International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Review of Strategies for the Bioremediation of Environmental Xenobiotics

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A B S T R A C T

The toxicity and accumulation of xenobiotic compounds in soil environment and food chain have become a concern due to their health risk potentials to human, animal and plants. These man made compounds, such as pesticides, solvents, heavy metals, persistent organic pollutant, petroleum hydrocarbon cause health problems when release either deliberately or accidently into the environment. Their degradation through bioremediation is a better option among the available techniques due to low cost of maintenance and operation, requiring no technical expertise, eco-friendliness, no excavation required, simplicity of application, etc. This review focuses on some of the strategies of bioremediation that are suitable for the general degradation of xenobiotic compound in the environment.

Keywords: bioaugmetation, bioremediation; biostimulation, bioventing, composting, biopiles, environmental contaminants; landfarming, xenobiotic compounds

1. INTRODUCTION

Xenobiotics contaminants are chemicals compounds, which living organisms are exposed to that are not naturally produced or supposed to be found natural within the organism. They are synthetic compounds that are applied in industries such as dye industries, pharmaceutical industries, pesticides manufacturing, explosives, agricultural and other industrial chemicals (Subbulakshmi et al., 2021, Okoro et al., 2014). However, they become environmental contaminants when released indiscriminately or accidently into the environment, thus they are compounds of concern, due to their environmental and health risk potentials. These xenobiotic compounds are persistent organic pollutants (POPs) including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine pesticides (OCPs), polybrominated diphenyl ethers (PBDEs) polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDFs), (Riaz et al., 2020) (Lu et al., 2017, Ren et al., 2017, Jiménez et al., 2015 & Yang, et al., 2019). Polycyclic aromatic hydrocarbons (PAHs) like phenanthrene, pyrene, anthracene, naphthalene (Prasad et al., 2021 & Nna Orji, 2019), petroleum, benzene (Singh et al., 2022), heavy metals and microplastics, medicine. Crude and spent oil-based xenobiotic compounds include hydrocarbon, polyaromatic hydrocarbons and polychlorinated hydrocarbon (Nna Orji, 2024a, Nna Orji, 2019). Other xenobiotic compounds are phenolics, azodyes, nitroaromatic compounds, and per- and polyfluoroalkyl, which cause serious negative impact when released in the ecosystems due to their high toxicity, recalcitrance, and slow degradation rate (Miglani et al., 2022 & Godheja et al., 2016). The pollution of soil and water are related to hydrocarbons based on oil-contaminates from mechanic workshops, oil refineries industries, filling stations and petrochemical industries and other anthropogenic sources (Al-hawash, et al., 2018).

The increase in environmental contaminants in the soil, water and air has led to the development of physical, chemical and biological techniques to clean up xenobiotic contaminant for a sustainable environment (Ayilara et al., 2023). In physical remediation, booms (Vocciante et al., 2019), skimmers and sorbent materials (Kumari et al., 2019) are used to absorb and adsorb the contaminants, preventing further spreading into the environment. Also, flocculation, adsorption, and filtration techniques are applied (Refka et al., 2020) to physically clean up contaminants. Chemical remediation involves the use of chemical substance to remove and degrade contaminants in the environment. The different approaches of chemical remediation include soil washing and flushing, precipitation, adsorption and ion exchange, flocculation, chemical oxidation and electrokinetic remediation (Jovanović et al., 2021), reduction and complexation (Xu et al., 2022), chemical leaching, chemical extraction and encapsulation (Waris et al., 2018). However, bioremediation has gained wide spread acceptance and application among the three techniques for the removal of toxic environmental contaminants due to its cost effectiveness, efficiency and environmental friendliness (Tripathi et al., 2021, (Alaira et al., 2021, Bala et al., 2022, Nna Orji, 2024a). Hence, the degradation of xenobiotic compounds in the environment through bioremediation is eco-friendly, safe, efficient to use the xenobiotic contaminants as their sole source of nutrients (nitrogen and carbon), food and energy (Subbulakshmi et al., 2021). The mineralization of these contaminants involves breaking down and converting the xenobiotic compounds to nontoxic compounds, which can occur at the site or outside the site of contamination (Bala et al., 2022). Therefore, this review focuses on the strategies for the bioremediation of xenobiotics in the environment.

2. BIOREMEDIATION AND BIO-DEGRADATION

In bioremediation, bio means biological, implying living organisms while remediate means to remedy or improve/correct an unpleasant situation (Kaur et al., 2020). Hence, bioremediation occurs via biodegradation, bioaccumulation and biosorption process, while utilizing the different abilities of living organisms such as plants and microorganisms (Singh et al., 2020), to change and breakdown complex environmental xenobiotic contaminants to harmless products of lower molecular weights (Saravanan et al., 2023, Mishra et al., 2020 & Subbulakshmi et al., 2021). Conditions necessary for the survival of the microorganisms in the presence of contaminants include optimizing aeration, controlling pH and adjusting temperature (Ogujoifor et al., 2021, Nna Orji, 2024a & Joshi et al., 2024). The microorganisms implored in bioremediation are yeast, fungi, algal species and bacteria (Prasad et al., 2021 & Mishra et al., 2020).

2.1. Approaches of Bioremediation

Hence, bioremediation may be carried out in situ or ex situ (Bala et al., 2022). For in situ technique, the cleaning up or degradation of the contaminant takes place at the polluted site without digging, disturbance or transporting the contaminated environment to another place while in ex-situ bioremediation, the polluted environment such as soil is excavated, transported for off-site treatment where degradation occurs (Singh and Christina, 2022 & Bala et al., 2022). The different approaches of bioremediation include bioventing, biostimulation, composting, bioaugmentation, bioslurping, biosparging (Debbarma et al., 2023, Singh and Christina, 2022 & Zhang et al., 2020). Bioventing, biosparging and phytoremediation are Some in situ bioremediation techniques used to clean up chlorinated solvents, dyes, heavy metals, and hydrocarbons polluted sites (Azubuike et al., 2016 & Frascari et al., 2015)

2.1.1 Composting

Composting is the breakdown of organic matter by aerobic microbes to form a stable and matured substance that acts as organic fertilizer and stimulant or amendment. Hence, Composting bioremediation, consists of mixing contaminated soil with nonhazardous fresh, stable and matured organic amendments, such as plant debris, sewage sludge or manure or agricultural wastes, resulting in the production of energy in form of heat, which accelerates the rate of degradation of contaminants by microbes to produce carbon dioxide, water, minerals and harmless compounds (Lau et al., 2023 & Sharma, 2012). Increased microbial growth and activities are supported by the organic amendment (Ubani, 2012). Lin et al., (2022) detailed the processes involved in the different phases of composting. The four phases of composting remediation are mesophilic, thermophilic, cooling and maturation, which have varying temperature, oxygen demand, microbial community structure, stability, carbon content, nitrogen content, and pH profiles. The mesophilic phase starts immediately after mixing the organic waste materials as the microorganisms use easily degradable organic matter as food. As the activities of the microbes increase, the temperature of the compost rises, initiating the thermophilic phase at 55 ℃. The pH may change depending on the production of ammonia gas, or acids from organic acids and fermentation of components of the compost. The reduction of available nutrients does not favours the thermophilic organisms, thus, the activities of microorganisms decrease, resulting in cooling of the entire system at the cooling phase. The maturation phase is when the compost is stable in temperature, pH and moisture content, etc. The lowered temperature then favours the growth of mesophilic microbes as at the beginning. Thereafter, the matured compost product is applied as soil amendment and organic fertilizer in the environment contaminated with xenobiotic compounds for their degradation.

The process involves watering to increase moisture content, tilling to increase the oxygen level for metabolic activities of microbes, and addition of controlled quantities of nutrients, bulking agents (wood-chips or hay) and micro-organisms to improve the bioremediation of contaminants such as oil sludge and control of pH (Lin et al., 2022, Ubani,2012). Benefits of composting include inexpensive, involves diverse microbial community, ease of operation (Lin et al., 2022), higher adsorptive capacity for volatile organic compounds (VOCs), high organic matter content, destruction of pathogens and odour-producing, nitrogen- and sulphur-containing compounds, environmentally friendly, reduces the concentration of PAHs which are difficult to degrade with other methods and improves soil fertility Ubani (2012). Limitation of composting are volatilization of gases, needs very large space, large volume of materials to be handled, possible generation of intermediate decomposition products with even higher levels of toxicity during the biodegradation, may contain nondegradable hazardous constituents Ubani (2012).

Much work has been carried out using composting remediation, these include: Ubani (2012) studied compost bioremediation of oil sludge by using different manures such as pig, cow, horse and poultry manure while Eramo and Brennan (ND) worked on bio-remediation of hydrocarbon contaminated soil with used mushroom compost. Chijioke-Osuji et al., (2014) studied biodegradation of crude oil polluted soil by cocomposting with agricultural wastes and inorganic fertilizer while Agbor et al., (2012) studied bio-stimulation of microbial degradation of crude oil polluted soil using cocoa pod husk and plantain peels using composting technique. In addition, researchers have used this technology to treat recalcitrant organic contaminants, including polycyclic aromatic hydrocarbons (PAHs) (Lu et al., 2019 & Ozaki et al., 2017), total petroleum hydrocarbons (TPHs) (Becarelli et al., 2019), diesel (Lin et al., 2012). Also, phthalate-based plasticizers (Tran et al., 2021), organochlorine pesticides (Ali et al., 2014), polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs) (Huang et al., 2019 & Jia et al., 2021) have been cleaned up using this technique. Scientist have also used inoculates as microbial agents to start up the aerobic composting of mushroom residue and wood chips at low temperature (Kästner and Miltner, 2016).

2.1.2. Landfarming

Landfarming bioremediation technique is an ex situ technique in which contaminated soil is excavated, spread over a prepared bed or thin layer on the ground surface and periodically tilled or ploughed for aeration with the addition of minerals, nutrients, and moisture for the stimulation of aerobic microorganisms, which will degrade environmental contaminants (Brown et al., 2017, Wang et al., (2016). Landfarming is a simple technique, also known as land treatment or land application. The enhancement of certain environmental parameters such as pH, nutrient and moisture content, and availability of oxygen, which increases the growth, reproduction and activities of microorganisms, make landfarming most efficient (Liu et al., 2017).

Abdulsalam and Omale (2009) studied the biodegradation of used motor oil contaminated soil via landfarming technique while Ebuehi et al (2005) considered remediation of crude oil contaminated soil by enhanced natural attenuation technique via landfarming. Brown et al., (2017) studied the degradation of oil in contaminated soils and the effect of nutrient addition, biosurfactant, Eisenia fetida (earthworm) enzyme extract, bulking and sorption agents and soil neutralization via landfarming while Wang et al., (2016) studied the bioremediation of diesel and lubricant oil-contaminated soils using enhanced landfarming system.

2.1.3. Biopiling

Biopile bioremediation involves excavating contaminated soil, piling it above the ground on a bottom liner and addition of nutrient amendment (Azubuike et al., 2016). The strategy is enhanced by aeration, irrigation and collection of leachate from the bottom liner, which promotes the growth and reproduction of microorganisms that degrade the environmental contaminant. Aeration of the bio-piles is by forcing air to move by injection or extraction through slotted or perforated piping placed throughout the cells unlike the landfarming where aeration is done by tilling or ploughing. Other materials for amending the biopiles include sand, sawdust, wood chips, compost or other similar bulking (Hazen et al., 2003), which stimulate the biological reactions of the microorganisms for the degradation of the xenobiotic contaminant. Biopiles are also known as bio-cells, bio-heaps, bio-mounds, and compost piles, which are refined version of landfarming. Biopiles are effective, cheap, (Whelan et al. 2015), less destructive (Gomez and Sartaj, 2014), reduces volatilization (Azubike et al., 2016), take a short time of between 6- 24 months and handles extreme environments such as the very cold regions (Dias et al., 2015, Akbari and Ghoshal 2014). However, some factors that affect biopiles bioremediation are epileptic power supply; lack of technical expertise; cost of excavation, maintenance and operation; extreme heat, which dries the soil, hinders growth, activities and survival of microbes; support volatilization and prolongs degradation (Azubike et al., 2016). Biopiles has been applied to degrade petroleum hydrocarbon contaminated soil at low temperature conditions (Gomez and Sartaj, 2014, Akbari and Ghoshal, 2014) while Whelan et al., (2015) discussed the fate and transportation of petroleum hydrocarbons in engineered biopiles in polar regions. Also, Dias et al., (2015) studied biostimulated biopile systems for the bioremediation of diesel-contaminated Antarctic soil

2.1.4. Bioventing

Bioventing involves supplying air at low rate through horizontal and vertical wells to the contaminated environment to stimulate the inherent microorganisms to use the contaminants as source of food, energy and carbon (Kaur et al., 2020). The inherent microorganisms are supplied sufficient oxygen, nutrients and moisture to improve their abilities to degrade the xenobiotic contaminants (Mohamed et al., 2024, Megharaj et al., 2014). Bioventing systems deliver air from the atmosphere into the soil above the water table through injection wells placed in the ground where the contamination exists (Debbarma et al., 2023). In this technique, there is minimal volatilization and release of contaminants into the atmosphere. Unlike biosparging, which involves pumping air and nutrients into the saturated zone, bioventing pumps the air only into the unsaturated or vadose zone (Azubuike et al., 2016 & Höhener and Ponsin, 2014). Oxygen provides the aerobic conditions needed for the survival of microorganisms to degrade less volatile organic contaminants and petroleum products such as crude oil, spent oil and diesel (Lim et al., 2016). The efficiency of bioventing is restricted by very low moisture content, low permeability of soils, low and very high temperatures that endanger the growth and survival of the inherent microbes and build-up of vapours in basements within radius of influence of air injection wells (Megharaj et al., 2014). In the literatures, chemists and other scientist have made discoveries with bioventing. Agarry and Latinwo (2015) explored the effects of bio-venting and brewery waste effluents amendment as biostimulation-bioaugmentation agent on biodegradation of diesel oil in unsaturated soil while Anekwe and Isa (2021) compared the evaluation of wastewater and bioventing system for the treatment of acid mine drainage-contaminated soils. Höhener and Ponsin, (2014), discussed the application of in situ vadose zone bioremediation while, Thomé et al., (2014) investigated the bioventing of residual clayey soil contaminated with a blend of biodiesel and diesel oil. Frascari et al., (2015) reviewed the in situ aerobic co-metabolism of chlorinated solvents: a review

2.1.5.Bioaugmentation

The bio-augmentation approach involves the addition of highly concentrated and specialized populations of specific microbes into the contaminated site, to enhance the rate of contaminant biodegradation in the affected soil or water (Nanda et al., 2019, Chen et al., 2024, Atakpa et al., 2024, Xie et al., 2024). This increase in the concentration, population and density of degraders in the contaminated site enhances the rate of degradation of the contaminants as the microbes use them as their sole source of food, energy and carbon. Bioaugmentation is useful when the microorganisms necessary to degrade the contaminants occur at very low concentration and population, thus microbes are added to make effective and efficient the process of degradation where the inherent microorganisms have been poisoned by the toxic contaminant. The microorganisms must have ability to degrade the contaminants, retain their genetic makeup in harsh and poisonous environment, maintain viability during storage and compete favourably with other microorganisms (Adams et al., 2015). Bioaugmentation is a mechanism for managing the degradation of xenobiotic contaminants by the addition of selected, pre-adapted microorganisms or enzymes with high biodegradation ability to specific pollutants (Ma et al., 2022)

Bioaugmentation has emerged as the most beneficial strategy for bioremediation of contaminated environment (Cycoń et al., 2017). It is safer and cleaner, easy to handle, cheap and eco-friendly (Mohamed et al., 2024, Chettri et al., 2023 & Ahmad et al., 2022). However, its disadvantages include reduced survival rate of microbes in highly toxic contaminated site, substrate competition, climatic conditions and remediation cycles (Muter, 2023). Non-biodegradability of targeted contaminants; uneven flow of liquid or gas containing the microbes as a result of heterogeneity of the contaminated soil or media, leads to uneven bio-degradation limits the use of this technique (Ubani, 2012; Zawierucha and Malina, 2011). More so, bioaugmentation under controlled conditions in the field remains challenging, due to the biodiversity of a whole system, competition between microbial agents and indigenous microorganisms, climatic conditions (Muter, 2023).

Bioaugmentation can be achieved in three technical ways: the isolates to be use can be isolated from the immediate environment or from the target site; subsequently cultured and inoculated into the same or different soil for bio-augmentation. Autochthonous Bioaugmentation is referred to the process of augmentation in which the inherent microorganisms for remediation is purified and inoculated into the same environment (soil and water) from which they were isolated (Fox et al., 2021, Refka et al., 2020 & Ntroumpogianni, et al., 2020). Isolated single strains or enriched cultures obtained prior to or after the contamination of the target sites, are inoculated into the same for degradation of the contaminants. The use of indigenous microorganisms with adapted biochemical potentials makes bioaugmentation the most powerful tools for bioremediation. Allochthonous bioaugmentation is the process where isolates or enrichments are not inoculated to the source (soil and water) of the original culture but to a strange environment (Fox et al., 2021, Refka et al., 2020, Agarry et al., 2015 & Fodelianakis et al., 2015). Only microorganisms that have proven abilities and capacities to degrade hydrocarbon can be used to degrade oil contaminated soil. These exogenous microorganisms can likely be obtained from remediated or contaminated sites, commercial suppliers and genetic engineering (Diaz-Ramirez et al. 2008). Thus, genetically engineered microorganisms (GEMs) produced via mutations and horizontal gene transfer using molecular biology can be utilized in bioaugmentation. These GEMs have increased ability and capacity to degrade and withstand toxic compounds (Vogel and Walter 2001). The application of this technique is aimed at developing the ability of newly generated strains to degrade a broader range of xenobiotic, and to increase the degradation effectiveness in comparison with “wild” (natural) strains (Mrozik and Piotrowska-Seget, 2010).

Several researchers have investigated the use of bioaugmentation in biodegradation of oil-based xenobiotic compounds. Vasilyeva et al., (2022) accelerated bioremediation of grey forest crude oil contaminated soil with the addition of natural sorbents such as minerals (zeolite, kaolinite, vermiculite, diatomite), organics (peat), carbonaceous (biochar) materials, and mixed sorbent (consisting of granular activated carbon and diatomite). They observed that the toxicity caused by the crude oil reduced, decreased the soil hydrophobicity and optimized soil pH after the process (Vasilyeva et al., 2022 & Chettri et al., (2023). Yotinov et al., (2023), modelled the Effect of Pseudomonas aureofaciens AP-9 on bioremediation of phenol-contaminated river sediments while Mohamed et al., (2024) investigated fungal metabolites and their function in remediation of environmental pollution whereas Cycoń et al., (2017) explored bioaugmentation as a strategy for the remediation of pesticide-polluted soil. Also, Agarry and Latinwo, (2015) examined the biodegradation of diesel oil in soil using bioventing and brewery waste to enhance the biostimulation-bioaugmentation processes. Fodelianakis et al., (2015) discussed allochthonous bioaugmentation for treating crude oil-polluted sediments using indigenous microbiome while Borowik and Wyszkowska (2018) studied bioaugmentation of soil contaminated with diesel oil. Kalniņš et al., (2022) explored the effect of bioaugmentation on the growth and rhizosphere microbiome assembly of hydroponic cultures of Mentha aquatic while Zorza et al., (2022) studied the changes in bacterial community structure in wastewaters in the presence of Saccharomyces Cerevisiae and Benzalkonium Chloride. Rimkus et al., (2021) investigated the stimulation of sewage sludge with carbon sources and bioaugmentation with a sludge-derived microbial consortium. Wang et al., (2023) considered the influence of microbial augmentation on contaminated manure composting. Pi and Boa (2022) investigation the kinetics of bioaugmentation of crude oil via high-throughput sequencing, enzymatic activities, bacterial community composition and functions. Benyahia and Shams Embaby (2016) studied effect of bio-stimulation, bio-augmentation and bioavailability in biopile for the bioremediation of crude oil contaminated desert soil. Furthermore, Arezoo and Salmah (2015) looked at bio-enrichment with bacillus 139SI and organic waste of waste crude oil polluted soil while Alexis et al (2016) researched on the use of bio-augmentation for the removal of important contaminants from industrial wastewater with an emphasis on recalcitrant compounds, and discussed strategies on the improvement of the efficiency of bio-augmentation. Herrero and Stuckey (2016) reviewed the application of bio-augmentation in wastewater treatment whereas Chen et al (2016) studied the treatment of full-scale diethylene glycol monobutyl ether (DGBE) wastewater by Serratia spp while Nna Orji (2018) evaluation the percentage degradation of crude oil in contaminated soil by isolated consortia.

2.1.6.Biostimulation

Bio-stimulation technique promotes the growth of inherent microorganisms in the contaminated environment (soil, sediment, sludge, or wastewater), via the addition of nutrient (phosphorus, nitrogen, or carbon), oxygen, surfactants, metabolites, electron donors/acceptors, enzymes; and adjusting other growth limited factors (such as soil temperature, pH, and moisture content, e.tc) that may slowdown the rate of biodegradation of the contaminant (Romantschuk et al., 2023, Mohamed and Samer, 2023, Curiel-Alegre et al., 2022, Macaya et al., 2019 & Ayangbenro and Babalola, 2018). This technique works well when the microorganisms necessary to degrade the contaminants are present but environment conditions do not favour their growth, survival and reproduction (Mohamed and Samer, 2023). Biostimulation is highly efficient, cost effective and eco-friendly (Goswami et al., 2018). Also, the strategy depends on the inherent bacteria that have already adapted and survived the harsh conditions of the contaminated site (Lee et al., 2018, Zawierucha et al. (2014). In addition, it requires no installation and technical expertise, easy to operate and manage, waste materials within and around the environment serves as raw materials for this process, leading to the clean up of the entire environment (Nna Orji, 2024a). The drawback of bio-stimulation include low efficiency due to poisoning or death of the inherent microbes in the presence of very high concentrations of the contaminants (Ueno et al. 2007; Zawierucha and Malina, 2011). Time allowed for incubation and degradation determines the extent of bioremediation. Environmental conditions (temperature, pH, nutrients and additives such as surfactants to stimulate the microbial growth) affect the strategy to a large extent. High concentration of contaminants affect the process negatively (Zawierucham et al. (2014).

Bio-stimulation approach has proven to be an effective strategy to enhance oil-based xenobiotic compounds degradation as it has been reported in so many literatures. Agarry and Latinwo (2015) investigated the biodegradation of diesel oil in soil and its enhancement by application of bioventing and amendment with brewery waste effluents as biostimulation-bioaugmentation agents, Nna Orji, (2024b) studied biodegradation of spent oil in soil using Citrullus colocynthis peels and other plant wastes. Zawierucha and Malina (2011) examined bioremediation of oil hydrocarbons in soil via enhanced bioaugmentation and biostimulation while Curiel-Alegre et al., (2022) evaluated bioremediation of recalcitrant hydrocarbons of soil via biostimulation, bioaugmentation, and organic amendments application. Goswami et al., (2018) discussed bioaugmentation and biostimulation as potential Strategies for environmental remediation whereas Ogbozige (2024) examined the modelling kinetics of selected organic amendments on biostimulation of crude oil contaminated soil while Romantschuk et al., (2023) surveyed biostimulation, bioremediation, biodegradation of organic contaminants. Tumolo et al., (2023) studied biostimulation effect of different amendments on cr(vi) recovering in microbial community while Udume et al., (2023) examined biostimulation of petroleum-contaminated soil using organic and inorganic amendments and Nna Orji (2024a) investigated bioremediation of spent-oil contaminated soil using biostimulants.

3. CONCLUSION

Bioremediation of environmental oil-based xenobiotic compounds is an eco-friendly technique that will add no hazardous product into the environment but reduce the toxicity of these compounds and the health risk they may cause to man and his environment. It is also cheaper and more efficient in clean up than the physical and chemical remediation techniques as it has successfully degraded different environmental contaminants with optimized environmental conditions such as pH, temperature, aeration, moisture and nutrient content. The wide application of both aerobic and anaerobic bioremediation processes is effective in the degradation of most xenobiotic compounds, thus, has earned popularity in the communities with environmental contamination challenges.

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