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Phytoremediation of Petroleum Hydrocarbons: An Update of Its Recent Progress

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ABSTRACT: Phytoremediation continues to play an important role in the remediation of soils contaminated with hydrocarbons, as demonstrated by the ongoing influx of research articles in this field. A review of the recent literature reveals that studies on phytoremediation continue to assess the effectiveness of both existing and new plant species, particularly in treating contaminated soils. Fertilization and soil amendments are commonly incorporated into these studies. There is significant interest in microbial-assisted phytoremediation and the optimization of phytoremediation with surfactants and root exudates. Phytoremediation using plants alone often encounters limited efficiency (<65% petroleum hydrocarbon removal). However, fertilization, soil amendments, and additives like root exudates can boost efficiency to slightly above 80%, particularly with compost. Microbial-assisted phytoremediation could further increase efficiency to more than 90%, depending on the microorganisms used. Endomycorrhizal fungi and *Acinetobacter sp.* Tust-DM21 appear to have pronounced enhancing effects on petroleum hydrocarbon removal. Combining and optimizing good agricultural practices, fertilization, soil amendments, additives, and microbial-assisted phytoremediation could enhance overall efficiency while improving plant growth, even in saline or highly contaminated soils. Research on phytoremediation of water contaminated with petroleum hydrocarbons is significantly less prevalent. This review contributes to the identification of effective phytoremediation strategies and suggests that future research could focus on further exploring plant-microbe interactions to improve petroleum hydrocarbon removal. Artificial intelligence could also be incorporated to optimize factors that positively influence phytoremediation.

KEYWORDS: Bioaugmentation; fertilizer; microorganisms; phytoremediation; optimization; soil amendment

1. Introduction

Oil is a valuable resource on a global scale, contributing to significant economic growth and intense competition among nations. Its energy is essential for both domestic and industrial purposes, such as heating, transportation, and manufacturing [1]. The export revenue from crude oil greatly contributes to GDP growth while also driving industrial development, especially in the petrochemical industries [2]. In pursuit of these advantages, a sequence of activities comprising exploration, extraction, processing, and transportation is carried out, resulting in environmental pollution, which has raised global concern [3,4]. Crude oil is a complex mixture of hydrocarbons in various forms, such as linear, branched, cyclic, and aromatic compounds. Some hydrocarbons, such as asphaltenes and resins, contain nonhydrocarbon components, particularly nitrogen, sulfur, and oxygen [5].

This review focuses on pollution from total petroleum hydrocarbons (TPHs), which include crude oil, creosote, diesel, gasoline, and other petroleum distillates. TPHs can contaminate soil through various means, such as leaks from underground storage tanks, oil spills, installation of petrochemical refining facilities, transportation, and improper disposal of petroleum-containing waste [6]. TPH accumulation negatively impacts the health of organisms and the environment, causing soil degradation, water pollution, inhibition of plant growth, and retardation of seed germination. Additionally, TPH components contaminate drinking water and contribute to health concerns due to their toxic effects [7]. TPHs in soil and water can enter the food chain, leading to the contamination of hydrocarbon contaminants in food. TPHs, particularly lighter ones, can volatilize and enter the air, thereby increasing the risks of human exposure through inhalation [8]. Exposure to TPHs has been linked to numerous health complications, including respiratory irritation, dizziness, headaches, skin and eye irritation, liver and kidney damage, as well as reproductive and developmental effects. This underscores the need for their removal from the environment [8].

Various methods for treating oil-contaminated soils have been implemented, including physical, chemical, thermal, electrical, and biological approaches [9]. However, physical and chemical remediation methods are costly, can lead to secondary soil contamination, and contribute to greenhouse gas emissions [10]. As a result, there is a need for efficient, environmentally friendly, and cost-effective methods to minimize the harmful effects of crude oil. Biological approaches have been identified as the most cost-effective and sustainable strategies, being safe and financially feasible [11,12]. Phytoremediation is a biological method that uses plants to remove environmental contaminants. It has gained significant attention due to its low cost, technological simplicity, and flexibility, as it can be combined with soil amendments and other biological approaches for enhanced effectiveness [13]. Most studies on phytoremediation focus on heavy metals [14,15]. However, phytoremediation has been shown to be effective against a wide range of organic contaminants, including TPHs.

There has been a steady influx of reviews on phytoremediation. Nonetheless, recent reviews predominantly focus on heavy metals. Shen et al. reviewed the efficiency and limitations of heavy metal phytoremediation and highlighted the lack of cost-effective methods for disposing of contaminated biomass used in the process [14]. Kafle et al. provided an overview of plant species suitable for phytoremediation and examined various mechanisms and amendments that can improve its effectiveness, as well as the advantages and disadvantages of this approach. However, their review does not address advances in treating petroleum hydrocarbons [16]. Liu and Tran outlined methods for disposing of and utilizing plants used in the phytoremediation of heavy metals, including compression landfill, extraction, heat treatment, and reutilization as nanomaterials. Their review does not cover the phytoremediation of petroleum hydrocarbons [17]. Additionally, Bhat et al. summarized various phytoremediation methods and biotechnological strategies aimed at eliminating heavy metal pollutants but did not extend their review to petroleum hydrocarbons [18]. Matheson et al. provided an updated review of indoor active and passive phytoremediation, focusing on the chemical removal effectiveness of different indoor systems, particularly for volatile organic compounds and nitrogen dioxide [19].

Despite the lack of reviews on the latest advances in the phytoremediation of petroleum hydrocarbons, research in this area has been ongoing. Steliga and Kluk explored the use of *Festuca arundinacea* to treat soils contaminated with petroleum hydrocarbons [20]. Rafique et al. employed beneficial bacteria with enzymes capable of breaking down an ethene precursor, which is tolerant to petroleum hydrocarbons, in combination with alfalfa to remediate soil contaminated with petroleum hydrocarbons [21]. Ekperusi et al. examined the potential of duckweed (*Lemna paucicostata*) to clean pollutants from water, focusing on its ability to remove petroleum hydrocarbons from water polluted with crude oil using a constructed wetland system over 120 days [22]. Nero et al. studied how *Jatropha curcas* and *Vetiveria zizanoides* affected the concentrations of hydrocarbons in mine spoils, with and without compost amendments [23]. Recent research on phytoremediation continues to explore the effectiveness of individual plant species or the use of other remediation strategies in conjunction with phytoremediation to remove petroleum hydrocarbons from soil or water. In addition to conventional plants, new plant species have been tested for their effectiveness in treating petroleum hydrocarbons. This mini-review aims to capture the latest developments in phytoremediation, both as a standalone method and in combination with other remediation strategies, for treating soil and water contaminated with petroleum hydrocarbons. It contributes to the identification and selection of new phytoremediation strategies that are effective in removing petroleum hydrocarbons from the environment and highlights the research trends and future directions in this field.

2. Methods

This mini-review examined more than 50 relevant scholarly papers to systematically present the latest updates in the phytoremediation of petroleum hydrocarbons. Online scholarly databases comprising Scopus, Web of Science, and ScienceDirect were used for the literature search [15]. Keywords comprising petroleum, hydrocarbons, phytoremediation, plant, and remediation were entered into the databases separately or in combination, yielding key terms such as phytoremediation hydrocarbon, plant remediation petroleum hydrocarbons, and phytoremediation petroleum. The articles retrieved were screened based on the inclusion criteria below:

1. They explicitly explore the effectiveness of phytoremediation in removing petroleum hydrocarbons from soil or water using individual plant species, with or without soil amendments. Soil amendments may include fertilization and compost addition.
2. They examine the effectiveness of phytoremediation in removing petroleum hydrocarbons from soil or water using plant and other remediation strategies.
3. They must have been published in the past 5 years.
4. They must focus on or include petroleum hydrocarbons.

3. Discussion

Recent literature on phytoremediation trends toward the use of previously identified or newly discovered plant species, alongside the optimization of soil conditions to enhance phytoremediation efficiency. Such optimization includes fertilization and soil amendments, such as the addition of biochar or compost. There is also growing interest in comparing the phytoremediation efficiencies of different plant varieties (Table 1). Additionally, combining phytoremediation with other remediation techniques, particularly microbial remediation, to improve the removal efficiency of petroleum hydrocarbons has received significant attention. These studies increasingly focus on alterations in the rhizosphere microbial composition and enzyme activities (Table 1). Therefore, this review is divided into two main sections: the first details phytoremediation with individual plant species or their varieties, while the second illustrates the co-application of phytoremediation with other remediation strategies. Soil amendments, which are an approach to optimize phytoremediation with individual plants, are discussed in the former section.

Table 1. Research articles on phytoremediation retrieved (2020-2024) after screening.

Year	Single-plant phytoremediation	Microbial-assisted phytoremediation*	Phytoremediation with soil amendments*
2024	2	4	2
2023	3	5	3
2022	3	5	4
2021	4	5	3
2020	2	6	4
Total	14	25	16

*It is possible for studies to combine microbial-assisted phytoremediation with soil amendments. When both components are present, the classification is based on the predominant component.

3.1. Phytoremediation with or without soil amendments or fertilization

Phytoremediation studies have traditionally employed single plant species or mixtures of species, with or without soil amendments or fertilization. One study examined the effectiveness of phytoremediation using fertilized pots of tall fescue (*Festuca arundinacea*) grown in soils contaminated with TPHs [20]. After 6 months, TPHs were reduced by 49.4-60.1%. The primary biodegradation of TPHs was attributed to basic bioremediation aided by optimal fertilization. Fertilization alone reduced TPHs by 35.8–43.3%, with lighter hydrocarbons (C12-C18) being more readily removed than heavier ones (C25-C36) (Figure 1). Lighter hydrocarbons are more biodegradable, while longer-chain hydrocarbons are more hydrophobic and less bioavailable [20]. Bacteria readily metabolize alkanes with chain lengths between C10–C22. Phytoremediation further enhanced this process by 17.4–23.1%. The greatest reduction, ranging from 45.6–55.5%, was observed for C12-C18 hydrocarbons, while the lowest reduction, at 9.1–17.4%, was for C25-C36. The translocation factor values were generally less than 1 [20]. Another study focused on optimizing moisture content, fertilizer content, and soil additives, achieving a 28.6% TPH degradation rate after 70 days (Figure 1) [24]. Additionally, peanut was identified as the best candidate among 20 plant species tested for phytoremediation, achieving a 31.1% degradation rate after 70 days. This was accompanied by an increase in soil bacterial count, with the plant demonstrating good germination and growth. When soil conditions were optimized, phytoremediation led to the removal of 38.9% TPHs over the same period [24].

Physic nut (*Jatropha curcas*) and vetiver grass (*Vetiveria zizanioides*) are popular candidates for phytoremediation [25-27]. Both plant species were used to treat hydrocarbons in mine spoils [23]. After 16 weeks, with the addition of compost, *J. curcas* led to a reduction of 78.8% in soil TPHs and 82.2% in total oil and grease (TOG) concentrations. In contrast, *V. zizanioides* resulted in a decline of 51.1% in TPHs and 39.7% in TOG concentrations. The addition of compost significantly lowered TOG and TPH concentrations compared to other treatments involving *J. curcas* and *V. zizanioides* without soil amendments [23]. However, both plant species did not show significant differences in their ability to remove TPHs and TOG when used alone. *J. curcas* exhibited more growth in collar diameter, height, and leaf number with compost addition compared to fertilization and control treatments, suggesting that compost addition could compensate for the negative effects of petroleum contamination on these parameters [23]. This finding is also supported by Steliga and Kluk, who demonstrated that adding biogenic substances could enhance TPH removal during phytoremediation [20].

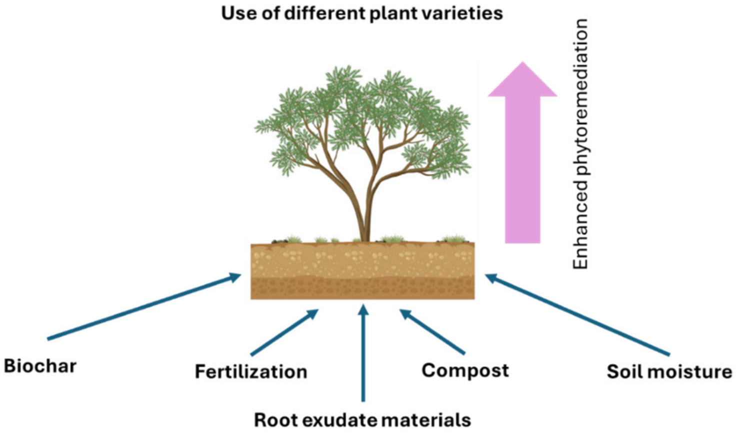

Figure 1. Phytoremediation can be enhanced with soil amendments and moisture control, and the use of different varieties of a particular plant.

A study examined the effectiveness of camelthorn (*Alhagi camelorum*) in removing TPHs from oil-contaminated soil [28]. While less commonly used for petroleum hydrocarbon remediation, earlier studies have explored its potential for remediating soil contaminated with metals [25,29]. The study found that after six months, the plant removed an average of 53.6% of TPHs, along with varying percentages of heavy metals (Cd: 45.4%, Cr: 47.6%, Ni: 48.1%, and Pb: 50%). The presence of the plant also increased the abundance of heterotrophic bacteria and microbial respiration in the soil, indicating that it may enhance soil microorganism growth. Furthermore, the pollutant removal rates followed first-order kinetics for all pollutants examined [28]. In a separate study, sweet sorghum (*Sorghum bicolor*) was tested for its ability to treat saline soils contaminated with petroleum and to identify high-performing varieties for this purpose [30]. The study evaluated the biomass, germination rate, and plant height of different sorghum varieties in polluted soil and their efficiency in removing petroleum hydrocarbons. The findings revealed that 24 of 28 sorghum varieties could germinate even in soil with 0.31% salinity and contaminated with 1.0×10^4 mg/kg of petroleum. After 40 days of treatment, the varieties Zhong Ketian No. 438, Ke Tian No. 24, Ke Tian No. 21 (KT21), and Ke Tian No. 6 were identified as the most tolerant, reaching a height of over 40 cm and a dry weight of more than 4 g. All four varieties significantly reduced petroleum hydrocarbons, with KT21 showing the greatest reduction (up to 56.5% for soil contaminated with 1.0×10^4 mg/kg of petroleum). This study highlights that different plant varieties have varying abilities to remove petroleum hydrocarbons (Figure 1).

Further to the above study, an evaluation was conducted to assess the efficacy of 10 varieties of tall fescue (*Festuca arundinacea*) in removing soil TPHs and examine the microbiomes in their root zones [31]. The study revealed that TPH removal efficiency did not significantly correlate with plant biomass. Among the varieties, Rhizing Star and Greenbrooks exhibited the highest (76.6%) and lowest (62.2%) TPH removal efficiencies, respectively, over a 120-day phytoremediation period. These findings confirm the differential phytoremediation abilities of different plant varieties. Differences in bacterial and fungal compositions in the root zone were observed between these two varieties, particularly in the early stages (day 30) of phytoremediation, although these distinctions diminished by day 90. Moreover, an increase in potential petroleum-degrading bacterial and fungal groups was noted in the presence of tall fescue. Treatments with higher TPH removal efficiency appeared to lower microbial network complexity. The tall fescue treatments, especially with the Rhizing Star variety, resulted in an increase in saprotrophic fungal populations and the levels of bacterial alkB and C120 genes involved in petroleum degradation, consistent with the observed efficiencies in removing TPHs [31]. This also aligns with the observations of Nemati et al., who noted that phytoremediation plants could enhance the population of certain soil microorganisms [28].

In another study, three soil types (sandy, loamy, and clayey) were tested along with three root exudates (citric acid, glycine, and maltose) using Sudan grass (*Sorghum sudanense*), perennial ryegrass (*Lolium perenne*), and tall fescue (*Festuca arundinacea*) as the phytoremediation plants [32]. The plants performed best in sandy soil compared to loamy and clayey soils. All plant species significantly removed TPHs, particularly from sandy soil, with removal rates of 45.23% to 60.52%, followed by loamy and clayey soils. Among the two root exudates tested, maltose (2,000 mg/L) was more effective in TPH removal than glycine (2,000 mg/L). Substituting glycine with maltose increased TPH removal rates for *Festuca arundinacea* (12.61%), *Lolium perenne* (14.47%), and *Sorghum sudanense* (19.26%) in sandy soil. Similar trends were observed in loamy soil [32]. This study suggests that soil type influences phytoremediation efficiency, likely due to interactions between soil particles and pollutants. Clayey soil may adsorb hydrocarbons more strongly, making them less bioavailable to plants and thus slowing down phytoremediation. Additionally, root growth is likely more restricted in clayey soil due to its low permeability, which reduces the plants' interaction with hydrocarbons [33]. Understanding how different soil types affect phytoremediation can help design more effective, tailored strategies. For example, in clayey soils, chelating agents could be added to enhance contaminant bioavailability. Ruley et al. analyzed the rhizobacteria found in phytoremediation plants grown in soils contaminated with hydrocarbons and treated with cattle manure [35]. The treatment involving plant species, 75 g kg^{-1} of soil hydrocarbons, and 5 g kg^{-1} of cattle manure resulted in a notable increase in rhizobacteria abundance. Thatching grass (Hyparrhenia rufa) had the highest amplicon sequence variant (4980), while Sudan grass (*Sorghum arundinaceum*) had the lowest (3955). Furthermore, the root zone of *H. rufa* had the highest bacterial diversity (Chao1 index = 10310), while *S. arundinaceum* had the lowest (Chao1 index = 8260). The main bacterial phyla identified were Proteobacteria, Firmicutes, and Actinobacteria [35]. These findings align with those of Steliga and Kluk and Li et al., who suggested that fertilization enhances phytoremediation by stimulating soil and rhizosphere microbial activities, contributing to petroleum hydrocarbon degradation (Figure 1) [20,24].

A study examined how soil amendments, specifically biochar and compost, affected phytoremediation plants from the Poaceae and Fabaceae families [36]. The plants tested included alfalfa (*Medicago sativa*), maize (Zea mays), ryegrass (*Lolium multiflorum*), wheat (*Triticum aestivum*), and white clover (*Trifolium repens*). The presence of 4% TPHs in the soil negatively impacted the physiological parameters (fresh and dry biomass, chlorophyll content, and root and shoot lengths) and microbial parameters (root and shoot endophytic counts) of the plants and soil [36]. The study found that when biochar was applied to soil planted with wheat, maize, and ryegrass (Fabaceae family), and when compost was used to amend soil planted with white clover and alfalfa (Poaceae family), plant growth and TPH removal were enhanced. Notably, ryegrass with compost showed the highest TPH removal rate at 68.5%, while white clover with biochar achieved a rate of 68%. In the absence of soil amendments, ryegrass and alfalfa achieved TPH degradation rates of 59.55% and 35.21%, respectively. Furthermore, using biochar and compost alone resulted in the removal of 27.24% and 6.01% of TPHs, respectively [36]. These findings align with Nero's research, which showed that compost addition substantially improves phytoremediation performance [23]. This study highlights that soil amendments tailored to plant species could optimize phytoremediation.

Root exudates play a crucial role in phytoremediation by influencing the interactions between plants, soil, and microorganisms. Root exudates include sugars, amino acids, organic acids, phenolic compounds, and various enzymes that can enhance phytoremediation effectiveness [37]. Experiments have been conducted to understand how glycine, a root exudate, affects phytoremediation in different soil types contaminated with petroleum hydrocarbons (Figure 1) [38]. The findings revealed that, at constant petroleum hydrocarbon concentrations, ryegrass exhibited the highest germination rate, followed by Sudan grass, white clover, tall fescue, alfalfa, Pennisetum, canine root, and maize grass. Additionally, a glycine concentration of 1000 mg/l significantly raised plant biomass and enhanced petroleum hydrocarbon degradation. The most significant degradation was observed in ryegrass with glycine, followed by ryegrass without glycine, Sudan grass with glycine, and Sudan grass alone. In loamy soil, all plants exhibited the greatest biomass and height, while petroleum hydrocarbons degraded most significantly (50.36% to 59.36%) in sandy soil. Notably, when 1000 mg/l of glycine was added to ryegrass in sandy soil, 59.35% of petroleum hydrocarbons were degraded [38]. Table 2 summarizes the soil TPH removal efficiencies of the various plant species reviewed.

Table 2. Plants used in soil TPH removal and their efficiencies.

Plant Species	Soil Amendment	Treatment Duration	TPH Removal Efficiency	Reference
Tall fescue (*Festuca arundinacea*)	Fertilization	6 months	49.4-60.1%	[20]
Peanut	Optimization of moisture content, fertilizer content, and soil additive content	70 days	38.9%	[24]
Physic nut (*Jatropha curcas*)	Compost	16 weeks	78.8%	[23]
Vetiver grass (*Vetiveria zizanioides*)	Compost	16 weeks	51.1%	[23]
Camelthorn (*Alhagi camelorum*)	None	6 months	53.6%	[28]
Sweet sorghum (*Sorghum bicolor*), Ke Tian No. 21 Variety	None	40 days	56.5%	[30]
Tall fescue, Rhizing Star Variety	None	120 days	76.6%	[31]
Perennial ryegrass (*Lolium perenne*)	Maltose (root exudate)	40 days	60.52% (sandy soil)	[32]
Sudan grass (*Sorghum Sudanese*)	Maltose (root exudate)	40 days	53.94% (sandy soil)	[32]
Tall fescue	Maltose (root exudate)	40 days	57.08% (sandy soil)	[32]
Ryegrass	Compost	62 days	68.5%	[36]
White clover	Biochar	62 days	68%	[36]
Ryegrass	Glycine	71 days	59.35% (sandy soil)	[38]

Compared to studies on soil phytoremediation, those on phytoremediation of water bodies to remove petroleum hydrocarbons are significantly fewer. Duckweed (*Lemna paucicostata*) has been observed to accumulate less than 1% and biodegraded 97.74% of hydrocarbons in wetlands at the end of a study aiming to investigate their ability to remove pollutants from an aquatic environment over 120 days [22]. The phytoremediation data aligned well with the first-order kinetic rate model. The study revealed the effectiveness of *Lemna paucicostata* in treating waters moderately contaminated with petroleum hydrocarbons [22]. The potential of water velvet (*Azolla pinnata*) to restore freshwater contaminated with petroleum has been evaluated by measuring the degradation percentage of TPHs and examining alterations in the composition of saturated and aromatic hydrocarbons [39]. The findings suggest that *A. pinnata* could remediate freshwater containing up to 0.5 g/l of TPHs. After seven days, the planted treatment demonstrated a 92% degradation rate of TPHs, in contrast to the unplanted control, which achieved only a 38% degradation rate [39]. M-Ridha et al. conducted a study on a constructed wetland utilizing barley to treat kerosene, representing TPHs, at different concentrations (1%, 2%, and 3% v/v) in a subsurface flow system. After a 42-day exposure period, they observed an average kerosene removal efficiency ranging between 56.5% and 61.2%, with the most effective removal occurring at the 1% v/v concentration. The researchers also examined the kinetics of kerosene breakdown at various initial concentrations, determining that the Grau model (assuming a linear relationship between the substrate removal rate and the substrate concentration) offered a closer fit [40].

In summary, studies on phytoremediation using individual plant species have continued to identify the abilities of existing or new plant species in removing petroleum hydrocarbons, primarily from soil, with the varieties of certain plant species compared. Fertilization and soil amendments are often required to boost phytoremediation efficiencies. Studies have shown the addition of compost to aid phytoremediation substantially, and biochar is another potential additive that could enhance phytoremediation. Matching soil amendments with plant species seems crucial to optimizing phytoremediation. The influence of soil properties on phytoremediation efficiency is also garnering attention, along with the stimulating effects of root exudates. While phytoremediation is generally time-intensive, the use of fast-growing plants or variants, hyperaccumulators, soil amendments, irrigation, and fertilization can potentially shorten the remediation time. The application of microbial associations, such as introducing mycorrhizal fungi and plant growth-promoting bacteria, could further improve the efficiency of phytoremediation. This is detailed in the subsequent section.

3.2. Phytoremediation in combination with other remediation strategies

The potential for synergistic interactions between plants and microorganisms has broadened the scope of alternative bioremediation techniques [41]. Recent studies have increasingly focused on the co-application of phytoremediation and microbial remediation. Italian multifloral millet (*Oloptum miliaceum*) and fountain grass (*Pennisetum setaceum*) are promising candidates for phytoremediation due to their extensive root systems, substantial leaf biomass, rapid renewal capacity, and ability to host endophytes in their roots [42]. After 240 days, plants in contaminated soil inoculated with an endomycorrhizal consortium (*Glomus versiforme*, *Funneliformis mosseae*, *Rhizophagus intraradicens*, and *Rhizophagus irregularis*) achieved a 94% TPH removal rate, while plants in contaminated soil without the consortium achieved 78% removal. The consortium was found to enhance overall biomass, improve redox biology, influence stress markers, and affect photosynthetic efficiency and soil dehydrogenase activity. The TPHs removed in the presence of the microbial consortium were primarily aliphatic hydrocarbons (C13–C36) [42]. This suggests that enriching the soil with endomycorrhizal fungi could significantly enhance phytoremediation.

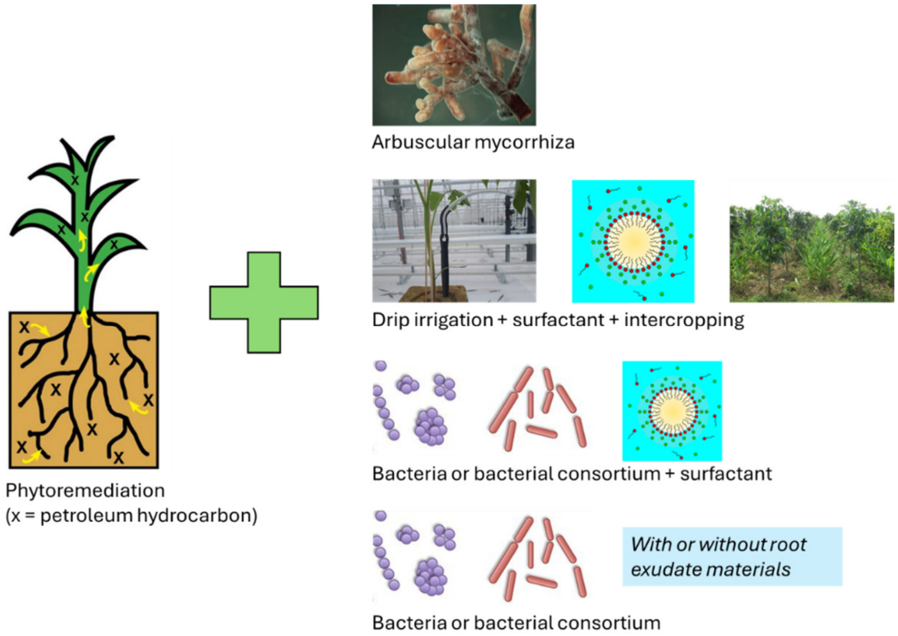

Figure 2. Phytoremediation is applied together with bioremediation, particularly by adding arbuscular mycorrhiza and bacteria or bacterial consortia, as well as good agricultural practices such as controlled irrigation and intercropping with surfactant or root exudate materials added.

Similarly, Wu et al. investigated the synergistic effect of common reeds (*Phragmites australis*) and arbuscular mycorrhizal fungi in remediating petroleum-contaminated soils under different flooding conditions [43]. They found that arbuscular mycorrhizal inoculation boosted the growth of *P. australis* above ground in non-flooded soils, while flooding led to a significant increase in the plant's biomass. The most effective removal of TPHs occurred in non-flooded soils. Flooding, however, notably hindered the dissipation of TPHs, suggesting that waterlogged conditions may reduce phytoremediation efficiency, likely by limiting root oxygen supply and plant uptake of contaminants [43]. Understanding how flooding conditions impact phytoremediation can aid in selecting plants that thrive under specific conditions, facilitating the formulation of effective, site-specific cleanup strategies. Moreover, plants inoculated with arbuscular mycorrhizal fungi showed improved TPH removal in flooded soils, with a positive correlation between TPH removal and dehydrogenase activity, while glomalin-related soil proteins were negatively correlated with TPH removal [43]. These findings highlight the potential of endomycorrhizal fungi to not only enhance phytoremediation but also confer stress tolerance to plants, possibly through increased root exudation and enhanced microbial activity in the rhizosphere.

Li et al. explored the effects of mixed surfactants on plant remediation capacity in two soil types under drip irrigation with varying alkalinity, salinity, and petroleum contamination levels [44]. This research supports the growing recognition of how agricultural practices and soil properties influence phytoremediation efficiency. The study found that drip irrigation promoted lateral movement of salts and alkali in the soil, enhancing localized plant growth. In loamy soil, intercropping ryegrass (*Lolium perenne*) with cotton (*Gossypium* sp.) increased total biomass by 35.6%, surpassing ryegrass grown alone [44]. Intercropping did not significantly impact petroleum hydrocarbon remediation (1042.7 mg/kg – 1256.3 mg/kg) in plants. The application of surfactants during drip irrigation reduced the infiltration of petroleum hydrocarbons, slowing the spread of pollutants underground. This also led to an increase in petroleum-degrading bacteria, enhancing the effectiveness of the intercropping system for soil cleanup. Importantly, the combined effects of these factors were more pronounced in loamy soil compared to sandy soil.

The ZCR5 strain of *Enterobacter ludwigii*, isolated from maize (*Zea mays*) leaves, was studied for its potential to promote plant growth, degrade petroleum hydrocarbons, and produce biosurfactants in hydrocarbon- and heavy metal-contaminated soil [46]. In bacterial-assisted phytoremediation, soil treated with living ZCR5 cells exhibited the highest TPH removal efficiency at 30.6%, compared to 17.6% removal in soil treated with microbial necromass [46]. Although ZCR5 genes involved in biosurfactant production and plant growth promotion were not detected in the ryegrass root zone or endosphere, genes associated with TPH breakdown, such as CYP153 and nahAC, were found. This study demonstrated that bacterial bioaugmentation can enhance phytoremediation efficiency, though the specific bacterial mechanisms involved remain unclear. In a greenhouse study, the effects of mineral fertilization, the anionic surfactant Triton X-100, and bioaugmentation with a hydrocarbon-degrading bacterial consortium were evaluated for their impact on the growth of blue pea (*Clitoria ternatea*) used to phytoremediate a Gleysol polluted with weathered petroleum hydrocarbons (39,000 mg kg^{-1}) [47]. The results showed that mineral fertilization promoted plant growth and biomass, while Triton X-100 increased root biomass by 11% and significantly improved the degradation of weathered petroleum hydrocarbons. Bioaugmentation with the bacterial consortium had little effect on plant growth, suggesting that bacterial compositions may have differential effects on phytoremediation. However, when soil amendment and bioaugmentation were applied together, they resulted in higher plant growth, increased hydrogen-degrading bacteria, and improved degradation of weathered petroleum hydrocarbons, demonstrating the beneficial effects of combining these treatments. A rhizobox system was developed to study the interaction between cowpea (*Vigna unguiculata*) and the beneficial bacterium *Micrococcus luteus* WN01 in crude oil-contaminated soil [48]. The results showed that introducing *M. luteus* WN01 significantly increased cowpea root biomass and exudation of phenolic compounds. The combined use of cowpeas and *M. luteus* in bioaugmented phytoremediation promoted TPH breakdown in the root zone, increased microbial activities, and improved soil bacterial diversity, thus enhancing the effectiveness of the phytoremediation process [48].

Ptaszek et al. investigated the removal of TPHs (~2.5%) from highly polluted soil using enhanced bio- and phytoremediation methods [49]. The study compared 10 experimental groups, including treatments with endophytic *Rhodococcus erythropolis* CDEL254, which could secrete biosurfactants, degrade petroleum hydrocarbons, and promote plant growth. After 112 days, the treatment involving ryegrass (*Lolium perenne*), living CDEL254 cells, and a rhamnolipid solution removed up to 31.1% of petroleum hydrocarbons, compared to 26.1% removal in control groups treated with inactivated CDEL254 cells and a rhamnolipid solution [49]. This study further emphasizes the beneficial role of surfactants in phytoremediation, particularly through the secretion of biosurfactants that facilitate the degradation of TPHs.

Wang et al. compared the efficiencies of natural attenuation, microbial treatment with *Acinetobacter* sp. Tust-DM21, plant-based treatment involving seepweeds (*Suaeda glauca*), and a combination of microbial and plant-based treatment in breaking down TPHs, stimulating enzyme activities in soil, and modifying microbial community structure in soil contaminated with TPHs [50]. The results showed that the *Suaeda glauca* roots could adsorb minute polycyclic aromatic hydrocarbons (PAHs), leading to changes in the microbial community structure in the soil. This study discovered that all three biostimulation/bioaugmentation treatments led to a notable reduction in PAHs, especially combined microbial and plant-based treatment, with a removal rate as high as 67–99%. This treatment also degraded substantial amounts of C9-C21 n-alkanes in the soil [50]. It demonstrated the greatest enhancing effect on the soil bacterial diversity (Shannon index = 8.965) and significantly improved the soil bacterial richness (Abundance-based Coverage Estimator index = 2608.3), second only to the microbial treatment. The introduction of exogenous petroleum-degrading bacterium Tust-DM21 promoted the growth of certain plant growth-promoting rhizobacteria, thus raising the ability of the plants to withstand stress [50]. Consequently, the co-application of Tust-DM21 and *Suaeda glauca* leveraged their respective strengths to alter the soil microbial composition. This led to the increased proliferation of petroleum-degrading bacteria and plant growth-promoting rhizobacteria, ultimately bringing about a faster breakdown of TPHs [50]. While phytoremediation could generally enhance microbial diversity and richness through the actions of root exudates, rhizosphere effect, and symbiotic relationships with beneficial microbes, the choice of bacteria used for bioaugmentation is crucial to enhancing phytoremediation efficiencies [24, 28].

Purple coneflower (*Echinacea purpurea*) has been used in phytoremediation to treat aged soil from an excavation pit and soil from an oil spill area over six months [51]. The treatments included non-inoculated controls, soils inoculated with the B1 microbial consortium, soils inoculated with the B2 microbial consortium, soils inoculated with the B1 consortium and supplemented with γ-PGA (γ-poly glutamic acid), soils inoculated with the B2 consortium and supplemented with γ-PGA, and soils supplemented with a γ-PGA solution [51]. The results showed that the most effective approach to remediating TPH-contaminated soil involved combining phytoremediation with bioaugmentation using the B2 microbial consortium and γ-PGA supplementation. This combination resulted in a 53.98% reduction in TPHs and a 49.54% reduction in PAHs in excavation pit soil, as well as a 60.47% reduction in TPHs and a 37.55% reduction in PAHs in soil from the oil spill area [51]. This study underscores that different microbial consortia can have varying effects on phytoremediation, and root exudate materials, such as γ-PGA, generally enhance phytoremediation efficiency.

As observed in Section 3.1, studies exploring the co-application of phytoremediation and microbial remediation for contaminated water are relatively scarce. A study examining the effects of a microbial consortium that degrades petroleum hydrocarbons on the phytoremediation capabilities and growth of water hyacinths in water containing lead and petroleum hydrocarbons found significant results [52]. The experiment used 12-liter buckets filled with water, water hyacinths, lead (10 mg L^{-1}), and petroleum hydrocarbons (2,400 mg L^{-1}). After 30 days, the results revealed that lead and petroleum hydrocarbons significantly decreased the growth characteristics (up to 62%) and photosynthetic efficiency (up to 49%) of water hyacinths. However, introducing the microbial consortium led to a marked improvement in growth (38%) and photosynthetic efficiency (22%) compared to the contaminated control without the consortium [52]. The combination of water hyacinths and the microbial consortium absorbed 93% of lead and degraded 72% of petroleum hydrocarbons. Additionally, when both water hyacinths and the microbial consortium were applied together to address the co-contamination of lead and petroleum hydrocarbons, there was a 68% decrease in petroleum hydrocarbons and a 74% decrease in lead levels in the water [52].

The use of microbial remediation or bioaugmentation in combination with phytoremediation is gaining traction in recent studies, with a focus on how bioaugmentation enhances phytoremediation. Biosurfactants may play a significant role in this enhancement. These surfactants can be added directly or produced by bacteria, such as ZCR5, used during phytoremediation. Similarly, other chemical surfactants like Triton X-100 also positively impact phytoremediation by enhancing the bioavailability and mobility of contaminants, which improves plant uptake. Adding root exudate materials, such as amino acids, has also been shown to improve phytoremediation efficiency. However, different microorganisms can have varying effects on phytoremediation, suggesting that careful selection of microorganisms for bioaugmentation is crucial for optimizing results.

4. Limitations and Scalability

The advantages and limitations of various phytoremediation strategies are summarized in Table 3. While phytoremediation is recognized as cost-effective, simple, sustainable, and versatile, it suffers from limitations such as being time-consuming and inconsistent in performance. These limitations persist despite the potential for enhancement through bioaugmentation, soil amendments, and well-planned cropping or agricultural practices [4, 36, 49, 53]. Additionally, the plants used in phytoremediation may not be suitable for consumption due to the risk of bioaccumulation of TPHs [54]. However, with proper optimization, phytoremediation can be a viable solution for removing TPHs, particularly in cases where quick land-use conversion is not required and the land is to be repurposed for recreation or rehabilitation. For recreational or rehabilitation purposes, the phytoremediation plants can be left in place with frequent monitoring of TPH levels in the environment and plant parts, allowing for actions to reduce associated risks if necessary [16]. Food crops should be avoided in phytoremediation to prevent unintended exposure. Plants with potential for bioenergy conversion, such as sunflower, physic nut, and vetiver grass, should be prioritized [11]. Plants that are not suitable for bioenergy conversion can be thermally treated once phytoremediation is completed.

The ability to combine various strategies enhances the flexibility and scalability of phytoremediation. Microbial-assisted phytoremediation can be integrated with soil amendments such as fertilizers, compost, and biochar [4, 41, 42]. While combining these strategies can improve effectiveness, it may also increase the costs of phytoremediation. Therefore, it is advisable to limit the use of combined strategies to areas with higher contamination levels. Additionally, indigenous microbial consortia should be prioritized in microbial-assisted phytoremediation because of their potentially better adaptability, survival, and performance, as well as their ability to reduce the risk of ecological imbalances. Scalable cultivation practices, including irrigation, intercropping, and crop rotation, can further enhance TPH uptake by high-biomass, fast-growing, and tolerant plants [11, 44]. A large-scale phytoremediation effort conducted in an industrial area of Italy, which was contaminated with heavy metals and hydrocarbons, demonstrates the potential for scalability. The initiative involved a diverse range of plant species, including *Populus nigra*, *Paulownia tomentosa*, and *Cytisus scoparius*, alongside naturally occurring vegetation. Over the course of three years, the hydrocarbon levels in the soil were reduced by 40%, eventually falling below national regulatory thresholds, making the site suitable for potential redevelopment. Additionally, the site showed signs of ecological recovery, as indicated by improvements in the soil's nutritional quality [55]. This case further supports the scalability of phytoremediation.

Table 3. Advantages and limitations of different phytoremediation techniques.

Technique	Advantage	Limitation
Single-plant phytoremediation	– Low-cost, sustainable method – Simple to implement – Suitable for diverse petroleum hydrocarbons – Enhances soil stability and prevents erosion	– Limited to surface contamination – Slow process – Limited by plant's tolerance to pollutants – May not degrade all contaminants effectively
Microbial-assisted phytoremediation	– Increases the efficiency of pollutant degradation by enhancing microbial activity – Synergistic plant-microbe interactions – Can target a wide range of petroleum hydrocarbons	– Requires inoculation of appropriate microbes, which can be expensive – Success is highly dependent on microbial survival in the environment – Potential for non-target effects on local microbial communities
Phytoremediation with fertilizers	– Enhances plant growth and nutrient availability – Improves root biomass, promoting deeper contaminant uptake – Can increase the rate of contaminant degradation	– Can cause nutrient imbalances if over-applied – Runoff may lead to environmental pollution – Fertilizers are not equally effective on different petroleum hydrocarbons
Phytoremediation with biochar	– Enhances soil structure, water retention, and nutrient availability – Adsorbs contaminants, preventing leaching – Improves microbial activity and root development	– Can be costly to produce and apply – Potential for long-term accumulation of biochar in soil – Effectiveness varies depending on biochar type and contaminant
Phytoremediation with compost	– Improves soil structure, aeration, and organic matter content – Promotes microbial activity and plant health – Increases contaminant degradation and bioavailability	– May introduce pathogens or weeds if not properly processed – Can lead to an imbalance in soil nutrients if over-applied – Slow process; effectiveness depends on compost quality and application rate
Phytoremediation with surfactants	– Increases the bioavailability of petroleum hydrocarbons – Enhances root uptake and microbial degradation	– Can be toxic to plants and microorganisms if overused – Potential for leaching of contaminants into groundwater – Surfactant residuals may persist in the environment
Phytoremediation with root exudate materials	– Can enhance microbial community activity and pollutant degradation – Improves plant health and root growth	– Root exudate materials can be difficult to optimize – May not be effective for all types of petroleum hydrocarbons – Potential for allelopathic effects on surrounding plants and microbes

5. Conclusions and recommendations

Phytoremediation has continuously occupied an important place in treating contaminated soil and water due to its simplicity, cost-effectiveness, environmental friendliness, and beneficial effects on soil health. Numerous studies have been published on phytoremediation. Like earlier studies, the recent phytoremediation studies continue to identify the potential of existing or new plants in remediating soil primarily. There is an interest in examining the phytoremediation efficiencies of different varieties of a particular plant species, and these studies revealed differential efficiencies of the varieties. However, using plants alone is met with limited phytoremediation efficiencies, often below 65%. Fertilization and soil amendments to improve soil conditions and stimulate soil bacteria for phytoremediation have been conducted to raise phytoremediation efficiencies, but they rarely exceed 85%. Therefore, other remediation strategies, especially microbial remediation, have been employed in conjunction with phytoremediation to increase its efficiency further. Microbial-assisted phytoremediation yields variable results depending on the microorganisms used. The employment of endomycorrhizal consortium and *Acinetobacter* sp. Tust-DM21 seems to substantially improve phytoremediation efficiency compared to other microorganisms. The efficiency of microbial-assisted phytoremediation can also be enhanced with fertilization, soil amendments, and the addition of surfactants and root exudate materials. This review contributes to the identification of the most effective phytoremediation strategies from the most recent phytoremediation literature. It also identifies the current research trends and proposes future improvement and research, as below:

- Plant-microbe interactions have yielded encouraging results, including almost complete removal of TPHs in some cases. Further investigation of the role of rhizosphere microorganisms, particularly mycorrhizae and plant growth-promoting rhizobacteria, in phytoremediation would benefit the advancement of the field.
- Selective breeding of native plants with desirable traits for TPH degradation can be continued.
- The roles of soil conditioners (biochar, compost), fertilizers, surfactants, agricultural practices, and root exudate materials in improving phytoremediation of TPH-contaminated soil can be explored.
- Future studies can focus on optimizing different factors that have been identified to positively influence the phytoremediation of TPH-contaminated soil. This may involve the use of artificial intelligence.
- There is a need to focus on remediating extreme conditions like arid or highly saline soils or environments affected by climate change.
- Large-scale field studies that test the effectiveness of phytoremediation technologies in different climates and ecosystems can be increased.

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Competing Interest

The author declares that there is no competing interest.

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