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Viable and sustainable strategies to manage the oil spills in the marine ecosystem: A review

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ABSTRACT

Oil spills in marine ecosystems remain a significant global environmental hazard, necessitating enduring, sustainable, and efficient mitigating measures. Historically, synthetic chemical dispersants—while initially economical—have demonstrated ecological dangers, often increasing toxicity in marine environments, as evidenced by substances such as Corexit. This recognition has redirected attention to eco-friendly alternatives that are non-toxic, biodegradable, and economically viable. Recent advancements highlight integrated sustainable methods, encompassing bioproduct utilization, microbial consortia, and interventions powered by nanotechnology. Nanoparticle (NP)-enhanced bioremediation is emerging as a viable technique, enabling tailored stimulation of marine oil-degrading microorganisms and enhancing degradation efficiency across diverse oil types and weathered environments. This study synthesizes existing knowledge on environmentally sustainable and biotechnological approaches for marine oil spill remediation, emphasizes the promise of nanoparticle-assisted microbial degradation, and delineates critical technological and research deficiencies. It seeks to offer a proactive approach to attaining zero environmental effect from unintentional oil spills in maritime ecosystems and their hazardous effects.

1. Introduction

Accidental oil spills in the ocean have adverse effects on the marine ecosystem and the economic systems that depend upon these ecological systems [1]. Each container of oil shipped by sea

around the globe puts the ecosystem at risk of oil spills. While any oil spill has the potential to be disastrous, the long-term impact is determined more by the speed of cleanup than by the amount of oil spilled. When oil reaches the surface, both its chemical makeup and characteristics change

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almost instantly [2]. Following the first spill, a variety of processes occur: oil-evaporated water, oxidation, dispersion, emulsification, biodegradation, and sedimentation. Oil spills have been occurring for many years, but remediation approaches remain largely unaltered [3]. Techniques such as thermal, mechanical, chemical, and biological approaches are all used to respond to oil spills. Although every approach has benefits and drawbacks, their effectiveness is frequently dependent on external influences, including oil volume, composition, location, viscosity, and atmospheric conditions [4]. Furthermore, oil spills from tankers have been identified as the worst disasters that affect the marine ecosystem. Because the majority of oil floats on the surface of the water, they mostly affect seabirds and marine life, while other living things, including terrestrial beings, are harmed when the oil washes ashore. Human beings are also affected by accidental oil spills. Over the years, scientists have studied the causes and effects of such spills on the marine environment and have developed different strategies and chemical agents for oil spill response [5]. However, the remediation technology that must be used is determined by both the quantity and location of the spill. The physical, mechanical, chemical, and biological approaches to oil spill removal are available. Booms, which are still floating barriers that prevent oil from moving, are one example of a physical and mechanical approach. The use of elevated temperature booms allows the oil to be burned in situ. Skimmers are either fixed or portable tools used for removing floating and emulsified or dispersed oils from the surface of the water [6]. Hydrophobic nets, which repel water while allowing oil to pass through, can be used in skimmers to improve the removal of oil. Dispersing agents sprayed upon the accidental oil spill to chop it into numerous tiny droplets are examples of chemical-based methods [7]. Furthermore, absorbent substances could be used for modest oil spills. Conventional oil spill response methods, such as in situ burning and chemical dispersants, can have secondary environmental effects that increase the importance of sustainable management of oil spills [8]. These effects include toxicity to marine life, long-term contamination, and greenhouse gas

emissions. Sustainable remediation, however, emphasizes environmentally sustainable, resource-efficient, and long-term solutions that minimize ecological impacts and facilitate natural recovery processes [8]. Alternatives such as biological remediation, biosurfactants, phytoremediation, and new green nanomaterials are effective, which can not only increase the removal ability of contaminants but also maintain marine biodiversity and ecosystem functions [9]. These sustainable solutions will boost the effectiveness of oil spill cleanup and help to improve the resilience of the ecosystem, reduce climate change, and conserve marine resources – all of which are global goals for sustainability and the circular economy. Biological approaches involve the addition of microorganisms in conjunction with nutrients and O_2 to enhance microbial growth and increase the biodegradation of the spilled oil [10]. Nevertheless, physiochemical approaches have limitations when it comes to crude oil removal, so biological approaches have taken precedence. However, the type of sorbent substance used is determined by the composition of the spilled oil [11]. The swiftest approach is dispersing agents applied via aircraft, and afterward skimming and in-situ burning. Furthermore, atmospheric factors, including wind, oil viscosity, currents, sensitivity to debris, and waves, influence the effectiveness of remediation approaches [12]. Regardless of its costs, in-situ burning emits high levels of particulate matter and CO_2 into the atmosphere. Selecting an oil spill cleanup strategy turns into an optimization assignment by minimizing both ecological effects and operational costs. Regional jurisdiction additionally has an impact on expenses because of potential penalties determined by the quantity of oil spilled, which restricts the effects of the spill. However, because certain remediation approaches break down oil in the marine environment, it could continue to harm the ecology. Therefore, it has been suggested to impose a fine based on the amount of oil loaded on ships for marine transportation. This would provide an economic motivation to prevent oil spill in shipping operations. The majority of the approaches discussed in this article seek to either recover spilled oil or improve oil biological breakdown/biodegradation. The most

effective approach in the event of an oil spill is dependent on a variety of factors. From both a sustainability and an economic standpoint, a combination of multiple approaches is often the best solution [13, 14]. As a result, rather than categorizing oil spill remediation techniques according to technical considerations, a solution-based categorization of oil biodegradation has been suggested.

Current chemical dispersants have been chemically resistant but non-biodegradable, so they persist in the marine for an extended amount of time [15]. Hence, there has been an increasing demand for viable, sustainable, simple, inexpensive sorbents made from bio-polymers to handle the cleanup of oil spills. Inorganic meshes, aerogels, surface-altered fabrics, and foam membranes have been frequently employed in the removal of oil-water blends in recent years. Furthermore, population growth has boosted food consumption, leading to enormous quantities of bio-waste worldwide [16]. Thus, instead of harmful chemical substances, it is prudent to use readily biodegradable biological waste or products to create low-cost sorbents that have greater oil absorption rates that are easy to scale up to facilitate the remediation of an oil spill. This review focuses on the potential of microbes and nanoparticles, as well as their interaction efficiency, in oil spill remediation/degradation/removal from the marine environment. These microbe-nano interactions have generated more curiosity in oil spill remediation approaches in marine environments. Biobased resources need to be thoroughly researched for long-term and successful oil spill remediation, as no single substance is appropriate in any prospective oil spill situation [17]. Furthermore, regional legislation has influenced the financial perspective of the substances, and approach design needs to be taken into account [18].

Oil degrades the insulation properties of fur-bearing marine mammals like sea otters and the repellent properties of bird feathers. Animals, such as birds and mammals, will perish from hypothermia if they lack the power to repel water and insulate themselves from the cold [19]. Young sea turtles can get entangled in oil and mistake it for nourishment. Oil is frequently inhaled by whales and dolphins, affecting their lungs, immunity, and

reproduction [20]. Birds and animals can swallow oil while cleaning themselves, causing them harm. Fish, crustaceans, and corals can't be directly exposed; nevertheless, they can come into contact with oil when it gets incorporated into the water column. Shellfish can also be subjected to harm in the intertidal zone, resulting in reduced growth, expanded livers, fluctuations in heart and breathing patterns, fin deterioration, and reproduction problems [21]. Fish eggs and larvae are particularly vulnerable to lethal and sublethal effects. Although no fatalities occur, oil can render such seafood unfit for human consumption [22].

2. Methodology

This review conducted an extensive literature search, and the aim was to identify, assess, and collate existing information regarding the management of oil spills in marine ecosystems in a sustainable manner. Articles from relevant publications were retrieved from the major scientific databases: PubMed, Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar from January 2000 to December 2025. The search was performed for keywords and Boolean operators (such as oil spill, marine pollution, oil spill remediation, bioremediation, biosurfactants, microbial degradation, phytoremediation, nanotechnology [23], adsorbent materials, green remediation, remote sensing, artificial intelligence, marine ecosystem restoration, and sustainable oil spill management). Peer-reviewed journal articles, authoritative reports, and technical documents, such as those published by the International Maritime Organization (IMO), the United Nations Environment Programme (UNEP), the National Oceanic and Atmospheric Administration (NOAA), and the International Tanker Owners Pollution Federation (ITOPF), were also regarded as sources that offer up-to-date regulatory and practical perspectives.

The retrieved literature was screened to identify studies relevant to marine oil spill remediation technologies, environmental impacts, sustainability, and emerging management approaches. Duplicate records were removed; studies were excluded if they were not marine related; conference abstracts were excluded if they

did not provide sufficient technical information; and publications were excluded if they were not scientifically validated. The data collected from the selected studies encompassed the remediation method, mechanism of action, efficiency of the treatment, environmental applicability, operational feasibility, ecological effects, benefits, limitations, and sustainability features. The evidence collected was then categorized thematically: physical remediation technology, chemical remediation technology, biological remediation technology, integrated remediation technology, recent advances in biosurfactants, nanotechnology, remote sensing, and ecosystem restoration. The results were not analyzed quantitatively with a meta-analysis but rather were compared qualitatively to highlight similarities, technological innovations, gaps in knowledge, and priorities for future studies to develop a comprehensive picture of the various strategies available and sustainable for marine oil spill management.

3. Accidental Oil Spills Fate in Marine Ecosystems

Oil spills in the ocean extend out and shift on the sea surface, creating a treacherous film a few millimeters thick due to the effects of wind and water currents. It undergoes an array of physical and chemical modifications over the same duration [24]. Figure 1 depicts the diverse physical, chemical, and biological processes that affect the behavior and outcome of oil spills in marine ecosystems. Upon release, oil experiences weathering and oxidation at the ocean's surface, with lighter components evaporating into the atmosphere. Simultaneously, processes like dissolution and natural dispersion result in the disintegration and amalgamation of oil constituents within the water column. Water-in-oil emulsions develop when water is integrated into the spilt oil, frequently resulting in increased viscosity. Biodegradation by indigenous microbial communities transpires over time at the sediment-water interface and throughout the water column, facilitating the natural attenuation of oil. The weathering process triggers the spilled oil to degrade and turn heavier compared to water. Several processes, such as natural oil distribution in water, result in the extraction of oil from the

marine surface as well as aid in its organic decomposition in the marine ecosystem [25]. Others, especially the development of water-in-oil emulsions, lead to oil deposits becoming longer-lasting and remaining at marine or along the coast for a longer duration of time [26]. A variety of factors influence the rate, as well as the significance of such procedures. Finally, spilled oil typically gets eliminated by the marine ecosystem through a lengthy biodegradation process [27]. Processes such as weathering, oxidation, evaporation, and biodegradation all represent natural processes that occur in the marine environment [28].

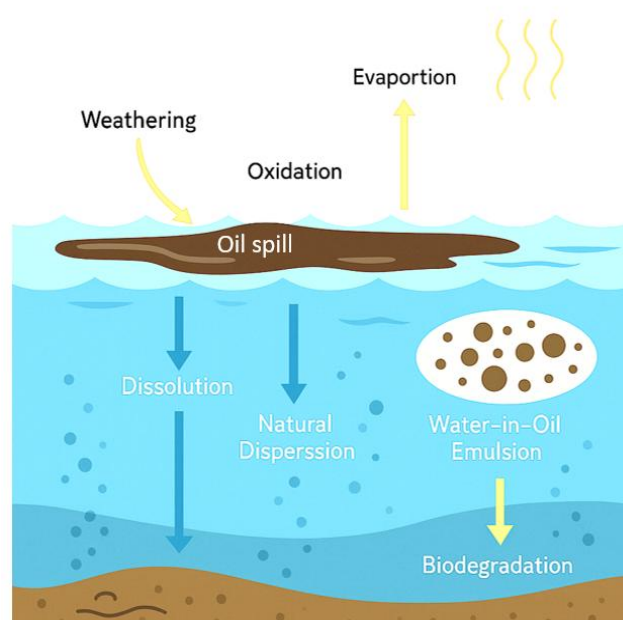


Fig. 1. Fate of accidental oil spills in marine ecosystems.

4. Impacts on Marine Life

The influence of oil spills on marine life is determined by the oil's destiny. While oil accumulates in the marine environment, it can be either distributed in the uppermost portion of the seawater (littoral zone) or stay on the surface of the water [29]. In this case, wind currents transport the oil to the coastline, where it harms coastal organisms such as invertebrates, birds, and mammals [30]. When the oil becomes dispersed, living things, including plankton, fish, and larvae, immediately come into contact with oil toxic substances [31].

4.1. On Benthic Life and Invertebrates

Oil spills (hydrocarbons) can accumulate in benthic invertebrates as well as larger forms, including the sand eel and *Ammodytes americanus* (feed for humpback whales), from marine water and oil-polluted sediments, resulting in these whales starving [32]. Bivalve mollusks gather and keep petroleum-based hydrocarbons at greater levels and for longer periods of time compared to other taxa [33]. This is primarily due to the absence of a mixed-function oxygenase (MFO) mechanism, which prevents them from converting the substances to undesirable polar metabolites [34]. Thus, they are likely to pass them on to their predators. Marine animals that eat bivalve mollusks, like walruses and otters, are more likely to consume petroleum-based hydrocarbons [35]. Benthic amphipods have been extremely sensitive to accidental oil spills. The majority of marine crustaceans possess an established MFO mechanism. Thus, they can rapidly metabolize and eliminate accrued hydrocarbons. Invertebrate communities, including the amphipod *Ampelisca* and sand hopper, are extremely susceptible to oil contamination and, for different reasons, have been sluggish to repopulate as well as 'recover' [36]. The rest of the marine plant biomass and resources were more efficiently utilized, as opportunistic species like the bivalve *Abra* and the polychaete *Nephtys* rapidly occupied the available ecological niches, so that these species could quickly replace *Ampelisca* in the ecosystem [37]. In many ways, marine invertebrates tend to be distinct creatures that live in the ocean. Thus, oil spill pollutants are being investigated as an example of a number of biological markers [38]. A number of biomarkers, such as acetylcholinesterase (AChE), malondialdehyde (MDA), deoxyribonucleic acid (DNA) adducts, glutathione S-transferase (GST), and catalase (CAT) (all associated with the metabolism of organic pollutants), were used to evaluate the mussel responses [39–41]. A number of examinations for validation demonstrated that there were no significant decreases in GST and CAT activity levels [42]. Inspections six months after the incident revealed that DNA adducts and MDA levels were high, while AChE quantities were substantially lower during the initial year of the investigation [43].

This proposed an overall state of stress. The merged biomarker reactions index, an easy multivariate graphic approach, was employed to integrate four out of five confirmed biomarkers and determine the level of adverse effects on mussels across various sites [44]. The research results demonstrated that the oil spill had an impact on mussel communities solely in the initial year following the accidental oil spill [44].

4.2. On Planktonic Life

Phyto and zooplankton have become a significant source of nourishment for whales. Consequently, this can impact or regulate primary output through top-down outcomes [45]. The bottom-up consequences of the population's dynamics can impact the overall biomass of other aquatic creatures such as fish. Copepods, mysids, and euphausiids directly absorb the hydrocarbons from marine water as well as through swallowing oil droplets along with oil-contaminated nourishment [19, 46]. Consumption of oil through such creatures frequently results in death, while survivors frequently exhibit growth and sexual anomalies [47, 48]. The influence of contamination from petroleum on plankton in the ocean is a major source of concern. Oil spill water accommodated fraction (WAF) harmfully impacts the oceans' phytoplankton, zooplankton, and animal newborn phases. Generally, the harmful effects of oil WAF increase as it grows carbonic chain diameter and benzene ring quantity [49]. It is recommended that future research areas focus on thorough assessments of the harm caused by petroleum contamination to marine ecosystems. According to WAF, plankton has the ability to accumulate polycyclic aromatic hydrocarbons (PAH) [49] owing to their high lipophilicity [50]. As a result, they cause a variety of negative effects. Researchers have discovered that marine plankton is extremely susceptible to petroleum-based substances, specifically WAF, with average effective and lethal concentrations. The toxic effects of ten PAHs related to the status of oil spill upon adult copepods were discovered to have narcotic adverse effects [51, 52].

4.3. On Coral Reefs

Besides being popular diving destinations, coral reefs tend to be essential elements of marine

ecological systems. This is due to the fact that they serve as similarly significant nurseries for prawns and other cultivable aquatic life [53]. The aquatic life that lives within and near coral reefs is vulnerable to harmful chemicals and faces suffocation [54]. In light of a number of environmental and human-caused pressures, they are quickly deteriorating. As a result, they are experiencing substantial shifts in diversity and abundance of species, as well as the layout of habitats around the world [55].

Oil dispersing agents have the potential to cause damage to marine organisms, including coral reefs [56]. Spread-out oil as well as oil dispersing agents are detrimental to both hard and soft coral types at their earliest stages, according to an investigation using coral nubbins within a coral reef ecological toxicology assessment. Researchers additionally performed a 'nubbin assay' on over ten thousand coral pieces to assess the acute- and chronic effects of dispersed oil fractions (DOFs) coming from six (Emulgal, Slickgone, Dispolen, Petrotech, Biorieco, and Inipol) commercial dispersing agents [57] and water-soluble fractions (WSFs) of Egyptian petroleum products on two branching coral (Indo-Pacific) species, namely *Pocillopora damicornis* and *Stylophora pistillata* [58]. They discovered that the producer's suggested dispersant quantities were extremely harmful, resulting in the death of every single nubbin. The toxicities of the scattered oil and dispersants were substantially greater than those of the oil spill WSFs [59]. Because corals are highly susceptible to oil detergents and dispersed oil, the outcomes of such assays indicated that the presence of any kind of oil dispersing agent in coral reefs along with the areas surrounding them had a detrimental effect [30]. The eco-toxicological effects of such dispersing agents on corals have been assessed. Observations revealed a scale ranging from the smallest to the highest dangerous agent in the following order: Slickgone, Petrotech, Inipol, Biorieco, Emulgal, and Dispolen [60].

4.4. On Fish

The majority of fish, regardless of extensively oil-polluted situations, are unable to accumulate and retain substantial amounts of petroleum-based hydrocarbons owing to their established liver mixed-function oxygenase (MFO) mechanism, and

also because of the responsiveness of the metabolic products that are unlikely to escape in a harmful form during digestion as well as absorption [61]. Thus, they are unlikely to pass them on to predators. As a result, no major danger is anticipated. Generally, marine predators are poor assassins of petroleum molecules in food. Since all kinds of prey can expel petroleum products from their organs, biomagnification in the food web of marine organisms is not observed [62]. Hence, there exists an indirect connection between the trophic state of an aquatic mammal and the quantity of leftovers that it may ingest. Polar bears and killer whales, which are regarded as the largest carnivores that survive on massive pelagic fish and seals, are less likely to become subject to petroleum-based substances in their diets than other species such as walrus and baleen whales, which feed on zooplankton and benthic invertebrates [63].

Studies demonstrate the influence of spilled oil on the early life stages of fish. Long-term exposure of young *Oncorhynchus gorbuscha* to Arctic North Slope petroleum products has caused a wide range of responses. Surprisingly phototoxicity from UV rays had no influence on the consequences, owing to the extremely pigmented nature of the fish's skin [64]. While [65] investigated the phototoxicity of water-adjusted proportions of endured crude oil, they discovered that *O. gorbuscha* could be less vulnerable to light enhanced toxic effects than the increasingly translucent early-life phases of a number of Alaskan organisms [66].

4.5. On Seabirds

Direct contact represents one of the most common ways of exposure for birds. Only the anticipated number of seabird deaths from numerous significant spills has been calculated, and determining the influence at the population-level remains challenging [30]. The variability of nature and the broad spectrum of factors that affect bird populations render assessing the influence of an oil spill on seabirds difficult. The magnitude of a petroleum disaster and the number of seabird deaths are not inversely correlated. Furthermore, predictions of the number of seabirds killed by oil slicks are extremely uncertain [30]. This is due to the fact that a certain number of oiled birds can die in the ocean and never reach the shoreline. For

instance, after the Exxon Valdez oil spill incident, more than 35,000 seabird carcasses were recovered across the northern Gulf of Alaska. Despite the fact that the Braer spill in Scotland was nearly 2.5 times the size of the Valdez spill, about 1,500 dead birds were identified following the accidental oil spill [67].

4.6. On Marine Plants

Marine plants are critical to the structure of marine ecosystems in a variety of ways. These involve the reality that they are able to produce O₂, have the capacity to capture carbon, and reside at the bottom of marine food webs [68]. They additionally function as nurseries, feeding grounds, and breeding grounds for an array of animals, including both recreational and economically important fish. Oil that comes into contact with marine plants and animals from accidental oil spills impacts them [69]. Researchers evaluated a phytotoxicity database primarily containing the findings from investigations conducted following oil spills into the oceans. They tested 41 crude oils and 56 dispersing agents for toxicity against 85, 28, 13, and 9 species of single/multicellular algae, wetland plants, mangroves, and seagrasses. In total, 107 response factors were examined [70]. The influence amounts accessible from this toxicology database vary, as well as being different due to exploratory diversity [71]. Hence, phytotoxicity forecasts and the identification of highly susceptible species, phases of life, and response factors are limited.

Thus, this information set failed to endorse the harmful effects of petroleum-based chemicals and dispersing agents on marine plants. In greenhouse studies, the influence of heavy petroleum product pollution on the growth of *Salicornia fragilis* Ball and Tutin was investigated. To evaluate the influence of petroleum on the growth of plants, toxicity examinations and PAH discharge analyses were used [72]. Chlorosis, growth reduction, yellowing, and modifications in growth-oriented parameters had all been noticed visually. Nevertheless, despite extremely tiny amounts of oil pollution, there was a substantial biological accumulation of PAHs in marine plant tissues [73]. These are strongly connected to the circumstances of oil exposure. This substantial connection between the PAH levels in *Salicornia* plants and development reduction suggests that fuel oil is

chemically harmful [74]. The researchers decided that the type and level of fuel oil spill pollution are two critical factors in determining the influence on marine plants [75].

4.7. On Marine Mammals

Accidental oil spills in marine conditions considerably affect marine mammals, such as sea otters, bottlenose dolphins, pinnipeds, fins, humpbacks, manatees, whales, and sperm whales, through physical contact [20]. The furred animals suffer because they are dependent on their external covering for buoyancy and warmth. Thus, while oil flattens and adheres to their exterior layer, such creatures frequently succumb to drowning, hypothermia, and suffocation [76]. All marine creatures spend a significant amount of time at the ocean's surface as a component of their daily activities [77]. They survive in these environments, and as a result, the likelihood of them coming into contact with an exterior slick, water-in-oil spill emulsion is substantial. This interaction may cause fouling in marine creatures with thick pelages, including fur seals, polar bears, and sea otters. Polar bears and otters groom themselves frequently to preserve the insulation qualities of their fur and can consume oil [19]. Animals with little or no fur and pelage, like seals, whales, dolphins, and manatees, have an advantage because oil adheres less to their exterior. Several baleen whales are surface feeders, meaning they feed at the ocean's edge [78].

This behavior can cause fouling in consuming equipment at a location with oil spills. Oil spills that pollute a shore can negatively impact pinnipeds [79]. A portion of the spilled oil eventually makes its way back into subtidal debris, where it can be transferred to grey whales, walruses, and seals. They rely extensively on benthic livestock for food. When marine mammals come into contact with fresh oil, they are more likely to breathe in volatile hydrocarbons that have evaporated from the outer layer of the slick. These flammable portions contain harmful monoaromatic hydrocarbons, such as xylenes, benzene, toluene, and anesthetic lower-molecular-weight aliphatics [80].

Inhaling such volatile hydrocarbon substances can be hazardous. Inhaling concentrated petroleum-based substance vapors can lead to inflammation that harms the membranes that produce mucus in

the airways, breathing problems, and pneumonia [81]. Breathed-in volatile benzene and toluene are swiftly transported from the blood vessels toward the respiratory system. In addition, they can be concentrated in the central nervous system and the liver via blood circulation, leading to neurological conditions and liver damage [82]. Marine mammals are likely to be poor accumulators of oil, whether through direct contact with oil or exposure to its distribution in seawater [83].

4.8. On Microbes

The microbial reactions to oil spills in the ocean are determined by a variety of factors. The makeup of the oil spill and the weathering process, especially temperature and nutrient amounts, determine microbial degradation [84].

Researchers reported various factors influencing the biodegradation of petroleum-based hydrocarbons through microbes. Both biological and environmental factors can affect the velocity and the degree to which petroleum products are eliminated from the marine ecosystem [33]. Accidental oil spills in marine environments alter microbial diversity and now include various kinds of coexisting microbes [85]. These can be explained through the collaborative use of resources. Various forms of hydrocarbons found in oil necessitate microbial communities, as well as microbial alteration of the oil's components and the marine environment, which will result in chronological succession [86].

5. Oil spills- Bioremediation

Microbes have been employed for decades for cleaning accidental oil spills and other hydrocarbon/oil pollution; nevertheless, the specific application of microbes to degrade oil has employed marine microbes to ingest oil [87]. Tables 1 and 2 compare the physical, chemical, and biological methods for oil spill/contamination remediation. Among them, biological approaches are highly sustainable and have demonstrated success in oil spill cleanup, with continued effectiveness in the years to come [88]. Figure 2 illustrates various particles used for oil spill treatment in oil-polluted marine environments. It has also been proposed that biological remediation for petroleum (oil) spills could be the sole large-scale cleanup approach with the potential for success. Several substances are found in crude oil, such as aromatics, resins, and alkanes [89]. Since each oil-degrading microbe can only metabolize a restricted quantity of hydrocarbons, a wide variety of species is needed to achieve successful remediation; also, the relative abundance of every species changes throughout the bioremediation process [90]. An example is the alkane-degrading microbes instantly after the Horizon oil spill in deepwater. PAH-degrading microbes propagated as the proportional distribution of alkanes reduced in the weeks after the oil spill [91] (Table 3). Figure 3 shows the fate of PAH degradation and cycling in the contaminated spilled oil marine environment.

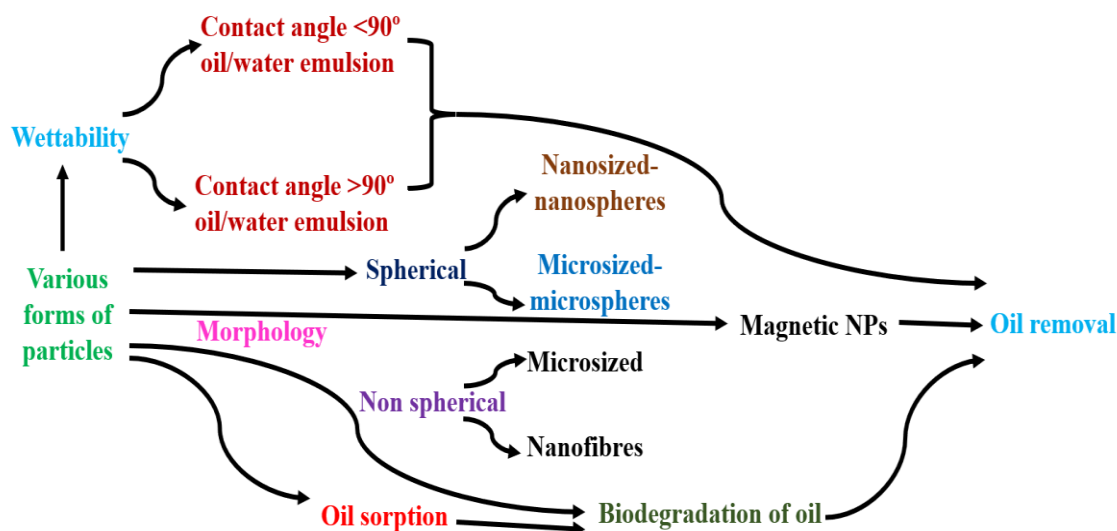


Fig. 2. Various sort of particles reported for spilled oil degradation.

Table 1. Comparative studies on oil spill remediation in various environments: physical, chemical, and biological.

Remediation category	Representative technology	Pollutant/oil type	Environmental setting	Major findings	Advantages	Limitations
Physical	Booms and skimmers	Crude oil	Coastal waters	Effective containment in the early stages of a spill	Rapid deployment	Ineffective in rough seas
Physical	Sorbent materials	Petroleum hydrocarbons	Shoreline	High oil absorption capacity	Simple operation	Sorbent disposal required
Physical	Mechanical recovery	Heavy crude	Open ocean	Good for spills on a localized scale	Oil recovery possible	Weather dependent
Chemical	Chemical dispersants	Light and medium crude oil	Offshore waters	More dispersion and fewer surface slicks	Rapid treatment over large areas	Possible toxicity to marine organisms
Chemical	Solidifiers	Heavy oil	Coastal environments	Converts oil to recoverable solid mass	Easy collection	Limited commercial use
Chemical	Oxidizing agents	Petroleum hydrocarbons	Contaminated sediments	Boosts hydrocarbon breakdown	Fast treatment	Secondary environmental effects
Biological	Bioaugmentation	Crude oil	Marine water	Improved microbial degradation	Eco-friendly	Dependent on environmental conditions
Biological	Biostimulation	Petroleum hydrocarbons	Shoreline sediments	Nutrient addition speeds up biodegradation	Low environmental impact	Slower than chemical treatment
Biological	Biosurfactants	Heavy hydrocarbons	Marine ecosystem	Enhanced Bioavailability of Hydrocarbons	Biodegradable and sustainable	Higher production cost
Biological	Phytoremediation	Weathered oil	Coastal wetlands	Persistent remediation of contaminated sites	Sustainable recovery	Long remediation period

Table 2. Approaches for oil spill remediation: a comparative analysis.

Parameter	Physical methods	Chemical methods	Biological methods
Primary objective	Containment and recovery	Dispersion or transformation	Biodegradation and ecosystem restoration
Typical efficiency	High during initial response	Moderate to high depending on the efficiency of the dispersant	High for long-term remediation
Best suited oil type	Fresh surface oil	Light to medium crude oil	Residual and weathered hydrocarbons
Optimal conditions	Calm waters, early response	Moderate sea conditions	Proper temperature, nutrients, availability of oxygen
Response time	Immediate	Rapid	Moderate to slow
Environmental impact	Low to moderate	Moderate to high (depends on chemicals used)	Low

Table 2. Continued.

Parameter	Physical methods	Chemical methods	Biological methods
Long-term sustainability	Moderate	Moderate	High
Operational complexity	Moderate	Moderate	High (Biological monitoring required)
Scalability	Small to large spills	Medium to large spills	Small to large spills (long-term restoration)
Typical cost	Moderate to high	Moderate	Low to moderate
Major advantages	Rapid containment and oil recovery	Fast treatment of extensive spills	Environmentally friendly and sustainable
Major limitations	Reduced efficiency in rough weather	Potential toxicity and secondary pollution	Slower treatment and environmental dependence

Table 3. List of microbes reported as oil-degrading microbes from various oil contaminated sites/states in marine environments.

Microbes/model microbes used for oil degradation	Microbial category	Degrading oil ingredients	Medium/site	References
Species of <i>Amphora</i> , <i>Dunaliella</i> , <i>Chlamydomonas</i> , <i>Chlorella</i> , <i>Ulva</i> , and <i>Prototheca</i>	Algae and Diatoms	Oil enriched with aromatics	Seawater	[92]
<i>Alcanivorax</i> sp	Bacteria	n-alkanes (C8–C32)	Sediment	[92]
<i>Dietzia maris</i>		n-alkanes, PAHs	Seawater, deep sea hydrothermal field	[93]
<i>Actinomyces</i> sp., <i>Marinobacter</i> sp. and <i>Gordonia</i> sp.		n-alkanes	Seawater	[94]
<i>Desulfococcus oleovorans</i>		n-alkanes, aromatic HCs	Sediment	[95]
<i>Bacillus</i> sp.		n-alkanes (C13–C30) and aromatics	Seawater	[96]
<i>Sphingopixis</i> sp.		PAHs	Seawater	[97]
<i>Pseudomonas</i> sp.		n-alkanes (C14–C30) and resins	Seawater	[92]
<i>Cycloclasticus</i> sp. and <i>Staphylococcus</i> sp.		Aromatics	Seawater	[98]
<i>Rhodococcus</i> sp.		n-alkanes (C13–C17) and aromatics	Sediment	[92]
<i>Cycloclasticus pugetii</i>		PAHs	Sediment	[99]
<i>Alteromonas naphthalenivorans</i>		PAHs	Seawater, sediment, and tidal flat	[100]
<i>Alcanivorax borkumensis</i> and <i>Alcanivorax dieselolei</i>		n-alkanes	Seawater, sediment, coastal salt marsh, and beach sand	[101]
<i>Acinetobacter venetianus</i>		n-alkanes	Surface water, and sediment	[102]
<i>Bacillus stratosphericus</i>		PAHs, BTEX	Seawater	[103]
<i>Oleiphilus messinensis</i>		n-alkanes	Seawater and sediment	[104]
<i>Bacillus pumilus</i>		n-alkanes, PAHs	Sediment	[104]
<i>Thermococcus sibiricus</i>		n-alkanes	Oil reservoir	[105]

Table 3. Continued.

Microbes/model microbes used for oil degradation	Microbial category	Degrading oil ingredients	Medium/site	References
<i>Dietzia maris</i>		<i>n</i> -alkanes, PAHs	Seawater and hydrothermal field	[104]
<i>Pseudomonas pachastrellae</i>		<i>n</i> -alkanes, PAHs	Sediment, and beach sand	[106]
Species of <i>Aspergillus</i> , <i>Trichoderma</i> , <i>Candida</i> , and <i>Fusarium</i>	Fungi	<i>n</i> -alkanes and aromatics	Seawater	[107]
<i>Dothideomycetes</i> -related taxa		PAHs	Beach sediment, salt marshes, and tarballs	[108]
<i>Penicillium</i> sp.		<i>n</i> -alkanes (C11–C25) and aromatics	Sediment	[109]
<i>Microcoleus</i> sp., <i>Oscillatoria</i> sp., and <i>Nostoc</i> sp.	Cyanobacteria	Aromatics	Seawater	[110]
<i>Plectonema</i> sp., and <i>Aphanocapsa</i> sp.		<i>n</i> -alkanes and aromatics	Sediment	[92]
<i>Anabaena</i> sp.		<i>n</i> -alkanes	Seawater	[111]

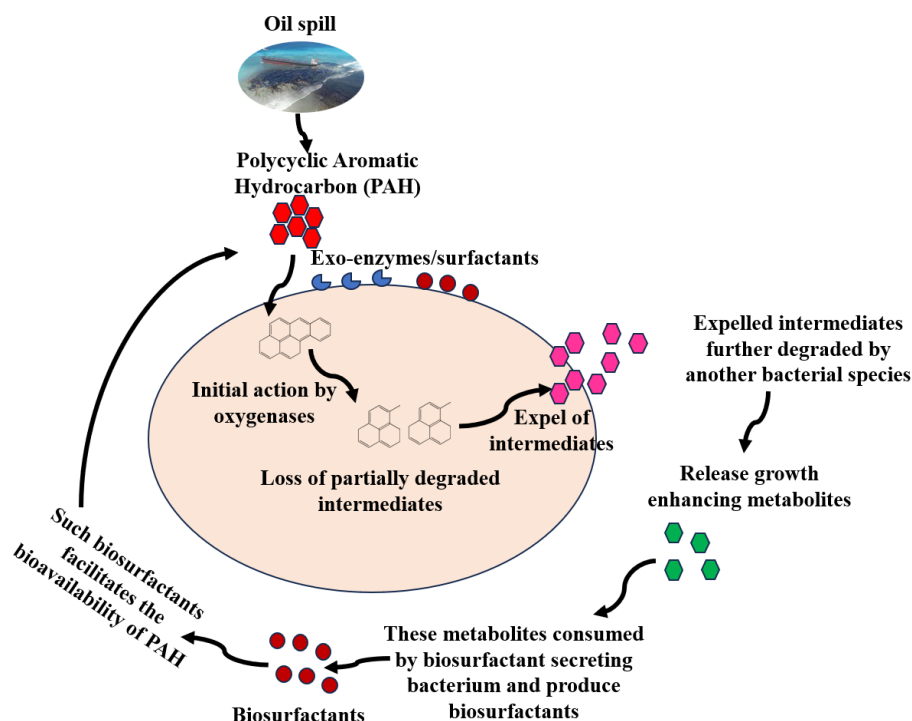


Fig. 3. Fate of PAH degradation under microbial consortium and possible interaction.

The potential of native species to metabolize oil as well as the speed by which populations become accustomed to oil being their sole carbon source constrain bioremediation [33].

Every species' lot is determined by oil components and quantity, as well as environmental factors including nutrient availability, salinity, weather, and temperature.

Investigators are striving to conquer minimal native microbial populations via biostimulation (the furtherance of growth-limiting nutrient content), bioaugmentation (the introduction of microbes that have previously been exposed to hydrocarbons), and the amalgamation of both [112] (Figures 4 and 5).

5.1. Biostimulation

Environmental factors, like temperature, pH, and nutrient (N and P) availability, are influencing the in situ bioremediation approaches [113].

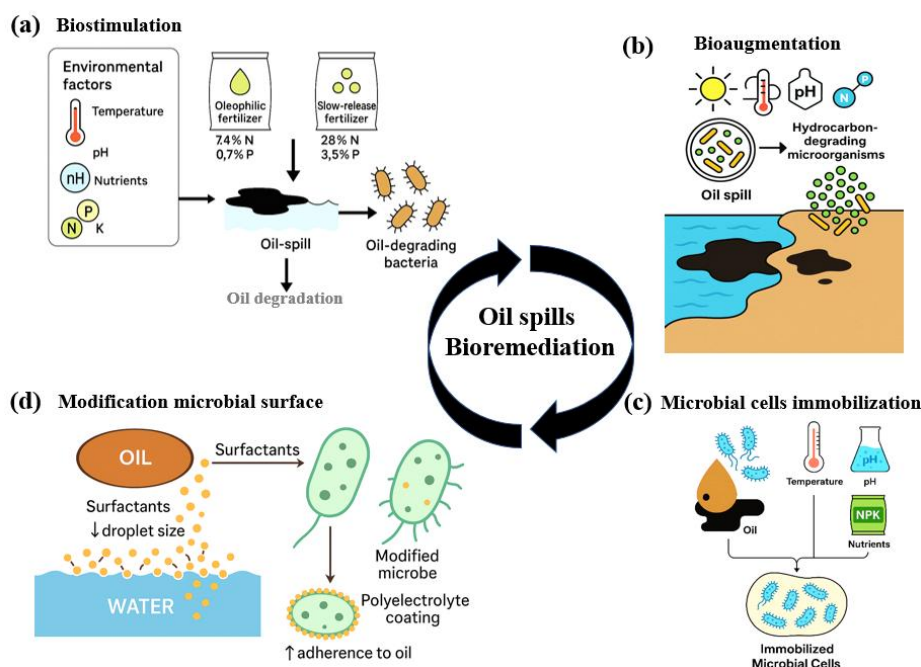


Fig. 4. Overview of key strategies in oil spill bioremediation.

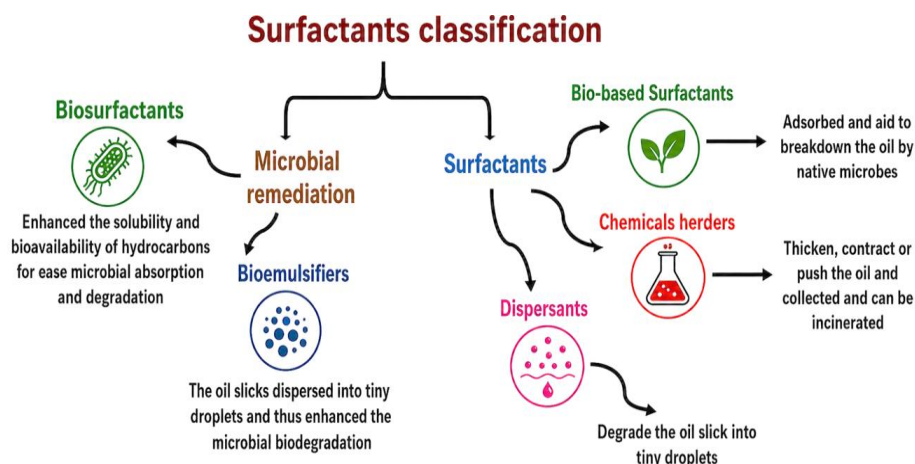


Fig. 5. Classification of surfactants for oil spill treatment.

Biostimulation represents the introduction of growth-limiting nutrients to native microbial populations, and that usually entails the utilization of oleophilic fertilizers in addition to inorganic substances such as N, P, and K. Oil spill biostimulation (Table 4) has resulted in an increase in the growth of oil-degrading bacterial species [114]. An oleophilic fertilizer (containing 7.4% of N and 0.7% of P) along with slow-release fertilizer (made up of 28% of N and 3.5% of P) were used to treat the Exxon Valdez oil spill and shorelines for

about 109 days [92]. Later, the results reported that the first treated sites had 44% to 63% PAH degradation. Control places that were not fertilized demonstrated no quantifiable degradation over the following 70 days. On the following day, fertilizer was blended to control places, and degradation took place identical to that noticed in the fertilized sites, proving the effectiveness of biostimulation through fertilizer blending. Biostimulation can alter microbial communities, and its success varies based on a variety of factors

such as oil structure, native organisms, and the state of the local environment [92]. Biostimulation can become inefficient owing to a water medium

with diluted supplemental nutrients; however, the incorporation of uric acid provides an alternative approach [125].

Table 4. Recent sustainable nanoparticle- and biosurfactant-assisted strategies for oil spill remediation.

S. No	Sustainable approach	Career	Microbes/Biosurfactant producer	Target petroleum pollutant	Treatment period	Oil removal/degradation efficiency	Major contribution	Refs.
1	Nanoparticles (NPs)-assisted biodegradation	Graphene oxide (GO) quantum dots	<i>Bacillus cereus</i>	Phenanthrene and anthracene	3.5 days	53% degradation	GO quantum dots enhance microbial degradation of PAHs	[115]
2	Immobilization	Chitosan (beads)	Metagenomic clones and <i>Bacillus</i> sp.	n-alkanes	10 and 30 days	90% and 100% degradation	Enhanced microbial stability and hydrocarbon degradation	[99]
3	Immobilization, bioaugmentation and biostimulation	Polyvinyl alcohol (PVA)	Mixed microbial consortium	Oil and grease	32 days	30%, 37%, 48%, and 54% degraded through biostimulation, bioaugmentation, immobilization, and Co-immobilization respectively	Co-immobilization improved the biodegradation efficiency	[116]
4	Biostimulation	Fertilizer	Mixed microbial consortium	Crude oil and hydrocarbons	30 days	62% of oil degradation	Nutrient amendment stimulated the native microbial activity	[92]
5	Biostimulation	Nontronite flakes	<i>Alcanivorax borkumensis</i>	Alkanes as well as naphthalene	37 days	58% - 83% degradation	Clay minerals enhance hydrocarbon degradation	[117]
6	Surface modification as well as immobilization	Poly (allylamine hydrochloride) with poly(styrene-sulfonate) and	<i>Bacillus cereus</i>	Tetradecane	5 days	75% - 97% degradation	Surface modification greatly improved the biodegradation	[118]

Table 4. Continued.

S. No	Sustainable approach	Career	Microbes/Biosurfactant producer	Target petroleum pollutant	Treatment period	Oil removal/degradation efficiency	Major contribution	Refs.
7	Pickering emulsions	immobilized in disodium phosphate Polyvinylpyrrolidone coated magnetite NPs carbonized kaolinite sheets	<i>Alcanivorax borkumensis</i>	Hexadecane	6 days	90% of oil degradation	Increased hydrocarbon bioavailability from stable emulsions	[119]
8	Surface modification	Iron oxide NPs	<i>Brevibacillus parabrev</i>	Tetradecane	16 days	90% of oil degradation	Nanoparticles promoted microbial attachment and degradation	[120]
9	Biosurfactant-assisted bioremediation	Rhamnolipid	<i>Pseudomonas aeruginosa</i>	Crude oil	7–21 days	High biodegradation efficiency (typically >80%)	Biosurfactants increased the solubility and bioavailability of hydrocarbons and decreased the necessity of chemical surfactants.	[121]
10	Biosurfactant-assisted bioremediation	Sophorolipid	<i>Candida bombicola</i>	Petroleum hydrocarbons	10–20 days	Enhanced degradation	Microbial degradation and emulsification with eco-friendly surfactant	[122]
11	Biosurfactant-assisted bioremediation	Surfactin	<i>Bacillus subtilis</i>	Diesel and crude oil	7–28 days	Enhanced biodegradation	Improved dispersion of low environmental toxicity hydrophobic hydrocarbons	[123]
12	Nano–biosurfactant integrated remediation	Microbial biosurfactants with iron oxide or silica nanoparticles	Mixed microbial consortium	Polycyclic aromatic hydrocarbons and crude oil	Variable	Improved degradation than nanoparticles or biosurfactants alone	Increased contaminant bioavailability, microbial attachment and remediation efficiency were caused by synergistic effects	[124]

Because uric acid is poorly soluble in fluids, it can be used as an N source within the oil-water interaction and is less likely to become diluted. Generally, all microbes demand N and P; biostimulation can encourage the reproduction of undesirable microbes, resulting in concurrence for hydrocarbon-degrading organisms. Targeting drops of oil to release nutrients has been shown to benefit oil-degrading organisms [92].

Bioremediation is regarded as one of the best and most successful approaches for oil spill cleanup; recent advances in immobilization, biostimulation, surface alteration, and approaches for more fully comprehending the microbial activity in oil-water edge possession have improved its effectiveness [92]. However, bioremediation continues to possess flaws, the most significant of which is that each oil spill location has a distinctive native microbial consortium, which means that there are no ubiquitous bacteria that can be employed at each oil spill site [126]. A number of mesocosm investigations on cell immobilization and alteration are recommended to show the possibility of its application in accidental oil spill circumstances; such investigations connect the gap between laboratory experiments and real-world sustainable applications. The use of NP when combined with bioremediation can additionally enhance the efficacy of the bioremediation process.

5.2. Bioaugmentation

Bioaugmentation has been utilized to enhance native marine ecosystems with hydrocarbon-degrading organisms and increase the variety of substances that are able to be degraded [127]. Bioaugmentation can potentially accelerate the cleanup process in regions where unique microbial populations are incapable of degrading every hydrocarbon present, or in which indigenous species are experiencing expanded lag stages as a result of hydrocarbon exposure. For enhanced biodegradation, additional microbes can either be propagated upon isolation from an earlier site or modified genetically. Bioaugmentation has drawbacks; inoculated organisms frequently fight with native organisms for vital nutrients, thus jeopardizing the regional environment [33]. Furthermore, an understanding of oil composition and local organisms is required for bioaugmentation to be effective, including their

ability to degrade and which species may establish a prosperous complementary interaction. Because hydrocarbonoclastic organisms are ubiquitous, bioaugmentation has proven advantageous for improving bioremediation, as these microbes constitute anywhere from 0.003% to nearly 100% of microbial populations [128]. In extreme circumstances, supplemental intake may aid biodegradation. Attempts to improve bioaugmentation have produced positive results in laboratory-scale and mesocosm investigations by altering and immobilizing cells.

5.3. Microbial Cells Immobilization

The majority of hydrocarbonoclastic microbes create biofilms, which enable the microbial cells to bind towards a hard surface and liquid-liquid interfaces, providing an extra defense from external stresses and leading to the development of microbial populations [92]. Investigators want to use biofilms to improve bioremediation and reconstruct this exterior barrier by immobilizing microbial cells [129]. Immobilized microbial cells have applications for effluent bioremediation and are currently being studied as an approach to improve oil spill remediation in marine. Immobilized cells provide identical advantages to biofilm-dwelling cells, including elevated cell quantities and growth rates, enhanced defense towards shear harm and unsafe conditions, and elevated biofilm fabrication. These factors could contribute to enhanced accidental oil spill bioremediation [130].

Transporters for immobilized microbial cells can be made of a wide range of substances, but they ought to be nontoxic, inexpensive [131], nonbiodegradable, easy, and extremely stable to regenerate and separate from polluted sites. Chitosan, organic polymers, inorganic clays, and inorganic polyelectrolyte coating materials are among the materials being studied. Although the immobilization of microbes provides successful oil degradation at a lower cost and in a sustainable way, few research investigations have been conducted to assess the appropriateness of using immobilized microbial cells on a mesocosm level [132]. Because of this lack of supply, it is challenging to estimate the of using immobilized microbes in contrast to the period needed to produce the carriers and the cost of implementing

this approach on a large scale.

5.4. Modification in Microbe Surface

Surfactants are critical to the achievement of biodegradation. Surfactants minimize the size and number of oil droplets, improving the surface area and, as a result, enhancing the oil's bioavailability [133]. Surfactants can minimize bacterial attachment to tiny particles by decreasing the interfacial tension in oil-water. Because of these effects—boosting bioavailability and the interfacial area, as well as reducing bacterial surface adhesion—the implementation of optimal surfactant substances for cleanup procedures needs to be carefully evaluated [25]. Surfactants produced by microbes can be adsorbed over the cell surface and enhance the hydrophobicity of the cell. Microbial surface modifications are generally achieved through layer-by-layer addition of polyelectrolyte coating to increase the activity of the cell, leading to the formation of a thin layer around the individual cells [134]. These surface modification/engineering methods are capable systems to improve bioremediation, by enhancing the cell adherence rate towards the oil-water interface, and thus boosting degradation potential. Although preliminary findings demonstrate an enhancement in spilled oil degradation abilities, additional investigation must be conducted—particularly on ecological implications with an emphasis on the impacts on regional marine microbial populations—before the significance of introducing microorganisms with altered cell surfaces into crude oil spill sites can be determined.

5.5. Genetic Engineering

Modifying the DNA (gene) of oil-degrading microbes through genetic engineering is a promising approach [135]. In a mesocosm investigation, metagenomic replicas, host cells that were genetically modified by expressing the genes of microorganisms collected from an oil spilled location, were wrapped in chitosan beads and grown. For instance, alkane degradation proved to be similar to that of *Bacillus subtilis* with oil-degrading potential. The mutants improved their PAH degradation rate to 85% in a month, compared to a wild strain (68%) as the control [136]. The metagenomic replicas were made up of

E. coli cells that were transferred into a fosmid DNA vector comprising approximately 40 kb of unknown biological DNA [137]. *E. coli* cannot be the best host microbe for petroleum degradation. *E. coli* is hydrophilic in nature, which means they are not bound to hydrocarbons, and they do not biodegrade them. The cells' hydrophilicity ought to be conquered, and the application of hydrocarbonoclastic bacteria as the host can be considered [138]. Genetic engineering may additionally be employed to change the metabolic processes by utilizing oil, transforming organic pollutants into beneficial products like polyhydroxyalkanoates (PHAs) [139]. Initially, microbial genetic engineering was suggested as a remediation approach; its long-term impacts on native species and the wider impacts on marine ecosystems brought about by the addition of organisms with genetic modifications have yet to be established conclusively [140]. One solution could be to employ "suicidal" microorganisms with genetic modifications that have been genetically engineered to perish once the harmful substance has been removed. This would reduce the hazards of using microorganisms with genetic modification as an approach to improving bioremediation, but it is not currently being carried out.

5.6. Oil Spill Remediation by Nanoparticles (NPs)

Nanosized substances can be enhanced and functionalized for highly specific applications, including the development of Pickering-type emulsions and magnetically adaptable sorbents. Nanoscience may provide a sustainable approach for improving post-oil spill response technological advancements (Figure 6). Nanotechnology has been widely investigated for about twenty years for water purification purposes; nevertheless, its application for spillage recuperation is a more recent field that has grown substantially in the past decade [141, 142]. Figure 5 shows the classification of sorbents and is preferably reported for spilled oil remediation.

5.6.1. Influence of NPs in Bioremediation of Oil Spill

Despite being effective, bioremediation can require months to years to complete the process. Although bioremediation is improving, combining nanoscience and bioremediation can speed up progress [92]. Over the last five years, methods for

improving bioremediation via nanoparticles (NPs) have appeared. Organic Pickering emulsifiers have been employed to promote proliferating bacterial cells on droplets, magnetic NPs have been coated on bacterial cells for simple removal, and nutrient-loaded (NP) particles are being used for targeted release promptly across the oil-water interface [143].

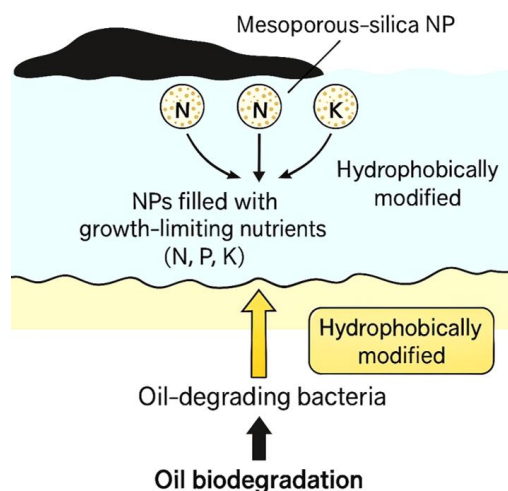


Fig. 6. Schematic depiction of nanoparticle-facilitated biostimulation for oil spill bioremediation.

5.7. Bacteria Reactive Magnetic NPs

In addition to biodegradation, marine microbes can help with oil spill removal. Hence, the cell surfaces are being altered to render microbes electromagnetically responsive [144]. Modifying the microbial cell surfaces to become more repellent (hydrophobic) to water, which might boost the speed at which microbial cells stick to the oil-water interfaces, could be a successful strategy for oil spill removal from the marine [92]. Microbial cells can also be modified in order to be magnetic-responsive. The above cell alterations can improve oil spill removal by enhancing the bacteria's interactions with magnetic NPs, which may then be eliminated by employing a magnetic field from the outside [1].

For instance, the magnetic alteration of *A. borkumensis* via cationic polyelectrolyte-altered magnetite NPs [145]. Magneto responsiveness was generated by a thick shell (70 to 100 nm) of magnetic NPs lightly connected to the cell's surface [146]. The oil was almost entirely removed as a result of such modification; however, cell growth had substantially slowed.

Pickering emulsions that are stabilized through magneto-responsive microbes are a different strategy for magnetized oil spill removal [92]. The ability of modified microorganisms to create solid Pickering emulsions, which can be eliminated with a magnetic field from the outside, has been shown. When juxtaposed with prior research on magnetic NPs for oil removal from polluted sites, the investigators assert that such altered bacteria proved to be more sustainable as well as inexpensive [147]. More research is being conducted to investigate the application of such altered bacteria in biological reactors for massive oil degradation. Based on their stronger attachment to the oil-water interfaces, magneto-responsive bacteria showed greater decomposition and oil removal in less time when contrasted with nonmodified microbes. Despite the initial investigation into magneto-responsive microbes appearing intriguing, little is understood about the consequences of including magnetic NPs in marine ecosystems.

5.8. Oil Spill Biostimulation

Nanotechnology additionally offers methods of targeted biological stimulation through the use of NPs, which are capable of being filled with growth-limiting nourishment that is released only near the oil-water interface [148]. This could reduce the possibility that nutrients are being metabolized through non-oil-degrading organisms and dilution. Mesoporous-silica NPs that have been engineered to be hydrophobically adaptable are able to be filled with growth-limiting nourishment like N, P, and P [149]. By incorporating an organic modification of a long-chain (C18) organosilane onto the exterior of the silica NPs, an enclosed mechanism for fragments that were capable of being opened by lipophilic alkanes was created [150] (Figure 6). While the fragments interacted with the oil-water interface or oil droplets, hydrocarbons dissolved the C18 gates and released nourishment encapsulated in the NPs [151]. This method could enable nutrients to become distributed only across the oil-water interface, hindering intensity as well as the emergence of microbes that cannot degrade oil. In addition, it was stated that the approach would be relatively simple to scale up and responsive to different nutrients [152, 153].

The use of nanomaterials to improve bioremediation is a new area of interest in oil spill cleanup. Initial accounts suggest enhancements for improved spilled oil bioremediation and oil removal for the improvement of spilled oil response, such as elevated biodegradation, effective oil removal, and targeted discharge of growth restricting nutrient-rich [154]. Regardless of proof that biological remediation can be increased with NPs as a sustainable post-oil spill response alternative, there has been little investigation in this rapidly developing discipline to date. Future research should concentrate on larger-scale investigations, such as the biological products and environmental effects of introducing NPs into marine environments. Also, studies should address the challenges of scaling up and cost analysis to confirm that NPs stimulated bioremediation actually represents a sustainable, affordable alternative to conventional oil spill remediation techniques [155].

5.9. Bacterial Proliferation

Surfactants are used to break down oil into smaller fragments (droplets) so that it is capable of being degraded by marine microbes [156]. However, certain chemical dispersing agents are toxic to marine organisms and improve the toxic effects of the oil, hindering bioremediation. Pickering's emulsifiers, such as NPs synthesized using organic precursors, could be a "green" option. Research suggests that suspended particulates could have an important role in stimulating oil biodegradation through marine microbes. Particle-stabilizing droplets of oil enhanced biodegradation five times when compared to non-dispersed oil, with a three percent raise in PAH breakdown across 32 days [17]. When contrasted to an oil slick, blended oil droplets that dissolve in water possess more surface area for deterioration, resulting in enhanced accessibility for microbes in the water's column.

Biofilm-forming bacteria choose to create biofilms upon hydrophobic solid substrates, according to evidence. Because bacteria choose surfaces that are hydrophobic, tiny droplets stabilized through particles have specific areas of hydrophilic properties in the marine water, as well as in bacteria, can more frequently stick to such droplets [157]. This happens due to the fact that the energy

at the bacteria's surface is frequently smaller than the kinetic energy found on the air surface of the marine water; therefore, this distinction attracts microorganisms to the particle-stabilized droplets [157]. In comparison with NPs stabilized oil-in-water drops of emulsion produced using conventional surfactants, adherence of cells to the particles stabilized droplet can result in enhanced microbial growth in the occurrence of hydrocarbons, and that could boost hydrocarbon/oil degradation [158].

The clay NPs have demonstrated potential for environmentally friendly Pickering emulsifiers, so there is an abundance of articles on the application of clay for improving bioremediation [159]. Following 37 days, nontronite, as well as smectite, have been shown to enhance the growth rates of *A. Borkumensis* five times and carried out alkylated PAH degradation. *A. Borkumensis*' metabolic rate was increased by halloysite and altered hydrophobic HNT [160].

Compared with different clay NPs, polypeptide-functionalized HNT produced tiny oil droplet dimensions. Thus, the particle-stabilized droplets proliferated more. Because clay is widely available, this Pickering emulsification has the capability to be scaled up for large-scale ecological uses. Although clay fragments when combined with marine microbes have the ability to enhance alkane degradation, inadequate PAH degradation constitutes a significant, yet often overlooked, concern. Graphene oxide (GO) quantum dots have been shown to enhance the proliferation as well as metabolic rate of the *Bacillus cereus* (PAH-degrading) [92]. Following 3.5 days, *B. cereus* deteriorated by 53% of the PAHs. This represented a significant improvement over the control (1.7%). Proteomic studies revealed an upsurge in the expression of protein molecules involved in the degradation of PAH that lasted up to 20 lifecycles [161]. Hence, the application of GO quantum dots may be an approach to improve bioaugmentation; nevertheless, the feasibility and expense of widespread implementation should be studied [162].

5.10. Case Studies and Lessons Learned by Region

The success of oil spill cleanup depends greatly on local environmental conditions, the characteristics of the spill, infrastructure, and local and national

regulations. Therefore, the experience gained from large-scale oil spills can be helpful in the implementation of sustainable response methodologies. The Deepwater Horizon spill in the Gulf of Mexico (2010) highlighted the importance of using mechanical methods, dispersants (with care), and long-term environmental monitoring [30]. Based on the results of subsequent intensive study, microbial bioremediation has been shown to be an important component of natural attenuation of petroleum hydrocarbons, and the potential for using indigenous hydrocarbon-degrading microorganisms in natural attenuation has been identified.

One of the first large scale demonstrations of nutrient enhanced bioremediation (biostimulation) was the Exxon Valdez spill in Alaska (1989) [163]. The use of nitrogen and phosphorus-based fertilizers was found to promote indigenous microbial populations to reduce residual hydrocarbon concentrations in the field studies and highlight the utility of environmentally friendly remedial activities [164].

The Spanish oil spill of 2002, which occurred off Spain's coast, brought into focus the need for the restoration of coastlines, long-term ecological monitoring, and international collaboration in response [165]. A post-spill investigation revealed that mechanical recovery and natural recovery led to reduced additional ecological disturbance and ecosystem recovery.

The MV Wakashio oil spill in Mauritius (2020), however, showed the increasing importance of community involvement and nature-based solutions [166]. Environmentally-friendly sorbent materials were deployed by local volunteers, government agencies and researchers, to recover sensitive coastal habitats and monitor ecological recovery. It was shown that public participation and remediation efforts tailored to local conditions are also options, in addition to traditional responses, particularly in ecologically important areas. These case studies demonstrate that there are no 'one size fits all' remediation solutions. For sustainable management of an oil spill, both biological and physical and emerging green technologies must be integrated, as well as adapting response strategies to the local environment, ecosystem sensitivity, and resources

and governance. Lessons from these events are used to guide development of more resilient, environmentally sensitive and regionally appropriate oil spill response regimes.

Progress has been made in sustainable oil spill remediation, but there remain a number of research gaps that limit the widespread application of technologies to clean up oil spills. Long-term ecological monitoring is required to determine the persistence, ecological safety, and recovery effects of remediation methods under various marine conditions. Moreover, a large number of potential green technologies that have successfully demonstrated promising results in laboratory or pilot testing would need to be assessed in a field trial at a larger scale to demonstrate technical reliability, cost-effectiveness, and operational scalability. Although there are no standardized protocols for assessing remediation performance, life-cycle environmental impacts, and potential secondary effects, this makes it difficult to compare across studies. Future studies should focus on an interdisciplinary approach, emphasizing the integration of real-time environmental monitoring and forecasting into remediation planning. Additionally, efforts should concentrate on developing scalable, cost-effective, and environmentally friendly remediation technologies that are applicable to various marine ecosystems and spill scenarios.

6. Artificial Intelligence for Sustainable Management of Oil Spills

Artificial intelligence (AI) is becoming an essential tool for improving the efficiency, accuracy, and sustainability of oil spill management. The combination of machine learning, deep learning, and computer vision with remote sensing technologies can help to quickly detect, track, and characterize oil spills using satellite imagery, unmanned aerial vehicles (UAVs), and autonomous marine platforms [167]. These methods allow rapid determination of spill extent, movement, and severity, thus allowing for more effective planning of the response. The oil spill transport and weathering processes can be simulated using AI-based predictive models, based on ocean currents, wind patterns, wave dynamics, and meteorological

data [168]. These models assist in predicting spill trajectories and in optimizing the deployment of containment booms, skimmers, and bioremediation resources, while minimizing unnecessary environmental disturbance. AI can also help in identifying environmentally sensitive locations based on ecological vulnerability and enabling response teams to better deploy resources.

AI is also increasingly being used in research into sustainable remediation. Machine learning algorithms can predict microbial degradation performance under different environmental conditions, select the appropriate microbial consortia, and identify the optimal nutrient amendment strategies to optimize bioremediation [169].

Furthermore, AI can fast-track the development of green sorbent materials and nanomaterials by predicting the adsorption efficiency and properties of materials, which can significantly reduce the exhaustive experimental screening. However, widespread adoption of AI is hampered by the availability of high-quality datasets, model generalization in different marine environments, computational requirements, and the need for standardized validation frameworks [169]. Future research should focus on the integration of AI with Internet of Things (IoT) sensor networks and geographic information systems (GIS), autonomous monitoring platforms, and decision support systems to allow for real-time, adaptive, and sustainable oil spill management. Integration of disciplines has the potential to improve response efficiency, reduce environmental impacts, and support evidence-based decision-making for protection and restoration of marine ecosystems.

7. Conclusion

This review indicates that there is no "universal" remediation technology for all marine oil spills because the effectiveness of each technology depends on the environmental conditions and response time, magnitude of the spill, and type of oil. Physical containment and recovery methods like booms, skimmers, and sorbents continue to be the most effective initial methods for containment and recovery of floating oil and the containment of its spread. Chemical dispersants can be rapidly

applied to large-scale offshore spills in certain environmental conditions, but their application should be carefully considered because of the potential ecological effects and regulatory limitations. Biological processes, including biostimulation, bioaugmentation, biosurfactant-assisted remediation, and phytoremediation, are environmentally friendly approaches that can be used for long-term degradation of residual petroleum hydrocarbons, causing minimal secondary pollution. Recently, nanotechnology has progressed to enhance oil spill remediation through an increase in the amount of oil that is adsorbed, the bioavailability of oil contaminants, the attachment of the microbes, and degradation efficiency. In this context, biodegradable/ bio-based nanomaterials, magnetic nanosorbents, and Pickering emulsion systems are among the most promising innovations, which offer high remediation efficiency along with low environmental impacts.

A more complete evaluation of the persistence, ecotoxicity, and long-term environmental fate of nanoparticles must be performed before being widely used.

Environmentally, remediation technologies should focus on those that cause the least environmental damage, are not associated with the presence of secondary pollutants that will persist in the marine environment, and support marine biodiversity in the affected area.

Thus, application of indigenous hydrocarbon-degrading microorganisms, biosurfactants, and biodegradable nanomaterials for integrated biological remediation is one of the most sustainable methods for the regeneration of the contaminated marine ecosystems.

In terms of an engineering approach, the operational managers should aim for a multi-stage remediation process, whereby mechanical containment is the initial step after spill detection, and site-specific biological or nanotechnology-based treatments are employed to deal with any residual contamination. Remediation technologies should be selected based on the characteristics of the oil, spill site, hydrodynamic conditions, water temperature, salinity, logistics, infrastructure, and regulatory needs. New technologies like remote sensing, autonomous monitoring systems, and AI

can improve the detection of spills, help optimize remediation plans, and aid in real-time decision making. From an economic viewpoint, mechanical recovery is still economically viable and can be used on localized spills to directly recover and reuse oil. The initial operating cost is typically higher for biological remediation, but the long-term operating costs are reduced, and the environmental liabilities are minimized. Although the laboratory-scale results have been good, there is a need to perform detailed techno-economic analyses, standardize manufacturing processes, carry out life cycle assessments, and cost benefit analysis to make this technology viable and commercially viable for large-scale remediation. More study is needed to compare capital investment, operating expenses, energy and environmental expenses of remediation technologies in realistic field conditions.

The development of mechanically recovered materials, environmentally friendly nanomaterials, and biosurfactant-assisted biodegradation should be integrated in pilot-scale and mesocosm studies to be validated in the future. Special focus on long-term eco-effects of nanomaterials is recommended, scaling up production of biodegradable nanoparticles and biosurfactants, standardized protocols for performance assessment, and life-cycle sustainability analyses. The synergy between AI-based solutions and future oil spill response technologies, including predictive modelling, remote sensing and autonomous response systems, combined with green remediation technologies, will enhance the efficiency, flexibility and sustainability of future oil spill management.

Through multidisciplinary approaches to reducing the effects of oil spills in various marine environments, operational managers, policy makers, and researchers will have scientifically sound, environmentally sound, and economically sound solutions.

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Author's contribution

Conceptualization, original draft preparation, data analysis, Narayanasamy Prabhu. and Kandasamy Gajendiran; writing—review and editing, Narayanaa Vembu Madhi: Review and editing. All authors have read and agreed to submit this manuscript.

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Generative AI was used solely for improving readability and language editing. The authors take full responsibility for the content and interpretation of the manuscript

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