UTILIZING MARINE BIOTECHNOLOGY TO ADDRESS POLLUTION IN THE BAY OF BENGAL, BANGLADESH

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ABSTRACT

Addressing marine pollution within Bangladesh's maritime boundaries through biotechnological methods is a vital undertaking in the battle against the environmental issues confronting this coastal nation. By harnessing biotechnology, creative solutions can be crafted to confront the various types of marine pollution, including plastic waste, oil spills, and chemical contaminants, which pose significant threats to the country's precious coastal ecosystems, biodiversity, and fisheries. These strategies employ agents for biodegradation, genetically modified organisms, and advanced filtration techniques to eliminate pollutants from aquatic environments and reinstate ecological equilibrium effectively. By integrating state-of-the-art biotechnological innovations with sustainable management practices, Bangladesh has the potential to safeguard its marine environment and ensure the lasting prosperity of its coastal communities and marine biodiversity.

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Introduction

Bangladesh, a low-lying South Asian nation, boasts a vast coastline along the Bay of Bengal, stretching for approximately 580 kilometers. This coastal region is vital to the country's economy and culture, characterized by the famous Sundarbans mangrove forest, home to the endangered Bengal tiger and numerous other unique species. The coast also includes major cities such as Cox's Bazar, known for having the world's longest natural sea beach, and Chittagong, a significant commercial and industrial hub. However, the coastal areas of Bangladesh are vulnerable to the adverse effects of climate change, including rising sea levels and cyclones, making them a focal point for global discussions on climate adaptation and mitigation efforts [1, 2]. Bangladesh's maritime landscape is a critical component of its geographical and economic identity, shaped by the confluence of the Bay of Bengal and a labyrinthine network of rivers and waterways. Its strategic location has made it a vital maritime player, with access to international trade routes, facilitating the movement of goods to and from South and Southeast Asia. The Bay of Bengal, with its rich marine biodiversity, offers significant resources and opportunities for fisheries while also posing environmental challenges. Bangladesh's maritime domain is central to its economic growth, encompassing vital ports like Chittagong and Mongla and the ongoing development of the Blue Economy, emphasizing sustainable ocean resource management. Moreover, Bangladesh's maritime history and culture are deeply intertwined, evident in its traditions of boat building, fishing communities, and coastal lifestyles, making the maritime domain a focal point of national identity and livelihoods [3, 4]. Bangladesh, endowed with a vast maritime territory along the Bay of Bengal, possesses significant marine biological resources. Its maritime land encompasses diverse ecosystems, including mangroves, estuaries, coral reefs, and the world's largest delta, the Sundarbans. These ecosystems host a rich variety of marine life, including numerous fish species, crustaceans, mollusks, and aquatic plants. The country's coastal waters are vital breeding grounds for several commercially important fish species, such as hilsa (*Tenualosa ilisha*), shrimp, and finfish. These resources support the livelihoods of millions of people through fisheries, aquaculture, and tourism. However, sustainable management practices are crucial to safeguard these valuable marine biological resources from overexploitation and habitat degradation due to climate change, pollution, and industrial activities [4].Marine pollution in Bangladesh's maritime territory is a pressing environmental concern, primarily driven by industrial discharge, untreated sewage, and shipping activities along its coastline, particularly in the Bay of Bengal. These pollutants, including heavy metals, plastics, and oil spills, harm the diverse marine ecosystems, endangering marine species and compromising the livelihoods of coastal communities heavily dependent on fisheries. Moreover, rising sea levels and extreme weather events associated with climate change exacerbate the problem, leading to increased salinity and contamination of coastal waters. Urgent measures and international cooperation are needed to mitigate these threats and safeguard the ecological and economic sustainability of Bangladesh's maritime lands [5]. Marine pollution mitigation in Bangladesh's maritime area is being addressed through innovative biotechnological approaches. One promising method involves the use of microbial bioremediation, where indigenous microorganisms are harnessed to break down pollutants in contaminated waters. For example, studies have explored the potential of oil-eating bacteria to remediate oil spills in the Bay of Bengal. Additionally, phytoremediation using salt-tolerant plants like mangroves is being employed to absorb and detoxify heavy metals and other contaminants. These biotechnological strategies not only offer sustainable and cost-effective solutions but also align with Bangladesh's commitment to preserving its coastal ecosystems and safeguarding the livelihoods of its coastal communities [6, 7]. A critical research gap in mitigating marine pollution in Bangladesh's maritime land lies in the application of biotechnological approaches specifically tailored to the region's unique environmental challenges. While various strategies have been explored globally to combat marine pollution, Bangladesh faces distinctive issues such as extensive riverine inputs of plastic waste and chemical contaminants, as well as the susceptibility of its vulnerable coastal ecosystems to oil spills and habitat degradation. Thus, pioneering research should focus on developing and implementing bioremediation techniques, utilizing indigenous microorganisms and plants, to effectively remove pollutants and restore the ecological balance in Bangladesh's marine environment. Moreover, the integration of biotechnology with traditional knowledge and community-based conservation efforts can offer sustainable solutions. Such research endeavors can build upon existing work in the field, as exemplified by studies like Ahmed et al. (2020) on microbial bioremediation of oil spills in coastal environments and Rahman et al. (2019) on phytoremediation potential of mangroves in Bangladesh, while also addressing the unique challenges of the region [8, 9]. This article addresses all type of marine pollution in Bangladesh coastal region and the possible marine biotechnological approaches to mitigate these pollutions.

What is Marine Biotechnology?

Marine biotechnology is the field of science that explores the diverse and valuable resources found in the world's oceans for various applications in industries like medicine, agriculture, and environmental management. This interdisciplinary branch of biotechnology harnesses the unique biochemical compounds, microorganisms, and genetic diversity present in marine organisms such as algae, corals, and deep-sea creatures to develop products and technologies with numerous commercial and environmental benefits [10]. Marine biotechnology is a rapidly advancing field that harnesses the diverse and often untapped resources of the world's oceans to develop innovative solutions for various industries. By leveraging the genetic and biochemical diversity of marine organisms, such as microorganisms, algae, and marine animals, researchers are exploring applications ranging from the development of novel pharmaceuticals and bioproducts to the design of sustainable aquaculture practices and the mitigation of environmental pollutants. Key areas in this field include studies on the bioprospecting of marine microorganisms for bioactive compounds [11], the use of marine algae for biofuel production [12], and the biotechnological advances in marine aquaculture for enhancing seafood production [13]. These efforts hold significant promise for addressing global challenges while simultaneously unlocking the economic and ecological potential of marine ecosystems.

Types of Marine pollution

Coastal pollution has been one of the greatest concerns on a regional and global scale, particularly in the last few decades, due to the intense pressures associated with human development. Coastal pollution refers to the contamination of coastal areas, which can have detrimental effects on marine ecosystems, human health, and local economies. The impact of coastal pollution is not limited to marine life; it can also affect human health through contaminated seafood and polluted beaches. There are several types of coastal pollution, each with its own sources and impacts. The definition of coastal pollution by the World Health Organization goes like this "The introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects such as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities" [14].

Marine Debris

Marine debris, consisting of persistent solid materials like plastics, fishing gear, and other refuse, poses a significant threat to marine ecosystems worldwide. Millions of tons of plastic waste enter the oceans annually, adversely affecting marine life by causing entanglement, ingestion, and habitat destruction. Research by Jambeck et al. (2015) highlights the alarming input of plastic waste from land into the ocean, emphasizing the urgency of addressing this issue to safeguard marine environments [15]. Microplastics, tiny particles derived from larger plastic debris, have been identified as a growing concern due to their potential to enter the food chain, posing risks to both marine life and human health [16]. Effective management strategies are essential, focusing on understanding debris sources, distribution patterns, and its impact on wildlife, as emphasized by studies like Moore et al. (2001), to mitigate the adverse effects of marine debris on our oceans and the life they support [17].

Table 1. Size-based classification of plastic detritus according to GESAMP [18]**.**

Definition	Size–Range	Description
Mesoplastics	1 mm–2.5 cm	The term "microplastics" was coined to describe tiny pieces of plastic that are large enough to be seen with the naked eye.
Microplastics	100 nm–1 mm	Light microscopy reveals microscopic plastic particles.
Nanoplastics	>100 nm	the tiniest bits of plastic that can be seen only with a scanning or transmission electron microscope.

Oil Spills

Marine oil spills, often originating from accidents involving oil tankers, offshore drilling rigs, or pipelines, pose severe environmental threats. When these incidents occur, crude oil is released into oceans or other water bodies, leading to widespread pollution and devastating consequences for marine ecosystems. The spilled oil forms thick layers on the water surface, coating marine life and disrupting their natural behaviors, leading to suffocation, poisoning, and death of various species. The impact is not limited to aquatic life; birds, mammals, and coastal vegetation also suffer as a result. The oil penetrates and contaminates sensitive habitats like coral reefs and mangroves, causing long-term damage. Additionally, these spills have significant economic implications, affecting fisheries, tourism, and local communities that depend on healthy marine environments [19–21].

Nutrient Pollution

Nutrient pollution, often from agricultural runoff or sewage, leads to excessive nutrient levels in coastal waters, causing harmful algal blooms and oxygen depletion. Algal blooms, caused by excess nutrients like nitrogen and phosphorus, reduce oxygen levels in coastal marine habitats, killing off marine life. Wastewater and run-off from agricultural land are two potential sources of such nutrients that end up in the sea [22]. Marine nutrient pollution, often referred to as eutrophication, is a critical environmental issue caused by excessive inputs of nutrients, primarily nitrogen and phosphorus, into marine ecosystems. These nutrients come from various sources, including agricultural runoff, industrial discharges, and sewage, leading to an overabundance of nutrients in coastal waters. As a result, harmful algal blooms proliferate; depleting oxygen levels in the water and creating "dead zones" where marine life struggles to survive. Eutrophication not only disrupts the balance of marine ecosystems but also has severe economic consequences, affecting fisheries, tourism, and coastal property values. It is a global concern with well-documented cases such as the Gulf of Mexico's dead zone caused by agricultural runoff from the Mississippi River and the Baltic Sea's eutrophication due to various nutrient inputs. Addressing this issue requires comprehensive efforts to reduce nutrient inputs, improve wastewater treatment, and promote sustainable land-use practices to protect the health and biodiversity of marine environments [23, 24].

Chemical Pollution

Marine chemical pollution is a pressing environmental issue with far-reaching consequences for marine ecosystems and human health. This form of pollution involves the release of harmful chemicals, such as heavy metals, pesticides, and industrial toxins, into the world's oceans and seas. These pollutants can originate from various sources, including industrial discharges, agricultural runoff, and oil spills, among others. The impact of marine chemical pollution is evident in the degradation of marine habitats, disruption of aquatic food chains, and the accumulation of toxic substances in seafood, posing risks to human consumption. This problem has been extensively studied and documented in scientific literature, with numerous references highlighting its detrimental effects on marine life and the urgent need for stricter regulations and pollution prevention measures [25, 26]. Addressing marine chemical pollution is critical to preserving the health and biodiversity of our oceans and ensuring the sustainability of marine resources.

Sediment Pollution

Marine sediment pollution is a pressing environmental concern, as it has far-reaching implications for marine ecosystems and human health. Contaminants such as heavy metals, pesticides, hydrocarbons, and plastic debris accumulate in sediments over time, posing a threat to marine life. These pollutants can disrupt the balance of delicate aquatic ecosystems, harm fisheries, and even find their way into the human food chain through seafood consumption. For instance, a study by Thompson et al. (2009) highlighted the widespread presence of microplastics in marine sediments, emphasizing the need for stricter waste management and plastic reduction strategies [27]. Moreover, research by Liu et al. (2020) showed that heavy metal contamination in marine sediments can lead to adverse effects on marine organisms and subsequently impact human health through the consumption of contaminated seafood [28]. Addressing marine sediment pollution requires concerted efforts in monitoring, regulation, and sustainable waste management practices to protect the health of our oceans and ourselves.

Noise Pollution

Marine noise pollution, caused primarily by human activities such as shipping, offshore drilling, and underwater construction, poses a significant threat to marine ecosystems. This form of pollution disrupts the natural acoustic environment of the oceans, affecting a wide range of marine life, from whales and dolphins to fish and invertebrates. Noise pollution can interfere with communication, navigation, and mating behaviors, leading to stress, disorientation, and even strandings in cetaceans. Additionally, it can mask important biological sounds and reduce the ability of marine animals to detect prey or predators, ultimately impacting their survival. Mitigating this issue requires a multi-faceted approach, including stricter regulations on vessel noise emissions and the development of quieter marine technologies, as well as continued research into the ecological consequences of noise pollution in the oceans [29–31].

Radioactive Pollution

Marine radioactive pollution refers to the release of radioactive substances into the world's oceans and seas, posing a significant threat to aquatic ecosystems and human health. This contamination can originate from various sources, including nuclear power plants, nuclear accidents, and the dumping of radioactive waste. One notorious example is the Fukushima Daiichi nuclear disaster in 2011, where large quantities of radioactive materials were discharged into the Pacific Ocean, impacting marine life and fisheries. Another example is the legacy of nuclear testing in the mid-20th century, which has left a long-lasting radioactive footprint in the oceans. Such pollution can have detrimental effects on marine organisms, leading to genetic mutations, disrupted ecosystems, and the bioaccumulation of radioactive elements in the food chain, ultimately posing a risk to human consumption of seafood [32, 33].

Trash Pollution

Trash pollution includes non-plastic litter such as glass, metal, and paper, which can accumulate along coastlines, impacting both aesthetics and wildlife. Marine non-plastic litter pollution composed of various materials such as glass, metal, and rubber, continues to pose a significant threat to ocean ecosystems. Research by Jambeck et al. (2015) estimated that 4.8 to 12.7 million metric tons of non-plastic debris enter the ocean annually [15]. These materials can persist for decades or even centuries, posing risks to marine life through ingestion, entanglement, and habitat disruption. For instance, abandoned or lost fishing gear, known as "ghost nets," can continue to trap and kill marine animals long after their intended use. Furthermore, glass and metal fragments can harm coral reefs and other sensitive habitats. Addressing non-plastic litter pollution requires coordinated efforts in waste management, recycling, and international regulations, as emphasized by the United Nations Environment Programme (UNEP) in their Global Partnership on Marine Litter initiative. This multifaceted approach is essential to mitigate the ongoing impact of non-plastic marine litter on our oceans [34].

Figure 1. Different Types of Marine Pollution

Impact of Marine Pollution on Marine Life

Marine pollution, resulting from various anthropogenic activities such as oil spills, plastic waste, chemical runoff, and sewage disposal, has profound and detrimental effects on marine life. It poses a significant threat to marine ecosystems by causing habitat destruction, entanglement and ingestion of plastics leading to injury and death of marine animals, disruption of food chains, and the introduction of toxic substances into the environment. Additionally, the acidification of oceans due to increased carbon dioxide levels can harm marine organisms with calcium carbonate shells and skeletons, such as corals and mollusks. These environmental stressors can ultimately lead to declining populations, altered behaviors, and the potential extinction of numerous species. Efforts to combat marine pollution and mitigate its impacts are essential to safeguard the health and biodiversity of our oceans [35, 36]. For human health reasons, chemical contamination of the food chain leads to bioac-cumulation and biomagnifications problems (Table 1). Toxic chemical poisoning in seafood causes several issues for people. The disease problems in the fishes/shrimps from the sea may be caused by the pathogenic bac-teria including pathogenic vibrios, salmo-nella contaminations from waste water disposal from the fish processing industry. Human illness can be spread through eating sick fish or shrimp. Pesticide residue has the potential to alter the endocrine system, lowering reproduction rates, lowering resistance to disease, and even causing cancer. Heart disease and cancer are caused in people by eating seafood because of the degraded derivatives such phenol, bisphenols, and phath-alates [37].

Table 1. Some synthetic compounds found in the ocean may have a negative effect on human health [37].

Chemical residues	Human health impacts
Vinyl chloride	Gastrointestinal problems, cardiovascular problems, kidney, liver, and lung damages
Carbon tetrachloride	lung damages, Cancer, liver, kidney and central nervous system
Trichloroethylene	skin problems, liver, cancers, and kidney damage and CNS
Ethylene dibromide	Cancer and Sterility
Polychlorinated biphenyls	Liver, lung and kidney damages
Benzene	Blood disorders, Anemia and chromosomal damage
Dioxin	Cancer and skin disorders

Problem Mitigation with Traditional Method

Marine pollution is a pressing global issue with significant environmental, economic, and social consequences. Mitigating marine pollution through traditional methods often involves strategies and techniques that have been used for centuries. These methods aim to reduce pollution and protect the health of our oceans. Here are some traditional methods for marine pollution mitigation, along with references to support their effectiveness:

Beach Cleanup Campaigns

Beach cleanup campaigns involve volunteers and organizations collecting and removing trash and debris from coastal areas. These efforts help prevent marine pollution by reducing the input of plastics and other pollutants into the ocean [38].

Fishing Gear Retrieval

Abandoned or lost fishing gear, known as ghost nets, can entangle marine life and contribute to pollution. Traditional methods involve retrieving these nets to prevent harm to marine ecosystems [39].

Oil Spill Cleanup with Sorbents

In the event of an oil spill, using traditional sorbents like straw or hay can help absorb and contain the spilled oil, preventing its spread and reducing its impact on marine environments [40].

Reef Restoration

Coral reefs are vital marine ecosystems that face threats from pollution. Traditional coral restoration methods, such as coral transplantation and coral farming, help rebuild and protect these ecosystems [41].

Mangrove Reforestation

Mangrove forests act as natural buffers against coastal pollution. Traditional methods involve replanting and conserving mangroves to protect coastal ecosystems from pollutants [42].

Traditional Fishing Practices

Promoting sustainable and traditional fishing methods, such as using selective gear and avoiding overfishing, can help reduce the impact of fishing-related pollution and habitat destruction [43].

These traditional methods, when combined with modern scientific knowledge and technology, can play a crucial role in mitigating marine pollution and preserving the health of our oceans. It is important to continue research and development in these areas to improve the effectiveness of these methods further.

Marine Biotechnology in Ocean Waste Management

Utilizing the distinct capabilities of marine organisms and microbes for various applications, marine biotechnology plays an essential role in ocean waste management. Researchers have identified marine bacteria such as *Ideonella sakaiensis* that are capable of degrading plastic waste [44], whereas marine-inspired coatings mitigate biofouling [45]. Bioremediation strategies employing oil-degrading bacteria are effective for oil spill removal, [46] and microalgae and seaweeds are used for phytoremediation of pollutants [47]. In addition, marine biotechnology extracts useful substances from waste, such as biofuels from organic waste and pharmaceutical compounds from marine organisms [48]. Sarkar et al. [49] state that DNA-based sensors and biosensors are utilized for marine pollution monitoring. These applications collectively contribute to more sustainable ocean refuse management practices, aiding in the preservation of marine ecosystems and mitigating pollution.An in-depth look at the role of marine biotechnology in marine waste management is provided here.

Plastic Waste Degradation

Marine biotechnology has the potential to play a significant role in addressing the problem of plastic waste in the world's oceans. Researchers are exploring various approaches to biodegrade plastic waste in marine environments using the unique capabilities of marine organisms. Some marine bacteria and fungi have been found to possess enzymes capable of breaking down plastics. For example, the bacterium *Ideonella sakaiensis* has been shown to degrade PET (polyethylene terephthalate), a common plastic used in bottles and packaging [50]. Researchers are exploring the use of enzymes derived from marine organisms, such as marine bacteria and algae, for breaking down plastic waste in marine environments. These enzymes could potentially be used in bioremediation efforts [51]. Some marine animals, such as certain species of mollusks and worms, have been discovered to ingest and biodegrade plastic materials. These organisms have unique digestive systems that can break down plastics [52]. Scientists are working on genetically engineering marine organisms to enhance their plastic-degrading capabilities. This field of synthetic biology holds promise for developing effective biodegradation solutions[53]. Researchers are also investigating the development of biodegradable plastics that can break down more easily in marine environments. These materials offer a proactive approach to reducing plastic pollution [54].
These are the point for exploring the field of marine biotechnology for plastic waste biodegradation.

Biofouling Prevention

Biofouling prevention in the marine environment is a critical concern for industries and ecosystems alike. Marine biotechnological approaches offer sustainable solutions to combat biofouling. Number of strategies related to biofouling prevention using marine biotechnology are existing. Many marine organisms produce natural compounds with antifouling properties. These compounds can be used to develop environmentally friendly antifouling coatings [55]. Probiotic treatments involving beneficial marine microorganisms can compete with and inhibit fouling organisms, reducing biofouling on surfaces [56]. Researchers are developing surfaces inspired by marine organisms, such as shark skin or lotus leaves, to create materials that discourage fouling and make it easier to remove [57]. Enzymes derived from marine microorganisms can be used to break down the extracellular matrix of fouling organisms, preventing their attachment [58]. Biocides sourced from marine organisms, such as algae and sponges, are being investigated for their potential to control biofouling while minimizing environmental impact [59]. Nanomaterials, including nanoparticles and nanocomposites, can be integrated into antifouling coatings to enhance their performance and durability [60]. Genetic engineering is being explored to create marine organisms with inherent antifouling properties or the ability to produce bioactive compounds to deter fouling [61].
These offer valuable insights into various marine biotechnological approaches for biofouling prevention.

Oil Spill Remediation

Oil spills pose a significant threat to marine ecosystems, necessitating effective remediation strategies. Marine biotechnological approaches offer promising solutions through the use of specialized microorganisms, enzymes, and natural compounds. Bioremediation, employing oil-degrading bacteria such as Alcanivorax and Marinobacter species, has shown success in breaking down hydrocarbons in contaminated waters [56, 57]. Additionally, enzyme technology, like lipases and biosurfactants, enhances oil dispersal and degradation [58, 62]. Furthermore, harnessing the metabolic potential of marine algae for bioremediation and phytoremediation can mitigate oil spill impacts [63]. These innovative marine biotechnological approaches hold promise for more efficient and sustainable oil spill cleanup while minimizing harm to delicate aquatic environments.

Phytoremediation

Phytoremediation, a sustainable and eco-friendly approach, holds immense potential for mitigating marine pollution using marine biotechnological methods. This strategy involves harnessing the unique capabilities of marine plants and algae to absorb, accumulate, and even degrade pollutants from the marine environment. Certain species, such as seagrasses, mangroves, and macroalgae, have demonstrated remarkable proficiency in removing heavy metals, nutrients, and hydrocarbons from coastal waters [64–66]. Moreover, the integration of biotechnological tools, including genetic engineering and algal bioreactors, can enhance the phytoremediation efficiency by optimizing pollutant uptake and degradation pathways [67, 68]. These innovative approaches offer a promising means to restore and preserve the health of marine ecosystems, mitigating the detrimental effects of pollution while harnessing the remarkable capabilities of marine plants.

Marine Bioproducts from Waste

Marine biotechnological approaches offer promising avenues for the sustainable conversion of marine waste into valuable bioproducts, addressing both environmental and economic concerns. Utilizing enzymatic hydrolysis, microbial fermentation, algae biotechnology, and bioremediation, researchers are able to extract proteins, biodegradable plastics, biofuels, nutraceuticals, and fertilizers from various marine waste sources, reducing pressure on marine ecosystems while creating economically viable alternatives. For instance, enzymatic hydrolysis can transform fish waste into valuable proteins, while algae biotechnology can harness nutrient-rich waste streams for biofuel and omega-3 fatty acid production [69–71]. By harnessing the power of marine biotechnology, we can mitigate marine pollution, promote circular economy practices, and foster sustainable marine resource management.

Pollution Monitoring and Detection

Marine pollution monitoring and detection have significantly benefited from the integration of marine biotechnological approaches, providing efficient and sensitive tools for assessing environmental quality and safeguarding marine ecosystems. Utilizing biomarkers derived from marine organisms, such as mussels, to detect chemical contaminants and toxins [72] or employing bioluminescent bacteria as biosensors for the rapid detection of pollutants like heavy metals [73], these biotechnological methods enable real-time, cost-effective, and environmentally sensitive monitoring of marine ecosystems. Additionally, the use of DNA-based techniques, such as environmental DNA (eDNA) analysis, has become a powerful tool for detecting and identifying species in aquatic environments, aiding in the early detection of invasive species [74]. Overall, these innovations not only enhance our understanding of marine pollution dynamics but also contribute to more effective pollution management and conservation efforts in marine ecosystems.

In summary, marine biotechnology plays a pivotal role in ocean waste management by offering innovative approaches to plastic degradation, biofouling prevention, oil spill remediation, phytoremediation, and the extraction of valuable products from waste materials. These applications collectively contribute to a more sustainable and environmentally responsible approach to managing ocean waste and preserving marine ecosystems.

Challenges and limitations

Mitigating marine pollution in Bangladesh through Marine Biotechnological approaches faces several challenges and limitations. Firstly, the lack of adequate funding and infrastructure for research and development hinders the establishment of advanced biotechnological solutions. Secondly, the complex and diverse nature of marine ecosystems demands a deep understanding of local biodiversity and their responses to biotechnological interventions. Additionally, regulatory frameworks for biotechnological applications in marine conservation are often underdeveloped, raising concerns about unintended ecological consequences. Moreover, community engagement and education are essential but challenging, given the socio-economic dynamics and widespread poverty in coastal areas. To address these challenges, interdisciplinary collaborations among scientists, policymakers, and local communities are crucial, along with an emphasis on sustainable practices and ethical considerations [75–77].

Regulatory considerations

Mitigating marine pollution in Bangladesh through marine biotechnological approaches requires a multifaceted regulatory framework. First and foremost, stringent legislation should be enacted to control and monitor industrial discharges and shipping activities in coastal areas, with a focus on enforcing international conventions like MARPOL and UNCLOS. Concurrently, the development and implementation of bioremediation techniques utilizing indigenous microorganisms and marine plants should be encouraged, necessitating guidelines for their safe application. Moreover, comprehensive environmental impact assessments (EIAs) must be mandatory for any new projects or activities near coastal regions, ensuring that potential pollution sources are rigorously evaluated. Collaboration with international organizations and neighboring countries is also essential to address transboundary pollution effectively. This comprehensive regulatory strategy must prioritize sustainable practices, adapt to evolving biotechnological advancements, and be underpinned by strong enforcement mechanisms to safeguard Bangladesh's marine ecosystem effectively [78–80].

Future Directions

The management of marine pollution using marine biotechnological approaches has become increasingly important in recent years as a response to the global environmental challenges posed by pollution in our oceans. This approach involves the use of biotechnology to develop innovative and sustainable solutions for monitoring, mitigating, and remediating marine pollution. Before the 20th century, there was limited understanding of the long-term impacts of marine pollution. Pollution was often localized, and its effects were observed primarily in coastal areas. Early references to marine pollution are found in historical documents describing incidents of oil spills and industrial waste discharges into water bodies. The mid-20th century saw a significant increase in industrialization and urbanization, leading to the release of various pollutants into the seas and oceans. This period marked the beginning of a growing concern for the environment and the need for management strategies to address marine pollution. Silent Spring by Rachel Carson, published in 1962, played a pivotal role in raising awareness about pollution, including its marine impacts. In the latter half of the 20th century, advances in biotechnology, particularly in molecular biology and genetics, laid the groundwork for marine biotechnological approaches to pollution management. Researchers began exploring the potential of marine organisms, particularly microorganisms, for bioremediation and monitoring purposes. Marine biotechnological approaches have been used to develop microbial-based bioremediation strategies for cleaning up oil spills and other hazardous substances in marine environments. Oil-degrading bacteria, such as Alcanivorax, have been identified and harnessed for their ability to break down hydrocarbons. From the late 20th century to present) marine biotechnological tools, including the use of genetically modified organisms (GMOs) and biosensors, have been developed to monitor pollution levels in marine ecosystems. These tools can detect the presence of pollutants and provide real-time data for decision-making[81].Algae, including microalgae and macroalgae, have been studied for their potential in removing nutrients and pollutants from marine environments through a process called phytoremediation[82].Contemporary research continues to explore new marine biotechnological approaches, such as the use of CRISPR-Cas9 gene editing for environmental applications, including enhancing the stress resistance of marine organisms to pollution[83].The development of marine biotechnological solutions for pollution management also involve complex regulatory and ethical issues, including concerns about unintended consequences and ecological impacts[84].The management of marine pollution using marine biotechnological approaches is a dynamic and evolving field, with ongoing research and innovations aimed at addressing the pressing environmental challenges facing our oceans. As the field continues to advance, it is crucial to balance the benefits of these technologies with their potential risks and ethical considerations to ensure the sustainable management of marine ecosystems. Bangladesh has grappled with a long history of maritime pollution, primarily driven by its strategic location along major shipping routes and rapid industrialization. This issue has been exacerbated by the unchecked discharge of industrial effluents, oil spills, and improper waste disposal from ship-breaking yards, which have resulted in severe environmental degradation in sensitive coastal ecosystems like the Sundarbans. One of the most notorious incidents was the 1994 oil spill from the oil tanker "M. V. Sea Empress," which had a devastating impact on the country's marine life and coastal communities. Efforts to combat maritime pollution have since been made, including the introduction of regulations and the establishment of the Bangladesh Marine Environment Management (BMEM) project, but the challenge remains a pressing concern for Bangladesh's coastal environment and the livelihoods of its inhabitants [85–87]. To mitigate maritime pollution in Bangladesh, it is imperative to leverage marine biotechnological approaches in the coming years. Firstly, the development and deployment of bio-remediation techniques using marine microorganisms can help break down oil spills and other pollutants in coastal waters, aiding in the restoration of fragile ecosystems. Secondly, the cultivation of algae for biofuel production can reduce the reliance on fossil fuels for shipping, thus lowering emissions. Thirdly, the use of biotechnology to engineer resilient, pollution-tolerant species can assist in revitalizing depleted fish stocks, ensuring food security for coastal communities. Lastly, continued research into biodegradable materials derived from marine sources can reduce plastic waste in the oceans. These multifaceted approaches, underpinned by marine biotechnology, can contribute significantly to a more sustainable and cleaner maritime environment in Bangladesh.

Conclusion

In conclusion, the mitigation of marine pollution in the Bangladesh coastal region through the application of modern biotechnological approaches represents a promising and innovative strategy for addressing the complex environmental challenges faced by this vital ecosystem. Utilizing bioremediation techniques, such as the deployment of specialized microorganisms to degrade pollutants, and the development of biofilters for wastewater treatment, offers a sustainable and cost-effective means of reducing contamination from industrial, agricultural, and urban sources. Additionally, the integration of genetic engineering for the enhancement of pollutant-degrading capabilities in indigenous species can further bolster the region's ability to restore and preserve its marine ecosystems. However, successful implementation demands concerted efforts in research, regulation, and public awareness to ensure the long-term health and sustainability of Bangladesh's coastal waters.

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