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REVIEW ARTICLE

Advanced bioremediation by an amalgamation of nanotechnology and modern artificial intelligence for efficient restoration of crude petroleum oil-contaminated sites: a prospective study

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Abstract

Crude petroleum oil spillage is becoming a global concern for environmental pollution and poses a severe threat to flora and fauna. Bioremediation is considered a clean, eco-friendly, and cost-effective process to achieve success among the several technologies adopted to mitigate fossil fuel pollution. However, due to the hydrophobic and recalcitrant nature of the oily components, they are not readily bioavailable to the biological components for the remediation process. In the last decade, nanoparticle-based restoration of oil-contaminated, owing to several attractive properties, has gained significant momentum. Thus, intertwining nano- and bioremediation can lead to a suitable technology termed 'nanobioremediation' expected to nullify bioremediation's drawbacks. Furthermore, artificial intelligence (AI), an advanced and sophisticated technique that utilizes digital brains or software to perform different tasks, may radically transfer the bioremediation process to develop an efficient, faster, robust, and more accurate method for rehabilitating oil-contaminated systems. The present review outlines the critical issues associated with the conventional bioremediation process. It analyses the significance of the nanobioremediation process in combination with AI to overcome such drawbacks of a traditional approach for efficiently remedying crude petroleum oil-contaminated sites.

Keywords Fossil fuel · Oil spillage · Nanoparticles · Bioremediation · Nanobioremediation · AI

Abbreviations

AI	Artificial intelligence
ANN	Artificial neural networks
ACA	Ant colony algorithm
BRT	Boosted regression tree
CNTs	Carbon nanotubes
DBT	Dibenzothiophene
DNA-SIP	DNA-stable isotope probing
DE	Differential evolution
GFP	Green fluorescent protein
IA	Immune algorithms
IARC	International Agency for Research on Cancer
LSTM	Long short-term memory network
LMW	Low molecular weight
MAPE	Mean absolute percentage error
MSERA	Maximally stable extremal region algorithm
MCS	Monte Carlo simulation
MLP	Multilayer perceptrons
NBR	Nanobioremediation
NPs	Nanoparticles
OC	Organic carbon
PAHs	Polyaromatic hydrocarbons
PLS	Partial least square
PMUA	Polyethylene glycol-modified urethane acrylate
RBCs	Red blood cells
RSM	Response surface modelling
RSME	Root mean square error
SVR	Support vector regression

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SPM	Support vector methods
TPHs	Total petroleum hydrocarbons
UAVs	Unmanned aerial vehicles
WBCs	White blood cells

Introduction

One of the prime factors of environmental pollution is the emancipation of crude petroleum oil into the environment. The rapid industrial development led to the growing demand for conventional fossil fuels, although the emphasis is given to the maximum possible utilization of non-conventional sources. Although due to economic instability due to the coronavirus pandemic, the global consumption of crude oil reduced to 91 million barrels per day from 99.7 million barrels, it increased to 96.5 million barrels in 2021 and is expected to rise further as the pandemic situation is gradually improving. Various activities related to the exploration of crude oil, its transportation, and refining processes lead to releasing hydrocarbon components into the environment (Patowary et al. 2018). Due to its low polarity and highly hydrophobic nature, crude oil remains confined to the soil particles. It is not readily available to the indigenous microbial population, so they are not preferably subjected to biodegradation (Hu 2020). The oil in the soil can penetrate to a depth of more than 10–30 cm, which eventually induces the degeneration of soil properties, finally affecting the vegetation of the crude oil-impacted areas (Ofeogbu et al. 2015). In aquatic bodies, for example, ponds, rivers, and oceans, crude oil components hinder the light from penetrating the surface of water bodies and reducing the amount of dissolved oxygen, thereby affecting the aquatic life forms (Inyinbor Adejumoke et al. 2018).

Specific components of crude oil, such as polyaromatic hydrocarbons (PAHs), are known to have mutagenic, teratogenic, carcinogenic, and even immunosuppressive properties (Patel et al. 2020). By food chain transfer of such recalcitrant components, humans also become indirect victims of crude petroleum oil pollution. Consequently, remediating the oil-polluted environment is of utmost necessity (Garcia-Villacis et al. 2021). Several conventional remediation technologies, such as precipitation, solvent washing, electrochemical techniques, incineration, coagulation, flocculation, and adsorption, have been applied; however, such techniques release toxic products and gases that further pollute the environment (Ali et al. 2020). Therefore, the exploration of efficient, cost-effective, and green technology for proper remediation of petroleum oil-contaminated sites is warranted for a sustainable future (Das and Mukherjee 2007; Mukherjee and Bordoloi 2011; Benjamin et al. 2019).

Bioremediation, employing the potential indigenous microorganisms or plants that can uptake and disintegrate crude petroleum oil components into nontoxic intermediates, is considered one of the major technologies for restoring crude oil-contaminated environment due to its environmentally friendly nature and cost-effectiveness. Furthermore, recent research emphasizing incorporating advanced technologies in bioremediation has gained significant momentum (Das and Mukherjee 2007; Mahjoubi et al. 2018; Sui et al. 2021; Gu 2021). Several bacterial genera such as *Bacillus*, *Acinetobacter*, *Rhodococcus*, *Burkholderia*, *Pseudomonas*, *Mycobacterium*, *Kocuria*, *Enterobacter*, *Arthrobacter*, *Marinobacter*, *Streptococcus*, *Staphylococcus*, *Alteromonas*, and *Achromobacter* are known to degrade hydrocarbon components from polluted sites (Heinaru et al. 2005; Das and Mukherjee 2007; Bordoloi et al. 2014; Varjani and Gnansounou 2017; Xu et al. 2018; El-Aziz et al. 2021). Such bacteria possess enzymes capable of triggering chemical reaction cascades that lead to the degradation of the hydrocarbon compounds. However, the reaction pathways may vary according to the type of bacteria mediating the degradation and the specific enzymes expressed by them (Xu et al. 2018). As shown in Table 1, apart from bacteria, fungi, and algae, several plant species also exhibit the potential to degrade and remove oily components from the contaminated environment by accumulating hydrocarbon components from the soil/water and converting them into simpler forms, a process known as phytoremediation (Mukherjee and Bordoloi 2011; Bordoloi et al. 2012; Cheng et al. 2017; Ekperusi et al. 2020; Hou et al. 2021).

Although bioremediation is a clean and cost-effective method for remediation of contaminated sites, quite often, it has been observed that it requires a long time, and the efficiency of bioremediation reduces if the microbes or the plants cannot tolerate the harsh environmental conditions of the site (Ubani et al. 2013; Cecchin et al. 2017; Gao et al. 2021). Thus, considering the drawback of conventional bioremediation processes, it is necessary to introduce advancements in the bioremediation techniques or employ a suitable combined approach to remove the hydrocarbon contaminants efficiently. In the present era, nanotechnology has gained much attention due to its unique properties and higher efficiency (Guerra et al. 2018). Compared to its bulkier and larger counter molecules, nano-molecules offer better efficiency and enhanced reactivity due to their higher surface-to-volume ratio (Khan et al. 2019).

Crude oil's components are highly hydrophobic and have low polarity; due to this, they remain tightly associated with soil particles and are not readily bioavailable to the microbial population, which carries the degradation process (Paria 2008). Nanotechnology, which implies the use of nanoparticles, is being used for cleaning up contaminated sites, including oil-polluted sites, and has been a newer approach in the last decade (Mahajan 2011; Younis et al. 2020). Global research has demonstrated that different

Table 1 A list of microorganisms and plants used for the bioremediation of hydrocarbon oil-contaminated environment

Organisms	Treatment method	Type of hydrocarbon	Treatment duration (days)	Degradation efficiency (%)	References
Bacterial bioremediation					
Pseudomonas arthrobacter	Bioaugmentation	Diesel	42	32	Adams et al. (2015)
Acinetobacter	Bioaugmentation	Total petroleum hydrocarbons (TPHs)	34	34	Wu et al. (2016)
Alcanivorax and *Thalassolituus*	Bioaugmentation	Crude oil	20	80	Hassanshahian et al. (2014)
Bacillus pumilus KS2 and *Bacillus cereus* R2	Bioaugmentation	Crude oil	35	84.2	Patowary et al. (2016)
Achromobacter sp. (PS1)	Bioaugmentation	Crude oil	7	46.62 (70.77 and 77.17% of aliphatic and aromatic fraction reduction)	Joy et al. (2017)
Consortium (*Bacillus* sp. and *Pseudomonas* sp.)	Bioaugmentation	Crude oil	14	80.64	Tian et al. (2018)
Oil-degrading bacterial population immobilized on biochar	Bioaugmentation plus biostimuation	TPH	60	58.08	Zhang et al. (2019)
Consortium (lyophilized two strains of *Rhodococcus erythropolis* and one *Pseudomonas* sp.)	Bioaugmentation	TPH	15	47	Perdigão et al. (2021)
Consortium (*Pseudomonas mendocina* BPB 1.8, *Bacillus cereus* BPB 1.20, *Bacillus cereus* BPB 1.26, and *Bacillus sphaericus* BPB 1.35)	Bioaugmentation plus biostimuation	TPH	60	85	Napp et al. (2022)
Fungi (mycoremediation)					
Scopulariopsis brevicaulis PZ-4	Bioaugmentation	Polyaromatic hydrocarbon (PAH)-aged soil	28	77 of total PAHs (phenanthrene (89%) and benzo[a]pyrene (75%))	Mao and Guan (2016)
Penicillium citrinum	Bioaugmentation	Crude oil	23	77% (with individual alkane removal of 95%)	Barnes et al. (2018)
Aspergillus sp. RFC-1	Bioaugmentation	Crude oil	7	60.3% (with 97.4%, 84.9%, and 90.7% removal of naphthalene, phenanthrene, and pyrene resp.)	Al-Hawash et al. (2019)
Aspergillus flavus	Bioaugmentation	Crude oil	30	80	Al-Dossary et al. (2019)
Penicillium, *Ulocladium*, *Aspergillus*, and *Fusarium*	Bioaugmentation + biostimuation	TPH	120	39.9 (with 5-ring PAHs, benzo(a) fluoranthene, benzo[a]pyrene degradation: 36 and 46 and 6 ring PAHs, benzoperylene degradation: 28	Medaura et al. (2021)
Co-culture of *Pestalotiopsis* sp. NG007/*Polyporus* sp. S133/*Trametes hirsuta* D7	Bioaugmentation	Crude oil	30	63–92%	Yanto and Hidayat (2020)

Table 1 (continued)

Organisms	Treatment method	Type of hydrocarbon	Treatment duration (days)	Degradation efficiency (%)	References
Alternaria alternata (AA-1), *Aspergillus flavus* (AF-3), *Aspergillus terreus* (AT-7), and *Trichoderma harzianum* (TH-5)	Bioaugmentation	Crude oil	14	73.6 (with 56.8%)	El-Aziz et al. (2021)
Algae (phycoremediation)					
Chlorella kessleri	Bioaugmentation	Benzo (a)pyrene amended	6	–	Takáčová et al. (2014)
Chlorella vulgaris	Bioaugmentation	Crude oil/water	14	94% and 88% of light and heavy compounds resp.	Kalhor et al. (2017)
Oscillatoria sp., *Chlorella* sp.	Bioaugmentation	Pyrene amended medium	30	95, 78.71	Aldaby and Mawad (2019)
Chlorella vulgaris BS1	Bioaugmentation	Formation water	14	98.63% TPH	Das and Deka (2019)
Plants (phytoremediation)					
Axonopus compressus	Phytoremediation	Hydrocarbon-contaminated soil	360	70	Bordoloi et al. (2012)
Iridaceae species (*Iris lactea* Pall. and *Iris dichotoma* Pall.)	Phytoremediation	Hydrocarbon-contaminated soil (10,000 ppm)		30.79%, 25.02%	Cheng et al. (2017)
Megathyrsus maximus	Phytoremediation stimulated with mushroom compost	Black oil hydrocarbon-contaminated soil	120	92.16–93.58%	Asemoloye et al. (2017)
Lemna paucicostata (aquatic plant)	Phytoremediation	Crude oil-contaminated wetland	120	97.19	Ekperusi et al. (2020)
Vetiveria zizanioides and *Jatropha curcas*	Phytoremediation	Hydrocarbon-contaminated soil	112	51.1, 82.2	Nero (2021)
Festuca arundinacea L	Phytoremediation	Hydrocarbon-contaminated soil	120	76.6	Hou et al. (2021)

nanomaterials can remediate petroleum oil pollution (Younis et al. 2020; Xu et al. 2020; Mishra et al. 2022). The suitable properties of nanomaterials resulted in attractive consequences. Thus, a combined approach of nanotechnology and bioremediation, termed nanobioremediation (NBR), can lead to a practical solution for the potential restoration of oil-polluted sites. Notably, several attractive nanoparticle (NP) properties can minimize the limitation of the conventional bioremediation process and lead to better removal of waste from a contaminated site.

Although, over the past decades, NPs are gaining wide applications and becoming 'wonder molecules', however, most of them are chemically synthesized where different chemical compounds are used as reducing or capping agents during the process of NP synthesis, which can pose hazardous effects on the environment (Verma 2018). Thus, the focus has been shifted towards the synthesis of green NPs, where biological components, including bio metabolite, plant parts, and microbes, are utilized for manufacturing the NPs for moving towards sustainable application of NPs (Aziz et al. 2015; Hussain et al. 2016; Al Zahrani et al. 2018; Singh et al. 2018; Fouda et al. 2020; Hassan et al. 2022).

Artificial intelligence (AI) is another tool that is gaining much importance in various fields due to its preciseness, high speed, and accuracy. Advanced machine learning techniques such as artificial neural networks (ANN) and support vector methods (SVM) are promising tools that provide in-depth pieces of information and help interpret nonlinear data in environmental science (Shadrin et al. 2020). The correlation between the origin and spatial distribution of contaminants, their concentration, and properties in a particular location can also be predicted by AI-based models, which aid the environmentalist in designing and executing the work appropriately (Ebrahimi et al. 2019; Fernandes et al. 2019; Kou et al. 2019).

In the past few years, limited studies on NBR have been conducted as a treatment regime for restoring crude oil-contaminated sites. Comprehensive work in this area is crucial for correctly understanding the NBR process and exemplifying ways to upgrade the technology for better outcomes. This review article attempts to provide insight into the adverse effects of crude oil and drawbacks of the conventional bioremediation process and the illumination of the scope and application of nanotechnology in the remediation of petroleum oil-contaminated sites. It ultimately confers the benefit of amalgamation of nano- and bioremediation processes, termed NBR technology, to remediate petroleum oil spills and reviews the work performed on NBR over the past decade. Additionally, the review also throws light on the potential applicability of AI for achieving better accuracy and efficiency of bioremediation processes for removing hydrocarbons from petroleum oil-polluted sites. It discusses the various research works that have involved AI in crude oil remediation till-date as searched in internationally recognized scientific journal archives and databases such as PubMed Central, ScienceDirect, and Scopus.

Composition of crude petroleum oil and its adverse effect on the ecosystem and humans' health

Crude petroleum oil is a complex of many individual compounds, and its composition and properties vary based on the geographical origin of the fossil fuel (Table 2). Mainly hydrocarbons in different forms, predominantly straight-chain alkanes, cycloalkanes, aromatic hydrocarbons such as benzene and its derivatives, and fused benzene ring compounds named polyaromatic hydrocarbons (PAHs), for example, anthracene, phenanthrene, and pyrene, are the dominating class of compounds present in crude oil (Han et al. 2009; Schobert 2013; Obi et al. 2020). Waxes are complex hydrocarbons consisting of paraffin and a low amount of naphthenic and aromatic compounds, creating three-dimensional networking systems that sequester the fluid components of the crude oil, thereby worsening the

Table 2 Composition of crude petroleum oil (sources: Welte and Tissot (1984); Mello et al. (2012); Speight (2015); Shishkova et al. (2022))

Composition of crude oil		
Elements (range in %)	Hydrocarbon classification (range in %)	Non-hydrocarbon components
Non-metals	Paraffin (4–89%)	Resin (0–66%)
Carbon (84–87)	Alkane (C_nH_{2n+2})	Asphaltenes (0–43%)
Hydrogen (11–14)	Olefin (formed during processing)	None
Nitrogen (0–1)	Alkene (C_nH_{2n})	
Oxygen (0–1)	Naphthenes	
Sulphur (0–5)	Cycloalkanes	
Metals and heavy metals	Aromatic (benzene ring) (3–59%)	
Copper, lead, iron, sodium, magnesium, vanadium, nickel, zinc, manganese	Polyaromatic hydrocarbons (PAHs) (have multiple fused benzene rings)	

fluidity of the crude oil. Focusing on developing efficient techniques to segregate the waxy components can enhance the properties of crude oil.

Apart from hydrocarbon compounds, non-hydrocarbon compounds, especially sulphur, nitrogen, and oxygen-containing compounds, are also present in crude oil (Mello et al. 2012; Speight 2015; Shishkova et al. 2022). Even metallic compounds are found in traces in crude oil from different regions. The rheological properties of crude oil can also have an impact on the composition of the crude oil (Djemiat et al. 2015). However, an in-depth molecular-level study on crude oil has not yet been reported. Thus, such an investigative study will help in detail understand the behaviour and properties of crude oil.

Crude oil contamination delivers adverse effects on life forms. Humans and animals come in contact with crude oil while drinking, bathing, and consuming fish collected from contaminated water bodies and crops cultivated in petroleum oil-polluted sites. Children, pregnant women, and older people are more susceptible to the adverse effect of crude oil (O'Callaghan-Gordo et al. 2016). Several studies have reported the negative impact of crude oil on the immune system. For example, Eyong et al. (2004) reported haematological changes in rat populations exposed to crude oil. They found that on being gavaged with 9-ml natural oil/kg body weight in rats, around 50% reduction of red blood cells (RBCs) was detected. In contrast, there was a significant increase in the population of white blood cells (WBCs), indicating that ingested petroleum oil leads to hemolysis or erythropoiesis, increasing susceptibility to various infectious diseases.

Similarly, in 2017, Bayha et al. reported the increased vulnerability of fish (southern flounder) towards bacterial challenge (*Vibrio anguillarum*) when exposed to crude oil. They observed a higher mortality rate (94.4%) of the fish exposed to crude oil before the bacterial encounter. A low mortality rate of $< 10\%$ was noted for the fish not exposed to the oil before the bacterial challenge. Occupational exposure to PAHs in crude oil accomplishes various symptoms, such as nausea, skin irritation, vomiting, and confusion. However, the exact mechanism of how the PAHs trigger such health problems is not adequately known (Unwin et al. 2006; Rahman et al. 2022).

Furthermore, a few components of crude oil are also known to have carcinogenic effects on humans. The International Agency for Research on Cancer, France, has declared that emissions from various petrochemical industries have carcinogenic properties (IARC 2018). There are reports where PAHs have been found to cause lung cancer. Studies were also conducted, where it was found that incidences of cancer diagnosis were more common in the area closer to the oil exploration sites or refineries (Williams et al. 2020).

Hydrocarbon contamination also leads to changes in the physicochemical properties of soil, including permeability, pH, total organic carbon, and soil mineral nutrients, such as sodium, sulphate, nitrate, and phosphate content, which affect the growth of plants and microbial flora present in the soil (Cheema et al. 2015; Nyarko et al. 2019; Zahermand et al. 2020; Hu et al. 2020). Devatha et al. (2019) observed a significant decrease in soil pH in soil contaminated with crude petroleum oil. Similarly, Wang et al. (2013) also reported changes in pH, total organic carbon, and phosphorus content in soil contaminated with crude petroleum oil. Hydrocarbons consist of ions that could also bond with ions in the soil. The entire organic carbon content also increases in the ground due to hydrocarbon contamination; thus, crude oil contamination severely affects the physicochemical properties of soil. Changes in soil porosity and enzyme activity (50% reduction in dehydrogenase and urease activity) due to oil contamination have also been reported (Polyak 2018; Ostovar et al. 2021). It was observed that the soil's porosity decreased and the soil's water resistance increased due to oil contamination. Thus, the alteration of soil properties ultimately affects plant growth in oil-contaminated sites.

Skrypnik et al. (2021) studied the effect of crude oil on rye cereal crops. It culminated that the root and shoot weight, plant height, and water content of the rye crop decreased when cultivated in crude oil-contaminated soil. It was also observed that the increasing concentration of crude oil pronounced affected plant growth. The authors interpreted that crude petroleum oil contamination decreased the total chlorophyll and carotenoid contents of affected plants and induced oxidative stress by producing higher quantities of hydrogen peroxide, malondialdehyde, and lipid peroxidation products in such plants. In another study, Baruah et al. (2014) reported that crude oil contamination leads to decreased chlorophyll content in *Cyperus brevifolius* (Rottb). It was also found that the plant biomass was significantly reduced, and structural deformation in leaves and tissues was observed due to crude oil contamination.

In one of our previous studies, it was corroborated that crude oil harmed the growth and yield of rice plant (*Oryza sativa* L.) which is considered as a staple crop of most Asian countries (Patowary et al. 2017). The rice plant parts, including the grains, were found to accumulate hydrocarbon compounds, and it can be assumed that consuming such contaminated cereals can lead to health issues. Our findings also suggest that it is necessary to investigate the soil quality before the land is utilized for other purposes, especially cultivation or animal rearing.

Thus, considering the hazardous effects of crude oil contamination, it is essential to develop sustainable and clean ways to remediate and restore the oil crude oil sites. Effective measures and technologies must be adopted to rehabilitate the polluted areas to be used for vegetation.

Key issues of conventional bioremediation processes

Bioremediation is one of the promising and cost-effective technologies that can be adopted to deal with and rehabilitate the contaminated environment. Several kinds of research have been carried out where potential bacteria had been isolated from contaminated sites and applied in either singlet or consortium form to degrade oil components into simpler forms (Das and Mukherjee 2007; Patowary et al. 2016; Tian et al. 2018; Ali et al. 2020; Zhang et al. 2020; Ambust et al. 2021). Bioremediation mainly comprises two prime strategies; one is bio-stimulation, and the other is bioaugmentation. Bio-stimulation involves the application of nutrients or components that enhance the indigenous microbes' activity to degrade the contaminants, whereas bioaugmentation is the addition of exogenous microorganisms into the contaminated environment to lessen the contaminant of interest (Ruffini et al. 2016; Heinaru et al. 2005).

Another popular conventional technique, known as phytoremediation, involves the potentiality of plants to neutralize or metabolize toxic components by their active enzymatic system and also rhizospheric microbes that helps in the filtration or degradation of the contaminants to nontoxic forms. Several studies have used various plant species for the phytoremediation of oil-contaminated sites (Bordoloi et al. 2012; Baruah et al. 2016; Tang and Angela 2019). Figure 1 depicts the overall process of bioremediation of hydrocarbons. Although bioremediation is one of the clean and most effective strategies to remediate contaminated sites, it has several drawbacks that prohibit it from being widely accepted on a field scale. The following are a few specific drawbacks of the bioremediation process:

Poor contact between oil and microbes

Hydrocarbons are highly hydrophobic and are not readily soluble in the aqueous phase. The bacterial cells must contact the hydrocarbons to mediate the degradation process. The bioavailability of pollutants is necessary for initiating a degradation process by microbes (Gao et al. 2021). Before the initiation of molecular mechanism and enzyme activity of the microbes to degrade hydrocarbons, the contact of microbial cells and the oily component is essential (Hua and Wang 2014). Thus, the poor bioavailability of hydrocarbons becomes the rate-limiting factor for efficient biodegradation.

Nevertheless, a few classes of microorganisms have evolved and developed features that enhance their ability to utilize oil contaminants. Few categories of microorganisms produce exopolysaccharides and biosurfactants, leading to improved bioavailability of oily pollutants and altering cell

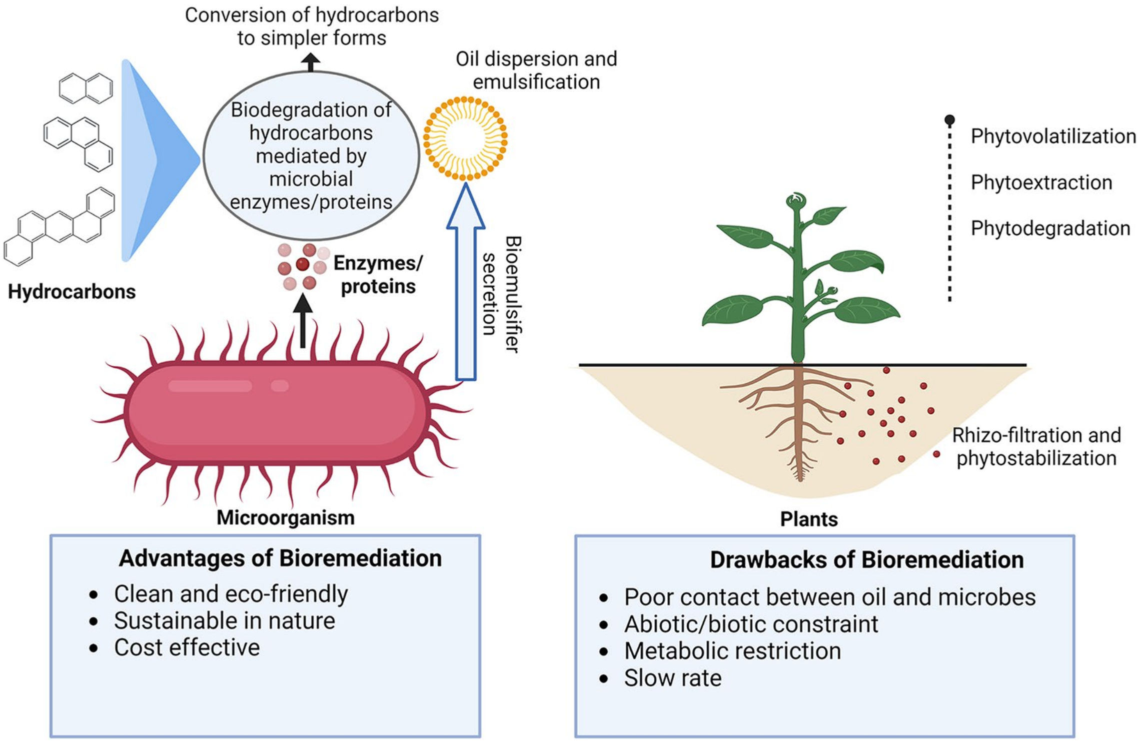


Fig. 1 Mechanism of bioremediation of contaminants (hydrocarbon) from contaminated sites

hydrophobicity for better uptake of the impurities (Liu et al. 2015; Patowary et al. 2018). Furthermore, future studies on the investigation of the availability of a particular pollutant by modern chemical analysis can be helpful for the execution of microbial degradation studies. They often alter surface properties and secrete metabolites such as bioemulsifiers and biosurfactants that enhance the bioavailability of hydrophobic contaminants (Das and Mukherjee 2007; Mukherjee and Das 2010; Alizadeh-Sani et al. 2018; Sharma and Pandey 2021).

Constraints of abiotic and biotic factors in the bioremediation process

Environmental factors such as temperature, salinity, nutrients, electron acceptors, and available metabolic substrates play an important role in bioremediation (Varjani and Gnansounou 2017). Due to the influence of such environmental factors, many microbes, although they exhibited promising results on a lab scale, may not show a similar effect in field conditions. Temperature plays a significant role in bacterial growth, soil texture, and mode of occurrence of the pollutant. Generally, the optimum temperature range for bacteria lies between 30 and 40 ℃ (Ubani et al. 2013). Furthermore, microorganisms require nutrients for their growth and metabolism. Besides carbon, nitrogen, phosphorus, oxygen, sulphur, and various trace elements are essential for the effective development of microbes (Ron and Rosenberg 2014; Xu et al. 2018). Thus, the availability of the nutrient components in the contaminated sites shall determine the fate of the biodegradation process. Salinity and pH also influence the actions of microbes towards bioremediation (Saha et al. 2019).

Additionally, the moisture content in the contaminated soil is a vital feature essential for microbial remediation of hydrocarbons. Sufficient moisture is required to bring the soluble pollutants and microbial cells in contact and their absorption (Ubani et al. 2013). Furthermore, oxygen is necessary for the action of oxygenase to degrade oil components. Thus, sufficient oxygen is essential for aerobic microorganisms' efficient biodegradation of pollutants (Ward et al. 2003). Furthermore, another factor that influences the biodegradation potentiality of microbes is the compatibility of microorganisms with indigenous microbes in the contaminated sites. Very often, it is difficult to achieve such abiotic conditions favouring the microbial degradation of contaminants that fails in situ bioremediation. The synergistic relationship of the microbes is essential for efficient degradation, whereas the antagonistic effect can down-regulate the biodegradation process. Additionally, the in-depth analysis of the microbial community in oil reservoirs shall aid in understanding the metabolic processes which lead to the degradation of the oily components, determine the intensity of contamination, and propose effective remediation strategies (Zhou et al. 2020, 2022). Adopting advanced culture-independent technologies shall provide more reliable information on the diversified microbial community in oil-contaminated sites.

Metabolic constraints

The concentration and composition of hydrocarbons severely influence the bioremediation process. It has been observed that microbes cannot work efficiently in exceptionally highly contaminated sites due to growth inhibition in higher concentrations of crude oil (Xu et al. 2018). Moreover, organic pollutants can impose toxicity towards microbial cells and inhibit their metabolism at a particular concentration, and thus, ecotoxicological studies find importance in this perspective (Gao et al. 2021). Additionally, in previous studies, it has been reported that the more straightforward form of hydrocarbons, i.e. linear and aliphatic alkanes, are more easily degraded than the aromatic hydrocarbons, and the PAHs are the complex hydrocarbons that are not easily degraded by the microorganisms (Das and Mukherjee 2007). Hydrocarbon compounds' various sizes and structures change their physicochemical properties and bioavailability, ultimately influencing their biodegradation.

The biodegradation of hydrocarbons by microorganisms also depends on the activity of special classes of oxidative enzymes, namely oxygenases, monooxygenases, and dehydrogenases (Mukherjee et al. 2017). Certain microorganisms possess enzymes mediating the conversion of complex hydrocarbon mixtures, while others can only degrade specific group of hydrocarbon compounds, especially linear ones (Varjani et al. 2017). Therefore, the existence of suitable microbes in a community that works together synergistically can lead to better degradation of contaminants (Gurav et al. 2017). Applying microbial consortia consisting of compatible microbes can be beneficial to bring about efficient degradation of hydrocarbons. In one of our previous studies, a bacterial consortium comprised of *Bacillus pumilus* KS2 and *Bacillus cereus* R2 led to efficient crude oil degradation. It could potentially degrade up to 84.15% of TPH after an incubation of 5 weeks in vitro conditions (Patowary et al. 2016.)

A slower rate of the overall bioremediation process

The microorganisms usually do not use hydrocarbons as carbon sources. In the absence of suitable carbon sources only, the microbes attempt to utilize hydrocarbon as carbon and energy sources. For such an action, the bacteria exclusively depend on the activity of hydrocarbonoclastic enzymes whose expression and activity depend on the bacteria's physiology (Mukherjee et al. 2017). It requires time to get acclimatized in the contaminated environment and express its enzyme, which ultimately catalyses the degradation process. Yet again, it has been seen that although some bacteria work very efficiently in laboratory conditions, they lose their efficiency when introduced to field conditions (Fida et al. 2017; Zheng et al. 2018).

Additionally, one core problem that hinders bioremediation is the ageing phenomena of the oily components. With time, the oily contaminants penetrate deeper into the soil particles, sequester themselves, and become less accessible to the microorganisms or plants, thus affecting the remediation process (Tang et al. 1998, 2012). There are reports based on experimental evidence, which culminate that as the age of organic contaminants progresses, the bioavailability reduces, hindering their bioremediation (Alexander 2000). But, the new contaminants can be subjected to bioremediation as they are mobilized better than the aged contaminants. Thus, the various factors, as discussed above, hinder the bioremediation process, making it time-consuming. To mitigate the drawbacks mentioned above, it is necessary to intertwine advanced technologies with the conventional bioremediation process.

Can nanotechnology and artificial intelligence (AI) revolutionize environmental pollution bioremediation?

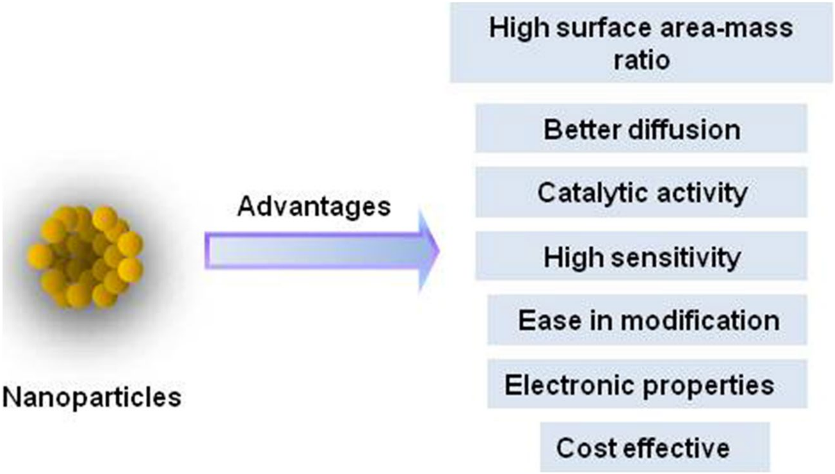
Today, nanotechnology is gaining much attention due to its numerous attractive properties. Nanotechnologies deal with the construction of nano-sized particles, the characterization of NPs, and their applications in various fields such as electrical, chemical, biotechnological, and medical (Rajan et al. 2011). Nanotechnology is an expanding study that involves structures, devices, or systems with extraordinary properties concerning their atoms of nanoscale size (Rajput et al. 2019; Rajput et al. 2021a, b). Recently nanotechnology has also been applied in the treatment of contaminated sites and remediation of groundwater and wastewater, although it is still at the bench-scale level with very scanty field applications (Singh et al. 2020; Hussain et al. 2022). NPs have several advantages that make them suitable candidates for vivid applications (Fig. 2). They can be synthesized cost-effectively (Prado-Audelo et al. 2021); they exhibit extraordinarily high surface area to mass ratio, catalytic behaviour, better diffusion, electronic properties, and present sensitivity (Corsi et al. 2018). The random distribution of active sites in their high surface area and the ease of coating modification add to their benefits for application in the remediation field (Guerra et al. 2018).

As shown in Fig. 3, NPs can be synthesized by various techniques in two basic phenomena—(a) top-down and (ii) bottom-up approaches. In the top-down process, the NPs are synthesized by minimization of size and are usually mediated by various physical and chemical techniques. In contrast, in the bottom-up approach, NPs are generated from smaller entities, such as atoms and molecules, by chemical reactions, usually oxidative-reductive ones.

Nano-based remediation of crude petroleum oil-contaminated sites

In the context of remediation, NPs allow the detoxification of toxic contaminants by catalysis or chemical reaction. Most importantly, adsorption is facilitated by its high surface-to-volume ratios and favourable distribution of active sites (Akharame et al. 2019; Blundell and Owens 2021). Usually, the remediation is carried out by two fundamental processes (Kharisov et al. 2014)—(i) adsorptive and (ii) reactive. In the adsorptive technique, the pollutants are sequestered or adsorbed from the contaminated sites. In contrast, in the reactive method, the NPs react with target pollutants and convert them into their intermediate forms.

Fig. 2 A schematic diagram showing the advantages of nanoparticles for practical bioremediation



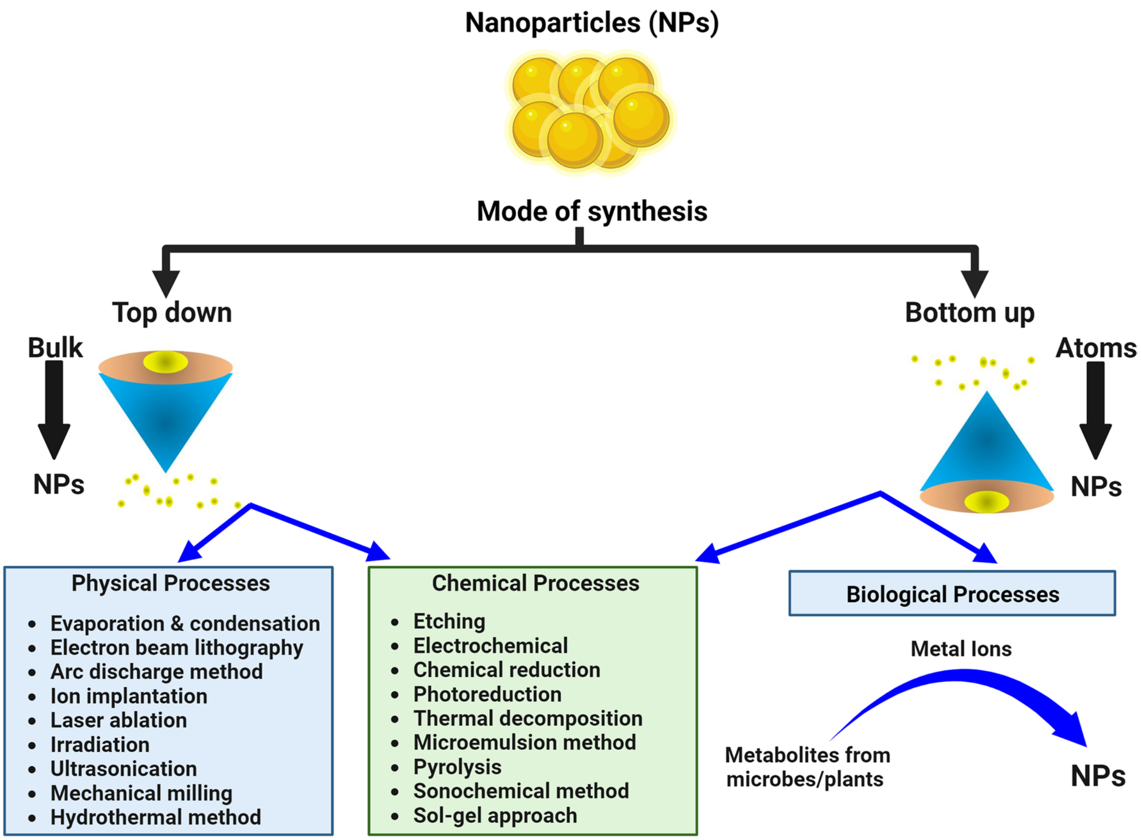


Fig. 3 A schematic diagram showing various processes for the synthesis of nanoparticles

Kharisov et al. (2014) have elaborately discussed the various nanomaterials that can be used for cleaning up oil spills. They are (i) aerogels, (ii) nanodispersions, (iii) magnetic nanocomposites, (iv) membranes, (v) foams and meshes, (vi) filters and pads, (vii) carbon nanostructures, (viii) nanostructure hydrophobic organoclays, and (ix) TiO_2. It has been stated that the selectivity of the nanomaterial is one of the main criteria determining the fate of oil sequestration from the oil–water phase.

Conventional nanomaterials such as polypropylene, raw cotton, and silicon-coated glass fibres tend to adsorb both water and organic solvents, but specific nanomaterials such as CNTs, nanowire membranes, and Recam provide selective adsorption and potentially adsorbs oil from an oil–water mixture (Kharisov et al. 2014).The high flexibility and attribute to withstand consecutive adsorption cycles make specific nanomaterials such as CNTs, aerogels, Recam, and Gigasorb highly effective in oil spill clean-up.

Based on their chemical compositions, NPs can be classified into inorganic, polymeric, carbonaceous, and composite substances (Ealia and Saravanakumar 2017). Inorganic NPs are synthesized from metal oxides such as silver, gold, titanium dioxide, zinc oxide, or silicon-based compounds. Polymeric NPs are made of chitosan, micelles, liposomes, alginate-based NPs, etc., whereas carbonaceous forms are constructed from carbon nanotubes, graphene nanosheets, graphene oxide nanosheets, nanofibers, and fullerenes. Composite NPs are usually multiphasic, consisting of different forms of NPs in combinations—for instance, gold NPs (AuNPs) combined with a polymer, biochar-supported zerovalent iron nanocomposites.

There are few reports on using NPs to remediate crude oil-contaminated sites. In a study, Guidi et al. (2022) reported the application of anatase titanium dioxide NPs (n-TiO_2) in remediating crude oil-fractionated water samples. It was found that the NPs were harmless to a model marine sp. *Dicentrarchus labrax*. It was found that the anatase n-TiO_2 did not possess a hazardous effect on aquatic organisms in terms of DNA damage, and it also reduced the impact of the genotoxicity of organic pollutants. In another study, Vu and Mulligan (2020) synthesized bimetallic Fe-Cu NPs of size 20-nm diameter that could potentially remove oil as indicated by total petroleum hydrocarbon estimation through gas chromatography. Murgueitio et al. (2018) also studied the effect of zerovalent iron NPs in removing petroleum oil from contaminated soil and water. They produced iron NPs of size ranging between 5 and 10 nm by using mortino berry (*Vaccinium floribundum*) as stabilizing and reducing agents. Applying the produced NPs led to removing 85.94% and 88.34% TPH from water samples contaminated with two varying concentrations of total petroleum hydrocarbon (TPH), viz. 9.32 mg/L and 94.20%, respectively. Furthermore, they also evaluated the effect of the nZVI NPs in the removal of oil from contaminated soil samples, and they corroborated that the NPs could efficiently remove 81.90% TPH after a treatment of 32 h. Their study culminated that the application of NPs created a reducing condition that fastened the removal of TPH from the contaminated samples. In another study, Atta et al. (2020) studied the effect of magnetic NPs capped with myrrh, a sap-like component secreted from trees, on the remediation of crude petroleum oil-contaminated water samples by water hyacinth (*Eicchornia crassipes* (Mart)). They used myrrh's hydrophobic hexane and ether extracts to cap onto magnetic NPs. They performed a greenhouse study, where water hyacinth was cultivated in bowls containing freshwater from the Nile River that was artificially contaminated at varying concentrations of crude petroleum oil, viz. 0.5, 1, 2, 3, and 5 mL/L for 1 month, after which plants were harvested, and plant parts were separated into roots and shoots and allowed to oven dry and then ground to obtain their powdered form. The sulphur and total hydrocarbon contents were estimated, and it was received that the plants bio-accumulated sulphur. A significant reduction of hydrocarbons was observed in the water samples.

Studies from our laboratory have shown that ZnO NPs can also be used to remediate oil field formation water. In the process, ZnO NPs were synthesized by the electrochemical method. GCMS results revealed that the NPs absorbed 131 hydrocarbon compounds out of 214 (Sharma et al. 2020). Thus, from the above discussion, it can be affirmed that nanotechnology can be widely used to remediate oil contamination.

Amalgamation of nanotechnology and bioremediation process for mitigation of petroleum oil pollution

Owing to the advantages and efficiency of nanotechnology, NPs can be used to nullify the drawbacks of the bioremediation process. Fabrication of nanotechnology with bioremediation leads to a process termed nanobioremediation (NBR), which is much faster, more efficient, and environmentally benign over the individual functions (Kumar et al. 2021). NBR has been defined as a technique that utilizes NPs together with microorganisms or plants to restore environmental contamination (Cecchin et al. 2017). NPs exhibit a quantum effect that helps minimize the activation energy required for initiating a reaction, making the biodegradation process faster than usual. They also acquire surface plasmon resonance data that aids in detecting a toxic compound of interest in a degradation process (Sadrolhosseini, et al. 2021).

In the present-day scenario, where the focus has been put forward on a sustainable approach towards environmental restoration, NBR is one of the most suitable techniques environmentalists can use to clean up polluted sites. It is an effective process that converts harmful contaminants into safer molecules by utilizing microbes along with nano-sized particles of a range smaller than 1–100 nm. NBR is usually classified into two broad classes: (i) NBR that involves microbes and NPs is referred to as microbial nanoremediation, and (ii) NBR that includes plants and nanoparticles, the process is referred to as phyto-nanoremediation (Singh et al. 2020; Kumari et al. 2022). NBR provides an economically feasible and eco-friendly solution to clean up polluted sites where microbes and NPs work synergistically to mediate the degradation phenomena (Shahi et al. 2021). In the NBR process, NPs act as a catalyst and enter within the contaminants (Chauhan et al. 2020) and aid the microbes in carrying out the actual degradation. This property makes NBR unique because the NPs are small and can penetrate the contaminants better than the micro-sized particles, making the overall degradation process faster and more efficient. The microbes then convert the harmful pollutants into simpler intermediates that can be used as growth metabolites for the microbes or even generate end products such as CO_2 and H_2O.

It is essential that the biological entity and the NPs, in NBR technology, should have compatibility (Paterlini et al. 2021), so that both can work together. Several factors influence the NBR process, viz. the size of the NPs, shape, surface properties, type of organic contaminants, type of microbes or plants, and environmental factors such as media, pH, and temperature, which have an impact on microbial growth and activity (Tan et al. 2018). Temperature is one of the prime factors determining an NBR process's fate. Temperature influences plant extract formation and nano crystal generation in the NBR process. However, future research to investigate such abiotic factors for developing a set of optimum conditions to enhance the efficiency of the NBR process shall be beneficial to achieve the desired outcome.

Some of the NPs that are being used in NBR technology are as follows: iron NPs, dendrimers, carbon nanotubes, and single enzyme NPs (Shahi et al. 2021). NPs can also immobilize microbial cells, which can degrade harmful contaminants. Shan et al. (2005) applied magnetic NPs that were functionalized with ammonium oleate and coated onto the cell surface of *Pseudomonas delafieldii*. They then used an external magnetic field, which led to the immobilization of the bacterial cells at a specific site of the reactor, separating them from the bulk reactor. The cells were used in a bioreactor to desulfurate organic sulphur from fossil fuels. In the NBR process, the sorption mechanism is fundamental and involves both adsorption and absorption. In the first one, sorption occurs at the surface, whereas, in the later one, the contaminants penetrate deep into the sorbent, which usually can occur by either chemisorption or physisorption (Vierra and Volesky 2000).

The behaviour of sorption of nanomaterials is essential, and extensive research is needed to be carried out for a proper understanding of the sorption mechanism of various nanomaterials used in NBR processes so that the efficiency of the process can be enhanced. Some researchers have elucidated models that describe such behaviour and biological matrix in remediation processes, viz. Freundlich and Temkin isotherms, Dubinin and Radushkevich model, and Langmuir model (Lopez-Luna et al. 2019; Abu-Nada et al. 2021; Hassan et al. 2022). There are several reports on using zerovalent metal ion NPs of iron, nickel, palladium, etc., along with biological entities for the remediation of sites contaminated with toxic substances. Nanoscale zerovalent iron NPs (nZVI), Ti, Mn, Ag, and Au, were used along with *Sphingomonas* sp. for remediation of decarbonated diphenyl ether in the water system where degradation of up to 67% was obtained (Kim et al. 2012).

Notably, iron NPs were utilized to coat bacterial sp. A3 to degrade azo dye, Basic Red 46 (Bekhit et al. 2020). After 24-h incubation, 91.6% of the original value (100%) was decolourized at the optimum dosage (5 mL/L) and dye concentration of 2200 ppm. The bacterial cells were successfully reused for a couple of cycles (4 times) with an efficiency of 86.34% by the magnetic separation method. Zinc sulphide NPs in crystalline form were entangled with bacterial enzyme organophosphorus hydrolase to disintegrate dinitrophenol and acid orange 7, and they could successfully remove more than 80% of the compound (Torres-Martínez et al. 2001). Nanocellulose was utilized to immobilize the bacteria *Arthrobacter deformis* D47 to remediate water system contaminated with herbicide diuron, where 90% degradation was obtained (Liu et al. 2018). In another study, a thin film composite polyamide nanomembrane and a natural extract of *Cynomorium coccineum* L. were used to clean up industrial wastewater contaminated with cyanide compounds. However, the degradation was not satisfactory and was estimated to be around 22% (Mechrez et al. 2014).

Although NBR technology is being used for the restoration of the contaminated environment, the literature review shows that there exists a paucity of research on NBR applications for the degradation of crude petroleum oil pollution, including PAH compounds which are of prime concern due to their extraordinarily resistant and toxic properties (Patel et al. 2020). The level of PAHs, one of the premium components of fossil fuel, has recently skyrocketed in various regions due to the excessive use of fossil fuels and rapid industrialization (Vecchiato et al. 2020). NPs can enhance the bioavailability of these hydrophobic crude oil contaminants, which usually remain sequestered in the nonaqueous phase.

Tungittiplakorn (2005) studied the utilization of polyethylene glycol-modified urethane acrylate (PMUA) for the disintegration of phenanthrene dissolved in an aquifer model. They affirmed that PMUA increased the discharge of phenanthrene and expanded its mineralization rate, making them available to a microbial population that carries out in situ biodegradation of the pollutant. In another study, the activity of halotolerant biosurfactant producer *Pseudomonas aeruginosa* NSH3 having the potential to degrade recalcitrant PAHs was enhanced by using magnetic iron NPs. They also carried out a study in artificially contaminated sediments at the microcosm level, where regression modelling and statistical analysis were smartly applied to provide information about the interactive impacts of such contaminants. Furthermore, they also used the NBR technology for the remediation of diesel-polluted sediments in an in vitro microcosm study where satisfactory results were obtained, and complete mineralization of various components of diesel was achieved. They stated that the NBR technology facilitates the mass transfer of hydrocarbon and subdues the steric hindrance of low molecular weight (LMW) hydrocarbons and alkylated PAHs.

In another study, Osadebe et al. (2022) utilized a nanocomposite comprising green-synthesized iron NPs embellished with biochar composed of cow bone for the degradation of petroleum-contaminated soil. The biochar was obtained by slow reaction pyrolysis at nearly 500 ℃ under meager oxygen, and the NPs were synthesized from pea eggplant (*Solanum torvum*). The composite was applied to soil in microcosm at 10% w/w and 15% w/w amendment, and the study was carried out for 60 days. It was obtained that the TPH removal was noticeably more pronounced in the nanocomposite-amended soil when compared to the control, where no composite was added. It was 28.4% and 26.2% greater in the 10% and 15% composite cases, respectively.

Moreover, heterotrophic bacterial abundance was more significant in the amended soil than in the control soil sample. The metagenomic study revealed the quantity of the Proteobacteria family. Thus, their study ratified that iron oxide NPs decorated with biochar could restore petroleum-contaminated sites by enhancing the natural attenuation process. A few other studies where NBR technology has been utilized for the remediation of hydrocarbon-contaminated sites are listed in Table 3. From the literature survey, it has been observed that detailed study on the stability of the NPs at adverse environmental conditions, determination of active sites in biological species where the NPs can bind efficiently, and the optimization of physical conditions at which the synergy between the natural component and the NPs is optimum are not yet carried out. Thus, future studies in these areas can amplify the efficacy of the NBR processes and pave the

Table 3 List of nanobioremediation (NBR) technology adopted for remediation of hydrocarbon oil-contaminated sites

NPs used	Biological entity	System where applied	Degraded pollutant	Removal efficiency	Reference
Magnetic NPs	*Rhodococcus erythropolis*	Water	Dibenzothiophene	56%	Ansari et al. (2009)
nZVI NPs	*Sphingomonas* sp.	Water	Diphenyl ether	67%	Kim et al. (2012)
PD/nFe NPs	*Sphingomonas wittichii*	Water	2,3,7,8-Tetrachlorodibenzo-p-dioxin	-	Bokare et al. (2012)
Carboxymethyl cellulose (CMC)-stabilized bimetallic (Pd/Fe) NPs	*Sphingomonas* sp. strain NM05	Water	Gamma-hexachlorocyclohexane (γ-HCH)	1.7–2.1 times greater than the individual entity	Singh et al. (2013)
(Pd/Fe) NPs	*Burkholderia xenovorans* LB400	Water	Polychlorinated biphenyl (PCB) Aroclor 1248	-	Le et al. (2015)
Silica NPs	Lipid bilayer of *Pseudomonas aeruginosa*	Water	PAH benzo[a]pyrene	-	Wang et al. (2015)
Graphene oxide NPs	Laccase enzyme-extracted *Trametes versicolor*	Aqueous	Anthracene	-	Patila et al. (2016)
Magnetic NPs	*Alcanivorax borkumensis*	Aqueous	Suggested for efficient hydrocarbon degradation	-	Konnova et al. (2016)
Iron oxide NPs	Biosurfactant, *B. licheniformis*	Aqueous	Crude oil	60% in 7 days, total paraffin degradation	El-Sheshtawy and Ahmed (2017)
ZnO NPs	Yeast consortium YC04		Benzo[ghi]perylene	63.83%	Mandal et al. (2018)
Iron NPs synthesized from mint leaf extract	*Candida tropicalis* NN4	Aqueous	Indeno(1,2,3-cd)pyrene (InP)	90.68%	Ojha et al. (2019)
Iron oxide NPs formed by using corn silk extract	*Alcaligenes faecalis* ADY25	Aqueous	Crude oil	-	Oyewole et al. (2019)
AgNPs	*Bacillus pumilus* (KY010576), *Exiguobacterium aurantiacum* (KY010578), *Lysinibacillus fusiformis* (KY010586), and *Pseudomonas putida* (KX580766)	Soil	Crude oil	70%	Sattar et al. (2022)
Magnetic NPs	*Pseudomonas aeruginosa* NSH3	Sediment microcosm level	PAHs, diesel	Complete mineralization of several components of diesel oil	Nassar et al. (2022)

way towards implementing the technology at a large scale. Additionally, hydrocarbon mass balance and investigation of reaction stoichiometries and microbial population study are equally important to measure a particular remediation process's biodegradation rate and success. Thus, the focus should be given to investigating the mechanism of hydrocarbon degradation by the NBR approach.

Overcoming the limitations of nanoparticle-mediated bioremediation: a challenge

The attractive and unique properties of NPs lead to their extensive application in various fields such as pharmaceuticals, drug delivery, and environmental remediation. In environmental remediation, the small-sized NPs enter deep into the target locations and aid in discharging the sorbed and sequestered hydrophobic substances. Although NPs are gaining importance in day-to-day life, there also exists a threat from NPs. They can enter deep into the cells and reach the organelles, distorting cell membranes and leading to cell death (Hondroulis et al. 2014; Exbrayat et al. 2015). NPs can be inhaled, sorbed through the skin, and ingested with food (Kharisov et al 2014). They also affect reproduction and negatively impact embryonic development (Sun et al. 2013; Yan and Wang 2022). There are also reports on the entry of NPs in the food chain and bio-magnifications when it reaches higher trophic level organisms.

Furthermore, NPs synthesized by various chemical and physical methods can have additional effects on the environment and microorganisms, and the overall manufacturing process is expensive (Ahmed et al. 2016). In recent years, emphasis has been given towards synthesizing green NPs, including biological components that can be used as dispersants and end-capping agents during NP synthesis. Green NPs are synthesized using microorganisms or extracts from different plant parts such as leaves, roots, seeds, flowers, fruit, and stems (Fig. 4). The green materials comprise

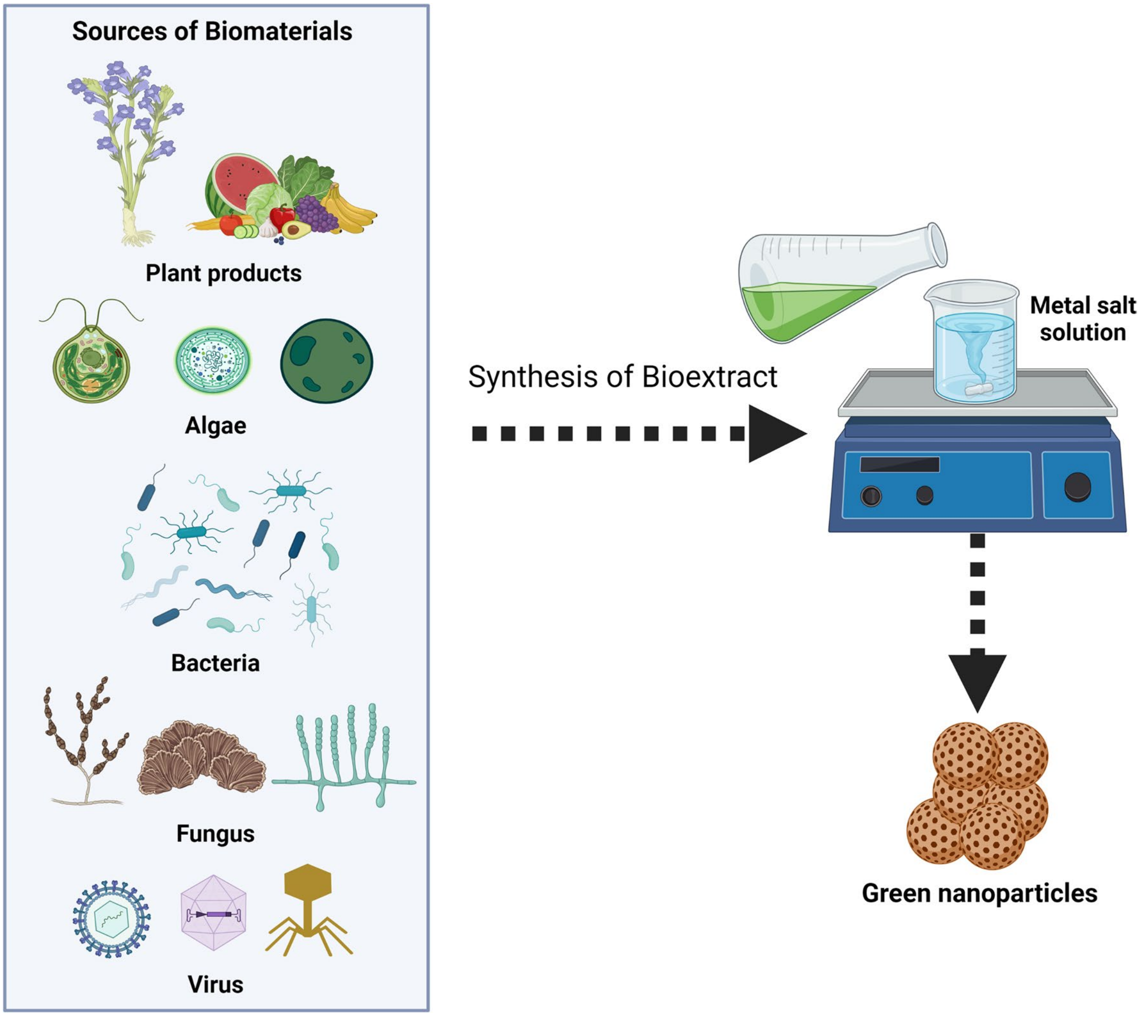


Fig. 4 Schematic representation for the biosynthesis of green nanoparticles

proteins and polyphenols that can act as reducing agents to efficiently reduce metal ions during NP synthesis. In some instances, it has been observed that biological substances work better than their chemical counterparts. Table 4 summarizes the various natural components, including plants, used to synthesize NPs.

Although several methods for synthesizing green NPs have been reported, there arises a gap in the thorough understanding of the synergy of the biological entities and the metal ions, the stability of the physical component, and the effect of various parameters on the synthesis of the green NPs. Furthermore, natural ingredients that are used in the synthesis of particular NPs may be seasonal; just like in some instances, the leaves of flowering plants can only be used for the synthesis of the NPs, or some raw materials can be limited to particular geographical location; thus, in such cases, the raw material collection might be delayed which ultimately constrains the production process of NPs (Ghaemi and Gholamipoor 2017; Sana and Dogiparthi 2018).

The biological components need to be preserved well after collection up to experimentation because they might alter in quality and composition or rot due to microbial actions. Furthermore, in some instances, the raw materials are secondary metabolites of plants. Hence, the extraction,

Table 4 List of biological entities that are utilized for the green synthesis nanoparticles

Organism	Type of the nanoparticle	Size of the nanoparticle (nm)	References
Bacteria			
Escherichia coli	CdS QDs	2–5	Midya et al. (2019)
Lactobacillus johnsonii	TiO_2	40–60	Al-Zahrani et al. (2018)
Pseudomonas deceptionensis	Ag	10–30	Singh et al. (2018)
Actinobacter sp.	Au	50–500	Camas et al. (2018)
Streptomyces capillispiralis Ca-1	Ag	5	Fouda et al. (2020)
Staphylococcus aureus	Ag	5–100	Agnihotri et al. (2014)
Bacillus strain CS 11	Ag	42–92	Das et al. (2014)
Deinococcus radiodurans	Au	43.75	Li et al. (2016)
Pseudomonas putida KT2440	Selenium	70–360	Avendaño et al. (2016)
Fungus			
C. glabrata	Cd	2	Raj et al. (2016)
Aspergillus fumigatus AA001	ZnO	12.6	Srivastava et al. (2016)
Aspergillus japonicus AJP01	Au	5–20	Bhargava et al. (2015)
Macrophomina phaseolina	Ag	16–20	Bhargava et al. (2015)
Algae			
Bifurcaria bifurcate	Copper oxide	5–45	Abboud et al. (2014)
Bifurcaria bifurcate	Au	0.25–30	Venkatesan et al. (2014)
Sargassum plagiophyllum	Ag chloride	18–42	Dhas et al. (2014)
Chlorella pyrenoidosa	Ag	300–700	Aziz et al. (2015)
Cystophora moniliformis	Ag	75	Prasad et al. (2013)
Plants			
Azadirachta indica	Ag	41–60	Kishanji et al. (2017)
Cymbopogon citratus	Au	20–50	Murugan et al. (2015)
Cocos nucifera	Pb	47	Uddin et al. (2020)
Banana	CdS	1.48	Zhou et al. (2014)
Raspberry, strawberry, blackberry	Ag	2–5	Demirbas et al. (2017)
Citrus medica	Cu	20	Shende et al. (2015)
Ginkgo biloba	Cu	15–20	Din et al. (2017)
Red ginseng	Ag	10–30	Sreekanth et al. (2018)
Pinus densiflora	Ag	30–80	Velmurugan et al. (2015)
Carnivorous plants	Ag	5–10	Banasiuk et al. (2020)
Beta vulgaris, *Cinnamomum tamala*, *Cinnamomum verum*, *Brassica oleracea* var. *italica*	Zn	2–20	Pillai et al. (2020)
Origanum vulgare L	Ag	34.4–1.3	Baláž et al. (2017)

separation, and purification of such components can increase the production cost of the NPs (Li et al. 2017). Noteworthy, the properties of the NPs synthesized in a green way should be appropriately investigated so that the applications achieve desirable outcomes. Above all, the production time, high energy consumption, and requirement of additional chemicals in the process are prime factors that should not be overlooked for the feasible production and utilization of green NPs (Guan et al. 2022).

There exists a lack of in-depth knowledge about the function and properties of green NPs. Thus, detailed research in this area can help us understand the mechanism of biosynthesis of the green NPs, ease the separation and purification of the green NPs from the bulk biomass, and also lead the way to improve their quality and overcome the limitations associated with the production of green NPs.

The role of artificial intelligence (AI) in the efficient treatment of hydrocarbon-contaminated sites

Artificial intelligence (AI) is gaining much attention in the present day. It is finding various applications such as pattern recognition, disease diagnosis, image understanding, intelligence search, automatic programming, and human and robotic games, which are influencing human life to a great extent (Fan et al. 2018). AI can be considered a branch of engineering that provides affordable solutions to challenges by implementing novel concepts (Hamet and Tremblay 2017; Baum et al. 2021). Continuous progress in the information technology sector, development of good software, and scale-up of electronic speed might lead to the invention of highly efficient super computers with extremely high speed and proficient accuracy.

AI involves the ability of machines to work intelligently and make a decision in response to inputs without any clear set of external instructions typically provided to standard computers for a particular task. AI systems are designed to use a model that is usually trained before making predictions. Different AI tools that are predominantly used are as follows: artificial neural network (ANN), Monte Carlo simulation (MCS), immune algorithms (IA), boosted regression tree (BRT), and ant colony algorithm (ACA). AI is now also being used to monitor environmental quality and in remediation to obtain accuracy and precision. Modern machine learning methods are aiding in interpreting high-dimensional and nonlinear data in research studies.

There are reports on the involvement of conventional mathematical or statistical models for optimizing different parameters playing a significant role in the microbial biodegradation of petroleum oil hydrocarbons. For example, Bordoloi et al. (2014) have applied response surface modelling (RSM) to optimize various growth conditions for studying the desulfurization of dibenzothiophene (DBT), which is predominantly present in diesel oil by the bacterium *Achromobacter* sp. isolated from petroleum oil-contaminated soil. Similarly, Ramasamy et al. (2017) have employed RSM to optimize various growth conditions for culturing *Enterobacter cloacae* (KU923381) to degrade diesel oil. Although statistical models and conventional mathematical algorithms have been incorporated in hydrocarbon degradation studies, however, only a few studies have employed AI in monitoring and hydrocarbon remediation. Figure 5 depicts the studies and reports on the involvement of AI in the bioremediation

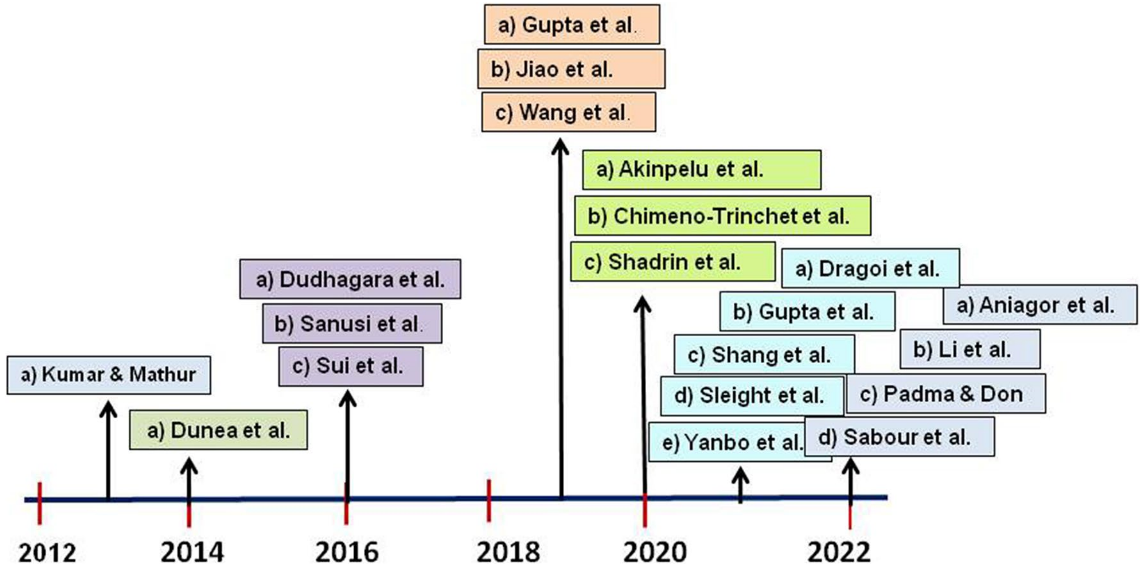


Fig. 5 AI application in hydrocarbon remediation in the last decade (2012–2022)

of hydrocarbon-contaminated sites in chronological order for the last decade.

Kumar and Mathur (2013) utilized an artificial neural network (ANN) in place of BIOPUME III to simulate in situ biodegradation of hydrocarbons. BIOPLUME III is a two-dimensional finite difference model that can simulate hydrocarbon biodegradation in aerobic and anaerobic conditions but is usually a time-consuming process. Thus, a proxy model is necessary for better efficiency. Therefore, their study fabricated the artificial neural network (ANN) using the Levenberg–Marquardt back propagation algorithm. In a study, Dunea et al. (2014) designed a decision support system (eSCAP: soil petroleum contamination assessment prototype) that elicits users to monitor the site and the characteristics of contaminants released from petroleum extraction and transportation processes and chooses the most suitable and feasible remediation technologies based upon database search. The selection of appropriate remediation technology is an essential task for a successful remediation process. The system was applied in several case studies of oil spills due to transportation leakage.

In another study, Dudhagara et al. (2016) utilized two models, a conventional response surface methodology (RSM) and an upgraded artificial intelligence model ANN for enhancing fluoranthene degradation by *Mycobacterium litorale*. The study involved optimizing media components: $CaCl_2$, KH_2PO_4, and NH_4NO_3. The designed ANN model maximized fluoranthene degradation through input neuron network topology. The neurons in the hidden layer were recognized by training several ANN topologies and then choosing the optimal one based on minimizing the root mean square error (RSME) and mean absolute percentage error (MAPE). It was obtained that the ANN model could efficiently simulate the degradation process of fluoranthene, and the values obtained in ANN were more reliable, precise, and reproducible because ANN is assigned with nonlinear polynomials of the system whereas RSM models rely on quadratic equations merely. They obtained a better degradation of 51.28% on the 3rd day compared to an un-optimized degradation method in which only 26.37% degradation was achieved after 7 days.

Sanusi et al. (2016) conducted a comparative study to optimize total petroleum hydrocarbon (TPH) degradation in diesel-contaminated soil *by Paspalum scrobiculatum*, a tropical plant, by using RSM and ANN. An optimum condition was attained at a diesel concentration of 3%, 72 sampling days, and 1.77-mL/min aeration in the case of RSM, which led to 76.8% TPH removal, whereas, in the case of ANN, the predicted optimum condition was at a diesel concentration of 3%, 72 sampling days, and 1.02-mL/min aeration, in which 85.5% TPH was removed. Thus, it was affirmed that the ANN was better than the conventional RSM model in estimation and data fitting. AI can also efficiently assist in monitoring the site of environmental contamination. The same group of researchers studied the adsorption and diffusion of 16 PAHs (polyaromatic hydrocarbons) in silica nanopores by considering adsorption energy, free surface area, mean square displacement, and volume fraction incorporating molecular dynamic simulation (Sui et al. 2016). An interpretation was drawn that the sorption of PAHs in silica nanopores was due to diffusion. They performed linear and nonlinear regression using the partial least square (PLS) method and machine languages, namely support vector regression (SVR), M5 decision tree (M5P), and multilayer perceptrons (MLP), to procure information about the influence of various factors on the adsorption. They interpreted that the combined approach, including molecular dynamics (MD) and machine languages, can aid in deciphering the sequestration of organic contaminants in the soil particles.

Jiao et al. (2019) also designed a novel method for automatically detecting oil spills which are usually not easily detectable. In the approach, they involved three units: UAVs (crewless aerial vehicles), deep learning, and traditional algorithms, which perform the task of oil spill detection. The job is divided into three sub-tasks, and the three units work independently to complete the task. Firstly, a model based on a deep convolutional neural network was constructed, which detects the oil spill as images and assures no exclusions. Secondly, an Otsu algorithm was utilized to increase the detection task's precision to eradicate other errors or noise in the seen images. Lastly, a maximally stable extremal region algorithm (MSERA) was used to procure the polygon from the detection box. They found that their method could successfully detect oil spill regions and also aided in the reduction of cost for oil spill detection by 57.2% compared to traditional detection methods.

Wang et al. (2019) utilized an AI system termed an integrated extended short-term memory network (LSTM) that uses cross-correlation and association rules (Apriori) for the identification of point sources of pollutants and trace industrial contaminants in water bodies. They developed water quality cross-correlation maps that helped them track contaminants' point sources. In another study, Shadrin et al. (2020) used various machine learning models, namely ANN (artificial neural networks) and support vector machine (SVM), to predict the phytotoxicity of TPH. They studied eleven soil samples collected from Sakhalin islands in greenhouse conditions. They obtained satisfactory results in predicting the phototoxicity effects of TPHs. The models can also help analyse the soil properties, which is usually time-consuming and laborious. In 2021, Dragoi and colleagues utilized a neuro-evolutive methodology involving ANN (artificial neural network) and DE (differential evolution) to predict TPH and OC (organic carbon), which are two main factors of oily sludge composting that determine the efficiency of the oil removal process. Experimental data were used to validate the findings of the ANN model, and it was obtained that the proposed model provides information comparable to the observed values.

AI can be extensively applied to interpret the rheological properties affecting petroleum's transportability and refining. Very recently, Stratiev et al. (2023) utilized an ANN-based model to predict the viscosity of crude oil. Thus, from the above discussion, it can be affirmed that AI can be widely used to determine oil pollution sites and enhance the accuracy of a particular remediation process, thereby making it more efficient. Therefore, the blend of the artificial brains, i.e. the machine learning algorithms with the conventional remediation technology, makes the restoration process better, more precise, faster, and more cost-effective. It can be observed that the trend of AI-based remediation studies has been tremendously escalating in recent years (Fig. 5). Again, advanced bio-informatics tools can be utilized to study the decomposition patterns of the hydrocarbon compounds and elucidation of the catabolic pathway adopted by the microorganisms for degradation of hydrocarbons in a contaminated environment. In the future, a database can be developed that would be destined to contain detailed information on different crude oil-contaminated sites, which shall provide insight to researchers and environmentalists about a particular contaminated area. Therefore, it may be well anticipated that the research studies on AI-based bioremediation shall find enormous importance in solving environmental issues.

Future perspective and conclusion

Crude oil contamination is a central concern of global environmental pollution that adversely affects the environment and life forms. Although bioremediation has been widely adopted as a clean and cost-effective treatment method, it has several drawbacks that must be tackled for better outcomes and efficiency. The emergence of nanotechnology as a research study and its various advantages has led to its copious application in vivid fields such as drug delivery, agriculture, optics, space industries, and environmental remediation of toxic pollutants. NPs are extensively studied and applied to remediate contaminated sites and restore the environment. The high surface area and attractive sorption capacity of NPs allow proper sequestration of hydrophobic pollutants from matrix solution; as a result, the contaminants become available to the microbes for their efficient biodegradation. The conglomerate of nanotechnology and bioremediation technology, or the NBR process, is expected to enhance the efficiency of the overall degradation process and nullify the drawbacks of the mere bioremediation process. The NBR technologies, where NPs are entangled with biological entities for remediation of the pollutant of interest, are gaining much attention due to their higher efficiency and environmentally friendly nature. Although there are studies on the combined approach of microbes and NPs, lacunae exist in the in-depth understanding of the mechanism of synergy between the NPs and the biological entities in NBR processes. Thus, a better understanding of the relationship between NPs and biological entities used in a particular NBR process and recognition of the factors that impact their synergistic relation shall help us enhance the process's efficiency. Currently, scanty research studies have been carried out on NBR of oil spill contamination where promising results have been obtained. In the coming future, more studies of NBR on oil spill remediation should be carried out to optimize and upgrade for practical and field-scale applicability.

Furthermore, the long-term impact of NPs on the environment must be clarified to avoid additional risks. Additionally, the focus should be on using green or bio-NPs rather than chemical or metallic NPs to make the overall process sustainable and eco-friendly. Thus, future research should search for suitable, cost-effective biological raw materials that can be used for NP synthesis and determine various ways to modify the NPs to enhance their efficiency for better outcomes. Developing biocompatible nanomembranes for the adsorption of oil pollutants can effectively treat crude oil-polluted water bodies. It can provide a solution to the increasing problem of water scarcity. Furthermore, the cost-effective manufacturing of the NPs should be emphasized so that the process becomes economically feasible for large-scale applications to restore contaminated sites.

The integration of AI with NBR is of utmost essential for more efficient bioremediation to be achieved. The high accuracy, precision, and ease of detection of pollutants, provided by AI algorithms and software, upgrade the efficiency and reduce the time a remediation process takes. The AI algorithms have extensive features that overcome the disadvantages of conventional mathematical models. There are very few studies on understanding the role of AI in remediation processes; hence, future studies and field trials on the involvement of AI in the monitoring of contaminated sites and remediation of contaminated sites are necessary to furnish our knowledge on the understanding of the role of AI in remediation processes. The focus should be on developing highly efficient algorithms, and their involvement in remediation studies should be carried out to achieve better outcomes. Additionally, creating a database that shall record all sorts of vital information about the oil fields of a particular region can aid researchers in planning and executing their work smoothly.

Furthermore, microbial enzymes also play a significant role in the biodegradation of contaminants in the environment. A depth study should be carried out on the microbial enzymes that catalyse a particular remediation process and search for techniques to modify them by involving NPs to enhance their efficiency. Enzymes are usually very unstable and have a short life as they lose their activity due to oxidation. Immobilizing hydrocarbon-degrading enzymes with NPs might increase the stability and longevity of enzymes, thereby making them a suitable candidate for remediation technology. Besides, the intervention of biotechnological tools with the NBR technology for removing toxic components from the environment should be studied to improve the remediation process. The involvement of marker genes to track the expression of a concerned gene can furnish additional knowledge and throw light on the genetic profile of microbes that shall contribute towards the up-gradation of the remediation process.

Furthermore, the fate of the hydrocarbon bioremediation process should be studied in detail by investigating growth kinetics, a study of the expression of specific genes and enzyme profiling, which would help us understand the metabolism of the microorganisms for mediating degradation of the hydrocarbon and also provide information on the extent of degradation. DNA-stable isotope probing (DNA-SIP) is an advanced and effective technique that aids in identifying the active microorganisms that utilize particular carbon sources for their metabolism. The mass balance and stoichiometry of the hydrocarbon contaminants subjected to bioremediation are also equally important to understand the compounds' conversion and estimate the remediation process's effectiveness.

Genetically engineered plants can also be developed to increase efficiency in stabilizing or degrading particular contaminants of interest. Indeed, the ethical issues that might arise due to the use of genetically modified microorganisms or plants in a specific site should be considered prior hand before their implementation. Again, intertwining environmental biotechnology and other remediation technologies, such as chemical or physical approaches, can lead to better outcomes.

Thus, in the coming days, a thorough study of NBR processes, their optimization, and the scale-up of the process by associating advanced AI and modern biotechnological approaches along with the incorporation of enzyme technology and genetic recombination shall provide sustainable solutions to combat environmental challenges.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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