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ORIGINAL RESEARCH ARTICLE

Microbial Bioremediation of Spent Engine Oil: Current Advances, Challenges, and Future Directions

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ABSTRACT

The extensive pollution of soil and water by spent engine oil (SEO) presents a considerable environmental hazard, especially because of its poisonous and recalcitrant characteristics. Traditional remediation approaches typically fall short in managing these toxins successfully, leading to an increased interest in bioremediation as a sustainable option. This review aims to compile current achievements/advancements in the microbial bioremediation of SEO, with emphasis on the effectiveness of several bacterial and fungal species in degrading the hydrocarbons in SEO under diverse environmental settings. Various studies published in the last decade (accessible via Google Scholar, Google, Scopus, and PubMed), reporting on microbial degradation rates on SEO, the impact of environmental conditions, and the efficacy of microbial consortia were objectively selected and analysed. Key findings showed that various genera such as *Alcaligenes, Acinetobacter*, *Bacillus*, *Candida, Flavobacterium*, *Pseudomonas*, and *Rhodococcus* were the most commonly reported microorganisms with potential SEO remediation because they have been reported to significantly degrade and used hydrocarbons in SEO as an energy source. Notably, *Pseudomonas alcaligenes* and *Klebsiella aerogenes* exhibited significant degradation rates of SEO, up to 68%, over 21 days under optimal conditions; *Acinetobacter*, *Bacillus*, *Micrococcus*, *Flavobacterium*, and *Pseudomonas* were found to exhibit a total hydrocarbon reduction of 86.7% over 60 days; while species like *Ochrobactrum thiophenivorans* were found to effectively degrade waste lubricating oil. However, there are significant differences in degradation rates among the reported species due to physiological factors such as temperature, pH, and available nutrients. Hence, it is inferential to conclude that microbial bioremediation shows promise in SEO management but its effectiveness is highly dependent on the type of microbial strain used and optimizing environmental conditions. Therefore, this review identifies several key knowledge gaps and proposed future research directions, such as the integration of bioremediation with emerging technologies to improve and ensure efficiency and scalability in real-world applications.

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INTRODUCTION

Spent engine oil, upon release into the environment, poses severe threats to ecosystems and human health due to its toxic and persistent nature (Jones and Brown, 2018). Notably, it contains various metals and heavy polycyclic aromatic hydrocarbons (PAHs) that can lead to chronic hazards like mutagenicity and carcinogenicity (Maki *et al.*, 2005; Mandri and Lin, 2017; Zengerer *et al.*, 2018; Oso *et al.*, 2019). Long-term exposure to high concentrations of oil may increase the risk of developing cancer, bone marrow damage, liver or kidney illnesses, among other diseases (Hossain *et al.*, 2022).

There are traditional methods such as thermal desorption, vitrification, excavation, air stripping, and bioleaching, however, these methods are often expensive, inefficient, time-consuming, and harmful to the environment and its biota (Johnson and Hall, 2015). In response, researchers have shifted focus towards microbial bioremediation, which offers several advantages over conventional methods, including cost-effectiveness, environmental sustainability, and the ability to completely mineralize organic pollutants (Jones *et al.*, 2016). This approach harnesses the metabolic capabilities of microorganisms to degrade and detoxify hydrocarbon pollutants present in spent engine oil, offering advantages such as non-invasiveness, ease of maintenance, large-area application, and minimal environmental disruption (Das and Chandran, 2011; Jones *et al.*, 2016).

While numerous studies, such as Oso *et al.*, (2019); Zengerer *et al.*, (2018); and Freimoser *et al.*, (2016), have explored the potential of microorganisms in breaking

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down petroleum compounds in soil, the information remains scattered, necessitating a comprehensive review to summarize current findings and identify essential processes for microbial remediation. Recent years have witnessed significant advancements in the bioremediation of spent engine oil, driven by ongoing efforts to optimize microbial degradation pathways, enhance biodegradation efficiency, and develop novel bioremediation technologies (Jaiswal *et al.*, 2019; Oliveira *et al.*, 2020).

These advancements comprise various aspects, including the identification and isolation of indigenous hydrocarbon-degrading microorganisms, optimization of environmental conditions for microbial growth and activity, and exploration of genetic and metabolic engineering approaches to enhance biodegradation capabilities (Oliveira *et al.*, 2020). Moreover, integrating bioremediation with other eco-friendly technologies like phytoremediation and bioaugmentation has shown promising results in enhancing the efficacy of spent engine oil remediation processes (Bento *et al.*, 2005; Khan and Liu, 2017). Additionally, the development of bio-based surfactants and biosurfactant-producing microorganisms has facilitated the solubilization and enhanced bioavailability of hydrophobic hydrocarbons in spent engine oil, thereby improving microbial access and degradation rates (Satpute *et al.*, 2010).

However, despite numerous studies demonstrating the potential of various microbial species to degrade hydrocarbons, there remains a significant knowledge gap regarding the optimization of these processes for large-scale applications. In particular, discrepancies in degradation rates across different studies highlight the need for a more nuanced understanding of how environmental factors influence microbial activity (Ismail *et al.*, 2014). Therefore, this review aims to critically assess the recent advancements in microbial bioremediation of spent engine oil, with a focus on identifying the most effective microbial strains and consortia, as well as the environmental conditions that enhance biodegradation. By synthesizing findings from the past decade, this review seeks to address the existing gaps in the literature and provide recommendations for future research that could lead to more effective and scalable bioremediation strategies. Specifically, the review will explore the potential integration of bioremediation with emerging technologies, such as nanotechnology and bioaugmentation, to improve the efficiency and applicability of this sustainable remediation approach.

Overall, the contribution of this review is multifaceted. It advances theoretical understanding by elucidating the complex interactions between microorganisms and pollutants at the molecular and ecosystem levels. Methodologically, it evaluates various approaches to enhance microbial bioremediation, from genetic engineering to the design of microbial consortia. Practically, it illuminates the pathways for the application of these biological techniques in contaminated sites, paving the way for more effective and sustainable remediation practices. By bridging research gaps and fostering an integrated view of microbial bioremediation, this review serves as a cornerstone for future investigations and applications in the pursuit of a cleaner and greener environment.

Literature selections and Scope of the review

This review includes a range of studies (available in Google scholar/Google/Scopus/PubMed search engines) published on the microbial bioremediation of spent engine oil, with a focus on the period from the last decade to the present to reflect the most recent scientific insights. Geographical limitations are not imposed, given the global nature of engine oil pollution. The literature included in this review covers empirical research on the efficacy of different microorganisms, the mechanisms of biodegradation, and the development of novel bioremediation technologies. Studies exclusively focusing on physical or chemical remediation methods without microbial involvement, as well as unrelated forms of environmental pollution, are excluded to maintain a clear focus on microbial processes (Figure 1).

INTRODUCTION TO ENGINE OIL BIOREMEDIATION TECHNIQUES

Bioremediation procedures can be used ex-situ and in-situ at the site of application (Figure 2).

***Ex-situ* bioremediation**: strategies involve excavating contaminants from polluted sites and moving them to another location for treatment (Thenmozhi et al., 2011).

***In-situ*, bioremediation techniques: entail** treating polluted substances at the site. It requires little excavation and causes little to no disruption to the soil structure. These strategies should be more cost-effective than ex-situ bioremediation procedures. Some in situ bioremediation techniques, such as bioventing, biosparging, and phytoremediation, can be improved, whereas others, such as intrinsic bioremediation or natural attenuation (Thenmozhi et al., 2011).

STUDIES ON COMMON ENGINE OIL BIOREMEDIATION APPROACHES

Phytoremediation of Soil Contaminated with Spent Engine Oil (SEO)

Phytoremediation is an eco-friendly, sustainable method that uses plants to mitigate or remove pollutants from the environment. Here, we synthesize the findings from recent research papers, categorizing them into groups based on the type of pollutants treated, plants used, and the method of phytoremediation employed (Table 1).

A substantial body of research has concentrated on the remediation of soils contaminated with spent engine oil (SEO) using various plant species, emphasizing the potential of phytoremediation as an effective strategy for mitigating soil and water pollution. These studies collectively highlight the effectiveness of certain plant species and organic amendments in enhancing the phytoremediation process, although the optimization of conditions for maximum efficiency remains an area requiring further investigation.

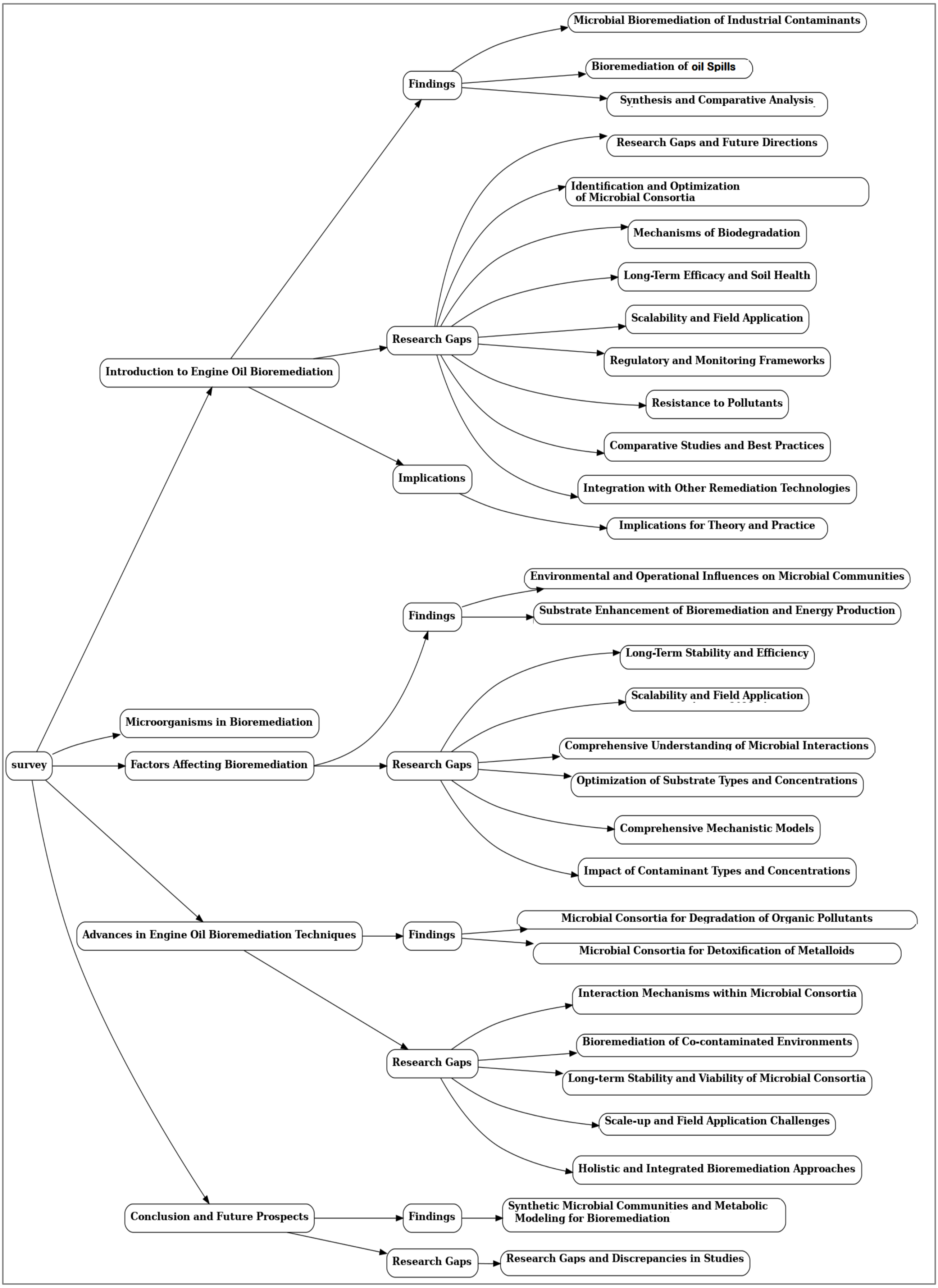

Figure 1: Conceptual framework and scope of the review

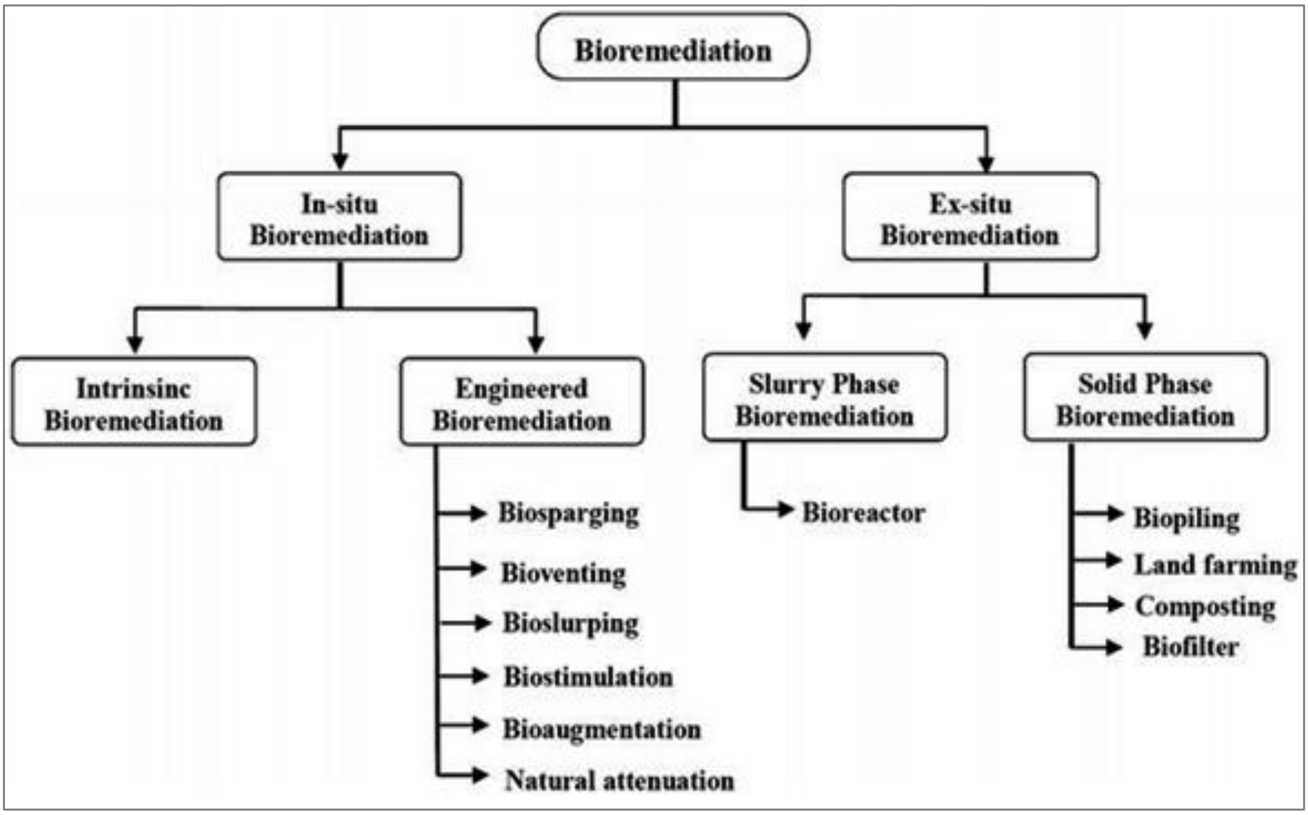

Figure 2: Bioremediation Techniques (Sharma, 2020).

For instance, Ayotamuno *et al.* (2006) explored the impact of SEO-contaminated soils on soybean growth parameters and mitotic chromosomes, revealing that SEO contamination significantly hindered growth and chromosomal stability. Similarly, Ogbo *et al.* (2009) studied the effects of SEO and industrial effluent on soil quality and air potato growth, finding notable reductions in both due to these pollutants. Ogboghodo *et al.* (2004) further demonstrated that the application of manure and *Glomus hoi* could improve soil properties and reduce heavy metal concentrations in SEO-contaminated soils, suggesting that such amendments may enhance phytoremediation outcomes. Additionally, Kayode *et al.* (2009) optimized the remediation of SEO-contaminated soil using maize leaves, which significantly accelerated SEO degradation in the soil.

Further research in this area includes studies like that of Ogbonna and Igwe (2012), who compared the exposure of edible vegetables to SEO and three commercially available PAH components, underscoring the significant contamination of these vegetables and the associated health risks. Isitekhale and Oghenerobor (2015) evaluated the efficacy of vermicast tea in remediating SEO-contaminated soil, concluding that it effectively improved soil quality and supported plant growth. In a related study, Odjegba and Sadiq (2002) assessed the effects of SEO on soil properties and the growth performance of *Amaranthus viridis*, finding that SEO adversely affected both, confirming the need for effective remediation strategies.

Agbogidi (2011) investigated the phytoremediation potential of *Sorghum bicolor*, *Helianthus annuus*, and *Telifaria occidentallis* on SEO-polluted soils with different textures, demonstrating that these plants could significantly reduce SEO contamination across various soil types. Nwite (2013) explored the survival and phyto-extraction capabilities of *Nauclea diderrichii* in SEO-contaminated conditions, highlighting the plant's ability to survive and extract heavy metals effectively. Similarly, Obire and Nwaubeta (2002) examined the impact of ginger on growth indices and lead bioaccumulation in tomato fruits grown in SEO- and lead-contaminated soils, finding that ginger could mitigate the adverse effects of these contaminants.

Enabulele and Ogbebor (2005) studied the effect of charcoal on the growth of *Rhizophora racemosa* in SEO-contaminated soil, concluding that charcoal amendments significantly improved plant growth. Ayotamuno *et al.* (2010) evaluated the phytoremediation potential of *Pennisetum glaucum* and *Vigna unguiculata*, showing that both species could substantially reduce SEO levels in contaminated soils. Ayotamuno and Kogbara (2007) investigated the anatomical changes in *Eruca sativa* leaves due to SEO pollution, noting significant stress and damage indicators.

In addition, Babatunde *et al.* (2002) examined the use of *Moringa oleifera* leaf extracts and hydrocarbon-degrading microorganisms for green remediation in crude oil-impacted soils, demonstrating enhanced remediation and metal accumulation. Ojo (2005) explored the use of water hyacinth biomass as an eco-friendly sorbent for petroleum oil spill cleanup, finding it highly effective. Ibrahim (2008) investigated the effect of SEO-induced toxicity on the germination, growth, and yield of *Pennisetum glaucum* (Var. Super Sosat), revealing significant negative impacts. Lastly, Nwaichi and Uzazobona (2011) assessed the use of rice husk manure and seaweed extract to enhance the phytoremediation potential of guinea grass (*Megathyrsus maximus*), finding these amendments significantly improved remediation outcomes.

Table 1: Summary of Phytoremediations of SEO

Year of Study	Pollutants Treated	Plants Used	Method of Phytoremediation Employed	Brief Findings	Reference(s)
2002	Spent engine oil, Lead	*Amaranthus viridis*, *Tomato*	Soil phytoremediation, Ginger application	SEO and lead contamination negatively affected soil properties and plant growth, mitigated by ginger	Odjegba and Sadiq (2002); Obire and Nwaubeta (2002)
2002	Crude oil	*Moringa oleifera*	Phytoremediation, Hydrocarbon-degrading microorganisms	Enhanced metal accumulation and soil remediation	Babatunde *et al.* (2002)
2004	Spent engine oil, Heavy metals	-	Soil amendment with manure and *Glomus hoi*	Improved soil properties and reduced heavy metal concentrations	Ogboghodo *et al.* (2004)
2005	Spent engine oil	*Rhizophora racemosa*	Soil amendment with charcoal	Charcoal improved plant growth in contaminated soil	Enabulele and Ogbebor (2005)
2006	Spent engine oil	*Soybean*	Growth parameter analysis	SEO contamination reduced growth and chromosomal stability	Ayotamuno *et al.* (2006)
2007	Spent engine oil	*Eruca sativa*	Anatomical leaf analysis	SEO caused significant anatomical changes in leaves, indicating stress	Ayotamuno and Kogbara (2007)
2008	Spent engine oil	*Pennisetum glaucum*	Toxicity stress evaluation	SEO contamination significantly reduced germination, growth, and yield	Ibrahim (2008)
2009	Spent engine oil, Industrial effluent	*Air potato*	Soil quality and growth assessment	SEO and industrial effluent reduced soil quality and plant growth	Ogbo *et al.* (2009)
2009	Spent engine oil	*Maize*	Phytoremediation using maize leaves	Maize leaves significantly enhanced SEO degradation in soil	Kayode *et al.* (2009)
2010	Spent engine oil	*Pennisetum glaucum*, *Vigna unguiculata*	Soil phytoremediation	Both plants significantly reduced SEO levels in the soil	Ayotamuno *et al.* (2010)
2011	Spent engine oil	*Sorghum bicolor*, *Helianthus annuus*, *Telifaria occidentallis*	Phytoremediation on various soil types	These plants effectively reduced SEO contamination in various soil types	Agbogidi (2011)
2011	Spent engine oil	*Guinea grass (Megathyrsus maximus)*	Phytoremediation with rice husk manure and seaweed extract	Rice husk manure and seaweed extract significantly enhanced phytoremediation potential	Nwaichi and Uzazobona (2011)
2012	Spent engine oil, PAHs	*Edible vegetables*	Exposure analysis	SEO and PAHs significantly contaminated vegetables, posing health risks	Ogbonna and Igwe (2012)
2013	Spent engine oil, Heavy metals	*Nauclea diderrichii*	Phyto-extraction	Plant survived and extracted significant amounts of heavy metals	Nwite (2013)
2015	Spent engine oil	-	Soil phytoremediation with vermicast tea	Vermicast tea effectively improved soil quality and supported plant growth	Isitekhale and Oghenerobor (2015)

Research Gaps and Future Directions in Phytoremediation of Soil Contaminated with SEO

While the literature reviewed here indicates promising results in the field of phytoremediation, there are several research gaps and discrepancies that warrant further investigation. These discrepancies arise from variations in experimental design, differences in soil types, pollutant concentrations, and plant species used in the studies. Here are some of the notable gaps:

Species-Specific Remediation Efficiency

Although the studies review the effectiveness of various plant species in phytoremediation, there is a lack of comprehensive cross-species comparisons under uniform conditions. Future research should focus on controlled experiments that directly compare the phytoremediation efficiencies of multiple species side by side.

Long-Term Impact Assessment

Many studies focus on short-term results, often within a single growing season. The long-term impact of phytoremediation on soil quality, ecological balance, and sustainability of plant species in contaminated environments is not extensively documented. Long-term studies would be useful to evaluate the persistence of benefits and any potential negative effects.

Mechanisms of Pollutant Uptake and Degradation

While it is evident that certain plants can absorb or degrade pollutants, the specific mechanisms at the molecular and biochemical levels are not well understood. Research into these pathways could lead to the development of genetically modified plants or tailored microbe-plant partnerships with enhanced remediation capabilities.

Optimal Conditions for Remediation

The efficacy of phytoremediation is influenced by various factors including soil type, pH, temperature, and pollutant concentration. However, the optimal conditions for maximizing phytoremediation efficiency are not well defined. Standardized protocols and more detailed studies on the influence of these factors are needed.

Role of Soil Microbiota

The interaction between plants and soil microbiota in the context of phytoremediation is an underexplored area. Although some studies have looked at the use of microbial inoculants, more research is needed to understand the synergistic relationships that could improve remediation outcomes.

Scalability and Economic Viability

Most studies are conducted on a small scale, often in controlled greenhouse conditions. There is a gap in research on the scalability of these methods to field conditions and their economic viability, especially in comparison to conventional remediation technologies.

Health Risks of Bioaccumulation

The potential risks associated with the bioaccumulation of heavy metals and other pollutants in plants used for phytoremediation are not always addressed. Studies are needed to assess the safety of using these plants for food or fodder to prevent secondary contamination.

Variability in Pollutant Types

Different pollutants may require different approaches to phytoremediation. The literature often focuses on specific pollutants like spent engine oil or heavy metals, but comprehensive studies that address a wider range of contaminants are lacking.

Post-Remediation Land Use

There is a lack of research on the appropriate post-remediation land use practices. Establishing guidelines for the safe use of remediated land for agriculture or habitation is crucial.

Standardization of Methodologies

Discrepancies between studies could be due to a lack of standardized methodologies for assessing phytoremediation effectiveness. Developing uniform methods for measuring pollutant levels, plant health, and soil quality post-remediation would help in comparing and validating results across different studies.

Microbial Bioremediation of SEO

Microorganisms are the first recyclers in nature, converting organic and inorganic matter into energy sources and building blocks for their own growth. This capability raises the possibility that cheaper and more environmentally friendly biological processes could replace costly chemical or physical purification methods. Therefore, microorganisms represent a promising and mostly untapped resource for novel environmental biotechnologies (Kumari *et al.*, 2014). A variety of bacteria and fungi can be used for bioremediation, making them a versatile tool in environmental management. Table 2 provides a summary of the common microorganisms used in the bioremediation of SEO.

Among the most common genera involved in oil degradation are *Rhodococcus*, *Alcaligenes*, *Mycobacterium*, *Bacillus*, *Rhodotorula*, *Nocardia*, *Pseudomonas*, *Acinetobacter*, *Flavobacterium*, *Micrococcus*, *Arthrobacter*, *Corynebacterium*, *Achromobacter*, *Candida*, and *Sporobolomyces* species (Hossain *et al.*, 2022). Additional significant bacterial hydrocarbon degraders include *Bacillus*, *Burkholderia*, *Collimonas*, *Corynebacterium*, *Dietzia*, *Flavobacterium*, *Gordonia*, *Micrococcus*, *Achromobacter*, *Nocardioides*, *Ralstonia*, *Sphingomonas*, and *Variovorax*. Similarly, fungi such as *Aspergillus*, *Candida*, *Cunninghamella*, *Fusarium*, *Mucor*, *Penicillium*, *Phanerochaete*, and *Trichoderma* are proficient in removing hydrocarbon pollutants from soil (Obayori and Salam, 2010; Duan *et al.*, 2013; Stephen *et al.*, 2016; Adeleye *et al.*, 2018).

Research by Castaldi *et al.* (2021) identified over 100 bacterial species capable of utilizing hydrocarbons as an energy source, facilitating the rapid degradation of crude oil spills across diverse environments. Key bacteria implicated include *Acromobacter*, *Pseudomonas*, *Mycobacterium*, *Alcaligenes*, and *Nocardia*, while yeasts and *Candida* species also contribute to the breakdown of specific hydrocarbons. For instance, *Geotrichum sp.*, *Rhodotorula mucilaginosa*, and *Trichosporon mucoides* have been actively involved in degrading petroleum compounds (Chipasa *et al.*, 2006).

Numerous fungi from various genera have shown promise in bioremediation efforts. For example, *Candida*, *Yarrowia*, and *Pichia*, alongside fungal taxa such as *Amorphoteca*, *Talaromyces*, *Neosartorya*, and *Graphium*, were isolated from petroleum-contaminated soils and exhibited potential for hydrocarbon degradation (Chaillan *et al.*, 2014). Additionally, Singh (2006) identified terrestrial fungi like *Aspergillus*, *Cephalosporium*, and *Penicillium* species as effective agents for remediating crude oil hydrocarbons.

Studies on hydrocarbon bioremediation often highlight the superior efficacy of indigenous oil-degrading bacteria compared to introduced microbial consortia. Indigenous microbes have been found to efficiently degrade oil in polluted environments without the need for bioaugmentation (Ali *et al.*, 2023; Ramdass and Rampersad, 2022). However, bioaugmentation has proven beneficial in enhancing marine oil pollution bioremediation, indicating that introducing efficient petroleum-degrading bacteria can significantly improve degradation rates (Gao *et al.*, 2022). These findings underscore the importance of environmental context and existing microbial communities in determining bioaugmentation success.

The reviewed literature consistently points to the critical role of microorganisms and their enzymes in bioremediation, with broad applications across various pollutants, including synthetic plastics, heavy metals, hydrocarbons, and textile dyes (Chaurasia, 2023). While the effectiveness of indigenous microbial communities and the benefits of bioaugmentation are generally agreed upon, specific outcomes may vary based on environmental conditions and the types of microorganisms involved (Hlihor and Cozma, 2023; Pande *et al.*, 2022; Lu *et al.*, 2022; William and Magpantay, 2023; Yang *et al.*, 2023). These outcomes highlight the need for further research to deepen our understanding of microbial mechanisms and to develop effective bioremediation strategies tailored to specific types of pollution and environmental contexts.

Research Gaps and Future Directions in Microbial Bioremediation of SEO

Despite the advancements and promising results presented in the current body of literature on microbial bioremediation, there are still notable research gaps and discrepancies between studies that warrant further investigation. Addressing these gaps through targeted research could lead to the development of more effective, sustainable, and environmentally sound bioremediation practices.

One major research gap is the lack of field-scale studies that verify the efficacy of microbial bioremediation techniques observed in laboratory settings. While many studies demonstrate the potential of microbial consortia in controlled environments, the translation of these findings to large-scale environmental applications has not been sufficiently explored (Ramdass and Rampersad, 2022). Field trials are necessary to validate the effectiveness of these biore mediation strategies under varying environmental conditions and to determine their practicality and cost-effectiveness.

Another gap is the limited understanding of the interactions between different microbial species within consortia and their collective impact on pollutant degradation (Gupta and Arunachalam, 2023).

Lastly, there are also discrepancies in the literature regarding the benefits of bioaugmentation. Some studies report the success of introducing specific petroleum-degrading bacteria to enhance bioremediation (Gao *et al.*, 2022), while others suggest that indigenous microbial communities are sufficiently effective without the need for bioaugmentation (Ali *et al.*, 2023). These conflicting findings may be due to differences in the environmental contexts of the studies, the types of pollutants, or the methodologies used. Further research is needed to determine when and where bioaugmentation is most beneficial.

Mechanism of Microbial Bioremediation of SEO

Most microorganisms follow two common mechanisms in the bioremediation process; metal sequestering or immobilization and enhancement of solubility properties of the metal, other organisms oxidize or reduce the heavy metals to a less toxic form (Donald 2013). The bioremediation process also could be accomplished in aerobic and anaerobic environments; however, the aerobic environment was found to be more efficient and faster than anaerobic conditions.

Due to the ubiquitous nature of microorganisms, they play a crucial role in the bioremediation of heavy metals, they can interact with heavy metals using different mechanisms to survive the toxicity of the pollutants. The two main concepts by which the organism can deal with contaminants are using the contaminant as a source of nutrition and protecting the organism itself (defense mechanism) from the toxic effect (Alvarez *et al.* 2017). As illustrated in Figure 3, the microorganism reacts with the environmental contaminants using direct or indirect mechanisms some of which are biosorption and biotransformation (Tang *et al.* 2021).

Table 2: Microorganisms used in Bioremediation of SEO

Year of Study	Type of Oil Degraded	Microorganisms Used	Brief Finding	Reference(s)
2006	Biodegradation of waste petroleum hydrocarbons	*Geotrichum sp.*, *Rhodotorula mucilaginosa*, *Trichosporon mucoides*	Yeasts and fungi contribute to petroleum compound degradation.	Chipasa *et al.*, 2006
2010	Biodegradation of waste petroleum hydrocarbons pollutants	*Aspergillus*, *Candida*, *Cunninghamella*, *Fusarium*, *Mucor*, *Penicillium*, *Phanerochaete*, *Trichoderma*	Fungi found capable of removing hydrocarbon pollutants from soil.	Obayori and Salam, 2010
2013	Biodegradation of waste petroleum hydrocarbons pollutants	Various bacterial and fungal strains from petroleum-contaminated soils	Fungal genera such as *Candida*, *Yarrowia*, *Pichia*, and *Amorphoteca* isolated and shown to degrade hydrocarbons.	Chaillan *et al.*, 2014
2014		Various bacteria and fungi, including *Achromobacter*, *Pseudomonas*, *Candida*	Microorganisms seen as a promising resource for environmental biotechnology.	Kumari *et al.*, 2014
2014	Biodegradation of waste SEO	*Pseudomonas alcaligenes LR14, Klebsiella aerogenes CR21, Klebsiella pneumonia CR23, Bacillus coagulans CR31, and Pseudomonas putrefacience CR33*	The listed species exhibited respectively 59%, 62%, 58%, 45% and 68% degredation rate of spent engine after a 21 day incubation period.	Ismail *et al.* (2014)
2015	Biodegradation of waste lubricants	*Ochrobactrum thiophenivorans, O. rhizosphaerae*	The two species were found to be positive in degradation of waste lubricating oil.	Bhattacharya, *et al.,* (2015)
2016		*Aspergillus*, *Candida*, *Cunninghamella*, *Fusarium*, *Mucor*, *Penicillium*, *Phanerochaete*, *Trichoderma*	Various fungi confirmed for bioremediation.	Stephen *et al.*, 2016
2018	Biodegradation of hydrocarbons pollutants in soil	*Aspergillus*, *Candida*, *Cunninghamella*, *Fusarium*, *Mucor*, *Penicillium*, *Phanerochaete*, *Trichoderma*	Highlighted fungi's role in hydrocarbon removal from soil.	Adeleye *et al.*, 2018
2018	Bacteria Isolates Use in Lubricant Oil in Vitro Bioremediation	*Pseudomonas aeruginosa, Bacillus sp1, Bacillus sp2 and Alcaligenes*	The hydrocarbonoclastic bacteria were used need in situ characterization and their actual activities for bioremediation was discovered to be positive.	Ahda *et al.,* (2018)
2021	Biodegradation of crude oil spill	*Acromobacter*, *Pseudomonas*, *Mycobacterium*, *Alcaligenes*, *Nocardia*	Over 100 bacterial species identified as hydrocarbon degraders, aiding in crude oil spill disappearance.	Castaldi *et al.*, 2021
2022	Biodegradation of crude oil spill	*Sphingomonas*, *Variovorax*, *Pseudomonas*, *Candida*, *Aspergillus*, *Penicillium*	Microbial consortia involving biosurfactant-producing microbes highly efficient in crude oil removal.	Ramdass and Rampersad, 2022
2022	Biodegradation of SEO	Indigenous microbial consortia	Indigenous microbes found effective in oil degradation without bioaugmentation.	Ali *et al.*, 2023; Ramdass and Rampersad, 2022

To be continued next page

Table 2 continued

Year of Study	Type of Oil Degraded	Microorganisms Used	Brief Finding	Reference(s)
2023	Oil waste bioremediation	Indigenous and bioaugmented microbial communities	Indigenous microbial communities effective in bioremediation; bioaugmentation benefits depend on context.	Hlihor and Cozma, 2023; Pande *et al.*, 2022; Lu *et al.*, 2022
2023	Bioremediation of waste plastics, metals, and hydrocarbons	Various microorganisms	Microorganisms and enzymes are crucial in bioremediation across various pollutants, including plastics, metals, and hydrocarbons.	Chaurasia, 2023; William and Magpantay, 2023; Yang *et al.*, 2023

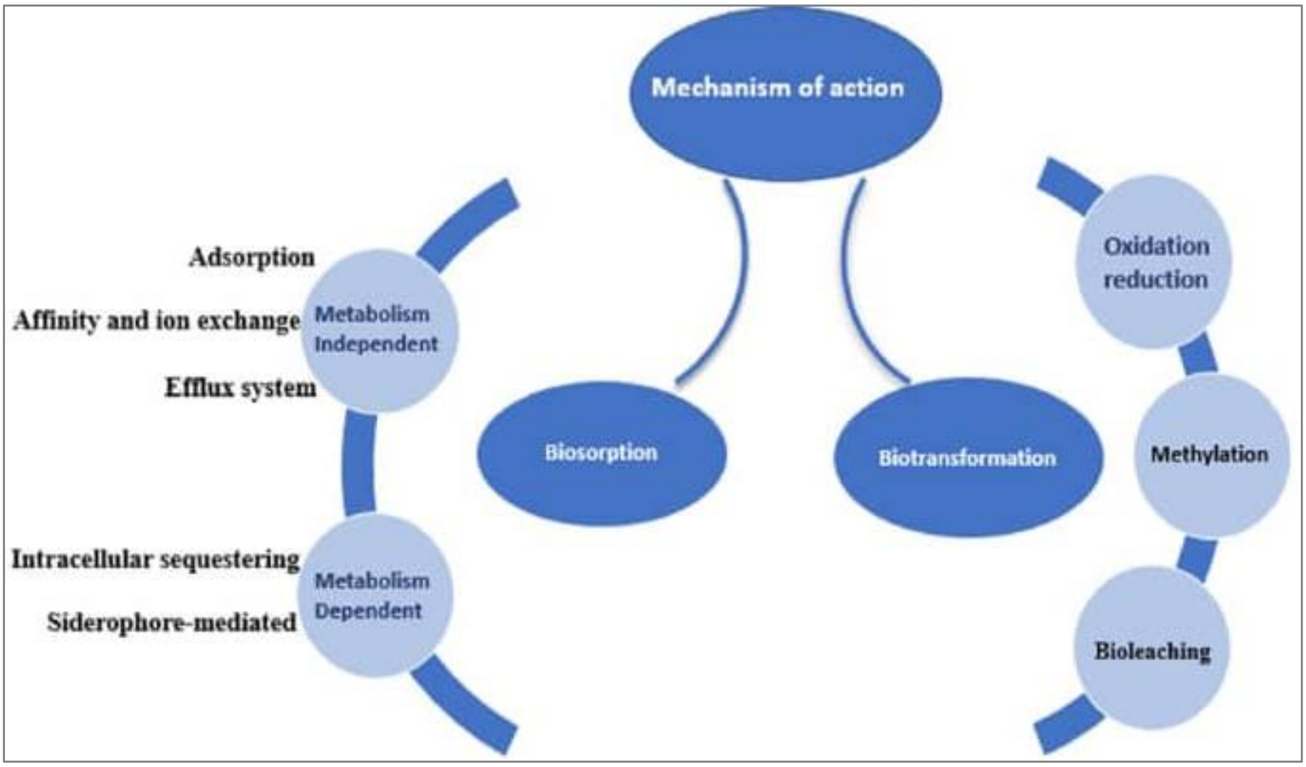

Figure 3: Diagram showing different mechanisms of bioremediation action

FACTORS AFFECTING BIOREMEDIATION OF SEO

Given the recent studies on factors affecting bioremediation, we can categorize the findings into two main groups. The first group focuses on the influence of environmental and operational conditions on microbial communities involved in bioremediation, while the second group explores the use of specific substrates to enhance bioremediation effectiveness and energy production.

Environmental Conditions

Environmental conditions can have a significant impact on the amount and rate of biodegradation. It is frequently possible to change factors at treatment sites, such as the availability of oxygen and nutrients, to hasten natural biodegradation. One such element that is frequently beyond our control is salinity. Lack of knowledge regarding how various environmental factors affect the pace and intensity of biodegradation is another source of uncertainty (Balogun *et al.*, 2015).

Oxygen

Oxygen is one of the most important factors in the microbial degradation of oil. However, its availability as a rate-limiting factor for the biodegradation of wastewater contaminated with oil occurs infrequently. The attack on oil is launched by microorganisms using oxygen-incorporating enzymes. Some oils degrade anaerobically, or without oxygen, though frequently at very slow rates. Such degradation occurs along a number of chemical pathways and is often regarded as having little ecological significance. Investigations of sediments damaged by the Amoco Cadiz accident show that anaerobic biodegradation is, at most, many orders of magnitude slower than aerobic biodegradation (Chaîneau *et al*., 2005). The initial breakdown of oil typically requires oxygen, and later reactions may also require its direct confinement. The amount of dissolved oxygen needed to thoroughly oxidize one part of oil to carbon dioxide and water can range from three to four parts.

Temperature

Lower temperatures reduce the rate of oil metabolism in microorganisms. This makes lighter petroleum fractions such as palm oil less volatile, increasing the time in which hazardous oil components can dissolve in water and reducing microbial activity. Biodegradation rates increase with temperature. Both lipid solubility and diffusion coefficients in aqueous environments increase significantly with temperature (Chipasa *et al*., 2006).

Evolution of Carbon Dioxide

According to the National Research Council (NRC, 1985), measuring CO2 evolution is a simple method that provides a quick estimate of the activity of samples rich in microorganisms. CO2 can be precisely measured by titration of BaCO3 or by means of infrared gas analysis. Because microorganisms are able to use these hydrocarbon pollutants as their only source of carbon and energy and convert them into less harmful products, which are mainly water and carbon dioxide, measuring carbon dioxide evolution would currently be a way to predict the degradation of waste oil polluted soils monitor to be close to precision (National Research Council, NRC 1985).

pH

The ability of microorganisms to grow or thrive in a given habitat is affected by pH, as is temperature. Bacteria, in particular, often thrive best in a restricted pH range of around 6.7 to 7.5. The pH (acidity or alkalinity) of the system under study can often be directly correlated to the metabolic activities of microorganisms within that system. Numerous studies have shown that bacteria are able to change the pH of their environment by creating metabolic waste products that can be either basic or acidic. Organic acids produced as a result of microbial activity help to drop the pH of the system, making it more acidic, as opposed to organic bases, which would raise the pH of the system and so make it more alkaline (Chaîneau *et al*., 2005).

Microbial Population Density

The growth of microorganisms in any system is expected to proceed through the lagging, exponential or logarithmic, stationary, and death phases of the microbial growth curve, as described by Khan and Rizvi (2011). Microbes often grow as pollutants are consumed, indicating that the pollutant is being used or broken down successfully.

Total Petroleum Hydrocarbon (TPH)

Total Petroleum Hydrocarbon (TPH) is also known as mineral oil, extractable hydrocarbons, hydrocarbon oil, or oil and grease. Essentially, a variety of analytical methods are available for measuring TPH concentrations in the environment (Khan and Rizvi, 2011).

Water

Microorganisms require water for their growth as it makes up a significant percentage of their cell cytoplasm. Water serves as the primary solvent in most enzymatic processes that occur in solution. Water is necessary for the transport of most components in and out of the cell. The water activity or water potential (aw) of a typical soil, for example, can range from 0.00 to 0.99, unlike aquatic situations where water potential is steady at a value near to 0.98 (Hossain *et al*., 2022; Stephen *et al*., 2016). As a result, the biodegradation of hydrocarbons in terrestrial habitats may be constrained by the amount of water available for microbial development and metabolism (Stephen *et al*., 2016).

Other Variables

A number of factors, including salinity and pressure, have been reported to have a significant impact on how quickly microbial oil is broken down (US Congress, 1991). The author reiterated that in a natural environment with a resident microbial population, the variables are not a major concern.

Research Gaps and Future Directions on Factors Affecting Microbial Bioremediation of SEO

Despite the promising findings in the aforementioned studies, there remain several research gaps and areas that require further exploration to fully harness the potential of bioremediation and energy production through microbial processes. By filling these gaps, we can move closer to developing robust, efficient, and sustainable bioremediation strategies that not only clean up environmental pollutants but also contribute to renewable energy generation. Some of these gaps include:

Comprehensive Mechanistic Models

There is also a need for the development of comprehensive mechanistic models that can predict the outcomes of bioremediation processes under various conditions. Such models would help in understanding the complex interplay of factors that influence microbial activity and could guide the design of more effective bioremediation strategies.

Impact of Contaminant Types and Concentrations

Finally, the impact of different types and concentrations of contaminants on microbial communities and their bioremediation capabilities is not fully understood. Different contaminants may require specific microbial consortia or conditions for effective degradation, and high concentrations of toxic compounds could inhibit microbial activity. Research that elucidates the tolerance limits and adaptive mechanisms of microbes in the presence of various pollutants is crucial.

ADVANCES IN ENGINE OIL BIOREMEDIATION TECHNIQUES

Recent studies have made significant progress in the field of bioremediation, focusing on the use of microbial consortia to degrade complex pollutants such as polycyclic aromatic hydrocarbons (PAHs) and metalloids. These advances are particularly relevant to the bioremediation of contaminated environments, including those affected by engine oil spills, which often contain a complex mixture of hydrocarbons and heavy metals. The following synthesis groups together recent research findings to provide an overview of the current state of bioremediation techniques as they apply to engine oil contamination.

Microbial Consortia for Degradation of Organic Pollutants

A common theme among recent studies is the use of microbial consortia to enhance the biodegradation of organic pollutants, particularly PAHs, which are common constituents of engine oil. The studies by Zhou *et al.* (2023) explore the potential of microbial consortia to degrade such compounds.

Zhou *et al.* (2023) specifically investigated the biodegradation of aged PAHs in soil, which is relevant to the remediation of environments contaminated with engine oil residue. Their study found that a bacterial consortium, identified as H6, achieved high degradation efficiencies, especially when combined with the addition of glucose and sodium dodecyl benzene sulfonate (SDBS) and immobilized on biochar.

Microbial Consortia for Detoxification of Metalloids in SEO

All studies agree on the efficacy of microbial consortia for the bioremediation of complex pollutants. There is a consensus that a combination of different microbial species can result in more effective degradation of pollutants than single strains alone. The studies also suggest that the optimization of conditions, including the addition of certain chemicals or the immobilization of microbes, can significantly enhance bioremediation processes Zhou *et al.* (2023).

Recent advances in bioremediation techniques emphasize the importance of microbial consortia for the effective degradation of complex pollutants, including those found in engine oil. These studies collectively suggest that the future of bioremediation could involve the strategic combination of different microbial species, optimized conditions, and potentially the use of synthetic biology to create more efficient biodegrading communities.

Research Gaps and Future Directions in Advances of SEO Microbial Degradation

Despite the promising developments in the use of microbial consortia for bioremediation, certain gaps in the research still need to be addressed to fully harness their potential. Below, we discuss some of these research gaps and suggest directions for future studies.

Interaction Mechanisms within Microbial Consortia

One significant gap identified in the current literature is the lack of comprehensive understanding of the interaction mechanisms within microbial consortia Zhou *et al.* (2023).

Long-term Stability and Viability of Microbial Consortia

Research by Zhou *et al.* (2023) showed promising results for the degradation of PAHs using immobilized consortia. However, the long-term stability and viability of such consortia in natural settings remain unclear. It is important to assess how these consortia behave over extended periods and under varying environmental conditions. The development of consortia that maintain their biodegradation capabilities over time and can adapt to changing conditions is crucial for their practical application in the field.

Holistic and Integrated Bioremediation Approaches

Finally, there is a need for a more holistic approach that integrates microbial consortia with other bioremediation technologies. Combining physical, chemical, and biological methods could potentially lead to more effective and efficient clean-up strategies. Research into integrated approaches that leverage the strengths of each method while mitigating their weaknesses is necessary to develop comprehensive bioremediation solutions.

In conclusion, while there are clear advancements in the use of microbial consortia for bioremediation, future research should focus on understanding microbial interactions, tackling co-contamination, ensuring long-term stability, scaling up to field applications, and developing integrated bioremediation strategies. Bridging these gaps will enable us to move closer to the practical and sustainable use of microbial consortia in remediating contaminated environments.

CONCLUSION

The need to adopt environmentally friendly approaches to the remediation and reclamation of environments polluted by spent motor oil and other petroleum hydrocarbons is paramount today. Hydrocarbon-related pollution disrupts ecosystem balance and health, necessitating effective cleanup strategies. Oil-degrading microorganisms show great potential for bioremediating environments contaminated with waste oil, provided favorable environmental and nutritional conditions are ensured for their optimal growth. Bioremediation technologies have long been recognized as valuable tools for restoring hydrocarbon-polluted habitats, but their practical application still requires enhancement through current novel concepts.

Significant progress has been made in utilizing microbial consortia for bioremediation; however, several knowledge gaps and discrepancies remain. Addressing these through targeted future research can help optimize the use of bioremediation strategies. More field-scale validation studies are needed to verify laboratory findings and better understand long-term performance under real-world conditions. Additionally, investigating microbial interactions at finer scales using advanced omics techniques may provide new insights for designing robust and efficient bioremediation approaches. Continued interdisciplinary collaboration between computational modeling, engineering, and environmental sciences will be key to overcoming current limitations and fully realizing the potential of microbe-mediated solutions to environmental pollution challenges.

Overall, microbial bioremediation holds promise as a sustainable remediation approach. Ongoing advances in this area could substantially impact practices and policies in environmental management and protection, ensuring effective cleanup of habitats damaged by spent motor oil and other petroleum hydrocarbons.

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