



<https://muthjas.mu.edu.iq/>

<http://doi.org/10.52113/mjas04/13.1/31>

## **Biotechnological and Chemical Technologies for Sustainable Treatment of Oil Well Drilling Waste: Current Trends and Future Perspectives**

**Rusul Jabbar Al-Jubour<sup>1</sup> Ameer K. Madhi<sup>2</sup>**

<sup>1</sup>**Babylon Environment Directorate, Ministry of Environment, Iraq**

<sup>2</sup>**Almuthana Environment Director, Ministry of Environment, Iraq**

**Email:**

**Ameer.kadhim89@gmail.com**

### **Abstract**

Hydrocarbon contamination from oil drilling operations poses a major threat to soil and groundwater because of the persistence, toxicity, and bioaccumulation potential of petroleum-derived pollutants. The oil and gas industry generates enormous quantities of hazardous waste, with produced water accounting for approximately 98% of the total waste generated during drilling activities. Conventional treatment technologies, including stabilization/solidification (S/S), are widely used to immobilize organic and inorganic contaminants; however, concerns regarding long-term stability, contaminant leachability, and the absence of biodegradation limit their environmental sustainability and long-term effectiveness. Biological treatment technologies represent cost-effective and environmentally friendly alternatives to conventional physical and chemical methods. Under favorable environmental conditions, microorganisms can degrade petroleum hydrocarbons into less harmful compounds through intracellular metabolic pathways. Nevertheless, the biodegradation efficiency depends on several factors, including nutrient availability, oxygen concentration, pollutant accessibility, and the molecular structure of hydrocarbons, particularly persistent compounds such as polycyclic aromatic hydrocarbons (PAHs). This review critically synthesizes the synergy between chemical and biological treatment technologies for sustainable oil drilling waste management. Particular emphasis is placed on the integration of bioremediation, phytoremediation, advanced oxidation processes (AOPs), nanotechnology-assisted remediation, and stabilization/solidification techniques to enhance hydrocarbon degradation efficiency while minimizing secondary environmental impacts. The

review further highlights the role of microbial consortia, pollutant-accumulating plants, and reusable nanophotocatalysts such as  $\text{TiO}_2/\text{TiO}_2$  and  $\text{ZnO}/\text{ZnO}$  in improving remediation performance. Overall, integrated hybrid treatment systems are identified as promising sustainable strategies for reducing total petroleum hydrocarbons (TPHs) and improving long-term environmental protection.

**Keywords:** "Hydrocarbon Biodegradation, Petroleum-contaminated Soil , Sustainable Drilling Technologies, Stabilization/solidification

## Introduction

The increasing global demand for energy has significantly accelerated oil and gas exploration and drilling activities worldwide. Although the petroleum industry remains one of the major contributors to global energy supply, it also generates enormous quantities of hazardous waste that pose serious environmental challenges. These wastes include drilling fluids, produced water, hydrocarbon-contaminated oily sludge, spent catalysts containing heavy metals, and gaseous emissions. Among these wastes, produced water represents the largest fraction, accounting for approximately 98% of the total waste generated during drilling operations [2]. The continuous release of such wastes into the environment has raised major concerns regarding soil and groundwater contamination, ecological imbalance, and long-term risks to public health.

Petroleum industry wastes are considered among the most hazardous contaminants in aquatic and terrestrial environments because they contain toxic, persistent, and potentially carcinogenic compounds, including polycyclic aromatic hydrocarbons (PAHs), benzene derivatives, and heavy metals [5]. These pollutants

consist of complex aliphatic and aromatic hydrocarbons characterized by long carbon chains and stable molecular structures, which increase their environmental persistence and resistance to natural degradation. The discharge of untreated oil waste into rivers, lakes, and soil ecosystems can severely disrupt ecological balance and threaten aquatic organisms due to its high toxicity and bioaccumulation potential [6].

Conventional physical and chemical treatment methods are widely used for managing oil drilling waste; however, many of these technologies are associated with high operational costs, secondary pollution, and limited long-term sustainability. Consequently, environmentally friendly and sustainable remediation technologies have attracted increasing scientific and industrial attention. Among these technologies, biodegradation is considered one of the most important natural processes affecting hydrocarbon compounds in contaminated environments, as microorganisms can transform complex petroleum hydrocarbons into simpler and less toxic substances [3].

The biodegradation of hydrocarbons is not restricted to a limited group of microorganisms. A wide variety of

bacteria, fungi, and microbial consortia are capable of utilizing petroleum hydrocarbons as sources of carbon and energy. The effectiveness of biodegradation processes depends strongly on environmental factors such as nutrient availability, oxygen concentration, temperature, salinity, and pollutant accessibility. Nutrients such as nitrogen and phosphorus play a critical role in maintaining microbial growth and enhancing the degradation efficiency of organic pollutants in wastewater systems [4].

Bacteria are among the most efficient microorganisms used in the biological treatment of hydrocarbon-contaminated wastewater and soils because of their rapid growth rates, metabolic diversity, and ability to produce degradative enzymes capable of breaking down complex organic compounds into simpler substances. In addition, bacterial cell walls possess the ability to adsorb various heavy metals, which further enhances their environmental remediation potential. For example, *Bacillus* species are well known for their high efficiency in degrading dissolved organic matter through specialized enzymatic systems [7].

In recent years, several sustainable non-chemical remediation approaches have been developed for the treatment of petroleum-contaminated soils and wastewater. These approaches mainly include bioremediation using beneficial microorganisms and phytoremediation using pollutant-accumulating plants capable of absorbing petroleum hydrocarbons and

heavy metals from contaminated environments. Despite their environmental advantages, significant challenges remain, particularly the limited ability of certain plant species to survive and grow efficiently under highly contaminated conditions. Therefore, the development of integrated and environmentally safe strategies is essential to improve the efficiency of biological treatment technologies and enhance the sustainable remediation of oil-contaminated environments [8].

### **Sustainable Biotechnological and Chemical Technologies**

- **Bioremediation:** This technique involves the use of microorganisms and biological agents to degrade hydrocarbon pollutants and toxic compounds present in soil and water. The efficiency of this process can be enhanced by adding nutrients and fertilizers that stimulate microbial activity and accelerate biodegradation.

- **Advanced Chemical Treatment:** - This approach includes several techniques such as oxidation, adsorption, and ion exchange to remove pollutants that are difficult to treat biologically, particularly contaminants present in produced water associated with oil extraction processes.

- **Use of Natural and Synthetic Materials:** -Natural fibers (such as palm fibers) as well as recycled synthetic materials like used nylon fibers can be utilized to control oil pollution and assist in breaking down petroleum crystalline structures.

- **Chemical Cleaning Agents (Surfactants):** -Surface-active agents, including amino acids and fatty salts, are used to break down and emulsify oil in

drilling fluids, facilitating the separation and removal of petroleum contaminants.

• **Sustainable Drilling Technologies:** - These technologies involve the use of

environmentally friendly and intelligent drilling fluids, in addition to advanced drilling methods such as directional and horizontal drilling, which help reduce the volume of generated drilling wastes

**Table 1: Comparative Analysis of Treatment Technologies.\*\* Compare Bioremediation, Chemical Oxidation, and S/S based on: Cost, Timeframe, Efficiency, and Secondary Waste Generation.**

Technology	Efficiency (TPH Removal)	Relative Cost	Timeframe	Environmental Impact	Key Limitation
<b>Bioremediation</b>	High (>80%)	Low	Long (Months)	Very Low	Sensitivity to toxicity levels and climate.
<b>Phytoremediation</b>	Moderate	Very Low	Very Long	Positive (Green)	Limited by root depth and soil salinity.
<b>Chemical Oxidation</b>	Very High	High	Short (Hours)	Moderate	Potential for secondary toxic by-products.
<b>S/S (Solidification)</b>	High (Immobilization)	Moderate	Short	Moderate	No degradation; long-term leaching risks.

<b>Technology</b>	<b>Efficiency (TPH Removal)</b>	<b>Relative Cost</b>	<b>Timeframe</b>	<b>Environmental Impact</b>	<b>Key Limitation</b>
<b>Thermal Incineration</b>	Total	Very High	Immediate	High	High energy consumption and air emissions.

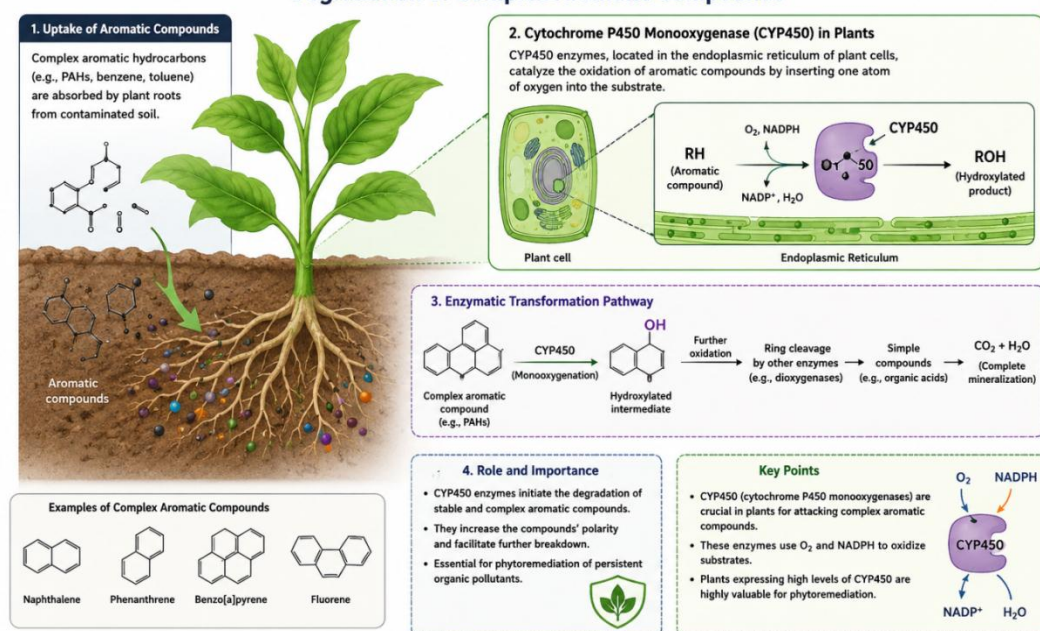
### **Various Phytoremediation Techniques**

Phytoremediation is an emerging green technology used for the detection, analysis, and removal of various environmental pollutants. Different plant species are used to remove contaminants that pose harmful effects on human health and other biological systems. These plants absorb pollutants from the environment and help detoxify them. Due to its environmentally friendly nature, this approach has significant advantages over conventional techniques, which may cause adverse effects on biological systems and the environment treatment of pollutants in water, particularly heavy metal contaminants, involves several mechanisms that convert toxic substances into less harmful compounds, thereby facilitating the removal of waste from water systems. These mechanisms include phytostabilization, rhizodegradation, phytofiltration (also known as rhizofiltration), phytoextraction, photodegradation, phytovolatilization, and phytoaccumulation [9].

In phytostabilization, accumulation or adsorption mechanisms are utilized. In this approach, pollutants present in groundwater or soil are adsorbed onto plant roots or immobilized within the rhizosphere, preventing their movement and spread to other

areas of the environment [10] Phytodegradation, also known as phytotransformation, involves the breakdown of pollutants through plant metabolic processes. In this process, plants absorb metals and various environmental pollutants and wastewater from the environment and convert them into less toxic compounds with the assistance of various enzymes [11]. In phytovolatilization, plants absorb different contaminants from wastewater and transform them into less toxic substances. These compounds are then released into the atmosphere through plant leaves during transpiration. Similarly, when pollutants are stored within different parts of the plant, such as roots, stems, and leaves, the process is referred to as phytoaccumulation [12]

## Role of Cytochrome P450 Monooxygenase Enzymes in Plant Degradation of Complex Aromatic Compounds



**Fig 1. Role of Cytochrome P450 Monooxygenase Enzymes in the**

### Phytoremediation of Aromatic Hydrocarbons (Strong, L. C., McTavish, 2000)

#### Bioremediation

Petroleum products are complex mixtures consisting of hundreds of hydrocarbon compounds, ranging from light, volatile, short-chain organic compounds to heavy, long-chain and branched molecules. The exact composition of petroleum products varies depending on the source of crude oil, as crude oil is derived from underground reservoirs that differ significantly in their chemical composition, as well as the refining processes used to produce final products. Bioremediation refers to the management of contaminated soil, sludge, and water through the use of various microorganisms, including bacteria, fungi, and genetically engineered organisms, to transform, detoxify, and degrade organic compounds such as petroleum hydrocarbons and other hazardous substances. This natural process reduces the toxicity, concentration, and mobility of pollutants by converting

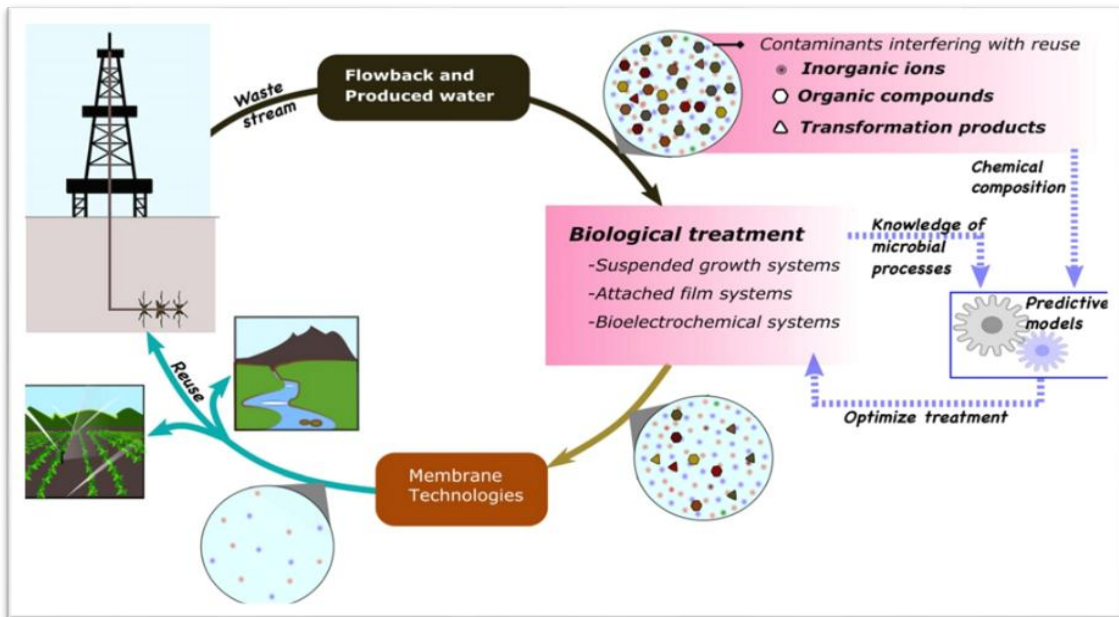
them into less harmful or non-toxic end products. Microorganisms use organic compounds as sources of carbon and energy to sustain their metabolic activities; therefore, they must remain active and viable to enable effective bioremediation. In general, indigenous microbial communities (i.e., naturally occurring at contaminated sites) possess the inherent ability to degrade petroleum hydrocarbons, provided that environmental conditions are favorable for microbial growth. Among microorganisms, bacteria are considered primary recyclers in nature due to their ability to decompose a wide range of compounds into their basic elements, and thus, they are widely used in environmental biotechnology. Bacteria are ubiquitous, occurring in soil, water, plants, animals, and even rocks. Their microscopic size (approximately 1 micrometer) enables efficient transport of compounds into and out of cells, making them highly effective

biological agents. After death, all living organisms decompose into basic elements such as water, carbon, nitrogen, phosphate, and trace elements through a process known as biodegradation or mineralization. Experimental studies have shown that most synthetic organic materials are biodegradable, making bioremediation a technically viable alternative. Furthermore, these technologies have demonstrated successful applications worldwide. Bioremediation is an environmentally friendly technique that protects surface and groundwater from contamination, mitigates environmental damage, and preserves ecological balance. Additionally, treated outputs such as clean water and drilling sludge can be reused. Treated drill cuttings, for example, may be suitable for construction, landfilling, soil amendment, or as nutrient sources for plants such as compost and humus. The importance of bioremediation technologies is increasing, as they enable the conversion of waste into useful products. Through this process, the hydrocarbon content of drill cuttings is reduced to acceptable environmental levels, transforming drilling residues into non-toxic, potentially beneficial materials. Bioremediation plays a crucial role in oil spill cleanup, as environmental pollution poses significant risks to human health and other living organisms. One of the key advantages of bioremediation over other technologies is its relatively low cost. Drill cuttings can often be treated on-site, thereby reducing transportation costs compared to other methods. Additionally, the process does not require shutdowns or extensive maintenance during operation. Bioremediation is also flexible and can be applied to various types of drilling wastes, including both oil-based mud (OBM) and water-based mud (WBM).

Regarding microbial selection, bacterial screening was based on the ability to degrade petroleum hydrocarbons in high-salinity soils. Two dominant bacterial strains capable of oil degradation and biosurfactant production were selected. Identification was conducted based on 16S rRNA gene sequencing, revealing that they belong to the genera *Nocardia* sp. and *Pseudomonas stutzeri*. To enhance bioremediation, a treatment mixture can be prepared to stimulate indigenous bacteria present in contaminated soils. This mixture typically consists of NPK fertilizers, animal manure, sawdust, and sand (for dilution), with periodic additions of water. The mixture is regularly turned every 3–4 days and aerated to improve oxygen availability, thereby enhancing microbial activity and reducing total petroleum hydrocarbons (TPH) to levels below 5%. In general, three main strategies are used to enhance the degradation of petroleum hydrocarbons in water: (a) the addition of surfactants to increase the contact area between oil and microorganisms; (b) the introduction of efficient hydrocarbon-degrading microorganisms to increase microbial populations; and (c) the addition of nutrients such as nitrogen and phosphorus to stimulate the activity of indigenous microorganisms [13]. It has been reported that approximately 100 genera and 200 species of hydrocarbon-degrading bacteria exist. Aerobic bacteria are commonly used to degrade pesticides and aliphatic and aromatic compounds, whereas anaerobic bacteria are typically employed in the bioremediation of compounds such as polychlorinated biphenyls (PCBs). Studies have shown that mixed microbial consortia can degrade a broader range of petroleum hydrocarbons compared to single strains [14]. However, a major

challenge in constructing effective microbial consortia lies in the lack of

rational design for selecting appropriate community members [16].



**Fig 2: The main stages of the bioremediation process for pollutants(Fakhru'l-Razi,2021)**

### Chemical Treatment Technologies for Oil Waste

Several methods for managing drilling wastes are described in detail within drilling waste management systems. These methods primarily include the following:

**Waste Minimization:** This approach reduces the volume and environmental impact of drilling waste by minimizing its generation through advanced drilling techniques, such as directional drilling, smaller-diameter boreholes, and reduced drilling fluid use. It also involves the use of environmentally friendly drilling muds and additives, such as low-impact mud systems, thin-film drilling fluids, and alternative weighting agents.

**Recycling and Reuse:**-This includes practices such as mud recycling, road spreading, reuse of drill cuttings for construction purposes, wetland restoration using drilling wastes, and even the use of oily drill cuttings as a fuel source.

**Waste Disposal :-** Waste can be

disposed of through on-site burial (pits or landfills), land application (agricultural use or soil spreading), or biological treatment methods such as composting, bioreactors, (earthworm treatment). Additional disposal options include offshore discharge, off-site disposal at commercial facilities, injection of drilling wastes, storage in salt caverns, and thermal treatment methods such as incineration and pyrolysis. For oil companies, the major challenge is achieving effective environmental protection without incurring high costs that could undermine their competitiveness. Therefore, the search for cost-effective and efficient treatment solutions represents a promising direction for the future.

**Stabilization/Solidification:** This technique converts liquid and semi-liquid wastes that are sensitive to hydrological conditions into a solid form that can be stored safely and easily. Stabilization involves

immobilizing waste components through chemical modification to form insoluble compounds or by encapsulating them within a solid matrix. Stabilization/solidification provides an effective method for treating oily wastes, resulting in a dry, environmentally safe material suitable for on-site disposal, land application, or disposal in authorized waste management facilities. Both direct treatment techniques (applied during or immediately after drilling) and indirect treatment techniques (applied after a certain period) can be used. These methods enable the treatment of accumulated drilling, maintenance, and production wastes from wells, in accordance with standardized procedures such as those established by [17]. Various physical and chemical processes can remove pollutants, including organic and inorganic compounds, from water in dissolved, suspended, or colloidal forms. In direct treatment processes, the main steps are as follows: oil removal, sedimentation, centrifugation, coagulation, and flocculation.

### **Hydrocarbon Removal**

Petroleum refineries and petrochemical industries release various hydrocarbons, including polycyclic aromatic hydrocarbons (PAHs), which are major contaminants in industrial wastewater. These compounds pose significant health risks due to their benzene-ring structures, including mutagenicity, carcinogenicity, and teratogenic effects [18]. Therefore, the development of safe and efficient treatment technologies is essential for removing these pollutants from industrial wastewater. Phytoremediation has emerged as a promising and environmentally friendly approach for removing hazardous contaminants such as PAHs. Among the available treatment

methods, phytoremediation is considered a novel technique in which plants are utilized to purify contaminated water. Plants strongly interact with aquatic systems, the surrounding environment, and microbial communities, thereby playing a positive role in pollutant removal [19]. PAHs are commonly analyzed using gas chromatography (GC) or liquid chromatography (LC), often coupled with mass spectrometry (MS). However, these methods are time-consuming and require careful sample preparation and pre-concentration steps. Typically, solid-phase extraction (SPE) is employed to concentrate PAHs onto hydrophobic sorbent materials prior to analysis. Due to the low biodegradability of PAHs, advanced oxidation processes (AOPs) have been extensively studied as alternative or complementary treatment methods to conventional techniques [20] [21]. Bioremediation can be applied either in situ or ex situ. Ex situ bioremediation involves the physical transfer of contaminated materials to another location for treatment. In this approach, contaminated waste is transported, treated under controlled conditions—often using microorganisms—and then either returned to the original site or managed appropriately. This method is faster and easier to control, and it can treat a wider range of pollutants. For example, the removal of hydrocarbons from contaminated soils can be achieved through aerobic composting techniques [22].

### **Laboratory Methods for Hydrocarbon Removal (Oil Waste**

- **Fabric-Based Containment:** - Fabric materials are widely used for oil containment and spill prevention. These fabrics are designed to prevent floating oil from spreading across the water surface. One type, known as

curtain booms, consists of a PVC barrier installed beneath polyethylene floats, with anchoring points at the bottom. In some designs, sections are connected using hinges approximately 6 feet in length, with total lengths ranging from 50 to 100 feet [23]

- **Chemical Methods:** -One approach to concentrating oil involves the application of chemical agents to contaminated water, which reduces oil dispersion and promotes the re-aggregation of oil into larger masses. This method is typically applied in real oil spill scenarios under calm-water conditions [24].

- **Microbial Treatment:** Numerous studies have demonstrated that microorganisms, including bacteria, fungi, and yeasts, are the primary agents responsible for the degradation of pollutants, including hydrocarbons, in both aquatic and terrestrial environments. Selected microorganisms must be capable of utilizing hydrocarbons as primary substrates and producing enzymes that accelerate their degradation, while ensuring that by-products are environmentally safe. However, no single microorganism can completely degrade crude oil independently [25]. The biodegradation of crude oil involves sequential reactions, in which specific microorganisms initiate the breakdown of petroleum compounds, producing intermediates that require further degradation by other microbial groups. Indigenous microorganisms present in groundwater and surface water in oil-contaminated areas are often well adapted to such conditions and can utilize hydrocarbons as carbon and energy sources, ultimately converting them into final products such as carbon dioxide and water.

- **Adsorption Method-** Adsorbent materials, including insoluble

substances or mixtures, are used to recover oil through physical adhesion or absorption processes [26]. Effective adsorbents must exhibit high oil absorption capacity and water resistance [27]. Although they can be used as a primary method for small spills, adsorbents are more commonly used to remove residual oil layers. Adsorbents can be classified into three main categories: natural, organic, and synthetic organic. Natural organic adsorbents include materials such as straw, sawdust, corn cobs, and feathers. These materials can absorb oil at rates of 3–15 times their weight; however, a major limitation is their tendency to absorb water along with oil, which can lead to sinking.

- **Photocatalytic Oxidation:** Among advanced oxidation processes (AOPs), heterogeneous photocatalytic oxidation has gained significant importance due to its high efficiency in degrading persistent organic compounds [28]. This process involves accelerating photochemical reactions in the presence of semiconductor catalysts. Photo catalysts are materials capable of generating electron-hole pairs upon light exposure, leading to chemical transformations of pollutants and their eventual mineralization. These materials are typically semiconductors. Common photo catalysts include titanium dioxide ( $\text{TiO}_2$ ), zinc oxide ( $\text{ZnO}$ ), iron oxide ( $\text{Fe}_2\text{O}_3$ ), cadmium sulfide ( $\text{CdS}$ ), and zinc sulfide ( $\text{ZnS}$ ). Among these, titanium dioxide ( $\text{TiO}_2$ ) is the most extensively studied due to its high reactivity, low toxicity, chemical stability, low cost, and strong capability to degrade organic pollutants into harmless end products [29].

- **Nanomaterials:** -Researchers at Rice University (Texas, USA) have explored the use of nanotechnology for environmental remediation,

particularly for cleaning oil spills in groundwater. Studies have shown that fine nanoparticles composed of metals and carbon can trap water droplets, leading to their aggregation into spherical clusters containing millions of droplets. Additionally, ultraviolet radiation and magnetic fields can be used to direct nanoparticles for controlled aggregation and release. Advanced nanostructures, such as multifunctional nanowires, have demonstrated the ability to separate oil from water when introduced into oil–water mixtures. Recent developments include nano-coatings based on zirconium particles and nanofiber mats capable of absorbing oil and organic pollutants at up to 20 times their own weight. A key advantage of these nanomaterials is their reusability without structural degradation. These technologies show significant promise for future applications in the oil industry, particularly given the lack of effective methods for managing large-scale oil spills, where more than 200,000 tons of oil may be released into the environment [30]

## Conclusion

Waste management in oil drilling relies on an intricate interplay of technological efficiency, economic feasibility, and ecological consciousness. Although chemical methods are effective at eliminating contamination, they are costly and generate additional waste. Biosolution methods, on the other hand, are eco-friendly. Nonetheless, their efficacy heavily depends on local environmental variables. The most promising solution lies in integrating biological methods, especially with nanofilm technology and rapid oxidation, to address individual waste problems. The main hurdle now is the lack of standard procedures in deciding what methods to adopt. Research

should emphasize the development of combined-stage processes underpinned by quantifiable metrics of their environmental benefit, coupled with a better understanding of bacterial teams and how plants and bacteria work together. We need a transition away from site-based solutions toward the use of optimized, multi-functional systems to sustainably address this challenge.

## References

- [1] Y. C. Santiago, A. M. González, O. J. Venturini, and D. M. Y. Maya, "Assessment of the energy recovery potential of oil sludge through gasification aiming electricity generation," *Energy*, vol. 215, p. 119210, Jan. 2021.
- [2] N. Hossain, *The Aid Lab: Understanding Bangladesh's Unexpected Success*. Oxford, U.K.: Oxford Univ. Press, 2017.
- [3] R. M. Atlas, "Microbial degradation of petroleum hydrocarbons: An environmental perspective," *Microbiol. Rev.*, vol. 45, no. 1, pp. 180–209, Mar. 1981.
- [4] E. Manchón-Vizueté, A. Macías-García, A. N. Gisbert, C. Fernández-González, and V. Gómez-Serrano, "Adsorption of mercury by carbonaceous adsorbents prepared from rubber of tyre wastes," *J. Hazard. Mater.*, vol. 119, no. 1–3, pp. 231–238, Mar. 2005.
- [5] P. Farmer *et al.*, "A stroma-related gene signature predicts resistance to neoadjuvant chemotherapy in breast cancer," *Nat. Med.*, vol. 15, no. 1, pp. 68–74, Jan. 2009.
- [6] D. Jackson and E. Chapman, "Non-technical competencies in undergraduate business degree programs: Australian and UK

- perspectives," *Stud. High. Educ.*, vol. 37, no. 5, pp. 541–567, Jul. 2012.
- [7] D. Mara and N. J. Horan, Eds., *Handbook of Water and Wastewater Microbiology*. Oxford, U.K.: Elsevier, 2003.
- [8] M. S. Almansoori *et al.*, "Financial analysis of ADNOC," *SSRN*, 2021. [Online]. Available: SSRN.
- [9] S. Jeevanantham *et al.*, "Removal of toxic pollutants from water environment by phytoremediation: A survey on application and future prospects," *Environ. Technol. Innov.*, vol. 13, pp. 264–276, Feb. 2019.
- [10] R. N. Schulman, D. E. Salt, and I. Raskin, "Isolation and partial characterization of a lead-accumulating *Brassica juncea* mutant," *Theor. Appl. Genet.*, vol. 99, no. 3, pp. 398–404, Aug. 1999.
- [11] R. Dixit *et al.*, "Bioremediation of heavy metals from soil and aquatic environment: An overview," *Sustainability*, vol. 7, no. 2, pp. 2189–2212, Feb. 2015.
- [12] D. S. Malik, C. K. Jain, and A. K. Yadav, "Removal of heavy metals from low-cost adsorbents: A review," *Appl. Water Sci.*, vol. 7, no. 5, pp. 2113–2136, Sep. 2017.
- [13] M. V. Murhekar *et al.*, "SARS-CoV-2 seroprevalence among the general population and healthcare workers in India," *Int. J. Infect. Dis.*, vol. 108, pp. 145–155, Jul. 2021.
- [14] W. S. Masika *et al.*, "Biodegradation of petroleum hydrocarbon waste using consortia of *Bacillus* sp.," *Bioremediation J.*, vol. 25, no. 1, pp. 72–79, 2020.
- [15] T. P. Sathishkumar, P. Navaneethakrishnan, and O. Shankar, "Tensile and flexural properties of natural fiber reinforced composites," *Compos. Sci. Technol.*, vol. 72, no. 10, pp. 1183–1190, Jul. 2012.
- [16] S. Santisi *et al.*, "Biodegradation of crude oil by bacterial strains and consortium," *Braz. J. Microbiol.*, vol. 46, no. 2, pp. 377–387, Jun. 2015.
- [17] S. Robert *et al.*, "Affinage des huîtres creuses *Crassostrea gigas*...", Rapport, 1998.
- [18] M. E. Simonsen, J. Muff, L. R. Bennedsen, K. P. Kowalski, and E. G. Søggaard, "Photocatalytic bleaching of p-nitrosodimethylaniline and comparison with other AOP technologies," *J. Photochem. Photobiol. A*, vol. 216, no. 2–3, pp. 244–249, Dec. 2010.
- [19] R. Alshgayer, A. Salmiaton, T. Mohammad, A. Idris, and C. F. Ishak, "Removal efficiencies of constructed wetland planted with Phragmites and Vetiver for PAHs," *Sustainability*, vol. 12, no. 8, Art. no. 3357, Apr. 2020.
- [20] *Toxicological Profile for Polycyclic Aromatic Hydrocarbons*, Agency for Toxic Substances and Disease Registry (ATSDR), U.S. Dept. Health and Human Services, 1999.
- [21] R. E. Caughlan *et al.*, "Fmbypass in *Pseudomonas aeruginosa* induces MexXY expression," *Antimicrob. Agents Chemother.*, vol. 53, no. 12, pp. 5015–5021, Dec. 2009.
- [22] W. Namkoong, E. Y. Hwang, J. S. Park, and J. Y. Choi, "Bioremediation of diesel-contaminated soil with composting," *Environ. Pollut.*, vol. 119, no. 1, pp. 23–31, 2002.
- [23] C. Olivier *et al.*, "Association between *Demodex* infestation and rosacea," *Arch. Dermatol.*, vol. 146, no. 8, pp. 896–902, Aug. 2010.

- [24] D. E. Nicodem *et al.*, "Photochemical processes and environmental impact of petroleum spills," *Biogeochemistry*, vol. 39, no. 2, pp. 121–138, Nov. 1997.
- [25] I. Snape *et al.*, "Evaporation and biodegradation of fuel spills in Antarctica," *Chemosphere*, vol. 61, no. 10, pp. 1485–1494, Dec. 2005.
- [26] A. Borhan, S. Yusup, J. W. Lim, and P. L. Show, "Characterization of activated carbon from rubber-seed shell for CO<sub>2</sub> adsorption," *Processes*, vol. 7, no. 11, Art. no. 855, Nov. 2019.
- [27] M. A. Hoisington, J. R. Duke, and P. G. Apen, "High temperature polymeric foams," *Polymer*, vol. 38, no. 13, pp. 3347–3357, Jun. 1997.
- [28] B. Karn, T. Kuiken, and M. Otto, "Nanotechnology and in situ remediation," *Environ. Health Perspect.*, vol. 117, no. 12, pp. 1813–1823, Dec. 2009.
- [29] C. J. Philippopoulos and M. D. Nikolaki, "Photocatalytic processes on the oxidation of organic compounds in water," in *Photocatalysis*, 2010.
- [30] B. Mahanty, S. Jesudas, and A. Padmaprabha, "Toxicity of surface functionalized iron oxide nanoparticles," *Environ. Nanotechnol. Monit. Manag.*, vol. 12, p. 100235, Dec. 2019.
- [31] Strong, L. C., McTavish, H., Sadowsky, M. J., & Wackett, L. P. (2000). Field-scale remediation of atrazine-contaminated soil using recombinant *Escherichia coli* expressing atrazine chlorohydrolase. *Environmental Microbiology*, 2(1), 91–98.
- [32] Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L. C., Biak, D. R. A., Madaeni, S. S., & Abidin, Z. Z. (2021). Review of technologies for oil and gas produced water treatment. *Water Research*, 170, 115356. <https://doi.org/10.1016/j.watres.2021.115356>