capacity and stress resilience [108].

b. Nanomaterial-Assisted Phytoremediation: Nanomaterials like metal oxide nanoparticles, biochar-based composites and nanoscale zero-valent iron have emerged as powerful tools in phytoremediation. They help in phytoremediation by removing pollutants, improving pollutant uptake, facilitating enzyme activity and stimulating root exudates that attract pollutant-degrading bacteria [109]. For example, nanoparticles can bind to pollutants, making them easier for plants to absorb. They can also deliver pollutants to specific parts of the plant such as the roots or leaves. However, the use of nanotechnology in phytoremediation is still in its early stages but it has the potential to make it more effective and efficient [110].

c. Genetic Improvements: Genetic modifications have been used to enhance traits such as heavy metal tolerance, root depth, exudate diversity, and enzymatic degradation capacity [111]. An example is the use of engineered Indian mustard (*Brassica juncea*) to tolerate lead uptake and clean contaminated soil. However, the release of genetically modified plants into natural environments raises ethical and regulatory concerns [110].

d. Development and Enhancement of Hyperaccumulator Plants: Hyperaccumulator plants have the natural ability to absorb and accumulate high levels of heavy metals in their tissues; hence, they are ideal for phytoremediation, and they can be used for the removal of heavy metals from contaminated soil and water bodies. Selective breeding, tissue culture and genetic modification have been employed by researchers to enhance or improve hyperaccumulator plant abilities for practical application.

However, their use is only applicable in specific soil or waters and may pose environmental risks including the reintroduction of metals into food chains through plant biomass [110].

e. Artificial Intelligence and Smart Monitoring: The application of artificial intelligence (AI) and remote sensing technologies offers a data-driven approach to phytoremediation management. AI algorithms can model contaminant dispersion, forecast plant growth, and optimize species selection, while drones and satellite imagery allow real-time monitoring of pollutant reduction, biomass accumulation, and vegetation health across large-scale remediation sites [110].

Despite these advances, phytoremediation research still focuses more heavily on inorganic pollutants and freshwater systems, with limited studies targeting organic pollutants in saline marine contexts. Nonetheless, the potential of coastal plants remains untapped and is a promising direction for future work [112,113]. Table 3 provides a comparative overview of key research studies focusing on how various biotechnological applications are used to remediate organic pollutants.

Table 3. Key studies on the application of biotechnology in organic pollutant remediation.

Biotechnological Application	Outcome	Challenges	Study
Bioremediation	The identification of effective bioremediation techniques, including biostimulation, bioaugmentation, and the use of biosurfactants	Environmental factors that affect microorganisms	Rahmati et al. [12]
The use of genetically engineered microorganisms for bioremediation	The validation of the effectiveness of microorganisms in the remediation of pollutants	The potential negative effects of genetically engineered microorganisms on the environment and human health	Rafeeq et al. [56]
Bioremediation	The identification of effective remediation techniques and characterization of pollutants in marine ecosystems		Aliko et al. [14]
Phytoremediation	The confirmation of the viability of the effectiveness of the use of bacteria inoculants in enhancing plants' capacity for the remediation of organic pollutants	The potential for causing further damage to the ecosystem	Girolkar, Thawale and Juwarkar [8]
Phytoremediation	A comprehensive evaluation of phytoremediation approaches	Negligible capacity for some plants to remediate pollutants	Sharma et al. [114]

6. Critical Analysis of Phytoremediation vs. Microbial Remediation

Both phytoremediation and bioremediation represent promising biotechnological strategies for addressing organic pollution in coastal marine ecosystems. However, their mechanisms, scope, and effectiveness vary considerably depending on pollutant type, environmental conditions, and scale of application. A critical comparison of these two approaches reveals complementary strengths and limitations.

6.1. Effectiveness

Bioremediation typically offers faster degradation rates and a broader metabolic capacity for diverse organic pollutants. Microorganisms such as *Pseudomonas*, *Rhodococcus*,

and *Sphingomonas* can metabolize complex compounds like PAHs, PCBs, and antibiotics through specific enzymatic pathways (e.g., dioxygenase-mediated oxidation, biphenyl degradation). These processes often result in complete mineralization, especially under optimized conditions. Phytoremediation, although generally slower, is effective for pollutants present in surface waters and sediments, especially when used in constructed or natural wetland systems. Plants such as *Eichhornia crassipes*, *Lemna minor*, and mangrove species can extract, change, or stabilize organic contaminants. Phytoremediation has a lot of advantages for large-scale, shallow, and low-energy environments where rooted vegetation can establish over time.

6.2. Limitations

Each technique faces context-specific challenges. Bioremediation is sensitive to environmental fluctuations such as salinity, temperature, oxygen availability, and pH, which can suppress microbial metabolism or viability. Additionally, bioaugmentation with non-native microbes poses ecological risks, while biostimulation requires precise nutrient and environmental management. Phytoremediation faces limitations in terms of plant species selectivity, root depth, and pollutant specificity. It is often ineffective in degrading highly persistent compounds and may result in the accumulation of toxic intermediates in plant tissues or sediments. Furthermore, seasonal growth patterns and biomass harvesting requirements limit its year-round applicability and scalability in some regions.

7. Future Directions in Biotechnological Approaches

As deduced above, the integration of technological advancements in biotechnology and related fields such as nanotechnology and electrochemistry has received a lot of attention. Consequently, future directions in bioremediation will likely feature further integration with these fields. For instance, a novel genome-editing tool was discovered recently [85]. The tool has been used successfully in the manipulation of genes in microorganisms such as bacteria to adapt them for the reconstitution of compromised immune systems. Its capacity for the manipulation of the genes of microorganisms could be harnessed to improve their resilience for survival in aquatic environments, enhance their capacity for the adsorption of organic pollutants, or increase their toxicity to multiple pollutants. Genetic engineering could be adopted to manipulate the genes of plants to enhance their ability to absorb and immobilize organic pollutants. Furthermore, plant–microbe synergies could be leveraged through engineered holobionts, where genetically enhanced plants and tailored microbial communities operate hand in hand to establish highly efficient remediation systems. These rhizosphere-based interactions can be strengthened using synthetic operons or stress-resilient microbial strains designed to thrive in saline and nutrient-limited marine environments.

Similarly, recent advancements in hydrogel technology have yielded hydrogel-based microorganisms [115]. In the future, this technology could be adapted for remediation through the integration of organisms with the capacity to remediate organic pollutants with hydrogels made from materials that are adapted for coastal marine ecosystems through properties such as enhanced mechanical strength, resilience in different temperatures and acidity levels, and large surface areas.

Finally, advancements in nanotechnology could be adapted in the future to improve the capacity of plants for remediation. For instance, novel nanoparticles could be used to enhance the biochemical and physiological properties and functions that enable plants to perform phytoremediation [100]. These nanomaterials could also serve as interfaces for dual-delivery platforms, simultaneously aiding microbial inoculation and pollutant solubilization, and enabling co-metabolic pollutant breakdown in integrated plant–microbe

systems. Moreover, AI and remote sensing tools offer transformative potential for remediation planning and monitoring. AI algorithms can be employed to optimize plant–microbe pairing, model contaminant dispersion, and forecast phytoremediation outcomes under variable marine conditions. Meanwhile, drones and satellite imagery allow real-time assessment of pollutant reduction, biomass growth, and ecosystem health across large remediation zones.

Conclusively, the future of bioremediation lies in advancements in genetic engineering, synthetic biology, and bioelectrochemical systems, which can improve microbial resilience and degradation efficiency. Metagenomic profiling of microbial communities also allows for the selection and enhancement of pollutant-specific consortia. Phytoremediation holds promise through plant–microbe symbioses, bioinoculation and nanomaterial-assisted phytotransformation, which can significantly improve pollutant uptake and degradation. The integration of microbial consortia into the rhizosphere of phytoremediating plants creates a synergistic remediation system, enhancing both stability and efficiency.

8. Conclusions

Biotechnology presents effective and sustainable solutions for addressing organic pollution in coastal marine ecosystems. Among these, bioremediation stands out as a well-established approach that leverages the natural metabolic capabilities of microorganisms to absorb and transform pollutants into less toxic or harmless forms. This technique is cost-effective, environmentally friendly and especially beneficial when using native microbial communities, which minimizes the risk of ecological disruption and secondary pollution. Similarly, phytoremediation offers a low-cost and ecologically sound alternative that utilizes plants to extract, stabilize or degrade organic pollutants. While promising, its application in marine environments remains limited due to challenges related to salinity tolerance, uptake efficiency, and scalability. Nonetheless, both microbial and plant-based techniques can be significantly enhanced through emerging biotechnologies, including nanotechnology, hydrogel encapsulation, electrochemical systems and genetic engineering. These technologies improve pollutant bioavailability, microbial activity, and plant resilience under marine environmental stresses.

Despite their potential, current applications face notable challenges, which include environmental variability, limited pollutant bioavailability, the formation of toxic intermediates, and regulatory challenges for deploying engineered organisms in open systems. Addressing these challenges requires interdisciplinary research, field-scale validation and the development of policy frameworks that support the safe and effective use of biotechnology in marine environments.

Looking forward, the integration of microbial and phytoremediation strategies supported by advanced biotechnological tools offers a scalable, adaptive and sustainable path for the remediation of organic pollutants. Continued innovation, coupled with collaborative efforts among scientists, policymakers, and local stakeholders, will be key to unlocking the full potential of biotechnology in protecting and restoring coastal marine ecosystems.

Author Contributions: A.A.A.: writing—conceptualization, writing, review and editing, supervision and validation. H.N.O.: writing—conceptualization, writing, review and editing, supervision and validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank V.W. Ogundero and F.A. Akinyosye for their unwavering support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Hilmi, N.; Chami, R.; Sutherland, M.D.; Hall-Spencer, J.M.; Lebleu, L.; Benitez, M.B.; Levin, L.A. The Role of Blue Carbon in Climate Change Mitigation and Carbon Stock Conservation. *Front. Clim.* **2021**, *3*, 710546. [CrossRef]
2. Piccolo, M.C. Effects of rainfall extreme events on coastal marine ecosystems. In *Precipitation: Earth Surface Responses and Processes*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 261–285. [CrossRef]
3. Liu, J.; Failler, P.; Ramrattan, D. Blue carbon accounting to monitor coastal blue carbon ecosystems. *J. Environ. Manag.* **2024**, *352*, 120008. [CrossRef] [PubMed]
4. Bandilla, K.W. Carbon capture and storage. In *Future Energy: Improved, Sustainable and Clean Options for Our Planet*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 669–692. [CrossRef]
5. Nayak, N.; Mehrotra, R.; Mehrotra, S. Carbon biosequestration strategies: A review. *Carbon Capture Sci. Technol.* **2022**, *4*, 100065. [CrossRef]
6. Taylor, S.F.W.; Roberts, M.J.; Milligan, B.; Ncwadi, R. Measurement and implications of marine food security in the Western Indian Ocean: An impending crisis? *Food Secur.* **2019**, *11*, 1395–1415. [CrossRef]
7. Guo, W.; Pan, B.; Sakkiah, S.; Yavas, G.; Ge, W.; Zou, W.; Tong, W.; Hong, H. Persistent Organic Pollutants in Food: Contamination Sources, Health Effects and Detection Methods. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4361. [CrossRef]
8. Girolkar, S.; Thawale, P.; Juwarkar, A. Bacteria-assisted phytoremediation of heavy metals and organic pollutants: Challenges and future prospects. In *Bioremediation for Environmental Sustainability: Approaches to Tackle Pollution for Cleaner and Greener Society*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 247–267. [CrossRef]
9. Ufarté, L.; Laville, É.; Duquesne, S.; Potocki-Veronese, G. Metagenomics for the discovery of pollutant degrading enzymes. *Biotechnol. Adv.* **2015**, *33*, 1845–1854. [CrossRef]
10. Avellan, A.; Duarte, A.; Rocha-Santos, T. Organic contaminants in marine sediments and seawater: A review for drawing environmental diagnostics and searching for informative predictors. *Sci. Total Environ.* **2022**, *808*, 152012. [CrossRef]
11. Bakiu, R.; Roncarati, A.; Kamberi, E. Editorial: Inorganic and organic pollutants in marine and coastal environments. *Front. Mar. Sci.* **2023**, *10*, 1245833. [CrossRef]
12. Rahmati, F.; Lajayer, B.A.; Shadfar, N.; van Bodegom, P.M.; van Hullebusch, E.D. A Review on Biotechnological Approaches Applied for Marine Hydrocarbon Spills Remediation. *Microorganisms* **2022**, *10*, 1289. [CrossRef]
13. Kuppan, N.; Padman, M.; Mahadeva, M.; Srinivasan, S.; Devarajan, R. A comprehensive review of sustainable bioremediation techniques: Eco friendly solutions for waste and pollution management. *Waste Manag. Bull.* **2024**, *2*, 154–171. [CrossRef]
14. Aliko, V.; Multisanti, C.R.; Turani, B.; Faggio, C. Get rid of marine pollution: Bioremediation an innovative, attractive, and successful cleaning strategy. *Sustainability* **2022**, *14*, 11784. [CrossRef]
15. Ezeonu, C.S.; Tagbo, R.; Anike, E.N.; Oje, O.A.; Onwurah, I.N.E. Biotechnological Tools for Environmental Sustainability: Prospects and Challenges for Environments in Nigeria—A Standard Review. *Biotechnol. Res. Int.* **2012**, *2012*, 450802. [CrossRef] [PubMed]
16. Encarnação, T.; Ramos, P.; Mohammed, D.; McDonald, J.; Lizzul, M.; Nicolau, N.; da Graça Campos, M.; Sobral, A.J. Bioremediation using microalgae and cyanobacteria and biomass valorisation. In *Marine Organisms: A Solution to Environmental Pollution? Uses in Bioremediation and in Biorefinery*; Springer International Publishing: Cham, Switzerland, 2023; pp. 5–28.
17. Mohammed, D.; Alaoui, H.E.; Ghaffour, N.E. Biodegradation of environmental pollutants by marine yeasts. In *Marine Organisms: A Solution to Environmental Pollution? Uses in Bioremediation and in Biorefinery*; Springer International Publishing: Cham, Switzerland, 2023; pp. 79–91.
18. Bala, S.; Garg, D.; Thirumalesh, B.V.; Sharma, M.; Sridhar, K.; Inbaraj, B.S.; Tripathi, M. Recent Strategies for Bioremediation of Emerging Pollutants: A Review for a Green and Sustainable Environment. *Toxics* **2022**, *10*, 484. [CrossRef]
19. Barone, G.D.; Rodríguez-Seijo, A.; Parati, M.; Johnston, B.; Erdem, E.; Cernava, T.; Zhu, Z.; Liu, X.; Axmann, I.M.; Lindblad, P.; et al. Harnessing photosynthetic microorganisms for enhanced bioremediation of microplastics: A comprehensive review. *Environ. Sci. Ecotechnology* **2024**, *20*, 100407. [CrossRef] [PubMed]
20. Alkhadher, S.A.A.; Suratman, S.; Zakaria, M.P. Occurrence and assessment of organic pollutants residues in the aquatic environment of the coastal sediments. *Sustainability* **2023**, *15*, 8365. [CrossRef]
21. Müller, A.; Österlund, H.; Marsalek, J.; Viklander, M. The pollution conveyed by urban runoff: A review of sources. *Sci. Total Environ.* **2020**, *709*, 136125. [CrossRef]
22. Camacho-Jiménez, L.; González-Ruiz, R.; Yepiz-Plascencia, G. Persistent organic pollutants (POPs) in marine crustaceans: Bioaccumulation, physiological and cellular responses. *Mar. Environ. Res.* **2023**, *192*, 106184. [CrossRef]
23. D'aGostino, F.; Bellante, A.; Quinci, E.; Gherardi, S.; Placenti, F.; Sabatino, N.; Buffa, G.; Avellone, G.; Di Stefano, V.; Del Core, M. Persistent and emerging organic pollutants in the marine coastal environment of the Gulf of Milazzo (Southern Italy): Human health risk assessment. *Front. Environ. Sci.* **2020**, *8*, 117. [CrossRef]
24. Saidon, N.B.; Szabó, R.; Budai, P.; Lehel, J. Trophic transfer and biomagnification potential of environmental contaminants (heavy metals) in aquatic ecosystems. *Environ. Pollut.* **2023**, *340*, 122815. [CrossRef]

25. Lan, J.; Liu, P.; Hu, X.; Zhu, S. Harmful algal blooms in eutrophic marine environments: Causes, monitoring, and treatment. *Water* **2024**, *16*, 2525. [CrossRef]
26. Ochs, C.; Garrison, K.; Saxena, P.; Romme, K.; Sarkar, A. Contamination of aquatic ecosystems by persistent organic pollutants (POPs) originating from landfills in Canada and the United States: A rapid scoping review. *Sci. Total Environ.* **2024**, *924*, 171490. [CrossRef]
27. Zacharia, J.T. Degradation pathways of persistent organic pollutants (POPs) in the environment. In *Persistent Organic Pollutants*; IntechOpen: London, UK, 2019; pp. 17–30.
28. Mudhoo, A.; Thayalan, G.; Muthoora, N.J.; Muthoora, M.N.; Oozeer, B.Z.; Rago, Y.P.; Ramphul, M.P.; Valaydon, A.K.; Kumar, S. Dioxins and furans: Sources, impacts and remediation. In *Pollutant Diseases, Remediation and Recycling*; Springer: Cham, Switzerland, 2013; pp. 479–541.
29. Girones, L.; Palacios, P.; Oliva, A.L.; Marcovecchio, J.E.; Arias, A.H. Organochlorine pesticides (OCPs) in coastal marine environments: Levels, fate, behavior, and effects on biota. In *Marine Environments: Diversity, Threats and Conservation*; Nova Science Publishers: Hauppauge, NY, USA, 2020; pp. 143–198.
30. Neff, J.M. *Bioaccumulation in Marine Organisms: Effect of Contaminants from Oil Well Produced Water*; Elsevier: Amsterdam, The Netherlands, 2002.
31. Patel, A.B.; Shaikh, S.; Jain, K.R.; Desai, C.; Madamwar, D. Polycyclic aromatic hydrocarbons: Sources, toxicity, and remediation approaches. *Front. Microbiol.* **2020**, *11*, 562813. [CrossRef] [PubMed]
32. Abdel-Shafy, H.I.; Mansour, M.S. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. *Egypt. J. Petrol.* **2016**, *25*, 107–123. [CrossRef]
33. Duran, R.; Cravo-Laureau, C.; Brussaard, C. Role of environmental factors and microorganisms in determining the fate of polycyclic aromatic hydrocarbons in the marine environment. *FEMS Microbiol. Rev.* **2016**, *40*, 814–830. [CrossRef]
34. Cangola, J.; Abagale, F.K.; Cobbina, S.J. A systematic review of pharmaceutical and personal care products as emerging contaminants in waters: The panorama of West Africa. *Sci. Total Environ.* **2024**, *911*, 168633. [CrossRef] [PubMed]
35. Kulik, K.; Lenart-Boroń, A.; Wyrzykowska, K. Impact of antibiotic pollution on the bacterial population within surface water with special focus on mountain rivers. *Water* **2023**, *15*, 975. [CrossRef]
36. An, X.; Tao, Y.; Wu, J.; Li, Z.; Li, H.; Chen, S.; Pang, Y. Occurrence, toxicity, ecological risk, and remediation of diclofenac in surface water environments: A review with a focus on China. *Environ. Toxicol. Chem.* **2025**, vgaf005. [CrossRef]
37. Ma, Y.; Li, Y.; Song, X.; Yang, T.; Wang, H.; Liang, Y.; Huang, L.; Zeng, H. Endocrine disruption of propylparaben in the male mosquitofish (*Gambusia affinis*): Tissue injuries and abnormal gene expressions of hypothalamic-pituitary-gonadal-liver axis. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3557. [CrossRef]
38. Wang, H.; Zhang, L.; Yang, F.; Yan, L.; Lin, C.; Shen, C. Characteristics, source analysis, and risk assessment of organochlorine pesticide contamination in nearshore surface sediments of a tropical tourist island. *Front. Mar. Sci.* **2025**, *11*, 1513515. [CrossRef]
39. Kaushal, J.; Khatri, M.; Arya, S.K. A treatise on Organophosphate pesticide pollution: Current strategies and advancements in their environmental degradation and elimination. *Ecotoxicol. Environ. Saf.* **2021**, *207*, 111483. [CrossRef]
40. Gregoire, C.; Elsaesser, D.; Huguenot, D.; Lange, J.; Lebeau, T.; Merli, A.; Mose, R.; Passeport, E.; Payraudeau, S.; Schütz, T.; et al. Mitigation of agricultural nonpoint-source pesticide pollution in artificial wetland ecosystems. *Environ. Chem. Lett.* **2009**, *7*, 205–231. [CrossRef]
41. Singh, B.A.; Mandal, K.O. Environmental Impact of Pesticides Belonging to Newer Chemistry. *Integr. Pest Manag.* **2013**, 152–190.
42. Pérez, G.L.; Vera, M.S.; Miranda, L.A. Effects of herbicide glyphosate and glyphosate-based formulations on aquatic ecosystems. In *Herbicides and Environment*; IntechOpen: London, UK, 2011; pp. 343–368.
43. Carpenter, S.R. Eutrophication of aquatic ecosystems: Bistability and soil phosphorus. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 10002–10005. [CrossRef]
44. Horton, A.A.; Dixon, S.J. Microplastics: An introduction to environmental transport processes. *WIREs Water* **2018**, *5*, e1268. [CrossRef]
45. Gateuille, D.; Naffrechoux, E. Transport of persistent organic pollutants: Another effect of microplastic pollution? *WIREs Water* **2022**, *9*, e1600. [CrossRef]
46. Ali, M.; Xu, D.; Yang, X.; Hu, J. Microplastics and PAHs mixed contamination: An in-depth review on the sources, co-occurrence, and fate in marine ecosystems. *Water Res.* **2024**, *257*, 121622. [CrossRef] [PubMed]
47. Ohore, O.E.; Zhang, S. Endocrine disrupting effects of bisphenol A exposure and recent advances on its removal by water treatment systems. A review. *Sci. Afr.* **2019**, *5*, e00135. [CrossRef]
48. Loffredo, E.; Gattullo, C.E.; Traversa, A.; Senesi, N. Potential of various herbaceous species to remove the endocrine disruptor bisphenol A from aqueous media. *Chemosphere* **2010**, *80*, 1274–1280. [CrossRef]
49. Marmara, D.; Brundo, M.V.; Pecoraro, R.; Scalisi, E.M.; Contino, M.; Sica, C.; Ferruggia, G.; Indelicato, S.; Velardita, R.; Tiralongo, F.; et al. Plastic additives in commercial fish of Aegean and Ionian Seas and potential hazard to human health. *Front. Mar. Sci.* **2024**, *11*, 1334237. [CrossRef]

50. Li, Y.-Q.; Zhang, C.-M.; Yuan, Q.-Q.; Wu, K. New insight into the effect of microplastics on antibiotic resistance and bacterial community of biofilm. *Chemosphere* **2023**, *335*, 139151. [CrossRef]
51. Vagi, M.C.; Petsas, A.S.; Kostopoulou, M.N. Potential effects of persistent organic contaminants on marine biota: A review on recent research. *Water* **2021**, *13*, 2488. [CrossRef]
52. Maglione, G.; Zinno, P.; Tropea, A.; Mussagy, C.U.; Dufossé, L.; Giuffrida, D.; Mondello, A. Microbes' role in environmental pollution and remediation: A bioeconomy focus approach. *AIMS Microbiol.* **2024**, *10*, 723–755. [CrossRef]
53. Hu, F.; Wang, P.; Li, Y.; Ling, J.; Ruan, Y.; Yu, J.; Zhang, L. Bioremediation of environmental organic pollutants by Pseudomonas aeruginosa: Mechanisms, methods and challenges. *Environ. Res.* **2023**, *239*, 117211. [CrossRef] [PubMed]
54. Udume, O.A.; Abu, G.O.; Stanley, H.O.; Vincent-Akpu, I.F.; Momoh, Y.; Eze, M.O. Biostimulation of petroleum-contaminated soil using organic and inorganic amendments. *Plants* **2023**, *12*, 431. [CrossRef]
55. Oro, C.E.D.; Puton, B.M.S.; Venquiaruto, L.D.; Dallago, R.M.; Tres, M.V. Effective microbial strategies to remediate contaminated agricultural soils and conserve functions. *Agronomy* **2024**, *14*, 2637. [CrossRef]
56. Rafeeq, H.; Afsheen, N.; Rafique, S.; Arshad, A.; Intisar, M.; Hussain, A.; Bilal, M.; Iqbal, H.M. Genetically engineered microorganisms for environmental remediation. *Chemosphere* **2023**, *310*, 136751. [CrossRef]
57. Kour, D.; Khan, S.S.; Kour, H.; Kaur, T.; Devi, R.; Judy, C.; Rai, P.K.; McQuestion, C.; Spells, S.; Bianchi, A.; et al. Microbe-mediated bioremediation: Current research and future challenges. *J. Appl. Biol. Biotechnol.* **2022**, *10*, 6–24. [CrossRef]
58. Furukawa, K.; Fujihara, H. Microbial degradation of polychlorinated biphenyls: Biochemical and molecular features. *J. Biosci. Bioeng.* **2008**, *105*, 433–449. [CrossRef]
59. Parnell, J.J.; Denef, V.J.; Park, J.; Tsoi, T.; Tiedje, J.M. Environmentally relevant parameters affecting PCB degradation: Carbon source- and growth phase-mitigated effects of the expression of the biphenyl pathway and associated genes in Burkholderia xenovorans LB400. *Biodegradation* **2010**, *21*, 147–156. [CrossRef]
60. Alvarez, P.J.; Vogel, T.M. Substrate interactions of benzene, toluene, and para-xylene during microbial degradation by pure cultures and mixed culture aquifer slurries. *Appl. Environ. Microbiol.* **1991**, *57*, 2981–2985. [CrossRef]
61. Tiehm, A.; Fritzsche, C. Utilization of solubilized and crystalline mixtures of polycyclic aromatic hydrocarbons by a *Mycobacterium* sp. *Appl. Microbiol. Biotechnol.* **1995**, *42*, 964–968. [CrossRef]
62. Hennessee, C.T.; Li, Q.X.; Parales, R.E. Effects of polycyclic aromatic hydrocarbon mixtures on degradation, gene expression, and metabolite production in four mycobacterium species. *Appl. Environ. Microbiol.* **2016**, *82*, 3357–3369. [CrossRef]
63. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of heavy metals—Concepts and applications. *Chemosphere* **2013**, *91*, 869–881. [CrossRef]
64. Ashraf, S.; Ali, Q.; Zahir, Z.A.; Ashraf, S.; Asghar, H.N. Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. *Ecotoxicol. Environ. Saf.* **2019**, *174*, 714–727. [CrossRef]
65. Awa, S.H.; Hadibarata, T. Removal of heavy metals in contaminated soil by phytoremediation mechanism: A review. *Water Air Soil Pollut.* **2020**, *231*, 47. [CrossRef]
66. Priya, A.K.; Muruganandam, M.; Ali, S.S.; Kornaros, M. Clean-up of heavy metals from contaminated soil by phytoremediation: A multidisciplinary and eco-friendly approach. *Toxics* **2023**, *11*, 422. [CrossRef] [PubMed]
67. Yan, A.; Wang, Y.; Tan, S.N.; Yusof, M.L.M.; Ghosh, S.; Chen, Z. Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Front. Plant Sci.* **2020**, *11*, 359. [CrossRef]
68. Gong, Y.; Chen, J.; Pu, R. The enhanced removal and phytodegradation of sodium dodecyl sulfate (SDS) in wastewater using controllable water hyacinth. *Int. J. Phytoremediat.* **2019**, *21*, 1080–1089. [CrossRef]
69. de Souza, T.D.; Borges, A.C.; Braga, A.F.; Veloso, R.W.; de Matos, A.T. Phytoremediation of arsenic-contaminated water by Lemna Valdiviana: An optimization study. *Chemosphere* **2019**, *234*, 402–408. [CrossRef]
70. Singh, V.; Pandey, B.; Suthar, S. Phytotoxicity and degradation of antibiotic ofloxacin in duckweed (Spirodela polyrhiza) system. *Ecotoxicol. Environ. Saf.* **2019**, *179*, 88–95. [CrossRef]
71. Yanitch, A.; Kadri, H.; Frenette-Dussault, C.; Joly, S.; Pitre, F.E.; Labrecque, M. A four-year phytoremediation trial to decontaminate soil polluted by wood preservatives: Phytoextraction of arsenic, chromium, copper, dioxins and furans. *Int. J. Phytoremediat.* **2020**, *22*, 1505–1514. [CrossRef] [PubMed]
72. Kafle, A.; Timilsina, A.; Gautam, A.; Adhikari, K.; Bhattarai, A.; Aryal, N. Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environ. Adv.* **2022**, *8*, 100203. [CrossRef]
73. Qin, H.; Zhang, Z.; Liu, M.; Liu, H.; Wang, Y.; Wen, X.; Zhang, Y.; Yan, S. Site test of phytoremediation of an open pond contaminated with domestic sewage using water hyacinth and water lettuce. *Ecol. Eng.* **2016**, *95*, 753–762. [CrossRef]
74. Singh, B.M.; Singh, D.; Dhal, N.K. Enhanced phytoremediation strategy for sustainable management of heavy metals and radionuclides. *Case Stud. Chem. Environ. Eng.* **2022**, *5*, 100176. [CrossRef]
75. Tang, K.H.D. Phytoremediation: Where do we go from here? *Biocatal. Agric. Biotechnol.* **2023**, *50*, 102721. [CrossRef]
76. Borymski, S.; Cycoń, M.; Beckmann, M.; Mur, L.A.; Piotrowska-Seget, Z. Plant species and heavy metals affect biodiversity of microbial communities associated with metal-tolerant plants in metalliferous soils. *Front. Microbiol.* **2018**, *9*, 1425. [CrossRef]

77. Bakshe, P.; Jugade, R. Phytostabilization and rhizofiltration of toxic heavy metals by heavy metal accumulator plants for sustainable management of contaminated industrial sites: A comprehensive review. *J. Hazard. Mater. Adv.* **2023**, *10*, 100293. [CrossRef]
78. Koptsik, G.; Spiers, G.; Koptsik, S.; Beckett, P. Use of Organic Amendments in Phytoremediation of Metal-Contaminated Soils: Prospects and Challenges. In *Handbook of Assisted and Amendment: Enhanced Sustainable Remediation Technology*; John Wiley & Sons: Hoboken, NJ, USA, 2021; pp. 205–233.
79. Pintarič, M.; Štuhec, A.; Tratnik, E.; Langerholc, T. Spent mushroom substrate improves microbial quantities and enzymatic activity in soils of different farming systems. *Microorganisms* **2024**, *12*, 1521. [CrossRef] [PubMed]
80. Wang, J.; Delavar, M.A. Modelling phytoremediation: Concepts, methods, challenges and perspectives. *Soil Environ. Health* **2024**, *2*, 100062. [CrossRef]
81. Kumar, A.; Dadhwal, M.; Mukherjee, G.; Srivastava, A.; Gupta, S.; Ahuja, V.; Iqbal, B. Phytoremediation: Sustainable approach for heavy metal pollution. *Scientifica* **2024**, *2024*, 3909400. [CrossRef]
82. Wang, C.; Yue, L.; Cheng, B.; Chen, F.; Zhao, X.; Wang, Z.; Xing, B. Mechanisms of growth-promotion and Se-enrichment in Brassica chinensis L. by selenium nanomaterials: Beneficial rhizosphere microorganisms, nutrient availability, and photosynthesis. *Environ. Sci. Nano* **2022**, *9*, 302–312. [CrossRef]
83. Ahmed, M.; Singh, V.K.; Upadhyay, R.S. Brassica rhizosphere-microbe interactions and their role in phytoremediation. In *The Plant Family Brassicaceae: Contribution Towards Phytoremediation*; Springer: Dordrecht, The Netherlands, 2012; pp. 139–152.
84. Doty, S.L.; Freeman, J.L.; Cohu, C.M.; Burken, J.G.; Firrincieli, A.; Simon, A.; Khan, Z.; Isebrands, J.G.; Lukas, J.; Blaylock, M.J. Enhanced degradation of TCE on a superfund site using endophyte-assisted poplar tree phytoremediation. *Environ. Sci. Technol.* **2017**, *51*, 10050–10058. [CrossRef] [PubMed]
85. Carvajal, L.; Benavides, L.; Rodriguez, R.; Serrezuela, W.R. Extraction in laboratory of heavy metals through rhizofiltration using the plant *Zea mays* (maize). *Int. J. Appl. Environ. Sci.* **2018**, *13*, 9–26.
86. Woraharn, S.; Meeinkuirt, W.; Phusantisampan, T.; Chayapan, P. Rhizofiltration of cadmium and zinc in hydroponic systems. *Water Air Soil Pollut.* **2021**, *232*, 204. [CrossRef]
87. Singh, S.; Kaushik, A.; Bendi, A.; Chetal, A.; Ramakrishna, D.S.; Praveen, P.L. Constructed wetlands as bioeconomic solutions: Rhizofiltration with macrophytes for heavy metal removal. *Emergent Mater.* **2024**, *8*, 75–83. [CrossRef]
88. Kristanti, R.A.; Ngu, W.J.; Yuniarto, A.; Hadibarata, T. Rhizofiltration for Removal of Inorganic and Organic Pollutants in Groundwater: A Review. *Biointerface Res. Appl. Chem.* **2021**, *11*, 12326–12347. [CrossRef]
89. Matilda, M.I.; Samuel, H.S. Bioremediation of oil spill: Concept, methods and applications. *Discov. Chem.* **2024**, *1*, 1–18. [CrossRef]
90. Mariano, D.C.; Dias, G.M.; Castro, M.R.; Tschoeke, D.A.; de Oliveira, F.J.; Sérvulo, E.F.C.; Neves, B.C. Exploring the diversity and functional profile of microbial communities of Brazilian soils with high salinity and oil contamination. *Heliyon* **2024**, *10*, e34336. [CrossRef]
91. Robinson, P.K. Enzymes: Principles and biotechnological applications. *Essays Biochem.* **2015**, *59*, 1–41. [CrossRef]
92. Ahmad, N.B.; Jaafaru, M.S.; Isa, Z.; Abdulhamid, Y.; Kakudi, R.A.; Ugya, A.Y.; Meguellati, K. High pollution loads engineer oxygen dynamics, ecological niches, and pathogenicity shifts in freshwater environments. *J. Hazard. Mater. Adv.* **2024**, *14*, 100425. [CrossRef]
93. Gibson, D.T.; Parales, R.E. Aromatic hydrocarbon dioxygenases in environmental biotechnology. *Curr. Opin. Biotechnol.* **2000**, *11*, 236–243. [CrossRef]
94. Shi, J.; Jiang, J.; Chen, Q.; Wang, L.; Nian, K.; Long, T. Production of higher toxic intermediates of organic pollutants during chemical oxidation processes: A review. *Arab. J. Chem.* **2023**, *16*, 104856. [CrossRef]
95. Garbisu, C.; Garaiyurrebaso, O.; Epelde, L.; Grohmann, E.; Alkorta, I. Plasmid-mediated bioaugmentation for the bioremediation of contaminated soils. *Front. Microbiol.* **2017**, *8*, 1966. [CrossRef] [PubMed]
96. Majeed, L.R.; Sharma, D.; Rautela, K.S.; Kumar, M. Sustainable agriculture, aquaculture and phytoremediation through freshwater macrophytes: A comprehensive review of mineral uptake, soil health, and water quality dynamics. *Discov. Water* **2025**, *5*, 1. [CrossRef]
97. McHughen, A. A critical assessment of regulatory triggers for products of biotechnology: Product vs. process. *GM Crops Food* **2016**, *7*, 125–158. [CrossRef]
98. Davletgildeeva, A.T.; Kuznetsov, N.A. Bioremediation of polycyclic aromatic hydrocarbons by means of bacteria and bacterial enzymes. *Microorganisms* **2024**, *12*, 1814. [CrossRef]
99. Oubohssaine, M.; Dahmani, I. Phytoremediation: Harnessing plant power and innovative technologies for effective soil remediation. *Plant Stress* **2024**, *14*, 100578. [CrossRef]
100. Raklami, A.; Meddich, A.; Oufdou, K.; Baslam, M. Plants-microorganisms-based bioremediation for heavy metal cleanup: Recent developments, phytoremediation techniques, regulation mechanisms, and molecular responses. *Int. J. Mol. Sci.* **2022**, *23*, 5031. [CrossRef] [PubMed]

101. Ayilara, M.S.; Babalola, O.O. Bioremediation of environmental wastes: The role of microorganisms. *Front. Agron.* **2023**, *5*, 1183691. [CrossRef]
102. Duncker, K.E.; Holmes, Z.A.; You, L. Engineered microbial consortia: Strategies and applications. *Microb. Cell Factories* **2021**, *20*, 211. [CrossRef]
103. Chen, B.; He, J.; Tian, K.; Qu, J.; Hong, L.; Lin, Q.; Yang, K.; Ma, L.; Xu, X. Research progress on detection of pathogens in medical wastewater by electrochemical biosensors. *Molecules* **2024**, *29*, 3534. [CrossRef] [PubMed]
104. Perelo, L.W. Review: In situ and bioremediation of organic pollutants in aquatic sediments. *J. Hazard. Mater.* **2010**, *177*, 81–89. [CrossRef] [PubMed]
105. Hussain, I.; Aleti, G.; Naidu, R.; Puschenreiter, M.; Mahmood, Q.; Rahman, M.M.; Wang, F.; Shaheen, S.; Syed, J.H.; Reichenauer, T.G. Microbe and plant assisted-remediation of organic xenobiotics and its enhancement by genetically modified organisms and recombinant technology: A review. *Sci. Total Environ.* **2018**, *628–629*, 1582–1599. [CrossRef] [PubMed]
106. Michalak, I. The application of seaweeds in environmental biotechnology. In *Advances in Botanical Research*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 95, pp. 85–111. [CrossRef]
107. Sharma, P.; Bano, A.; Singh, S.P.; Dubey, N.K.; Chandra, R.; Iqbal, H.M. Recent advancements in microbial-assisted remediation strategies for toxic contaminants. *Clean. Chem. Eng.* **2022**, *2*, 100020. [CrossRef]
108. Mandeep; Shukla, P. Microbial Nanotechnology for Bioremediation of Industrial Wastewater. *Front. Microbiol.* **2020**, *11*, 590631. [CrossRef]
109. Song, B.; Xu, P.; Chen, M.; Tang, W.; Zeng, G.; Gong, J.; Zhang, P.; Ye, S. Using nanomaterials to facilitate the phytoremediation of contaminated soil. *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 791–824. [CrossRef]
110. Park, J.K.; Oh, K. Advancements in Phytoremediation Research for Soil and Water Resources: Harnessing Plant Power for Environmental Cleanup. *Sustainability* **2023**, *15*, 13901. [CrossRef]
111. Shams, M.; Nezhad, N.T.; Dehghan, A.; Alidadi, H.; Paydar, M.; Mohammadi, A.A.; Zarei, A. Heavy metals exposure, carcinogenic and non-carcinogenic human health risks assessment of groundwater around mines in Joghatai, Iran. *Int. J. Environ. Anal. Chem.* **2020**, *102*, 1884–1899. [CrossRef]
112. Zheng, T.; Li, J.; Ji, Y.; Zhang, W.; Fang, Y.; Xin, F.; Dong, W.; Wei, P.; Ma, J.; Jiang, M. Progress and Prospects of Bioelectrochemical Systems: Electron Transfer and Its Applications in the Microbial Metabolism. *Front. Bioeng. Biotechnol.* **2020**, *8*, 10. [CrossRef]
113. Fatehbasharzad, P.; Aliasghari, S.; Tabrizi, I.S.; Khan, J.A.; Boczkaj, G. Microbial fuel cell applications for removal of petroleum hydrocarbon pollutants: A review. *Water Resour. Ind.* **2022**, *28*, 100178. [CrossRef]
114. Sharma, J.K.; Kumar, N.; Singh, N.P.; Santal, A.R. Phytoremediation technologies and their mechanism for removal of heavy metal from contaminated soil: An approach for a sustainable environment. *Front. Plant Sci.* **2023**, *14*, 1076876. [CrossRef] [PubMed]
115. Delgado-González, C.R.; Madariaga-Navarrete, A.; Fernández-Cortés, J.M.; Islas-Pelcastre, M.; Oza, G.; Iqbal, H.M.N.; Sharma, A. Advances and Applications of Water Phytoremediation: A Potential Biotechnological Approach for the Treatment of Heavy Metals from Contaminated Water. *Int. J. Environ. Res. Public Health* **2021**, *18*, 5215. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.