Role of Vermiremediation in the Management of Heavily Polluted Oil Spill Environment: Current Trends

By

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Abstract

The surge in energy utilization in recent years can be attributed to quick population size, industrial advancements, and economic improvement in both developed and developing nations. Oil spills occurring from petroleum product exploration cause significant environmental damage. Paraffin, naphthalene, and aromatics are the primary hydrocarbon compounds that make up crude oil's chemical composition. Soil contaminated with crude oil is being treated using various methods to reduce the potential harm and danger to humans and the environment caused by crude-contaminated soils. The chemical, thermal, physical, and biological processes are the most used. Vermiremediation is an eco-friendly technology that utilizes earthworms to remove soil pollutants. Earthworms' ability to change the physical, chemical, and biological constituent of the soil results in a decrease in pollutant spread. This review has revealed the potential in different earthworms sp. like Eisenia fetida, Dendrobaena veneta and Eiseninus trilobatus, to be successful vermiremediators. The biphasic degradation curve during vermiremediation is influenced by factors such as particulate diameter distribution, organic matter percentage changes, crude oil constitution, and the addition of adjusted microorganisms. Vermiremediation is the foremost cleaning up process for large scale applications and it is also imperative for elimination of oil from polluted sites.

Keywords: Vermiremediation, Pollution, Oil spill, Environment, Hydrocarbons.

1. Introduction

The commercial revolution has led to a fast and expanding rate of industrialization in Europe, America, and Asia, while other regions are experiencing significant soil contamination from natural chemicals[1] [2]. The environment is often affected by natural chemicals, including petroleum hydrocarbons, volatile organic compounds, polycyclic aromatic hydrocarbons, halogenated

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hydrocarbons pesticides and polychlorinated biphenyls[3]. Organic pollutants in soil, as the primary source of natural chemicals, can pose potential hazards to humans and environmental health[4].

Accordingly, there has been a rise in the focus on purifying soils that are affected by natural chemicals[5]in recent years. Natural pollutants in soil are typically treated through chemical and physical methods, such as soil vapor removal, soil cleaning, stabilizing, and hardening, electrokinetic remediation, thermal desorption, in situ chemical oxidation, pumping, treatment, flushing techniques, monitoring, and natural attenuation[6].

Most of these techniques involve laborious procedures, high expenses, the disturbance of native soil microflora, and reversible changes in soil physicochemical characteristics[7 8 9]. Bioremediation has emerged as a promising alternative technology[10]. Typically, bioremediation involves the use of microbes, green plants, animals, or their enzymes to reinstate contaminated sites to their original state[11].

Bioremediation research has primarily focused on plant-remediation and bioremediation (micro-remediated), whereas employing soil fauna like earthworms to combat soil pollution has been given little awareness[12]. The constraint of plant-remediation and its lack of practicality are being evaluated, the focus should be on using earthworms as an innovation for soil therapy, with potential benefits[13].

Vermiremediation is a blend of 2 Latin words: -vermis (worm), and remedium (removal of evil). Vermiremediation is a bioremediating hi-tech that utilizes the earthworm's life span. The accumulation, transformation, hollowing, digestion, and secretion of pollutants in the soil environment are influenced by their interaction with other nonliving and living factors. Invertebrates, such as earthworms, consume harmful substances found in oil-contaminated soil through vermiremediation to reduce pollution of soil. The use of earthworms can effectively change the physical, chemical, and biological constituent of soil and decrease the spread of pollutants from the soil[14]. The gut of earthworms harbors many different microbes that initiate the

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process of decay[15]. The role of earthworms in blending contaminated soil and encouraging the production of enzymes that break down poisonous hydrocarbons in soil polluted with oil[16], is significant. A multitude of studies have illustrated that earthworms can endure in soil with elevated amount of oil content[17] [18]. Earthworms can survive in oil-rich soil due to their ability to effectively eliminate hydrocarbons.

2. Chemical Component of Oil Crude

Crude oil is a mixture of hydrocarbons (HCs), that occurs naturally on the surface of the earth. There are multiple crude oil types obtainable for sale. Bulkiness, sulfur, metals, and other factors determine its price. The constitution of crude oil is influenced by the locality, duration, and depth of the wells. HCs are present in crude oils up to 97 percent in crude Paraffin, but only as much as 50 percent is present in heavy and crude Bitumen. The refinery process is challenging, and the handling of heavy crude oils is problematic. The refinery performance and design of novel plants require knowledge of crude oil[19] [20]. Most of the HC compounds found in crude oils are paraffins, naphthenes, and aromatics. Paraffins are the primary HCs in crude oil, and they are highly valued in the market because they make up a sizable portion of gasoline[21]. Naphthenes, which are present in all liquid refined products, also make up some of similar heavy asphaltic remains of refineries[22]. Most crudes have a low proportion of aromatics. A popular petro-chemical industry feed, Benzene, is the most common aromatic component in crude oil[23].

2.1. *Paraffin or Alkanes*

The most prevalent HCs in crude oil are saturated (CnH2n+2) with paraffin or Alkanes[24]. Straight-chain paraffins, iso-paraffines with branched chains, and cyclic alkane are all examples paraffins. All Carbon elements possess a common bond like Methane (CH_4), and Propane(C_3H_8) (Figure 1). At atmospheric pressure, the 1st four composites are gas-like, while Pentane is in liquid form, followed by Hexane, Heptané, Octane, and others. Thermal or catalytic procedure called the isomerisation response are used to convert common paraffins into iso-paraffins compounds. Iso-

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[24] Olah, G. A. et al (2017). Op-cit

paraffins, which are branched composites that react more strongly than regular paraffin' and are recommendable in gasoline[25 26 27].

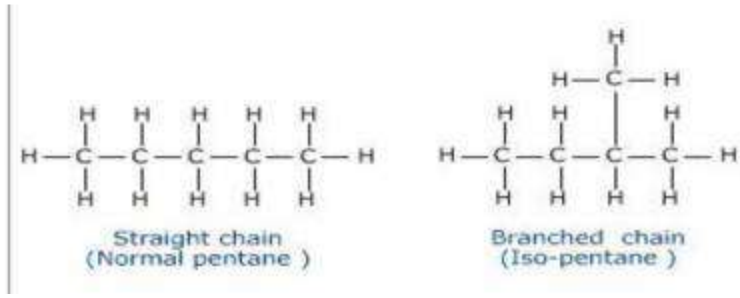

Figure 1: Structure of Paraffin/Alkanes

2.2. Naphthene's or Cyclo-alkanes

The HCs that are saturated and have a one carbon atom ring (CnH2n) are known as 'Cyclo-alkanes' as shown in Figure 2. Alkanes have a lower boiling point and higher carbon atom concentration than Naphthenes. Rings of 5 or 6 carbon atoms are frequently found in crude oil. These rings usually have alkyl replacement. Heavy amounts of crude oil contain numerous ring naphthenes. Naphthenes, which are saturated and proportionately inert, are preferred for the production of aromatic compound and high-quality lubricate base merchandise [28 29 30]

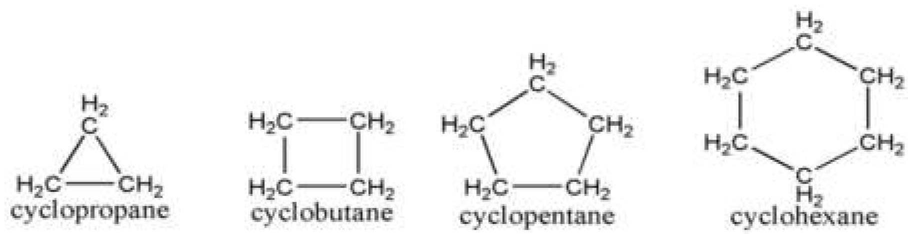

Figure 2: Structure of Naphthenes/Cyclo-alkanes

2.3. Aromatics

The formula (CnH2n-6) in unsaturated HC is found in aromatics, as shown in Figure 3. Organic acids are formed when O_2 attacks HCs. Aromatics can be obtained by dehydrating Naphthenes with platinum catalytic reaction. Lesser aromatic compounds, like benzene, toluene, and xylenes, are effective solvents and start-up materials in various petroleum derived chemicals [31]. The crude

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oil is a polynuclear aromatic complex, and it has dozens of Benzene rings that make it heavier. Coking and catalyst inactivation occur during refining when aromatics, particularly those with high concentration, are present. Crude oil products can be split from their aromatics using solvents like phenol, or diethylene glycol[32 33]

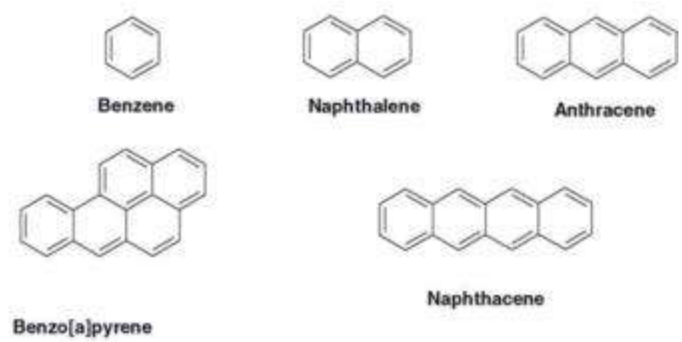

Figure 3: Structure of Aromatics.

2.4. Asphaltic

It is the most substantial element in crude oil. Its high quantity can cause significant refining issues. High density and gravitational attraction may hinder transportation. Coke is produced and metal is deposited on the catalyst exterior, causing it to become inactive (Figure 4) [34 35]

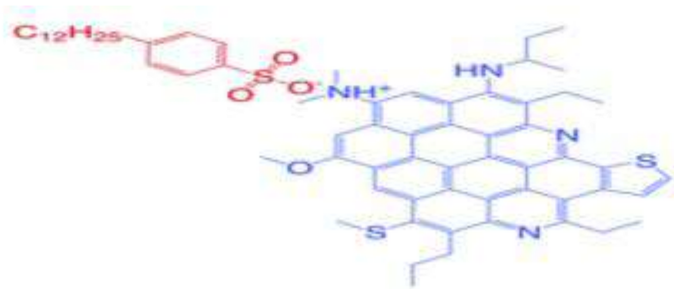

Figure 4: Structure of Asphaltic

2.5. Sulphur

Oil that is less than one percent is known as 'Sweet crude' and oil that exceeds one percent is called 'Sour.' Elements of sulfur heteroatoms in crude oil include native sulfur S, abiotic forms, and principally biotic forms where sulfur atom(s) are located within organic HC molecules. The alkyl radicals of sulphur are R and R1, with the universal formula being R-SH, R–S-R1, R-S-S-R1, and as such, they are appearing as single and double sulfides. The corrosion of methane is intense, whereas single and di-sulfides are not[36].

[32] Sugiura, K. et al. (1997). Op-cit
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2.6 Hydrogen sulphide (H_2S)

Hydrogen sulphide is found in crude oil in its dissolved form, and it is liberated under heat (Figure 5). Excessive temperature and moisture can lead to corrosive effects of hydrogen sulphide. When petroleum products are burned, sulfur results in diverse oxides of sulfur (SOx), which are powerful environmental contaminants. Hydrogen sulphide can be withdrawn from gases by sucking up in an amine mixture. Sulfur is present in hydrogen sulphide, mercaptans, and most HCs in weightier fractions of crude oil, 80 to 90 percent are typically found in the complex ring form. The sulfur atom in this mix is both stable and unreactive. The removal of sulfur from weightier petroleum requires a catastrophic reaction, such as critical thermal or reaction using catalyst. Today, sulphur is mined during purifying and the products are sold. Multiple catalysts are harmed by sulphur [37 38].

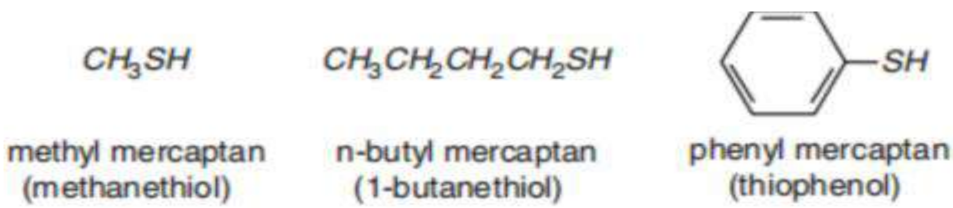

Figure 5: Structure of Sulphur compounds.

2.7 Nitrogen (N_2) compounds:

Nitrogen (N_2) in HCs are commonly gotten in the large components of crude oil (Figure 6). Certain catalysts can be poisoned due to the presence of N_2 and colour alterations. The asphaltic nature of oil results in a lager N_2 content. NOx, which are oxides of N_2 are produced when N_2 is in petroleum fuels, are also significant air contaminants. Catalytic addition of hydrogen atom to unsaturated oil, takes out N_2 from crude oil products. N_2 compounds have more stability as compared to sulphur, making them difficult to take out despite their minute concentration[39].

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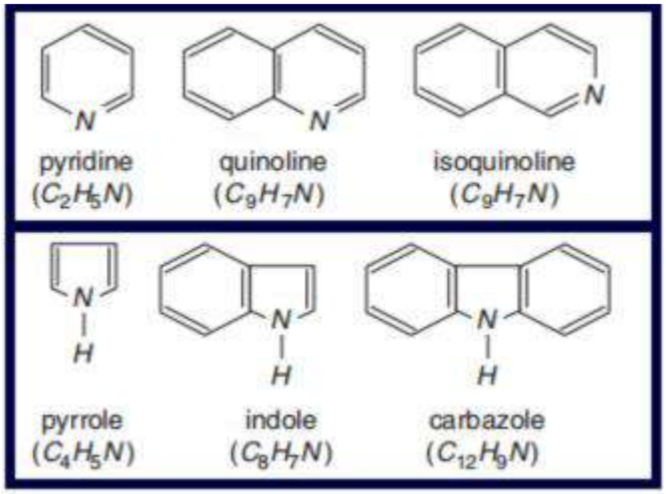

Figure 6: Structure of Nitrogen Compounds.

2.8 Oxygen compounds

Oxygenic compounds, like naphthenic acids, phenols, and cresols can be found in petroleum products due to their corroding properties. Many catalysts can be poisoned by O_2. This can be eliminated by means of addition of hydrogen atom to oil products by catalyst. Excessive O_2 compounds can even trigger an outburst (Figure 7).

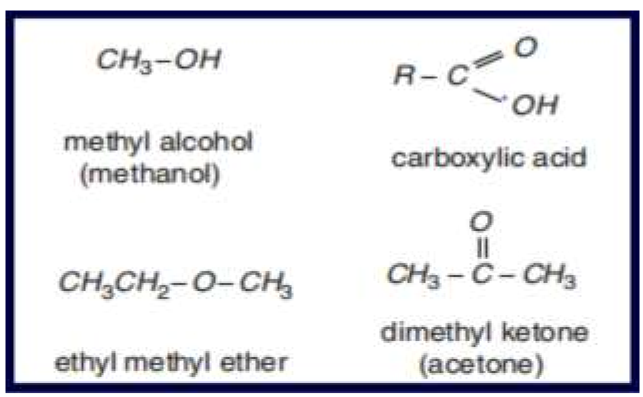

Figure 7: Structure of Oxygen Compounds.

2.9 Metallic compounds

Metallic substances, including vanadium (V), lead (Pb), nickel (Ni), and arsenic (As) are present in petroleum. The weightier fractions of petroleum contain porphyrins, which are organo-metallic compounds that can be found in the form of V and Ni. These metallic compounds are known to cause destruction to the burners, lines and burning chamber walls in petroleum products[40].

[40] Podgorski, D.C. et al. (2013). Op-cit

3. Soil Remediation (SR) Approaches

Soil remediation is the application of effective innovations to reduce and control risks from polluted environments that may pose health risks or adverse environmental consequences. The presence of polluted soil is frequently linked to past industrial activities and unchecked waste discarding customs. Despite following all relevant regulations, the negative consequences were later revealed due to improvements in trial techniques. Various origins, like chemicals, inappropriate discarding of industry wastes and leaks from tanks and pipes over the years, can lead to soil pollution.

Oil HCs polluting the soil are known to cause health risks[41]. Approaches involved in remediation play essential role in the polluted environment's total clean up, confinement, eliminating, recovery and repairing[42]. The remediation approach used in a polluted soil is unique to the site, considering the contaminants and their constitutions, as well as the environmental factors that affect it. Whether a remediation approach is effective in any tainted site or environment depends on the system's design and adaptation to contaminants, soil state, and system production[43]. The following section describes the key methods used for soil cleanup.

3.1 *Chemical process*

Chemical therapy involves the transfer of electrons between molecules through both oxidation and reduction reactions (Figure 8). The conversion of poisonous pollutants into less harmful ones occurs[44]. The use of multiple oxidants is being applied in advanced oxidation procedures to treat oil or polyaromatic HCs in soils. Chemical oxidation can be applied to polluted soil caused by petroleum, such as H_2O_2, potassium permanganate, Fenton's reagent, peroxymonosulfate, ozone, and chlorine[45] .

The utilization Fenton's reagent (FeII)–H_2O_2) for cleanup *via* chemical processes, an OH- radical can be produced using H_2O_2 as an oxidant in the presence of ferrous sulfate [46]. The OH- radical is an excellent oxidizing agent. Chemical oxidation can be achieved in soil polluted with polycyclic aromatic HCs using Fentons reagent[47]. A chemical procedure called electrical kinetic remediation is used to clean up soil polluted with crude HCs when utilizing direct electrical current in small quantities between the electrodes that are evenly distributed[48] .

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47 Sakshi, Singh, S. K., & Haritash, A. K. (2019). Polycyclic aromatic hydrocarbons: soil pollution and remediation. International Journal of Environmental Science and Technology, 16:6489-6512.

The mass of petroleum polluted soil is filled with electrodes that create a field of energy around the region. The liquid medium is drawn together by the resultant voltage [49] and flows towards the cathodes.

3.2 *Thermal procedure*

To clean up soil polluted with petroleum, this technique uses heat (Figure 9). The thermal procedure is composed of three main phases: thermal adsorption, incinerate, and oven frequent heat[50]. Contamination in the environment is of significant concern when using the incineration technique to remove pollutants from the soil. In order to eliminate contamination, an incinerator is used to burn oil that has been polluted with crude oil from 300 to 10000C [51]. Manipulating the temperature of HCs and enhancing their steam pressure, the thermal adsorption process can cause volatilization and deamination by dispersing contaminants from the soil [52]. By using microwave frequencies, a heating process can be used to convert heat from oven energy and remove contaminants through volatilization. The absence of microwave absorption prevents the adsorption of energy by soil particles and contaminants. Consequently, connecting microwave absorbers with soil that has been contaminated by crude oil, the oven energy can be converted into heat energy[53]. Thermal procedures with elevated heat are highly effective in removing crude oil contamination from soil.

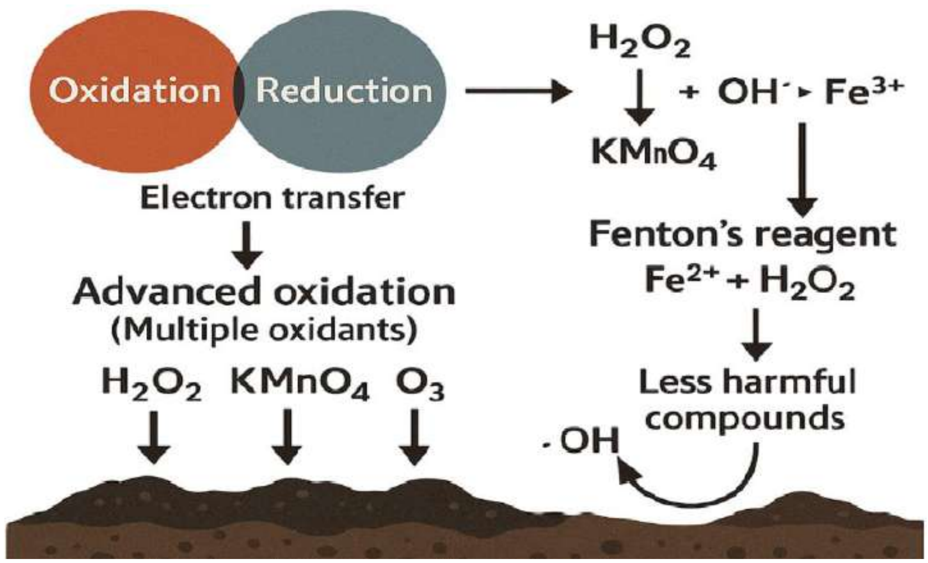

Figure 8: Chemical process of remediation

49 Hassan, I. A. (2016). Electrokinetic Enhanced bioremediation of soils contaminated with petroleum hydrocarbons (Doctoral dissertation, The University of Western Ontario (Canada).
50 Varjani, S. J., & Upasani, V. N. (2017). A new look on factors affecting microbial degradation of petroleum hydrocarbon pollutants. International Biodeterioration & Biodegradation, 120, 71-83.
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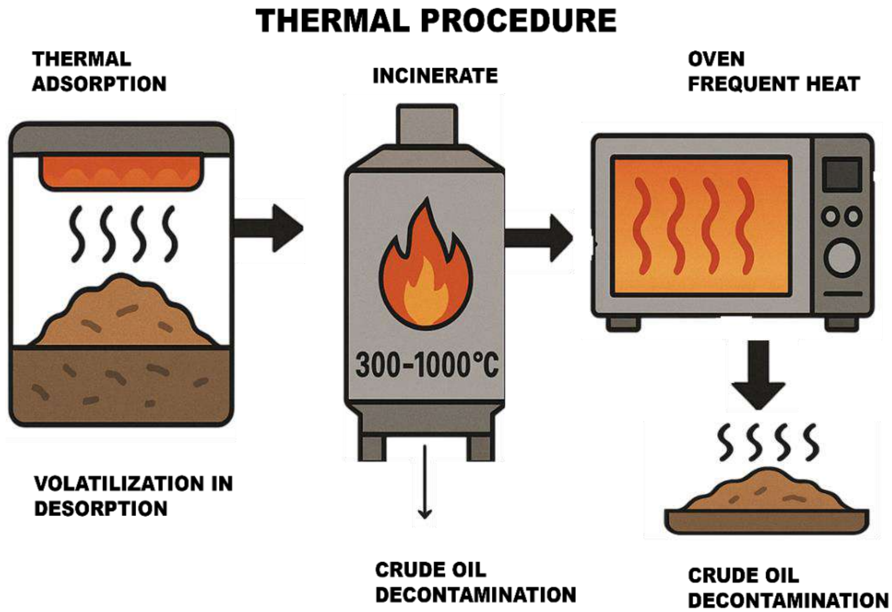

Figure 9: Thermal Process of Crude Oil Decontamination

3.3 *Physical procedure*

Ultrasonic and floating are both primary physical cleaning up methods for removing petroleum HC contaminants from environment[54]. The formation and fall in of cavitation bubbles, which are caused by shocked waves, are used to remove petroleum from contaminated soil through ultrasonication[55]. Bubbles will fall in implosively and bubble up at artificial nucleation, forming confined hot points in the fluid. The depletion of oil contamination from particles of soil and bond rapture are intensified by elevated heat [56]. Vacuum flotation depends heavily on the separation of contaminants from bubble-contaminant, interfacing between crude oil HCs and bubbles. It is correlated with great effectiveness in eliminating petroleum contamination and has low operating expenses. Mineral ore refining often employs flotation, a method to remove minerals physically and chemically. The process of flotation is intricately intertwined with a variety of factors, including the type and quantity of collectors, the speed and duration of conditioning for each batch, the duration required for processing, air flow, pulp size, pH level, temperature, and additives[57]. This method is best in the elimination of both biotic and abiotic compounds from contaminated environment.

[54] Ossai et al (2020)
[55] Mat-Shayuti, M. S., Tuan Ya, T. M. Y. S., Abdullah, M. Z., Megat Khamaruddin, P. N. F., & Othman, N. H. (2019). Progress in ultrasonic oil-contaminated sand cleaning: a fundamental review. Environmental Science and Pollution Research, 26, 26419-26438.
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The most efficient and safe approach to excavating crude oil-contaminated soil is not a cost-effective and advanced method. The unclean soil is dispatched to the applicable landfill for discarding. Soil is taken from the base and edges of the dig out region to determine if the site is uncontaminated or not[58]. A physical approach can be used to clean unkempt soil. Solvents (organic) like ethanol-water combination and ethyl acetate-acetone-water combination were used to wash the contaminated soil, resulting in the elimination of HCs from the soil[59]. Washing of soil not only removes heavy metal but also provides a solution to clean up oil polluted soil. Adding surfactants can increase the effectiveness of washing. Research revealed the potential of both artificial and native surfactants to remove petroleum. The removal of crude oil can be induced by various surfactants, for example, aliphatic HCs were eliminated from the polluted soil by sodium dodecyl sulfate (SDS), and polycyclic aromatic HCs, which were extracted from it by native surfactants such as saponin and rhamnolipid[60]. Although it is a simple and effective technique, it requires countless hours of time and money. Another significant issue is the movement of polluted soil to an appropriate site for disposal.

3.4 *Biological Techniques*

Microbes have been increasingly used to break down polyaromatic HCs for the past two decades and have received acceptance publicly. The worldwide attention in bioremediation is due to its environmental benefits and sustainability [61]. Through bioremediation, microbes have the ability to degrade pollutants into a less dangerous substance by producing enzymes that cleanse or mineralize polyaromatic HCs and facilitate their breakdown[62]. Indigenous microbes isolated from polluted sites have evolved to thrive in the *In situ* biological cleanup uses soil microbes to clean organic pollutants such as crude oil by changing the species of microelements to lessen their accessibility. These treatments can be executed in the presence or absence of air. Aerobic therapy involves the use of O_2, which can be aspirated *via* soil to motivate aerobic microbes. In contrast to anaerobic therapy, O_2 is absent and often supplemented with reduction agents. Non or somewhat chlorinated HCs are typically degraded by aerobic biogenic therapy, while remarkably high chlorine HC is decontaminated by anaerobic biogenic therapy[63].

The activation of native microbes or introducing specific microbes to the indigenous inhabitants, a microbial population can increase their ability to break down organic pollutants within soil. This process is also known as increased biological clean up. Addition of air, nutrients and change of pH

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[59] Fenyvesi, É., Gruiz, K., Morillo, E., & Villaverde, J. (2019). Traditional and innovative methods for physical and chemical remediation of soil contaminated with organic contaminants. *Engineering Tools For Environmental Risk Management*, 4:285-362.

[60] Zhao, Y., Sun, Y., Sun, H., Zuo, F., Kuang, S., Zhang, S., & Wang, F. (2024). Surfactant-Based Chemical Washing to Remediate Oil-Contaminated Soil: *The State of Knowledge. Toxics,* 12(9), 648. https://doi.org/10.3390/toxics12090648

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[62] Tripathi, S., Singh, V. K., Srivastava, P., Singh, R., Devi, R. S., Kumar, A., & Bhadouria, R. (2020). Phytoremediation of organic pollutants: current status and future directions. *Abatement of environmental pollutants*, 81-105.

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and temperature control can be used to enhance states for the microbes in breaking down of organic contaminant[64]. Many microbes that are native of the soil, including *Bacillus, Pseudomonas, Arthrobacter* and *Mycobacteria, Aeromonas, Corynebacterium, Sphingomonas, Xanthomonas* as well as *Acinetobacter* and *Micrococcus* [65].

3.4.1 *In situ* biological treatment

(i) Bioventing and Biosparging

Direct ingestion of air into the soil through bioventing and biosparging are similar methods that promote the breakdown of degradable compounds in the present of air. Biosparging is done in the saturated area below the groundwater table, while the bioventing process is conducted in the soil above the groundwater level or vadose zone. To breakdown organic pollutants, air is pumped at lesser rates for the stimulation and sustainability of existing soil microbes. The utilization of less air flow rate, organic matter can be reduced in evaporation and liberated into the atmosphere, which is commonly used to treat soil with less volatile HCs. Active carbon filtration or catalyst oxidation may be required to fix vapour removal and therapy for vaporous pollutants. The use of these method is prevalent in soil contaminated with crude oil, as they tend to emit less vaporous vapours[66].

(ii) Phytoremediation

Plant remediation is an *in-situ* technique that employs plants to treat contaminated soils. Its primary roles are to stabilize contaminated soils so that they are less moveable and harmful, and to remove them by reducing their breakdown or spreading to other mediums[67]. Plant remediation can be divided into several techniques, such as plant-stabilization, plant-extraction, and plant-degradation. Plant-remediation methods are highly dependent on the properties of the pollutants and soil, as well. The relationships between the soil's microbes and the root systems of plants are also crucial[68]. Plant remediation is a common solution for soil contamination with microelements; it can also help to biodegrade and eliminate organic pollutants[69].

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[68] Ma, Y., Oliveira, R. S., Freitas, H., & Zhang, C. (2016). Biochemical and Molecular Mechanisms of Plant-Microbe-Metal Interactions: Relevance for Phytoremediation. *Frontiers in Plant Science*, 7, 918. https://doi.org/10.3389/fpls.2016.00918

[69] Huang, X.-D., El-Alawi, Y., Gurska, J., Glick, B. R. and Greenberg, B.M. (2005). A multi-process phytoremediation system for decontamination of persistent total petroleum hydrocarbons (TPHs) from soils. *Microchemical Journal,* 81(1): 139–147.

(iii) Vermiremediation

Numerous chemical pollutants, like microelements and organic pollutants, can be absorbed by earthworms and biologically accumulate in their matters. The removal of lipid affinity organic pollutants, like pesticides and polycyclic aromatic HCs, from the soil is a known effect of earthworm species. Their moist wall bodies allow them to take in chemicals from the soluble soil fraction in intercellular fluid and consume them. The earthworm gut processes soil to either biologically break them down or biologically transform pollutants, making them non-poisonous or harmful (Figure 10). Consequently, by upgrading and dispersing the soil, worms can improve the physical, chemical, biological and environmental characteristics of the soil by providing essential nutrients such as N2, K, and trace elements in the form of vermicasts with other advantageous microbes[70]. The presence of earthworms and a proprietary blend of nitrogen-fixers, yeasts, and mushrooms in soil contaminated with 20 gram per kilogram to 60 gram per kilogram resulted in 99 % reduction of HCs content at the end of 22 weeks[71].

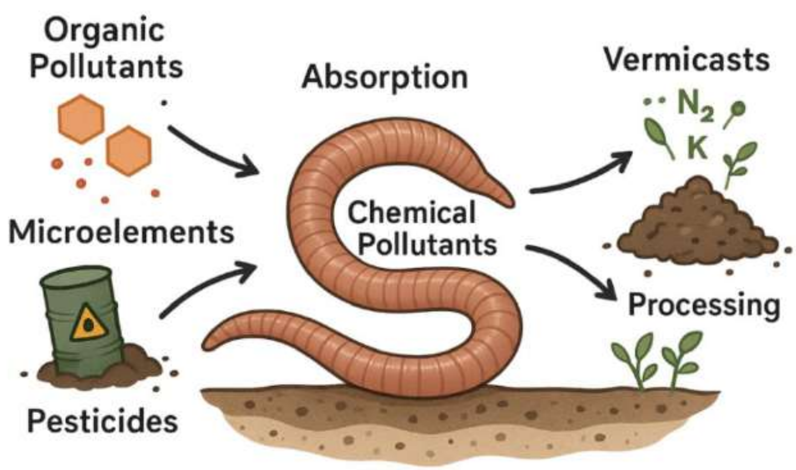

Figure 10: Remediation by earthworms

3.4.2 Ex- situ biological treatment

The soil is removed and treated on site or at a specialized soil therapy facility for external off-site biological treatment. Bioremediation procedures are akin to in-site treatment techniques. Ex-situ techniques offer greater control over biological remediation procedures, such as simple monitoring and control of soil uniformity, better mixing and connection between pollutants and microbes, and efficient use of macronutrients. Ex situ techniques are generally speedy and more certain; they

[70] Sinha, R., Bharambe, G. and Ryan, D. (2008). Converting wasteland into wonderland by earthworms – A low-cost nature's technology for soil remediation: A case study of vermiremediation of PAHs contaminated soil. *Environmentalist*, 28: 466–475

[71] Chachina, S. B., Voronkova, N. A., & Baklanova, O. N. (2016). Biological remediation of the petroleum and diesel contaminated soil with earthworms Eisenia fetida. *Procedia engineering,* 152, 122-133.

tend to be pricier than in situ alternatives. The soil structure and microorganisms are more easily affected by offsite procedures, resulting in lengthier post-remediation recovery time[72].

(i) Biopiles

Bio-piling, a biological cleanup process, is commonly employed to remove pollution from soils caused by various chemicals and petrochemicals. In this process, the removed soil is making uniform and altered to improve breakdown by microbes. These piles are frequently built and worked on like a windrow composting. A biological pile is also known as a biogenic cell. By adding macronutrients, minerals, moisture, or pH balancing, microbial inhabitants can be stimulated to grow under optimal conditions[73].

(ii) Bioleaching

Biological leaching employs the use of solutions inoculated with microbes. This is an effective method of extracting microelements from contaminated environment. The mining industry employs this substitute method to cyanide for recovering metals from those with small amount of minerals or mined wastes[74] . Soil reclamation is regarded as an efficient and less expensive option to physical and chemical therapeutic technology[75]. The contaminated soil is deposited off site with the inoculated liquid. Microbes target ore pollutants as the liquid travels through the soil, dissolving into the leachate and accumulating in its place at bottom of pile. The leachate undergoes additional processing to retrieve or safely discard the ore. One likely drawback of the techniques is that flow passage could form without treatment of escaped soil.

(iii) Composting

The removed contaminated soil is mixed with compost and non-toxic bulking agent in the present of air in offsite technique, similar to bio-piliation, which provide optimal air and moisture supply for microbes. The blend typically consists of 75% contaminated soil and 25% organic content, which can be adjusted based on the nature of contamination and accumulation of these substances' concentration[76]. Mechanical churning of the pile can promote the composting process by homogenizing the blend, promoting aeration during clogging, and maintaining biogenic consistency throughout.

(iv) Landfarming

The offsite biological cleanup process of farming involves transporting removed contaminated soil to a landfarming site and spreading it thinly onto biogenically active land or an impenetrable surface. Manure is sometimes added to contaminated soil, which is then dug down into the soil

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[73] Pavel, L. & Gavrilescu, M. (2008). Overview of ex situ decontamination techniques for soil cleanup. *Environmental Engineering and Management Journal,* 7: 815–834.

[74] Liu, Y.-G., Zhou, M., Zeng, G.-M., Li, X., Xu, W.-H. & Fan, T. (2007). Effect of solids concentration onremoval of heavy metals from mine tailings via bioleaching. *Journal of Hazardous Materials*, 141(1): 202–208.

[75] Chen, S.-Y. & Lin, P.-L. (2010). Optimization of operating parameters for the metal bioleaching process of contaminated soil. Separation and Purification Technology, 71(2): 178–185.

[76] Kumar, A., Bisht, B.S., Joshi, V.D. & Dhewa, T. (2011). Review on Bioremediation of Polluted Environment: A Management Tool. *International Journal of Environmental Sciences,* 1079–1093

surface. The process triggers breakdown in the natural environment, with ploughing (aerobic stimulation) and growth-promoting nutrients being used. In KwaZulu-Natal province, South Africa, soil contaminated with creosote has been treated through land reclamation[77 78].

(v) Bioreactors

Open or closed bioreactors are used to stir the soil and add nutrients that activate microbes to breakdown pollutants. Depending on the biodegradable pollutants and microbes, they can be operated in the presence of or absent of air. The cleanup approach is typically quicker than static remediations. The two primary phases are solid and liquid. A solid-state bioreactor is typically a closed reaction chamber with agitators found inside which are used in the process and can be completed in 42 days. Bioreactors are successful in treating tropical soil that has been contaminated with Petroleum HC. A liquid state bioreactor is used to stir the polluted soil with water and stirrers. The procedure is a batch type. When wanted level of pollution is attained, the soil solids are sieved back into the location and H_2O is stored for next time. Solid and liquid state reactors facilitate a highly controlled and rapid breakdown process due to balancing of materials' and the microbes' contact with pollutants[79 80].

3.5 Earthworm Ecology

The primary fauna and a crucial useful part of earthly soil structure are earthworms. By consuming roughly twice as much soil per day of their own body weight, they were able to notable impact the growth of soil profile[81] . The soil matrix's earthworm activity has a notable impact on the chemical, physical, and microbial characteristics of the soil and the activities of other organisms in there. The role of earthworms makes them ecosystem designers[82]. Earthworms are classified into three eco-friendly groups, i.e., epigeics, endogeics and anecics[83]. Inhibiters, or epigeics, thrive on leaves debris and occasionally on bark of tree, and they consume significant quantities of unprocessed material. They do not form tunnels but alternatively, they feed on the leaf debris[84]. They exhibit a brief life span, are tiny and often red brown, have high predation resistance, and are relatively exposed to climate change and prey forces. The use of *Eisenia foetida* (redworm) in vermicomposting is quite common. Among the species of epigeics are *Satchellius mammalis, Dendrobaena octaedra, Heliodrilus oculatus, Lumbricus festivus, Eiseniella tetraedra, Dendrodrilus rubidus, Dendrobaena attemsi,* and *Lumbricus friendi.*

The upper part of the soil is where Endogeics live and occupy by creating non-permanent parallel tunnels. Waste integration and breakdown are less important for these species as they consume

[77] Pavel et al (2008). Op-cit
[78] Kumar et al (2011). Op-cit
[79] Pavel et al (2008). Op-cit
[80] Kumar et al (2011). Op-cit
[81] Bartlett, M. D., Briones, M. J., Neilson, R., Schmidt, O., Spurgeon, D., & Creamer, R. E. (2010). A critical review of current methods in earthworm ecology: from individuals to populations. *European Journal of Soil Biology,* 46(2), 67-73.
[82] Pavel et al (2008). Op-cit
[83] Römbke, J., Jänsch, S., & Didden, W. (2005). The use of earthworms in ecological soil classification and assessment concepts. Ecotoxicology and Environmental Safety, 62(2):249-265.
[84] Nielsen, U. N. (2019). Soil fauna assemblages. Cambridge University Press.

subterranean matter. In addition to other soil development processes, they are crucial for root breakdown, soil mix, and air circulation. They exhibit a range of dimensions, have varying life cycle, slow migration, and are white in color[85]. Draught triggers torpor in some individuals, leading to less predation forces from exterior habited animals. *Octolasion lacteum, Allolobophora chlorotica, Apporectodea rosea* and *Appirectovade caliginosa* are all examples of endogeic earthworms. The mineral horizon of the soil is where anecics, or perpendicular tunnellers, stay always and are believed to thrive[86]. Large, dark-colored, sluggish-moving insects that feed on leaves found on the exterior layer of the soil, are decomposers and can force them into tunneling where they can maintain a lengthy lifespan. Anecics live in tunnels that form a tiny weather gradient, and worms can be found in different depths depending on the environment. Anecics play important roles in decomposing organic matter, balancing nutrients and soil development. Predation is intense at the surface, but anecics are shielded in their tunnels. In a subdued state, they usually endure dry periods. Nightcrawlers (*Lumbricus terrestris* and *Aporrectodea longa*) are the most prevalent sold by fish-bait.

3.6 *Vermiremediation studies*

Vermiremediation, worms convert solid organic matter and litter into vermi-manure, which serves as a soil moisturizer and nutrient-rich compost[87]. Earthworms have the potential to notable reduce the pollution in the soil due to organic debris. Vermiremediation has gained awareness in recently[88]. The following is a compilation of published research on the efficacy of soil remediation for organic contamination.

Almutairi, utilized *Lumbricus terrestris* and *Eisenia fetida* to treat soils with petroleum HC contamination over 60 days. The conclusion of these tests revealed a significant decline in total HCs present in polluted soil[89]. Biological stimulant preparation containing bacteria was used to investigate its effectiveness of biological cleanup of polluted soil with oil, petroleum, and diesel fuel by *Dendrobaena veneta*. After twenty-two weeks of soil remediation, the HC content in the soil reduced to 95 percent [90]. The existence and cleaning up abilities of worms were examined in the presence of bacteria and fungi (biostimulant) when subjected to motor oil-polluted soil [91]. After a 4-month pilot study, only 99.9 percent of participants reported success [92]. Another study by

[85] Le Bayon, R. C., Bullinger, G., Schomburg, A., Turberg, P., Brunner, P., Schlaepfer, R., & Guenat, C. (2021). Earthworms, plants, and soils. Hydrogeology, chemical weathering, and soil formation, 81-103.
[86] Capowiez, Y., Marchán, D., Decaëns, T., Hedde, M., & Bottinelli, N. (2024). Let earthworms be functional-Definition of new functional groups based on their bioturbation behavior. *Soil Biology and Biochemistry,* 188, 109209.
[87] Hajam, Y. A., Kumar, R., & Kumar, A. (2023). Environmental waste management strategies and vermi transformation for sustainable development. *Environmental Challenges*, 100747.
[88] Lacalle, R. G., Aparicio, J. D., Artetxe, U., Urionabarrenetxea, E., Polti, M. A., Soto, M., Garbisu, C., & Becerril, J. M. (2020). Gentle remediation options for soil with mixed chromium (VI) and lindane pollution: biostimulation, bioaugmentation, phytoremediation and vermiremediation. *Heliyon*, 6(8), e04550. https://doi.org/10.1016/j.heliyon.2020.e04550
[89] Lacalle, R. G. et al. (2020). Op-cit
[90] Almutairi, M. (2019). Vermiremediation strategy for remediation of Kuwaiti oil contaminated soil. *SN Applied Sciences*, 1(11), 1312.
[91] Chachina, S. B., Voronkova, N. A., Shadrin, M. A., & Evdokimov, N. S. (2019). The recultivation of the soils, contaminated with petrol and diesel fuel, with the help of earthworms *Dendrobena veneta* and the complex of microorganisms. In IOP Conference Series: *Earth and Environmental Science* (Vol. 315, No. 5, p. 052065). IOP Publishing
[92] Chachina, S. B. (2019). Op-cit

Chichina *et al*. [93] the worm sp. *E. fetida* was reported that within 22 weeks, low HC concentrations were cleaned up to about 99 percent with and without a biological preparation liquid.

In other investigations, *Eisenia fetida* could increase elimination to 91 percent of pyrene, 99 percent of phenanthrene, 91 percent of anthracene, 16 percent of benzo[a]pyrene (BaP) and 43 percent of fluoranthene from crude oil polluted soils accordingly. Earthworm's gut microbes, such as *Pseudomonas* and *Acidobacterium*, *Penicillium*, *Mucor*, or *Aspergillus*, may also contribute to the elimination rate[94]. The effectiveness of vermiremediation is influenced by the accumulation and constitution of crude oil and the microbes present in soil. Worms can increase the elimination of petroleum HC by stirring with or supplying air in the soil.

Earthworms, bacteria the undergoes photosynthesis, nitrogen fixing bacteria and fungi were used to remove engine oil from soil; these methods removed 4 to10 times as much of the solute than with no earthworm, but when products such as microbiologic products were added together, the remove effectively 99 percent[95]. These studies suggest that earthworms may have the ability to remove inorganic pollutants from the surrounding soil [96] Additionally, worms play a crucial role in the cleanup of crude oils at greater concentrations and shows accelerated decomposition of aliphatic HCs <C21. According to Patel *et al*. [97]petroleum HC was degraded at a rate of 90 mg per day 1. Earthworms can be utilized for Insite vermiremediation in soils polluted with crude oil, provided the HC levels are at average (4000 mg kg-1)[98].

3.7 Role of earthworms in the stimulation of microbial soil populations

In the community of microorganisms, earthworms are an essential fauna group that has significant figure and organic matter, making their impact crucial [99]. Furthermore, earthworms can take in substrate or soil at a high frequency. Curry and Schmidt suggest that epigeic earthworms can consume dung or litter amounts of 3 to 50 milligram per gram of worm per day, while geophagous worm types can take in 200 to 6,700 milligram per daily meal. The bounty activity of soil microbes is affected by earthworms, which have different functional groups[100].

The impact of epigeic worms on microbes' diversity is not uniform. Evidence suggests that they have the ability to either reduce or increase microbial organic matter. The number of microbes is

[93] Chachina, S. B. (2019). Ibid

[94] Zeb, A., Li, S., Wu, J., Lian, J., Liu, W., & Sun, Y. (2020). Insights into the mechanisms underlying the remediation potential of earthworms in contaminated soil: A critical review of research progress and prospects. *Science of the Total Environment*, 740, 140145.

[95] Zeb, A. et al. (2020). Ibid

[96] Dada, E. O., Akinola, M. O., Owa, S. O., Dedeke, G. A., Aladesida, A. A., Owagboriaye, F. O., & Oludipe, E. O. (2021). Efficacy of vermiremediation to remove contaminants from soil. *Journal of Health and Pollution,* 11(29), 210302.

[97] Patel, A. B., Shaikh, S., Jain, K. R., Desai, C., & Madamwar, D. (2020). Polycyclic aromatic hydrocarbons: sources, toxicity, and remediation approaches. *Frontiers in Microbiology*, 11, 562813.

[98] Zeb, A. (2020). Op-cit

[99] Medina-Sauza, R. M., Álvarez-Jiménez, M., Delhal, A., Reverchon, F., Blouin, M., Guerrero-Analco, J. A., ... & Barois, I. (2019). Earthworms building up soil microbiota, a review. *Frontiers in Environmental Science*, 7, 81.

[100] Curry, J. P., & Schmidt, O. (2007). The feeding ecology of earthworms – A review. *Pedobiologia* 50, 463–477.

not frequently affected by their action, as reported. Epigeic worm species *Eisenia andrei* and *E. fetida*, are the primary subjects of literature that were conducted in artificial laboratory settings [101].

3.8 The Endogeics

The effects of endogeic worms on the abundant of microbes differ from those of epigeics, despite limited research being conducted. Most research on endogeics compares the effect of earthworms on the microbiota in soils with and without the worms. The research on "flashpoint" (gut and fresh vermicompost) is insufficient. In regions where soil from arable land (3.8 percent of biomass) and remainder of potatoes on the exterior, the endogeic *Aporrectodea caliginosa*, did not affect the biomass of soil microbes measured by confocal laser scanning microscopy[102]. Unlike others, Bohlen *et al*. [103]. conducted a PLFA analysis which showed that *Octolasion lacteum* increases bacterial organic matter in soil blended with waste Bohlen *et al*. made comparable observations for a pot experiment and found that soils with *Pontoscolex corethrurus* earthworm had higher number of bacterial 16S rRNA genes than those without worms [104].

A study revealed that the gut of *P. corethrurus* contained a 6-fold increasement in the activity of microbes. In comparison to the environmental vertisol, the vermicompost were found to have a 1.6-fold increasement and more colony-forming unit in the vermicompost *via* plate count[105]. On the other hand, with an increase in endogeic earthworm organic matter, soil microbial organic matter reduces[106]. Chapuis-Lardy *et al*. [107] showed a significant reduction of 2-fold in the organic matter of fungal and bacterial vermicompost. The earthworm vernicompost activity did not affect the proportion of bacteria to fungi, but vermicompost from *P. corethrurus* remained similar to the parent soil. According to Sheehan *et al*. [108]the effect of deepness of soil on endogeic worms may be directly proportional to the biomass of soil microbes

3.9 The Anecics

Anecic earthworms feed on the exterior and construct lasting underground passage to blend with various soil layers. The burrowers create scrap heaps on the soil surface at the entrance, which contain clear humus and vermicompost that are later removed into the soil horizon [109]. Anecics can have a broad effect on the soil, unlike other operational groups. Although the majority of research

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[101] Postma-Blaauw, M. B., Bloem, J., Faber, J. H., Van Groenigen, J. W., De Goede, R. G., & Brussaard, L. (2006). Earthworm species composition affects the soil bacterial community and net nitrogen mineralization. *Pedobiologia*, 50(3):243-256.

[102] Postma-Blaauw, M. B. et al. (2006). Ibid

[103] Bohlen, P.J., Parmalee, R. & Blair, J. (2004). Integrating the effects of earthworms on nutrient cycling across spatial and temporal scales. In C. Edwards, ed. *Earthworm Ecology*. 161–180.

[104] Bohlen, P.J., et al. (2004). Ibid

[105] Medina-Sauza, R. M., Álvarez-Jiménez, M., Delhal, A., Reverchon, F., Blouin, M., Guerrero-Analco, J. A., ... & Barois, I. (2019). Earthworms building up soil microbiota, a review. *Frontiers in Environmental Science*, 7, 81.

[106] Sheehan, C., Kirwan, L., Connolly, J., & Bolger, T. (2008). The effects of earthworm functional diversity on microbial biomass and the microbial community level physiological profile of soils. *European Journal of Soil Biology*, 44(1), 65-70.

[107]Chapuis-Lardy, L., Brauman, A., Bernard, L., Pablo, A. L., Toucet, J., Mano, M. J., ... & Blanchart, E. (2010). Effect of the endogeic earthworm Pontoscolex corethrurus on the microbial structure and activity related to CO2 and N2O fluxes from a tropical soil (Madagascar). *Applied Soil Ecology*, 45(3), 201-208.

[108] Sheehan, C. (2008). Op-cit

[109] Medina-Sauza, R. M., Álvarez-Jiménez, M., Delhal, A., Reverchon, F., Blouin, M., Guerrero-Analco, J. A., ... & Barois, I. (2019). Earthworms building up soil microbiota, a review. *Frontiers in Environmental Science*, 7, 81.

indicates a good or neutral influence on the abundance of soil microbes, this may be due to influence of some studies using *Lumbricus terrestris* as graft material in temperate regions, and insufficient data collection techniques.

The number of colony-forming unit in the soil outer surface (0.5–5 cm) was found to be 60–320 times higher in vermicompost of *L. terrestris*. The soil around *L. terrestris* was enriched with lettuce, unlike the other soil. Despite being lower in size, the increase in depth (5-22 cm) was still significant, with the drilosphere having 6-32 times more bacterial colony-forming unit than in the soil. The effect of soil deepness was also supported by Sheehan *et al*. who also reported the effects of anecic worms *Lumbricus friendi* and *Aporrectodea longa* on the biomass of microbes, which were found to be different in the soil layer in this study[110]

The anecic *L. terrestris* was tested in a blend of soil with waste from lime model trial. *L. terrestris* generated a greater proportion of biomass in soil than the other soil[111]. The results of this experiment relay on waste and the Corg and N content of soil, repetition of same investigation with beech litter soil, which has three times the Corg and Nitrogen content in the same amount as lime litter soil, showed a lesser increase in the biomass of tunneled microbes. PLFA measurements revealed a greater number of microbes in the tunnel walls of *L. terretris*[112]. The bulk soil is compared to *L. terrestris* (89.4 and 56.7 nmol per gram soil accordingly) as reported by Stromberger *et al*. [113]. Sampedro and Whalen [114] and Aira *et al*. [115] in scrap heap found that *L. terrestris* also had indistinguishable outcome with microbial PLFA in their guts. Numerous literatures suggest that anecics have a positive impact on biomass of microbes in their tunnel, scrap heaps or vermicompost; however, some studies have shown impartial influence[116] or detrimental effect [117].

Even though most research centers on how one species of earthworm or species from the same ecological group affects, it is important to note that all three functional groups are co-localized in native states. The study of earthworms' influence on soil microbes must involve the entire earth worm population. This point has been a relatively insignificant subject, but only Postma-Blaauw *et al*. [118] demonstrated that *L. terrestris* (anecic) that resides in soil, did not affect microbes present in it. *L. terrestris* and *L. rubellus* (epigeic) led to a rise in the number of microbes. The biomass was found to be lower by these authors when tried out together, and when all three functional

[110] Sheehan, C. (2008). Op-cit
[111] Tiunov, A. V., Bonkowski, M., Tiunov, J. A., & Scheu, S. (2001). Microflora, Protozoa and Nematoda in Lumbricus terrestris burrow walls: a laboratory experiment. *Pedobiologia*, 45(1), 46-60.
[112] Stromberger, M. E., Keith, A. M., & Schmidt, O. (2012). Distinct microbial and faunal communities and translocated carbon in Lumbricus terrestris drilospheres. *Soil Biology and Biochemistry*, 46: 155-162.
[113] Stromberger, M. E. et al. (2012). Op-cit
[114] Sampedro, L., & Whalen, J. K. (2007). Changes in the fatty acid profiles through the digestive tract of the earthworm Lumbricus terrestris L. Applied soil ecology, 35(1):226-236.
[115] Aira, M., Monroy, F., & Domínguez, J. (2009). Changes in bacterial numbers and microbial activity of pig slurry during gut transit of epigeic and anecic earthworms. *Journal of Hazardous Materials*, 162(2-3):1404-1407.
[116] Postma-Blaauw, M. B., et al. (2006). Op-cit
[117] Yu, J., Hu, F., Huixin, L., and Chunyun, M. (2008). Earthworm (*Metaphire guillelmi*) effects on rice photosynthates distribution in the plant–soil system. *Biology and Fertility of Soils* 44:641–647.
[118] Postma-Blaauw, M. B. et al. (2006). Op-cit

groups were merged, the microbial biomass decreased Scheu *et al.* explains on the significance of exploring the combined influence from different earthworm functional groups [119].

During a controlled outdoor experiment, it was discovered that the biomass of soil microbes increased notably when three species of epigeics and endogeics were combined, surpassing the biomass of independent earthworm groups. The dimensional diversity of earthworm influence may be concealed when evaluating the biomass of soil microbe entirely. In flashpoint, the microbial number may be increased while in bulk soil, it may decline due to factors such as soil consuming rate, denseness of earthworm and functional group presence [120]. Considering the total number of microorganisms may help identify areas where taxa may have been successful but others not so much.

3.10 Vermiremediation technique using earthworm species in reducing total petroleum hydrocarbons (TPHs) and polycyclic aromatic hydrocarbons (PAH) concentrations in crude oil polluted soil.

Crude oil is used to make petroleum products, TPHs are a mixture of hydrocarbon compounds from in crude oil. Aliphatic and aromatic compounds are included in TPHs, with the most of concern being PAH which is poisonous and can cause mutations. They contain aromatic HCs that have two or more benzene rings in different configurations according to Tagliabue *et al*. [121]. These compounds are toxic to the environment because of their tenacity, stable molecularly and are immiscible with water[122]. Multiple studies have revealed that various earthworm species can decrease PAH and TPH levels in polluted soil.

In their research, Nassar and Said analyzed samples that contained two different amounts of light crude oil, 5ml or 7.5 ml once every 60 days [123]. The activity of *A. caliginosa* of was recorded for TPH loss at 33. 56 percent and 54.98 percent of soil polluted with 5 ml of crude oil after 22 and 60 days accordingly. Although 32.24 percent and 71.05 percent of TPH were lost due to the pollution of 7.5 ml soil with crude oil during the same timeframe[124].

Three earthworm species, including *A. chlorotica, E. fetida* and *L. terrestris*, were evaluated for about 28 days in soil polluted with petroleum as part of a separate study. TPH levels decreased by 17-18 percent, 30-40 percent, and 31-31 percent accordingly). Even so, the TPH levels in unicorn samples showed a decline of 9-17 percent from the initial THP values[125]. Nobili *et al*. [126] reported the trial of vermiremediation with *E. fetida* and *A. morrisi*, both single and in combination with

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pre-composted matrix polluted with TPHs[127]. The breakdown of TPHs in nutrients with worms was notable and obvious, surpassing the negative control. Treating polluted soil with *E. fetida* indicates the greatest decrease of 60.81 percent, then 46.74 percent decrease by *A. morrisi* and the inclusion of both species result in a 45.25.2 percent decrease. According to this research, *E. fetida* is an efficient species for vermiremediation process over *A. morrisi.*

In 2007, Schaefer and Juliane examined the impact of crude oil on soil by analyzing its TPH. The compass 9500 mg/kg of crude oil were present. Earthworm species were also included in it, that is *E. fetida, A. chlorotica* and *L. terrestris* with 0.6 percent of the animal excrement [128]. It was determined that *E. fetida* and *A. chlorotica* caused the removal of 1.8 times greater, while *L. terretris* display a 4.6-fold elimination greater than the soil used as control that is, in the absence of earthworms. The addition of 0.5 percent of the excrement dumped in cattle to affected soil with crude oil with the TPH content of 10,000 mg/kg, it was determined that *L. terrestris* led to 2.5-fold increase in breakdown process and *E. fetida* exhibited 1.9-fold crude oil breakdown. In contrast to soil lacking earthworms, *A. chlorotica* displayed comparable outcomes as described previously. The influence of earthworms on the polluted oil is influenced by rays strictly on specie. The test revealed that *A. chlorotica* is sensitive and has a lesser chance of survival[129].

E. fetida potentials to restore PAHs soil health according to the investigation Fawole *et al*. Among the contaminants used in this experiment, Benzo(e)pyrene (BeP), Acenaphthylene (AcPY), and Benzo(ghi)perylene (BP), they differ in the configuration of their structure[130]. It was found that the polycyclic aromatic HCs vermiremediation in soil performed perfectly. The findings showed that these contaminants were broken down into different metabolites. Particularly *E. fetida* is responsible for the rapid elimination and subsequent cleanup of polycyclic aromatic HCs[131]. *P. corethrurus* was mixed with grass and bacteria leads to high elimination of polycyclic aromatic HCs from 2 and 3 rings 54 to 62 percent, 4 rings 56 to 92 percent, 5 rings 80 percent and 6 rings 70 percent within 112 days. TPH was highest in unsterilized therapy when used with worms with the addition of bacteria (E+B) which yielded 86.4 percent, was followed by E+G+B 82.7 percent and B 82.6 percent[132] .

A research work was conducted by Yang *et al*. [133] to ascertain the breakdown of pyrene, PAH that is highly resistant to decomposition by earthworm (*E. Fetida*) and microorganisms found in soil. A container containing 200 grams of pyrene was used to artificially pollute the soil with microorganisms and earthworms. The addition of *E. fetida* to this polluted soil led to a decrease of

127 Nobili, S. et al. (2022). Ibid

128 Schaefer, M. & Juliane, F. (2007). The influence of earthworms and organic additives on the biodegradation of oil contaminated soil. Applied Soil Ecology 36:53–62

129 Schaefer, M. & Juliane, F. (2007). Ibd

130 Fawole, C., Salami, S. J., Dashak, D. A. & Chimezie-Nwosu, H. A. (2021). "Bioengineered Approach for Ex Situ Vermiextraction of Acenaphthylene, Benzo (E)Pyrene and Benzo (Ghi) Perylene Soil Contamination". Current Journal of Applied Science and Technology 40 (32):29-36. https://doi.org/10.9734/cjast/2021/v40i3231556.

131 Fawole, C., J. et al. (2021). Ibid

132 Rodriguez-Campos, J., Perales-Garcia, A., Hernandez-Carballo, J., Martinez-Rabelo, F., Hernández-Castellanos, B., Barois, I., & Contreras-Ramos, S. M. (2019). Bioremediation of soil contaminated by hydrocarbons with the combination of three technologies: bioaugmentation, phytoremediation, and vermiremediation. Journal of soils and sediments, 19:1981-1994.

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68.7 percent of pyrene. This decrease in the non-sterilized soil was caused by earthworm and microorganisms [134].

In a separate study, the potentials *D. modesta* (epigeic) and *L. mauritii* (anecic), worms were examined together. The *D. modesta* (epigeic) and *L. mauritii* (anecic), is utilized to rehabilitate the soil that has been contaminated by PAHs and TPHs. These species chosen by the researcher, which are generally known for their potential to remove toxic HMs in industrially polluted nutrients; nevertheless, they remain few in research with crude oil pollution[135] .

Co-inoculation of these worms with authors has been found to modify the pollution level until the intermediary dose (7.5 mL), with total petroleum hydrocarbons and polycyclic aromatic hydrocarbons decreased by 68.6 percent and 34.3 percent as mentioned by Rajadurai *et al*. [136].

3.11 The time scales are required for vermiremediation

The vermiremediation process lacks a specific time frame, but the reports of myriad studies on the pollution of crude oil demonstrate that there may be differences in the required time to achieve success as shown in Table 1. Depending on the type of earthworm and the level of soil pollution, vermiremediation may take a few days or weeks [137]. The limited time in vermiremediation studies makes the level if break down after one or some months is not known, leading to a significant information gap. The determination of the duration of petroleum degradation in the presence of worms is a crucial aspect of vermiremediation's suitability[138].

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[134] Yang, W. et al. (2020). Ibid

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[136] Rajadurai, M. et al. (2022). Ibid

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Table 1: Shows the time scale for vermiremediation

Earthworm species	Time scale	Reference
Lumbricus rubellus	60 days	[139]
E. fetida, E. andrei, D. veneta	4 months	[140]
E. fetida	22 weeks	[141]
E. Andrei	30 days	[142]
Eisenia Fetida	3 weeks	[143]
E. fetida, L. terrestris	60 days	[144]
Eisenia fetida	5 weeks	[145]
Dendrobena veneta	22 weeks	[146]
Alma millsoni, Eudrilus eugeniae and Libyodrilus violaceus	8 weeks	[147]
Eisenia fetida	90 days	[148]
Eisenia fetida and *Amynthas morrisi*	60 days	[149]

There are different earthworm species that have been reported to be efficient in vermiremediation processes. Most common reported earthworm species used for vermiremediation are *A. chlorotica*, *E. fetida, L. terrestris, Allopophora caliginosa, E. andrei, D. veneta, Lumbricus rubellus, D. modesta, L. mauritii, L. terrestris, Alma millsoni, Eudrilus eugeniae, Libyodrilus violaceus* and *Amynthas morrisi.* Nassar and Said [150] has reported using Allopophora caliginosa an Egyptian species which as reduced crude oil at 45.2 and 62.4 mg kg^{-1} concentration by 54.9 percent and 71 percent. A. *caliginosa* was emphasized as the culprit behind the greatest reduction in TPHs concentration. These pollutants were effectively treated and have a good cleanup potential for

[139] Azizi, A.B. and Liew, K.Y., Noor, Z.M. & Abdullah, N. (2013) Vermiremediation and mycoremediation of polycyclic aromatic hydrocarbons in soil and sewage sludge mixture: a comparative study. *International Journal of Environmental Science and Development,* 4 (5). pp. 565-568

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[144] Almutairi, M. (2019). Op-cit

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[148] Javed, F., & Hashmi, I. (2021). Op-cit

[149] Schaefer, M., & Juliane, F. (2007). Op-cit

[150] Nassar, S. E., & Said, R. M. (2021). Bioremediation assessment, hematological, and biochemical responses of the earthworm (*Allolobophora caliginosa*) in soil contaminated with crude oil. Environmental Science and Pollution Research, 28(39):54565-54574.

pollutants. The previous research by Teh *et al.* [151] accessed E. *fetida* ability to withstand pyrene, a PAH that is resistant in soil. Authors have chosen this type of earthworm for its potential to thrive in extremely polluted soils; *E. fetida* is also recognized to stimulate and coordinate with other beneficial microbes which results in the breakdown of crude oil in soils. Despite the observed dose and duration trend, *E. fetida* survival rates in polluted soils are highly recalcitrant [152]. Almutairi, utilized *Lumbricus terrestris* and *Eisenia fetida* to purify soil polluted with HCs in their study, which also highlights the importance of earthworms for vermiremediation [153].

The finesses uncovered a substantial decline in the HCs present in unclean soil after conducting the experiments. Biological activating preparation containing bacteria was used to investigate the effectiveness of biological cleanup of oil polluted soil, petroleum, and diesel fuel by *Dendrobaena veneta*. Subsequent to 22 weeks of soil pollution, the HC content in the soil was reduced by 95 percent Chachina *et al*. [154] evaluated the cleanup capacity and survival potential of earthworms (*E. fetida, E. andrei, D. veneta*). In the presence of bacteria and fungi, worms are exposed to oil polluted soil [155]. After a 4-month trial, 99.9 percent of participants reported success. Studies have revealed that the earthworms mentioned above are effective and suitable for the vermiremediation[156] .

3.12 *Factors that might cause the biphasic degradation curve during vermiremediation*

A biphasic breakdown curve has been observed in biological cleanup process, which is caused by a combination of increasing recalcitrant to breakdown and selective sequestration[157]. A phasic breakdown is marked by a quick decrease in pollutant accumulation, which then disappears with little or no decrease. The pattern is often referred to as a "hockey stick" because the breakdown curve looks like tying ties. Earthworms were found to have a significant impact on crude oil concentrations in diverse types of soil with variety of oils content, as demonstrated by various experiments[158]. The biphasic breakdown curve in the course of vermiremediation, could be accounted for by three different approaches in the experiments. Variations in particle dimension, percentage of organic matter, adjusted microorganisms, and crude oil constituent are factors that contribute to the biphasic breakdown curve.

Petroleum, a nonpolar substance, which can absorb fine particles of compost and soil or diffuse into the humus matrix[159]. Soil contains 6.1 percent fine particles of soil, has more compost, and has more sequestration sites than other soil types. Break down process can only occur when

[151] Teh, Z. C., Lestari, D. V., Yulisa, A., Musa, M., Chen, T. W., Darwish, N. M., ... & Hadibarata, T. (2022). Tolerance of earthworms in soil contaminated with polycyclic aromatic hydrocarbon. *Industrial and Domestic Waste Management,* 2(1), 9-16.
[152] Shi, Z. et al. (2020). Op-cit
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[155] Chachina, S. B. et al. (2019). Op-cit
[156] Chachina, S. B. et al. (2019). Ibid
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[158] Martinkosky, L. (2015). Ibid
[159] Saeedi, M., Li, L. Y., & Grace, J. R. (2020). Effect of co-existing heavy metals and natural organic matter on sorption/desorption of polycyclic aromatic hydrocarbons in soil: A review. Pollution, 6(1):1-24.

molecules diffuse out of soil openings, which are too small for microorganisms to access[160] . The solubility of heavy HCs in residual soils is lesser as compared to lesser weight HCs as demonstrated by Gospodarek *et al.* [161]. Based on this logical thinking, it is likely that many HCs were concentrated in manured soil and then released at a slow pace, leading to lengthier break down periods [162].

Dual phases break down process can be influenced by the variation in biomass from microbes. A higher biomass from bacteria in the initial stages may lead to faster break down of petroleum in soil, as the microbial inhabitant has already been well-adjusted to it[163] . The crude oil content in the polluted soil varied due to the difficulty of degrading certain constitutes. A higher plateau in break down may have been caused by the relative concentration shift to bulky, more resistant aromatic HCs over a period. Due to their less solvability and high resistant microbes, weightier HCs are hard to break down [164]. The lesser breakdown level in natural soil may be partially attributed to the crude oil constitution.

3.13 Role of vermiremediation as a sustainable remediation technology in moving to commercial application

Soil pollution caused by crude oil is a concern in some industries, including the petroleum sector. A range of treatment options have been devised to address soils polluted with crude oil. The vermiremediation treatment system is highly effective in real-life scenarios. The knowledge of polluted sites, whereby the use of vermiremediation depends on site-specific factors such as the nature of the pollutant, the soil's characteristics, and climate. Additional factors to consider include the benefits, problems, cost of alternative remediation approach, implementation feasibility, and potential environmental impact. The use of vermiremediation as a top-notch remediation technique on crude oil is essential for the elimination of oil from polluted sites. Even so, each form of remediation has its own set of benefits and limitations, and a single treatment method cannot be employed in the complete cleanup of petroleum products. Integrated treatment techniques can enhance crude oil break down and elimination efficacy by merging two or more cleanup methods for different soil types in future research.

4. Conclusion and future recommendations

The exploration of oil causes petroleum contamination in soil across the globe. The increasing use of biogenic in site alternatives is a response to the excessive cost and environmental break down associated with traditional physical and chemical cleanup techniques. Vermiremediation has been extensively researched in years back. These studies indicate that earthworms' responses to crude oil contaminants and their capacity to eliminate these pollutants from the environment have been highly effective. The literature revealed that earthworms played a crucial role in the changing of

[160] Semple, K. T., Morriss, A. W. J., & Paton, G. I. (2003). Bioavailability of hydrophobic organic contaminants in soils: fundamental concepts and techniques for analysis. *European journal of soil science,* 54(4), 809-818.

[161] Gospodarek, J., Petryszak, P., Kafel, A., & Paśmionka, I. B. (2022). Porcellio scaber Latr. and Lumbricus terrestris L.—PAHs content and remediation of long-term aging soil contamination with petroleum products during a single- and two-species experiment. *Energies*, 15(21), 7835.

[162] Gospodarek, J. et al (2022). Ibid

[163] Puntus, I. F., Borzova, O. V., Funtikova, T. V., Suzina, N. E., Egozarian, N. S., Polyvtseva, V. N., ... & Solyanikova, I. P. (2019). Contribution of soil bacteria isolated from different regions into crude oil and oil product degradation. *Journal of Soils and Sediments*, 19:3166-3177

[164] Abdel-Shafy, H. I., & Mansour, M. S. (2018). Microbial degradation of hydrocarbons in the environment: an overview. *Microbial action on Hydrocarbons*, 353-386.

organic contaminants. Vermiremediation is a viable option for biogenic clean-up, but it can only be used on soil that is slightly polluted. Vermiremediation can be employed as a secondary method to eliminate residual pollutants from the soil after employing physical and chemical clean-up methods on overt petroleum contaminated soil. It is also important to study the mechanisms and procedure involved in vermiremediation. Additional methods to enhance the vermiremediation process for widespread use must also be explored.

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