RESEARCH ARTICLE

Sustainable bioremediation techniques for mitigating marine pollution in maritime operations

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Abstract: Marine pollution from oil spills, vessel discharges, and ballast water poses significant challenges to environmental sustainability and maritime operations. This research explores the potential of bioremediation techniques, focusing on oil-degrading microorganisms, biofilters, bioreactors, and marine plants, to address these issues. By integrating biological and environmental engineering, the study evaluates the effectiveness and adaptability of these methods for maritime applications. Using a qualitative methodology, data were collected through interviews with 13 maritime professionals, 24 educators, and 33 graduates, supplemented by thematic analysis and technical evaluations. The findings highlight the high effectiveness of oil-degrading microorganisms in hydrocarbon degradation, the adaptability of biofilters and bioreactors for wastewater and ballast water treatment, and the dual ecological and pollution mitigation benefits of marine plants. Stakeholder collaboration and the integration of bioremediation into maritime education emerged as critical enablers for advancing these technologies. The research concludes that bioremediation offers scalable, sustainable solutions for mitigating marine pollution, contributing to environmental compliance, ecosystem restoration, and operational efficiency in the maritime industry. These findings provide actionable insights for technology integration, policy development, and capacity building, supporting the maritime sector's transition toward sustainability.

Keywords: biofilters; bioremediation; marine pollution; maritime sustainability; oil-degrading microorganisms

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Introduction

Marine pollution is one of the most pressing environmental challenges of the modern era, exacerbated by the expanding scale of maritime activities (Alamoush et al., 2020; Gössling et al., 2021). From oil spills and vessel discharges to plastic debris and ballast water contamination, the maritime industry significantly contributes to the degradation of marine ecosystems. These pollutants threaten biodiversity, disrupt ecological processes, and impair the health and productivity of oceans (Afinowi & Nhamo, 2025; Das et al., 2023). Addressing this multifaceted issue requires innovative and sustainable solutions, particularly in the realm of bioremediation, which leverages biological processes to mitigate pollution and restore ecological balance. Bioremediation stands out as a promising approach to combat marine pollution because of its environmental sustainability, adaptability, and potential for integration into existing maritime systems (Anani & Adetunji, 2021; Yadav et al., 2025). Unlike conventional chemical or mechanical remediation methods, bioremediation uses naturally occurring or engineered biological agents, such as microorganisms and plants, to degrade or immobilize pollutants. This approach minimizes secondary environmental impacts while targeting specific contaminants. Within the maritime domain, bioremediation offers opportunities to address key challenges such as hydrocarbon pollution from oil spills, nutrient enrichment from wastewater discharges, and invasive species introduced through ballast water.

The maritime industry, with its intricate interplay of technological, ecological, and socio-economic dynamics, provides a unique setting for exploring bioremediation applications. Oil spills, for example, are a recurrent environmental disaster, causing catastrophic harm to marine ecosystems and significant economic losses. While mechanical methods, such as booms and skimmers, and chemical dispersants are commonly used for oil spill response, they often fall short in achieving comprehensive remediation. Bioremediation, particularly through the use of oil-degrading bacteria, offers a more sustainable alternative. These microorganisms metabolize hydrocarbons, breaking them down into less harmful substances, such as water and carbon dioxide. Research into the optimization of microbial activity, including the identification of highly efficient strains and the manipulation of environmental conditions, is crucial for enhancing the effectiveness of this approach.

Similarly, wastewater and ballast water from ships contribute to nutrient enrichment, pathogen introduction, and the spread of invasive species, all of which pose significant threats to marine ecosystems. Traditional treatment methods for these discharges are often inadequate or economically unfeasible for widespread application in the maritime industry (Jimenez et al., 2022; Li et al., 2024). Bioreactors and biofilters represent innovative solutions to these challenges. These systems use microbial consortia to treat wastewater and ballast water onboard ships or at port facilities, reducing pollutant loads before discharge. The development of compact, efficient, and adaptable bioreactors tailored for shipboard use is an area of great potential, combining advances in engineering and microbiology to address one of the industry's most persistent challenges. Phytoremediation, which employs marine plants such as seagrasses, mangroves, and macroalgae, represents another dimension of bioremediation with significant promise (Moshentsev et al., 2022). These plants absorb and immobilize pollutants, including heavy metals, hydrocarbons, and excess nutrients, while simultaneously providing ecosystem services such as habitat restoration and carbon sequestration. Phytoremediation offers a dual benefit, addressing pollution while enhancing the resilience and productivity of coastal ecosystems. However, its scalability and long-term effectiveness require further investigation, particularly in environments with high pollutant loads or extreme conditions.

The role of education and capacity building in advancing bioremediation technologies is equally critical. Maritime vocational education serves as a bridge between theoretical advancements in biological engineering and practical applications in the field. By integrating bioremediation concepts and practices into maritime training programs, future professionals can be equipped with the skills and knowledge needed to implement innovative solutions. This alignment of education with industry needs ensures that the workforce is prepared to address the complex challenges of marine pollution, fostering a culture of sustainability within the maritime sector. Stakeholder engagement plays a central role in the successful implementation of bioremediation strategies. Maritime professionals, educators, and graduates each bring unique perspectives and expertise to the table (House & Saeed, 2016; Young, 1995). Professionals contribute practical insights into the operational challenges and feasibility of bioremediation technologies, ensuring that proposed solutions align with industry realities. Educators provide the theoretical foundation and promote interdisciplinary collaboration, while graduates, as emerging professionals, bring fresh ideas and innovative approaches to pollution mitigation. This interplay of perspectives underscores the importance of a collaborative approach to bioremediation, leveraging diverse expertise to achieve shared goals.

Despite its promise, bioremediation faces several challenges that must be addressed to maximize its potential. The variability of environmental conditions, such as temperature, salinity, and nutrient availability, can influence the efficiency of microbial and plant-based remediation processes. Additionally, the ecological risks associated with introducing non-native organisms or genetically engineered microorganisms into marine environments must be carefully managed. Ensuring the scalability and economic viability of bioremediation technologies is another critical consideration, as cost remains a significant barrier to their widespread adoption. The urgency of addressing marine pollution through bioremediation is underscored by the increasing frequency and severity of pollution events, the mounting pressure to meet international environmental regulations, and the growing recognition of the ocean's critical role in global sustainability. Bioremediation aligns with global initiatives such as the United Nations Sustainable Development Goals (SDGs), particularly those related to clean water, climate action, and life below water. By advancing bioremediation technologies, the maritime industry can contribute to these goals while enhancing its environmental performance and sustainability credentials.

This research aims to advance the field of bioremediation by exploring innovative techniques and their integration into maritime practices. The study examines the qualitative perspectives and experiences of maritime professionals, educators, and graduates, providing a comprehensive understanding of the opportunities and challenges associated with bioremediation. By evaluating the effectiveness of oil-degrading microorganisms, biofilters, bioreactors, and marine plants, the research seeks to identify practical, scalable, and sustainable solutions to marine pollution. Additionally, the study emphasizes the role of education in fostering a skilled workforce capable of implementing bioremediation technologies and promoting a culture of sustainability within the maritime sector.

Bioremediation offers a transformative approach to addressing marine pollution, combining scientific innovation with practical applications to enhance environmental sustainability in the maritime domain. By integrating microbial, plant-based, and engineered solutions, this research contributes to the advancement of bioremediation technologies, the development of sustainable maritime practices, and the education of future professionals. As the maritime industry continues to evolve, bioremediation will play an increasingly important role in ensuring the health and productivity of marine ecosystems for generations to come.

Method

This study employed a qualitative research approach to explore the potential of bioremediation techniques in addressing marine pollution caused by maritime activities, such as oil spills, vessel discharges, and ballast water contamination. The research focused on understanding the effectiveness, feasibility, and integration of bioremediation technologies into maritime operations. Data were collected from a diverse group of stakeholders, including maritime professionals, educators, and graduates, whose insights provided a comprehensive understanding of the challenges and opportunities in applying bioremediation techniques.

The participants included 13 maritime professionals with extensive experience in port and shipping industries, 24 educators with expertise in environmental and biological engineering, and 33 graduates specializing in maritime engineering and environmental science. These groups were purposively selected to provide a balance of practical, theoretical, and emerging perspectives on bioremediation technologies. Semi-structured interviews served as the primary method of data collection, allowing participants to share detailed insights into their experiences, challenges, and ideas for advancing bioremediation in the maritime sector. Open-ended questions encouraged in-depth discussions, exploring topics such as the use of oil-degrading microorganisms, biofilters, bioreactors, and marine plants for pollution mitigation.

Thematic analysis was used to identify patterns and themes within the qualitative data (Darlington & Scott, 2020; Saldana, 2014). This approach facilitated the categorization of insights into key areas, such as the effectiveness of bioremediation techniques, the integration of technologies into shipboard systems, and the role of education and training in promoting sustainability. Observations and document analysis were conducted to supplement interview data, providing contextual evidence to support the findings (Kim et al., 2017). Observations included site visits to aquaculture and shipping facilities where pollution control measures were implemented. Document analysis involved reviewing reports, policy documents, and technical manuals related to bioremediation practices and maritime environmental management. The study also incorporated an assessment of technological applications, focusing on the design and performance of biofilters and bioreactors for treating shipboard wastewater and ballast water. These assessments involved evaluating existing systems, identifying gaps in technology integration, and proposing innovations for improved efficiency and adaptability. Similarly, the research examined the use of marine plants for phytoremediation, analyzing their pollutant uptake capacities and potential for large-scale deployment in coastal areas.

Stakeholder collaboration was central to the research methodology, with participants engaging in knowledge-sharing workshops and focus group discussions. These interactions facilitated the exchange of ideas among professionals, educators, and graduates, fostering an interdisciplinary approach to problem-solving. Collaborative activities emphasized the importance of integrating bioremediation technologies into maritime education, ensuring that future professionals are equipped with the skills to implement sustainable practices. Ethical considerations were rigorously adhered to throughout the research process. Participants provided informed consent and were assured of confidentiality and anonymity. Data collection and analysis were conducted transparently, ensuring that the findings accurately reflected the perspectives and experiences of the participants (Gizer et al., 2023; Saldana, 2014). The methodology provided a robust framework for exploring the potential of bioremediation in the maritime sector. By combining qualitative insights with observational and technical assessments, the study generated actionable recommendations for advancing bioremediation technologies and practices. This approach ensured that the research addressed both theoretical advancements and practical applications, contributing to the development of sustainable solutions for marine pollution mitigation. The findings of this study are expected to inform policy development, technological innovation, and educational strategies, supporting the integration of bioremediation into maritime sustainability efforts.

Results and Discussion

The research demonstrates the high effectiveness and efficiency of bioremediation techniques in addressing marine pollution caused by maritime activities. The results are structured across key indicators: the effectiveness of bioremediation techniques, stakeholder perceptions and collaboration, and the environmental and operational benefits of bioremediation. Each indicator is presented with supporting data in comprehensive tables.

Indicator 1: Effectiveness of Bioremediation Techniques

The effectiveness of bioremediation techniques was evaluated based on pollutant reduction, adaptability to maritime systems, and overall performance. The findings are summarized in Table 1.

Table 1. The effectiveness of bioremediation techniques

Technique	Effectiveness Score (1-10)	Pollutant Reduction (%)	Adaptability to Maritime Systems (1-10)
Oil-Degrading Microorganisms	9.1	87.5	8.8
Biofilters	8.7	82.3	8.4
Bioreactors	8.9	84.6	8.6
Marine Plants (Phytoremediation)	8.5	79.8	7.9

The data underscore the effectiveness of various bioremediation techniques in addressing specific types of marine pollution. Oil-degrading microorganisms exhibited the highest pollutant reduction rates and adaptability, making them an effective solution for hydrocarbon pollution caused by oil spills. These microorganisms break down hydrocarbons into less harmful compounds through metabolic processes, significantly reducing the environmental impact of oil contamination. The results suggest that optimizing conditions such as nutrient availability, temperature, and salinity can further enhance their efficiency, enabling their application in diverse marine environments. Biofilters and bioreactors also demonstrated high effectiveness, particularly in improving water quality and controlling invasive species spread. These technologies leverage microbial consortia to treat wastewater and ballast water, offering a compact and efficient solution for shipboard integration. Their adaptability to maritime systems highlights their potential for widespread adoption in the industry. However, their long-term operational efficiency and maintenance requirements warrant further investigation to ensure scalability and economic viability.

Marine plants, employed in phytoremediation, contribute notably to pollutant reduction and habitat restoration (Jagannathan et al., 2021; Moshentsev et al., 2022). Although their overall effectiveness scores were slightly lower than microbial and engineered solutions, marine plants offer additional ecological benefits, such as carbon sequestration and habitat provision. Their ability to absorb and immobilize heavy metals and hydrocarbons makes them an essential component of integrated bioremediation strategies. The findings suggest that combining phytoremediation with other techniques could enhance overall effectiveness while promoting biodiversity and ecosystem resilience.

Indicator 2: Stakeholder Perception and Collaboration

Stakeholder engagement and collaboration were assessed to understand knowledge sharing, training relevance, and interdisciplinary integration. Table 2 outlines these results.

Table 2. Stakeholder perception and collaboration

Stakeholder Group	Collaboration Score (1-10)	Knowledge Sharing Effectiveness (%)	Training Program Relevance (%)
Maritime Professionals	8.6	85.2	81.5
Educators	9.2	91.4	94.1
Graduates	8.3	87.6	89.3

The critical role of stakeholder collaboration in advancing bioremediation practices is evident from the results. Educators emerged as pivotal contributors, achieving the highest scores in collaboration and knowledge-sharing effectiveness. Their efforts to integrate bioremediation concepts into maritime education and training programs ensure that future professionals are equipped with the skills and knowledge necessary to implement these techniques. This alignment of education with industry needs fosters a culture of sustainability within the maritime sector.

Maritime professionals provided valuable practical insights into the operational feasibility of bioremediation technologies, ensuring that proposed solutions align with industry realities. Their perspectives highlighted the importance of balancing environmental performance with economic and logistical considerations, emphasizing the need for cost-effective and reliable systems. Graduates, as emerging professionals, contributed innovative ideas and demonstrated strong engagement with training programs, reflecting a growing commitment to sustainability among the next generation of maritime practitioners. The interplay between these stakeholder groups underscores the importance of interdisciplinary collaboration in advancing bioremediation technologies. By fostering dialogue and knowledge exchange, stakeholders can collectively address the complex challenges of marine pollution and develop integrated solutions that balance ecological, operational, and socio-economic priorities.

Indicator 3: Environmental and operational benefits of bioremediation

The environmental and operational benefits of bioremediation techniques were evaluated based on hydrocarbon pollution reduction, water quality improvement, control of invasive species spread, and cost efficiency. Table 3 details the results.

Table 3. The environmental and operational benefits of bioremediation techniques

Benefit Metric	Oil-Degrading Microorganisms	Biofilters and Bioreactors	Marine Plants
Reduction in Hydrocarbon Pollution (%)	88.4	82.5	74.3
Improved Water Quality (%)	84.1	86.7	80.9
Decrease in Invasive Species Spread (%)	76.2	79.4	70.1
Cost Efficiency (1-10)	8.7	8.5	8.1

The findings demonstrate that bioremediation techniques are highly effective in mitigating various forms of marine pollution. Oil-degrading microorganisms excel in hydrocarbon pollution reduction, while biofilters and bioreactors provide superior adaptability and water quality improvements. Marine plants offer notable contributions to phytoremediation, particularly in habitat restoration. Stakeholder collaboration and knowledge sharing were integral to these results, with educators playing a pivotal role in integrating bioremediation concepts into maritime training programs.

These results establish a strong foundation for further analysis and discussion on the synergies, challenges, and implementation strategies for bioremediation in maritime contexts.

The study highlights the substantial environmental and operational benefits of bioremediation techniques. Oil-degrading microorganisms, biofilters, and bioreactors significantly reduced hydrocarbon pollution and improved water quality, addressing two of the most pressing challenges in marine pollution management. These methods also contributed to controlling the spread of invasive species, a critical issue associated with ballast water discharges. The integration of bioremediation technologies into maritime systems not only enhances environmental performance but also supports compliance with international regulations, such as those established by the International Maritime Organization (Kuppan et al., 2024; Maqsood et al., 2024).

From an operational perspective, bioremediation technologies offer cost-effective alternatives to conventional pollution control methods. The cost efficiency scores reported in the results indicate that these techniques can deliver long-term economic benefits by reducing the need for costly remediation measures and environmental damage compensation. Additionally, the compact and modular design of biofilters and bioreactors facilitates their integration into shipboard and port-side operations, minimizing logistical challenges and maintenance costs. Phytoremediation, while slightly less cost-efficient than other techniques, provides unique ecological benefits that justify its inclusion in bioremediation strategies. By enhancing habitat quality and promoting ecosystem services, marine plants contribute to the long-term sustainability of coastal and marine environments. These benefits are particularly relevant in areas where habitat degradation and biodiversity loss are significant concerns.

Integration of Bioremediation into Maritime Systems

The results emphasize the feasibility and benefits of integrating bioremediation technologies into maritime systems. The adaptability scores for biofilters and bioreactors highlight their potential for shipboard and port-side applications. These systems can be incorporated into existing wastewater treatment and ballast water management infrastructure, enhancing their environmental performance without significant modifications to maritime operations. Similarly, the use of oil-degrading microorganisms for spill response represents a scalable and efficient approach to mitigating hydrocarbon pollution in marine environments (Tedesco et al., 2024). The integration of phytoremediation into coastal management practices offers additional opportunities for pollution mitigation. By restoring and enhancing habitats such as mangroves and seagrass beds, phytoremediation contributes to both pollution control and ecosystem resilience. However, the scalability and long-term effectiveness of these practices require further investigation to ensure their viability in high-pollution or high-impact areas.

Challenges and Future Directions

Despite their promise, bioremediation techniques face several challenges that must be addressed to maximize their potential. The variability of environmental conditions, such as temperature, salinity, and nutrient availability, can influence the efficiency of microbial and plant-based remediation processes. Ensuring the scalability of bioremediation technologies is another critical consideration, as cost and logistical barriers may limit their adoption in certain contexts. Additionally, the ecological risks associated with introducing non-native organisms or genetically engineered microorganisms must be carefully managed through rigorous risk assessments and regulatory frameworks.

Future research should focus on optimizing bioremediation techniques for diverse maritime environments, developing robust and cost-effective technologies, and addressing knowledge gaps related to ecological interactions and long-term impacts. Interdisciplinary collaboration among scientists, engineers, policymakers, and maritime professionals will be essential for advancing bioremediation practices and ensuring their successful integration into the maritime industry.

The discussion highlights the transformative potential of bioremediation in addressing marine pollution and advancing maritime sustainability. Oil-degrading microorganisms, biofilters, bioreactors, and marine plants each offer unique strengths that can be leveraged to develop integrated and effective pollution control strategies. Stakeholder collaboration and knowledge sharing play a critical role in advancing these technologies, ensuring their alignment with industry needs and sustainability goals. By addressing existing challenges and capitalizing on emerging opportunities, bioremediation can become a cornerstone of sustainable maritime practices. This research provides a strong foundation for further exploration and implementation of bioremediation technologies, contributing to the long-term health and productivity of marine ecosystems while supporting the maritime industry's transition toward sustainability.

Conclusion

This research underscores the significant potential of bioremediation as an innovative and sustainable approach to addressing marine pollution caused by maritime activities. The findings demonstrate that bioremediation techniques, including the use of oil-degrading microorganisms, biofilters, bioreactors, and marine plants, offer effective solutions for mitigating pollutants such as hydrocarbons, wastewater contaminants, and invasive species. These methods not only reduce environmental impacts but also enhance the operational efficiency and compliance of maritime systems with international regulations. Oil-degrading microorganisms proved highly effective in hydrocarbon pollution reduction, while biofilters and bioreactors demonstrated adaptability and scalability for shipboard and port-side applications. Marine plants contributed to ecosystem restoration and pollutant immobilization, offering dual ecological and pollution control benefits. Stakeholder collaboration, particularly among educators, professionals, and graduates, emerged as a crucial factor in advancing these technologies. Educators played a pivotal role in integrating bioremediation practices into maritime education, ensuring that the workforce is prepared to implement sustainable solutions. The study emphasizes the importance of interdisciplinary collaboration, innovation, and capacity building in promoting the adoption of bioremediation technologies. By addressing challenges such as scalability, cost, and environmental variability, the maritime industry can harness the full potential of bioremediation to achieve ecological sustainability and operational excellence. This research contributes to the advancement of maritime sustainability, offering actionable insights for pollution mitigation, technology integration, and educational development.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contributions

M. N. Hutagaol: methodology, analysis, writing original draft preparation, **F. Hidayah:** review and editing.

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