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A Review of the Efficiency and Novel Approaches of Landfarming for the Remediation of Soils Contaminated with Petroleum Hydrocarbons

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1. ABSTRACT

Petroleum hydrocarbon contamination is a major environmental concern because of the persistence, toxicity, and adverse effects of these compounds on soil quality and ecosystem functions. Landfarming is a widely applied ex-situ bioremediation technique because of its operational simplicity, relatively low cost, scalability, and compatibility with biological treatment processes. This review aimed to evaluate the mechanisms governing landfarming performance, identify the major factors controlling contaminant removal, and assess recent strategies developed to improve its efficiency. A systematic literature search was conducted in Scopus, Web of Science, PubMed, and Google Scholar for studies published between 2000 and 2026 using keywords related to landfarming, petroleum hydrocarbons, soil bioremediation, biostimulation, bioaugmentation, and polycyclic aromatic hydrocarbons. From 145 initially identified studies, 63 eligible studies were selected for the final analysis. The reviewed evidence indicates that landfarming efficiency is mainly controlled by the interaction among contaminant transport, bioavailability, and biodegradation. Soil texture, contaminant characteristics, moisture, temperature, pH, aeration, nutrient availability, microbial activity, and operational management strongly influence treatment performance. The review further indicates that integrated approaches, including biostimulation, bioaugmentation, chemical pre-oxidation, vermiremediation, and electrokinetic treatment, can overcome specific process limitations. Based on these findings, a bottleneck-oriented framework is proposed for selecting enhancement strategies according to the dominant limitation of each contaminated soil.

Keywords: Landfarming; Petroleum Hydrocarbons; Bioavailability; Bioremediation; Soil Pollution

2. INTRODUCTION

Petroleum hydrocarbon contamination is a widespread environmental problem associated with oil extraction, processing, transportation, storage, and accidental releases. Petroleum compounds can persist in soil for long periods and adversely affect soil physical, chemical, and biological properties. Among available remediation technologies, biological approaches are attractive because they can reduce energy consumption, treatment costs, and the generation of secondary pollutants compared with many physicochemical technologies. Landfarming is one of the established ex-situ bioremediation technologies for petroleum-contaminated soils. The process generally involves spreading contaminated soil in relatively thin layers and periodically tilling and irrigating it to promote aeration, microbial activity, and

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contaminant degradation [1]. Its major advantages include relatively simple operation, low equipment requirements, suitability for large volumes of contaminated soil, and the possibility of integration with other remediation technologies. However, its performance varies considerably among sites because contaminant characteristics, soil properties, environmental conditions, and operational practices affect the availability and biodegradability of petroleum hydrocarbons. Previous studies have demonstrated that the effectiveness of landfarming cannot be predicted solely from total petroleum hydrocarbon (TPH) concentration. Contaminant composition, carbon-chain distribution, aging, sorption to soil organic matter and minerals, and contaminant bioavailability can substantially determine treatment efficiency [2]. Therefore, the objective of this review was to critically examine the mechanisms controlling landfarming, identify the principal factors responsible for variations in treatment efficiency, evaluate emerging enhancement strategies, and develop a process-oriented framework for selecting suitable integrated remediation approaches.

3. MATERIALS AND METHODS

A systematic literature search was conducted using Scopus, Web of Science, PubMed, and Google Scholar. The search covered publications from 2000 to 2026 and used combinations of the keywords “Landfarming,” “Petroleum hydrocarbons,” “Soil bioremediation,” “Biostimulation,” “Bioaugmentation,” and “PAHs.” Eligible studies were peer-reviewed original research articles that reported landfarming treatment and quantitative measurements of contaminant removal, particularly TPH or PAHs. Technical reports and studies without sufficiently reliable quantitative removal data were excluded. From 145 initially identified publications, 63 studies met the eligibility criteria and were included in the final analysis. Information extracted from the selected studies included soil physicochemical characteristics, contaminant type and concentration, operational conditions such as soil-layer thickness, tilling frequency and nutrient amendment, environmental conditions including temperature, moisture and pH, and contaminant removal efficiency. The reviewed evidence was subsequently synthesized according to the dominant processes controlling landfarming performance. Particular attention was given to contaminant transport, bioavailability, biodegradation, and the interactions among these processes. Enhancement technologies were then evaluated according to the process limitation they were intended to overcome.

4. RESULTS AND DISCUSSION

4.1. Governing Mechanisms of Landfarming

Landfarming performance is governed by the simultaneous contribution of volatilization, adsorption–desorption processes, contaminant transport, and, most importantly, aerobic biodegradation. Volatilization may contribute substantially to the initial removal of low-molecular-weight hydrocarbons; however, it represents transfer of contaminants from soil to the atmosphere rather than their actual destruction. Consequently, biodegradation remains the principal environmentally desirable mechanism for permanent removal. Aerobic degradation depends on the activity of indigenous or introduced hydrocarbon-degrading microorganisms and requires adequate oxygen, moisture, nutrients, and suitable environmental conditions. Strong sorption of hydrophobic and high-molecular-weight hydrocarbons to soil organic matter and clay minerals can substantially reduce their bioavailability and consequently limit microbial degradation [2]. Accordingly, the review indicates that the overall efficiency of landfarming can be interpreted through three interconnected processes: contaminant transport, contaminant bioavailability, and biodegradation capacity. A limitation in any one of these processes may become the principal bottleneck controlling treatment performance.

4.2. Factors Controlling Treatment Efficiency

Soil texture strongly affects oxygen transfer, permeability, water movement, and microbial accessibility. Coarser-textured soils generally provide more favorable conditions for aerobic degradation, whereas fine-textured soils may restrict contaminant and oxygen transport. Soil organic matter also has a dual role: it can provide carbon resources for microorganisms while simultaneously increasing sorption of hydrophobic petroleum compounds and decreasing their bioavailability. Contaminant characteristics are equally important. Hydrocarbons with lower molecular weight and shorter carbon chains are generally more readily removed, whereas aged hydrocarbons and high-molecular-weight PAHs are more strongly sorbed and resistant to biodegradation. Consequently, similar initial TPH concentrations may result in substantially different landfarming efficiencies when the chemical composition of the contamination differs [3]. Environmental and operational factors, including temperature, moisture, pH, aeration, nutrient availability, microbial population, tilling frequency, and amendment type, also play important roles. Appropriate moisture is required to sustain microbial activity and contaminant transport, whereas excessive moisture may restrict oxygen diffusion. Similarly, periodic tilling improves aeration and mixing, while nutrient management can stimulate indigenous hydrocarbon-degrading microorganisms. Reported studies demonstrate that landfarming can achieve substantial contaminant removal under appropriate conditions. However, its efficiency varies considerably among sites, and its performance generally decreases when contaminant concentrations are very high, compounds are strongly aged or sorbed, or soil permeability and bioavailability are low.

4.3. Innovative Approaches for Improving Landfarming

Several enhancement strategies have been investigated to overcome the limitations of conventional landfarming. Biostimulation is particularly promising where indigenous microorganisms possess sufficient hydrocarbon-degrading potential. Addition of nitrogen and phosphorus, pH adjustment, moisture management, and suitable organic amendments can increase microbial activity and accelerate degradation. Bioaugmentation involves introducing selected hydrocarbon-

degrading microorganisms. However, its performance can be inconsistent because introduced microorganisms may fail to compete with indigenous communities or adapt to the physicochemical conditions of the contaminated soil. Evidence reviewed in the present study suggests that bioaugmentation is more effective when combined with appropriate biostimulation, particularly in soils where environmental conditions are otherwise limiting. Chemical pre-oxidation can be useful for aged and resistant hydrocarbons, particularly high-molecular-weight PAHs. Oxidants such as hydrogen peroxide, ozone, and photo-Fenton systems can alter the molecular structure and reduce the hydrophobicity of resistant compounds, thereby increasing their subsequent bioavailability and biodegradability. The integration of chemical pre-oxidation with landfarming can therefore reduce treatment time and improve overall PAH removal [4]. Vermiremediation provides another complementary strategy by improving soil structure, aeration, contaminant distribution, microbial colonization, and enzymatic activity. Electrokinetic treatment is particularly relevant for fine-textured soils where contaminant transport and bioavailability are restricted. Sequential electrokinetic–landfarming systems can facilitate contaminant mobilization and subsequent biological degradation, making them promising for low-permeability soils.

4.4. Bottleneck-Oriented Framework for Strategy Selection

The central finding of this review is that no single enhancement technology can be considered universally superior for all petroleum-contaminated soils. The selection of an appropriate strategy should instead be based on the dominant process bottleneck. The proposed framework classifies landfarming enhancement strategies into three major groups:

Enhancement of biological capacity: biostimulation, bioaugmentation, nutrient management, and microbial-support strategies are appropriate when microbial degradation capacity is the principal limitation.

Improvement of contaminant bioavailability and transport: surfactants, biosurfactants, vermiremediation, and electrokinetic approaches are suitable when strong sorption, poor transport, or limited contaminant accessibility restricts biodegradation.

Pretreatment and reduction of contaminant resistance: chemical oxidation and other pretreatment technologies are particularly relevant for aged, highly persistent, or high-molecular-weight hydrocarbons that resist biological degradation.

This process-oriented approach is consistent with evidence showing that landfarming is advantageous because of its simplicity, relatively low cost, low energy demand, scalability, and compatibility with integrated technologies, but its major limitations are relatively long treatment periods and strong dependence on soil conditions and contaminant bioavailability.

5. CONCLUSION

Landfarming remains a practical and relatively sustainable technology for the remediation of petroleum-contaminated soils, but its effectiveness is highly site-specific. The review demonstrates that contaminant transport, bioavailability, and biodegradation constitute the principal process controls governing treatment performance. Therefore, enhancement strategies should be selected according to the dominant process limitation rather than applied uniformly. Future research should emphasize long-term field-scale studies using standardized protocols and simultaneous assessment of contaminant concentration, bioavailability, toxicity, and microbial indicators to provide a more reliable evaluation of actual remediation performance

6. REFERENCES

[1] Maila, M. P., Cloete, T. E., Bioremediation of petroleum hydrocarbons through land farming: A review, Bioremediation Journal, 8, pp. 101–113, 2004.

[2] Chen, C.-H., Liu, P.-W. G., Whang, L.-M., Effects of natural organic matters on bioavailability of petroleum hydrocarbons in soil-water environments, Chemosphere, 233, pp. 843–851, 2019.

[3] Kim, S. H., Woo, H., An, S., Chung, J., Lee, S., Lee, S., What determines the efficacy of landfarming for petroleum-contaminated soils: Significance of contaminant characteristics, Chemosphere, 290, 133392, 2022.

[4] Kulik, N., Goi, A., Trapido, M., Tuhkanen, T., Degradation of polycyclic aromatic hydrocarbons by combined chemical pre-oxidation and bioremediation in creosote contaminated soil, Journal of Environmental Management, 78, pp. 382–391, 2006.

[5] Bang, S., Kim, M., Chun, M., Kim, J., Ahn, H., A Study on the Quality Management Method for Landfarming Technique Applied to Petroleum Contaminated Soil, Journal of Soil and Groundwater Environment, 29, pp. 22–34, 2024.