Microsphere (2023) 2(1): 180-190
https://doi.org/10.59118/IETP8431

Review

Pesticide persistence and strategies for the microbial bioremediation of contaminated soil

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Received: 20 January 2023 / Accepted: 29 May 2023 / Published online: 24 July 2023

Abstract

Owing to the widespread use of pesticides all over the world and the lack of effective remediation technologies, the persistence of pesticides in the soil has emerged as a serious environmental issue. Although pesticides have a great impact on increasing yield and benefitting cultivators economically, the indiscriminate application of pesticides in croplands has become a threat to the well-being of the natural ecosystems. Pesticides represent one of the most toxic soil pollutants and represent a significant risk to human wellness as well as the natural ecology. The bioremediation process, which utilizes bacteria, fungi, algae, and other organisms, has proved to be one of the most cost-effective and environmentally beneficial solutions to this growing problem. A number of approaches employing bioremediation technologies have successfully been implemented in the field. However, more adaptable, cost effective and easily implementable approaches need to be developed that can deliver the intended outcome. This review elucidates the present status of pesticide contamination and highlights the predominant role played by microbes in pesticide remediation, along with the advances made in recent years.

Keywords: Pesticides, Bioremediation, Microbial remediation, Soil contamination

1. Introduction

Pesticides are the chemicals utilised to eliminate or control pests in order to manage their populations at endurable proportions [1]. They are a broad and diverse category of chemicals that are used to destroy biological creatures such as weeds, insects, and rodents [2]. Pesticides are frequently employed worldwide for managing pests. However, the extensive usage of pesticides has led to pesticide accumulation in agricultural soil which has adversely affected its fertility [3]. Apart from agricultural fields, pesticides are utilised in a variety of other settings as well, including industrial, household, and marine environments. Due to the harmful effects of pesticides on plants, wildlife, and human health, continuous monitoring and regulation of pesticide usage in agriculture is critical [4].

Pesticides have been classified using three criteria: the pests being targeted, the mechanism of pest entry, and the type of chemicals used. [5]. In addition to these, pesticides can also be characterised according to their toxicity level and mechanism of action [6] (figure 1).

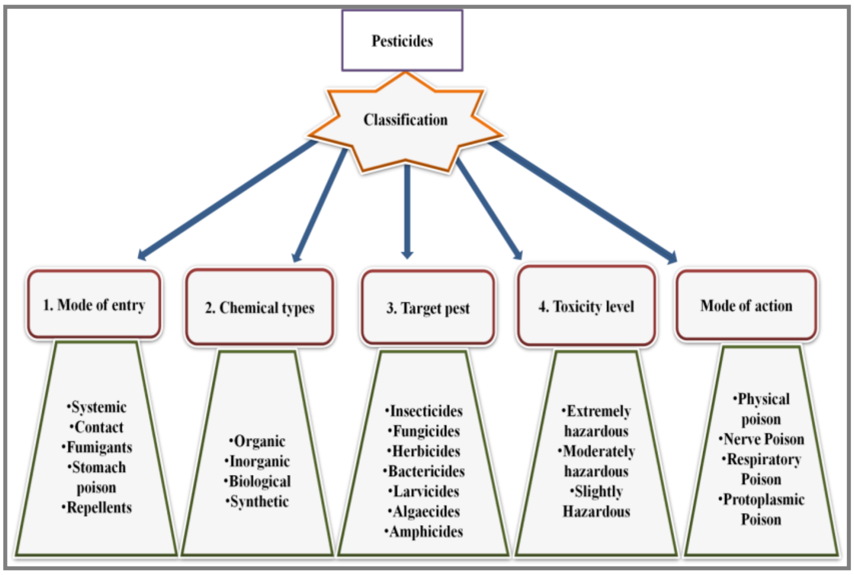

Figure 1: Pesticide classification based on the mode of entry, types of chemicals, pest targets, toxicity level, and mode of action.

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eISSN: 2583-5327

Pesticides are divided into various categories according to the pests they are intended to control, these are agrochemicals, larvicides, aphicides, molluscicides, miticides, ixodicides and fertilizers as well as insecticides, fumigants, weedicides, algaecides, nematicides, and acaricides. [5, 6, 7]. Additionally, pesticides can also be grouped on the basis of their chemical nature, such as organic, inorganic, synthetic, and biological. Four major groups of pesticides exist, namely, organophosphorus, organochlorine, carbamates, and pyrethroids [5] (table 1). Others include flavonoid compounds, nitrophenol derivatives, phenoxyacetic acid derivatives, triazine variants, organotin, pyrazoles, and thiocarbamates, as well as some heavy metals [7]. Lethal dose or LD50 value is another criterion of classification which indicates their toxicity. According to the LD50 value, pesticides can be extremely toxic, highly dangerous, moderately toxic, slightly harmful, and unlikely to cause an acute harm [6, 7]. Furthermore, the mode of action is another criteria used for the classification of pesticides, categorising them into physical poisons, neurological poisons, breathing poisons and chitin blockers [8]. Among the major classes of pesticides being used, the majority (47.5%) are herbicides, subsequent to which are insecticides (29.5%), fungicides (17.5%), as well as pesticides such as bactericides, acaricides, and rodenticides (5.5%) [9, 10].

Table 1: Pesticide classification on the basis of chemical constitution along with examples and their harmful effects.

Pesticides	Examples	Harmful effects	References
Organophosphorus	Diazinon, dichlorvos, dimethoate, malathion, parathion	Confusion, anxiety, loss of memory, loss of appetite and depression.	[11]
Carbamate	Carbaryl, propoxur, aldicarb methiocarb	Abdominal cramping, vomiting, diarrhoea, sweating, cyanosis, pin -point pupils (miosis).	[11]
Organochlorine	DDT, methoxychlor, toxaphene, mirex and kepone	Convulsions, headache, dizziness, nausea, vomiting, muscle weakness, slurred speech.	[11]
Nitrogen-based	Picloram, atrazine, diquat and paraquat	Nitrates reduce the oxygen carrying and delivering capacities of RBC.	[12]
Pyrethroids	Permethrin, deltamethrin and cypermethrin	Nausea, twitching muscles, decreased energy, altered awareness, convulsions, and loss of consciousness.	[13]

A healthy, fertile soil is vital to agriculture which is an important aspect of terrestrial ecosystems. Pesticide contaminated soils are a global concern due to the dangers posed to humans, animals and other biota [14, 15]. During the agricultural to residential transition, floodwaters may carry pesticides from treated land and storage locations to soils downstream [16]. Although pesticides are used to boost output, their excessive use has over time has led to a detrimental effect on soil fertility, in addition to drinking groundwater getting contaminated.

Pests are accountable for the loss of a third of global agricultural produce each year, despite the use of over 4.1 million tonnes of pesticides [17]. Pests in India generate yearly crop losses of more than INR 6,000 crores, with weeds accounting for 33%, diseases for 26%, insects for 20%, birds and rodents for 10%, and other factors accounting for the remaining 11% (figure 2) [18]. Therefore, it becomes important to focus on parallel strategies such as integrated pest management so that total reliability on chemical pests can be reduced. Apart from this, agricultural lands already contaminated need to be recovered through approaches such as bioremediation. The conversion of hazardous contaminants into less harmful or harmless chemicals by systematically utilizing the ability of microorganisms to metabolize and degrade these contaminants is known as bioremediation [19, 20]. Through bioremediation strategies, the pollutants can be degraded or detoxified using naturally occurring bacteria, fungus, or plants or a consortium of microbes that have been tested by field scale studies [21]. A number of natural solutions or techniques, such as biostimulation, bioaugmentation and natural attenuation are included in this technology [22]. Living creatures degrade contaminant molecules in the course of their metabolic activities, resulting in the clean-up of polluted water and land environments [23, 24, 25, 26]. Microbial bioremediation has been shown to be successful in detoxifying harmful pesticide contaminants. Microorganisms in natural ecosystems usually live in consortiums, which, in comparison to single strains, seem to be more effective in remediating pesticides. As a result, a microbial consortium can breakdown many pesticides at the same time. In addition to environmental bacteria, some researchers revealed that insect gut resident microbes are capable of decomposing pesticides [27].

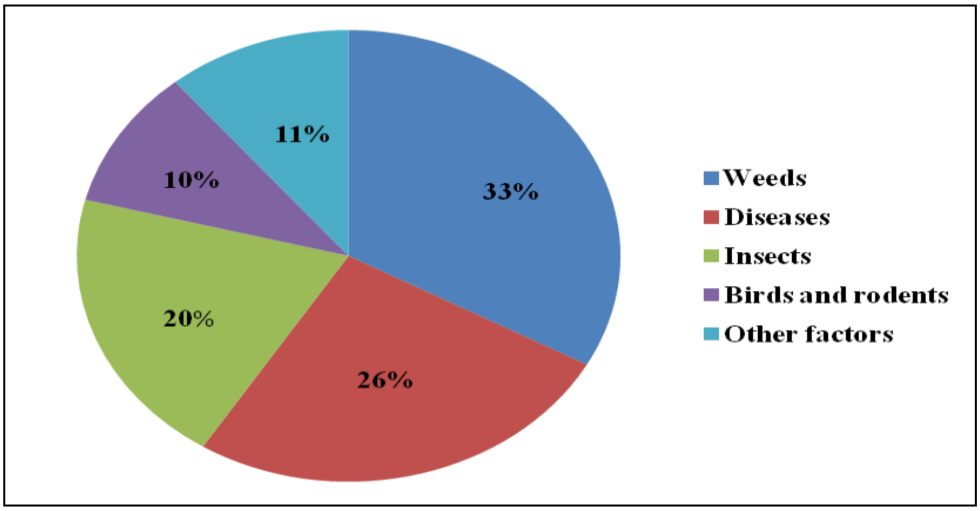

Figure 2: A pie diagram depicting the percentage of crop yield loss due to the use of pesticides in India.

Pesticide residues in numerous crops have also hampered agricultural commodity exports in recent years, leading to financial losses. Pesticide safety, regulation, and usage are some of the issues requiring immediate attention and detailed research. Primary techniques for avoiding human exposure to pesticides, maintaining/enhancing soil fertility in a sustainable manner for better productivity and integrated pest management are thrust areas of research in the field of agriculture and toxicology. Microbial bioremediation is regarded as a safe, cost-effective, and ecologically friendly approach for removing dangerous toxins from the natural environment [19, 28, and 29]. Due to the vast amount of knowledge being generated and field scale studies being conducted in this arena, a comprehensive understanding is needed to plan and carry out further research. This review highlights the current status of pesticide contamination and the methods that have been used in the remediation of pesticides.

2. Status of pesticide contamination worldwide and in India

A study on 76 pesticide residues in 317 agricultural topsoil samples from 11 European Union member states and six major agricultural types revealed that the overall highest pesticide concentration was 2.87 mg/kg, with several soil samples containing multiple pesticides [30]. This study observed that for glyphosate, the detection thresholds were 0.05 mg/kg and 0.01 mg/kg, while in case of LC–MS and MS, they were 0.005 mg/kg. Additionally, this analysis described the pesticide residue content in terms of the field's percentage. Among the tested soils, 80% of the soil contained pesticide residues, 25% of sample had single residues, and 55% of sample contained more than two residues [30, 14]. According to previous studies, pesticide consumption globally is approximately two million tons per year, of which 24% was consumed in the United States, 45% in Europe, and 25% in the rest of the world (figure 3A). China ranks the highest among Asian countries for pesticide usage followed by Korea, Japan, and India [31, 32]. In India, the pesticide usage is at 0.5 kg/ha, with organochlorine pesticides accounting for the major pesticide being used. This is because there are more insect infestations, which are generally brought on by the warm and humid climate of the country. [33]. Pesticides have a major impact on human and animal health owing to their biological longevity and enhanced level of lipid solubility in food items [34]. Therefore, their build-up in soil and water over decades has a detrimental effect on the well-being of living organisms.

In India, the encouragement of high-yielding cultivars during the green revolution resulted in the extensive usage of pesticides [35]. Consequently, the green revolution was the primary driver of rising pesticide consumption in India, which ranks as the topmost pesticide manufacturer among Asian countries. The country is the world's twelfth-largest user of pesticides, with a yearly output of 90,000 tones [36]. As a core premise of its plant protection strategy, India has now embraced the integrated pest management (IPM) technique as an effective and sustainable strategy against pests, which might reduce sole dependence on chemical pesticides in the future [37]. The top consumer states of pesticides in India are Maharashtra, followed by Uttar Pradesh, Punjab, Haryana, West Bengal, and Orissa (figure 3B). Cotton accounts for 45 percent of pesticide use throughout agricultural crops, followed by rice at 25%, chilies, vegetables, and fruits at 13–24%, plantations at 7-8%, cereals, millets, and oil seeds at 6-7%, sugarcane at 2-3%, and other crops at 1-2% [38].

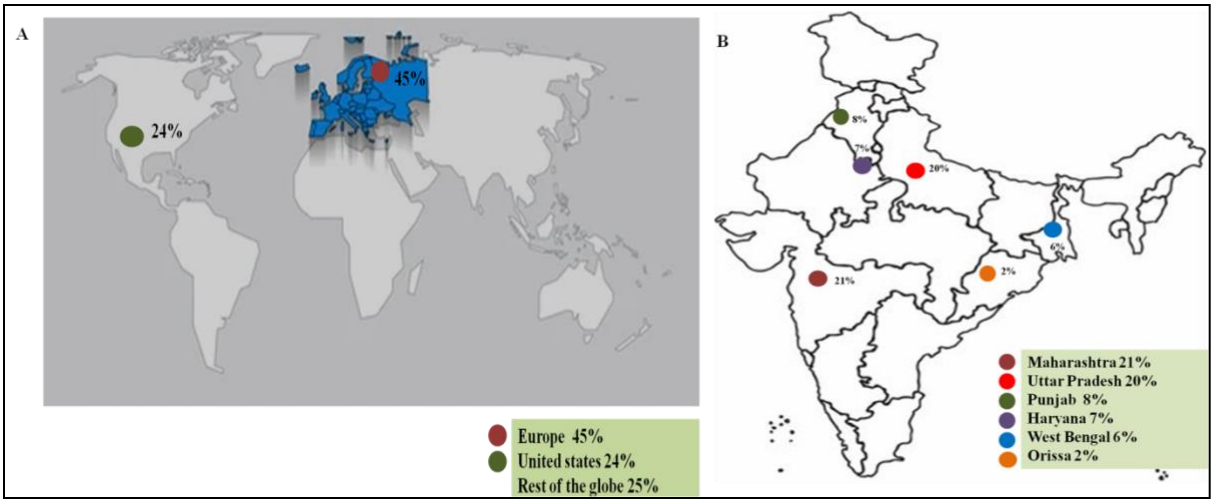

Figure 3: (A) A world map illustrating the percentage of pesticide usage in the world. (B) A map of India depicting the percentage usage of pesticides in different states of India.

3. Microorganisms in pesticide remediation

Pesticide wastes have become a major issue because of limited and inadequate waste management technologies [39]. The capacity of bacteria and some plants to detoxify environmental contaminants makes bioremediation technologies as desirable techniques for pesticide remediation. Microbial genera such as *Mycobacterium*, *Pseudomonas*, *Bacillus*, *Klebsiella*, *Pandoraea*, *Phanerochaete* and *Chrysosporium* are some of the microorganisms that have demonstrated the potential for pesticide bioremediation [40]. These microbes can convert pesticides into less toxic metabolites by employing it as a carbon or nitrogen source, as a source of minerals or as a final electron acceptor in their respiratory chains. They harbour metabolic pathways for degrading the contaminants and utilising it as raw resources for their metabolic processes (table 2). For instance, *Achromobacter xylosoxidans* CS5 can utilise endosulfan and endosulfan sulphate as sources of sulphur, carbon, as well as energy, leading to the degradation of endosulfan entirely through the hydrolytic pathway [41].

Table 2: Microorganisms involved in pesticide degradation, along with their enzymes and degradation pathways.

Pesticides	**Microorganisms involved in degradation**	**Enzymes/ Degradation pathway**	**References**
Atrazine	*Pseudomonas* strain ADP	Atz A (dechlorination of atrazine), Atz B (dehydrochlorination of hydroxyl atrazine), Atz C	[42]
DDT	*E. coli*, *Klebsiella pneumonia*, *Enterobacter aerogenes*, *Enterobacter cloacae and Bacillus* spp.	Reductive dechlorination	[43]
Herbicide 2,4-D	*Flavobacterium*, *Arthrobacter*, *Azotobacter*, *Burkholderia*, *Pseudomonas*, *Klebsiella pneumoniae*	Oxygenases, Hydrolases, Hydroxylases, Isomerases	[44]
Methoxychlor	*Enterobacter aerogens*	Dechlorination	[45]
Gamma-HCH	*Chromohalobacter*, *Marinimicrobium*, *Idiomarina*, *Salinospharea*, *Malomonas*, *Sphingophyxis*, *Novosphingobium*, *Sphingomonas*, *Pseudomonas*, *Sphingobium*	Dehydrogenation, dechlorination, hydroxylation, dehydrochlorination, mineralization	[46, 47]
Beta-cypermethrin	*Aspergillus niger*	Esterase, hydrooxylase	[42]
Aldrin	*Clostridium glovolium*	Oxidation, reduction, hydroxylation and hydrolysis	[48]

Microbial enzymes have the potential for efficiently transforming and detoxifying polluting chemicals, therefore, they are suitable for restoring contaminated ecosystems by degrading contaminants at a significant pace [49]. Several microbes have been proposed as pesticide degraders, including *Arthrobacter, Flavobacterium*, *Azotobacter,* *Pseudomonas* and *Burkholderia* [50]. Microbial hydrolytic enzymes produced by *Pseudomonas* sp. and *Klebsiella pneumoniae*, for instance, are able to degrade s-triazine herbicides. Similarly, several enzymes, including hydrolases, oxygenases, hydroxylases, and isomerases produced by *Pseudomonas* and *Alcaligenes* sp. have been demonstrated to break down the herbicide 2,4-D [44]. Moreover, the theoretical oxygen demand (TOD) enzyme from *Pseudomonas putida* and related enzymes have been utilized in the catalysis of processes that are crucial to the environment. In addition to bacterial enzymes, fungal enzymes, in particular oxidoreductases, laccases, and peroxidases, are used in a number of processes to remove polyaromatic hydrocarbons (PAHs) from freshwater, marine water, and soil ecosystems [51]. Fungi breakdown pesticides by creating slight alterations in the structure of pesticides, removing their toxicity, and then releasing them into the soil, where bacteria can further degrade them [52]. A number of fungi, including *Hypholoma fasciculare, Pleurotus ostreatus, Agrocybe semiorbicularis, Auricularia auricula, Stereum hirsutum*, *Avatha discolour*, *Hypholoma fasciculare,* and *Pleurotus ostreatus* have demonstrated the potential for breaking down pesticides such as phenylamide, phenylurea, triazine and organophosphorus compounds [53]. Additionally, chlordane, DDT, gamma-hexachlorocyclohexane (γ-HCH), aldrin, heptachlor, dieldrin, mirex, and other pesticides have been demonstrated to be degraded to variable degrees by white-rot fungi [54].

Gamma-HCH (or lindane), is one of the synthetic insecticides used to control pests in crops, fruits, and vegetables. Its widespread use over decades has contaminated agricultural soils around the world [55]. The community of microorganisms accountable for the *in situ* biological breakdown of HCH was elucidated by Sangwan et al. [46]. They observed that some bacterial taxa, including *Chromohalobacter, Marinimicrobium, Idiomarina, Salinospharea, Malomonas, Sphingophyxis, Novosphingobium, Sphingomonas*, and *Pseudomonas,* are more prevalent in the soil of HCH dumpsites and contribute to the HCH decomposition via the lindane degradation genes they harbor. The HCH dumpsite soil was also abundant in several archeal genera, including *Halobacterium*, *Haloarcula*, and *Halorhabdus*, as well as some fungal genera, including *Fusarium.* Moreover, genes coding for chemotaxis, chloroaromates, and lindane degradation were found to be enriched at this dumpsite. This study identified the unculturable microbial diversity and its potential in HCH degradation. However, among all the strains of bacterial species, some strains have higher HCH degradation abilities. For example, phylogenetic relationships, core genomes, and variation in *lin* system analysis as well as functional profiles of *Sphingobium* spp. demonstrated that strains B90A, HDIPO4, and IP26 could have a higher potential for HCH isomer degradation [56]. Therefore, the selection of bacterial strains that have higher bioremediation potential is crucial to achieve effective outcomes.

The majority of pesticides undergo incomplete deterioration in soil ecosystem due to restrictive environmental circumstances. As a result, pesticide residues are produced and deposited in the soil. The toxicity of these metabolites is usually higher than the pesticides themselves. Additionally, their low solubility as compared to the original molecule hinders their decomposition process in the soil by the soil microbiota resulting in partial pesticide degradation. For example, endosulfan is degraded by oxidation and hydrolysis carried out by the soil resident fungi and bacteria, resulting in the creation of hazardous endosulfan sulphate and less hazardous endosulfan diol [57]. DDT represents one of the best examples of partial degradation since it breaks down into hazardous substances like DDD and DDE, both of which being more toxic as well as persistent as compared to the original molecule [41]. Introduction of specific and targeted microbial populations in the contaminated soil or in soils containing partially degraded pesticides can lead to the complete degradation of pesticides and by improving environmental conditions such as optimum aeration and nutrients, the breakdown of these contaminants along with their by-products in the soil could be accelerated.

Among the key benefits of bioremediation are its cost-effectiveness and environmental-friendly attributes. Moreover, the fact that bioremediation techniques do not necessitate an extensive preparatory evaluation of the polluted site ahead of implementation makes the initial step of the process quick, easy, and affordable.

4. Mechanisms of microbial bioremediation

Numerous technologies have been developed to employ microorganisms for the remediation of pesticides. Natural bioremediation has long been used by civilizations to treat waste water. However, recent advances in molecular biology and ecology have provided opportunities for the employment of efficient biological processes including bioremediation technology that are being used to reduce the impact of hazardous pesticide residues [58]. Living organisms utilize their metabolic processes to transform the contaminated compound into less toxic forms. In the vast majority of instances that have been reported, one of the main strategies employed by microorganisms for bioremediation is enzymatic degradation. The microbial diversity residing at a pesticide contaminated site can be isolated and identified either using culture dependent methods or via culture independent methods using metagenomic sequencing. Culture independent studies are fruitful for obtaining not only a complete picture of the diversity and community dynamics among key microbial players, but also for identifying the functional pathways responsible for the degradation of the pesticide. Microorganisms isolated through culture dependent methods are investigated in the laboratory for their pesticide degradation potential, followed by field-scale experiments to assess their catabolic activity at the contaminated site. Further, through laboratory testing and biochemical assays, the process of bioremediation is monitored constantly [58].

Bioremediation can be brought about by two approaches, namely *in-situ* and *ex-situ* methods. The *in-situ* method involves treatment of contaminated soils at the original site. Contrary to this, contaminated materials are removed and treated elsewhere using the *ex-situ* method of bioremediation (figure 4).

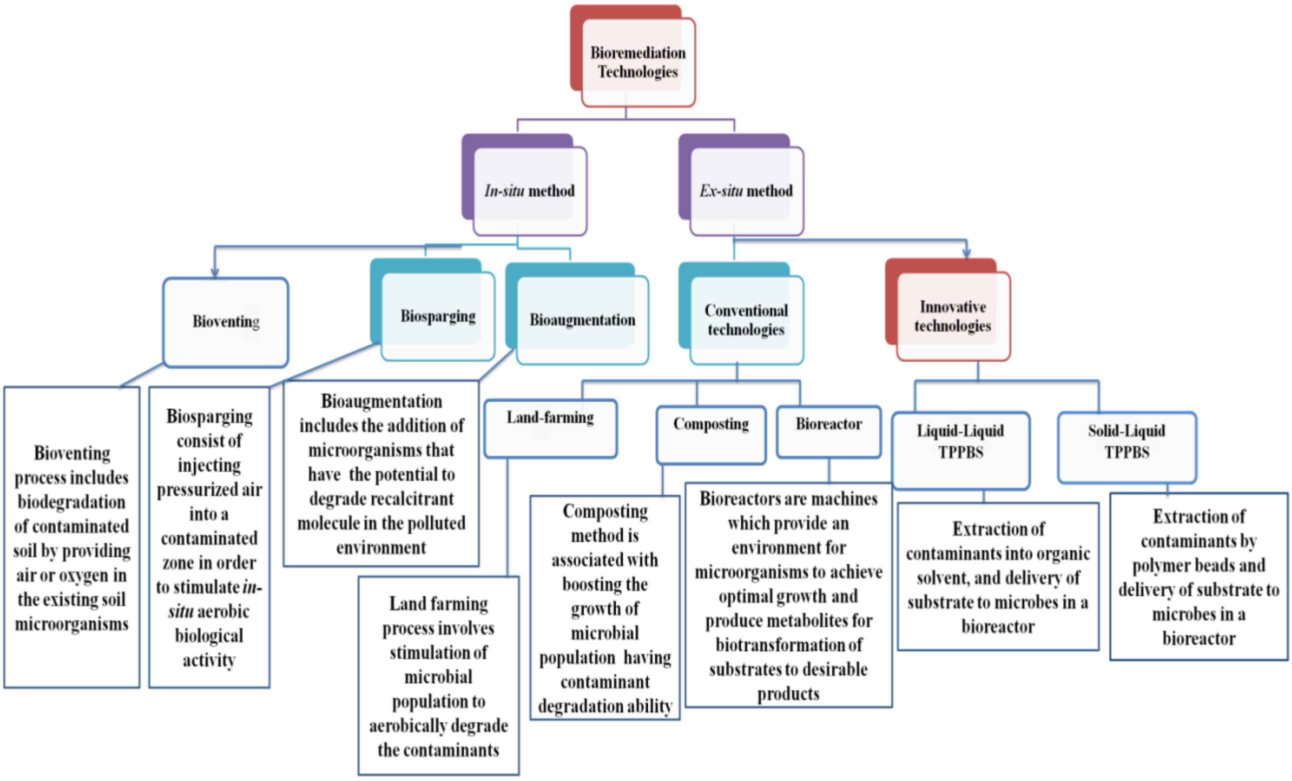

Figure 4: An overview of the classification of bioremediation technologies into two groups, *in-situ* and *ex-situ* techniques, on the basis of where the remediation is taking place. These two groups are further subdivided into different techniques on the basis of their mechanism of action.

4.1. *In-situ* techniques

The *in-situ* method - a less disruptive method - is administrated immediately to the contaminated region without digging or transportation. In order to use this technique, contaminated areas must be administered the required nutrients and microbes. Moreover, for healthy microbial growth at the contaminated site, environmental conditions need to be optimized. In order to encourage naturally occurring bacteria to break down the organic pollutants, oxygen and nutrients are supplied by circulating an aqueous solution through the contaminated soil. Due to its low cost, this bioremediation approach is more advantageous. Bioventing is the most commonly used *in-situ* technique for the degradation of simple hydrocarbons. This technique involves the supply of nutrients through wells in contaminated soil to stimulate indigenous bacteria. In this technique, only the required amount of oxygen is provided, which is necessary for bioremediation, through a low air flow rate, minimizing volatilization and release of contaminants in the atmosphere. Apart from this, the biosparging method, which is based on the idea of generating high oxygen concentrations in underground water to enhance the biological breakdown of pollutants by indigenous microbes is also employed. In this method, pressurized air is injected beneath the ground water table with force [59]. Additionally, bioaugmentation is one of the widely used methods of bioremediation that involves the introduction of laboratory-cultivated microorganisms into contaminated soil, where fewer naturally occurring microorganisms are present for the biodegradation of contaminated materials.

4.2. *Ex-situ* techniques

Techniques for *in-situ* bioremediation are typically unsuitable for situations involving severe contamination or when quick treatment is necessary. The *ex-situ* method involves digging up or removing the contaminated soil, and its off-site treatment. This remediation technique has the potential significance of requiring less time to achieve the intended result. The breakdown of the contaminant occurs significantly and more quickly during *ex-situ* bioremediation than it does during *in-situ* bioremediation because the material is often properly mixed, thoroughly aerated, and given enough nutrients. The fact that the contaminated material is controlled and contained means that the contaminant cannot spread, which is another advantage of this technique.

4.2.1. Conventional technologies

4.2.1.1 Biopiling

Biopiling technique involves excavating soil and building above-ground piles, which are then treated with nutritional additives, competent bacterial isolates, and oxygen to boost bioremediation. The first step in the biopiling procedure is experimental evaluation of the soil sample to ascertain its potential for biodegradation. Further, the soil sample is purified by removing any plastic or other polluting components that may have been incorporated. Following disintegration, the mixture is blended with microbes, oxygen, and minerals to start the reaction [60].

4.2.1.2 Bioreactors

This *ex-situ* method of bioremediation involves a sequence of biological interactions, after the polluted soil and hazardous raw materials are fed into the bioreactor [61]. Different applications can be carried out in batch, sequencing batch, fed-batch, continuous, and multiphase bioreactors. The choice of mode can be influenced by financial factors. Pesticide-contaminated soil may be added to the reactor as sludge or as a solid powder. To enhance the bioconversion mechanism, the parameters inside the bioreactors can be altered in accordance with our needs, such as oxygen content, bacterial species, and minerals. Slurry bioreactor techniques are based on the concept of selective cultures in a controlled reaction environment. This technology is used to remediate hydrocarbons, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), and explosive pesticide contaminations.

4.2.1.3 Land-farming

Land farming is the most basic and cost-effective bioremediation technology because it requires very little equipment to operate. It is one of the most commonly used technologies for soil remediation. An efficient approach of land farming involves extracting polluted soil and placing it in guarded beds. This is based on the principle of promoting the native microbial community to breakdown pollutants aerobically. Therefore, the beds are regularly tilled for providing the adequate aeration to the polluted soil till the completion of the degradation process. According to Nikolopoulou [62], bioremediation is feasible without digging when a pesticide is present less than 1 m below the surface of the earth. However, for efficient bioremediation, a pesticide that is greater than 1.7 m beneath soil surface must be transported to the surface. Remediation of hydrocarbon-polluted sites, such as polyaromatic hydrocarbon-contaminated sites, frequently involves land farming. Some parameters need to be controlled in land farming for optimal biodegradation outcomes, for example, the optimal moisture content of soil should range from 40–80% and the optimal pH range should be from 6–8 [63].

4.2.1.4 Composting

This technique involves the mixing of organic materials with contaminated soil. It is frequently used to influence the growth of bacterial communities in agricultural wastes that have the potential to break down pollutants through the catabolic pathway [64]. In the compositing technique, the polluted soil is first excavated, and then the organic material, such as timber, straw, compost, and plant residues, are added. An ambient temperature of 54º - 65°C must be maintained for this approach to work. Native microorganisms can carry out this task while the toxicants are being degraded. The best method for getting rid of PA, TNT, and RDX is through composting. After composting, the toxicity of the products needs to be evaluated. Some positive attenuation has been observed when soil pesticides are composted by adding manure and other wastes to the soil [64] by microorganisms that can breakdown pesticides.

4.2.2. Innovative Technologies

The physical treatment process was developed much before the advent of innovative technologies. Therefore, before discussing the innovative technologies, a discussion of the physical treatment technique is necessary. The Environmental Protection Agency investigated the Terra-Kleen physical treatment method in 1993 while conducting a study on the soil at three different locations [65]. This approach involved the removal of organic solvents from the soil, sludge, and sediments. The batch process used by the Terra-Kleen system runs at room temperature and extracts organic pollutants from soils to get rid of them into explosive, commercial solvents. After the soils have been cleaned with a solvent, the polluted solvent is passed via a recovery unit where impurities are concentrated and isolated from the solvent, lowering the quantity of contaminant that needs to be disposed of.

4.2.2.1 Liquid-Liquid two phase partitioning bioreactor (TPPB)

TPPBs consist of an insoluble organic phase that was formerly an organic substance and an aqueous phase containing cells. This organic phase has a large capacity to store hazardous compounds while preserving semi-inhibitory amounts in the aqueous solution. In this ternary mixture, the solute partition coefficient-based preferential separation of organic molecules into the organic phase leads to a difference in concentration of substrate between the two phases. To keep the systems in thermodynamic balance, more substrate separates into the aqueous solution when the microbes consume substances from it. This allows for the addition of extremely large amounts of harmful substrates to a bio-treatment system without endangering the cells.

Thermodynamic balance and cellular metabolism regulate the operating process. The basic idea behind this technology is the administration of nutrients to microorganisms in a bioreactor while contaminants are extracted into organic solvents. In order to treat polluted soil, regular interaction between the solvent and the topsoil is necessary, much like the Terra-Kleen procedure. However, for TPPBs, the solvent containing the contaminant would also be placed in a bioreactor, where the pollutant would undergo biological degradation rather than just being concentrated by distillation [66]. Furthermore, it has been demonstrated that thermoplastic polymers and magnetic beads can be combined to make it easier to remove the polymers polluting water as well as soil [67].

4.2.2.2 Solid-Liquid TPPBs

The solid-liquid TPPB technique is a novel technology that uses polymer beads to extract contaminants in a bioreactor. TPPB techniques are applicable for the remediation of explosives, hydrocarbons, PAHs, and phenolic compounds using microbes.

6. Future perspective and Conclusion

Bioremediation is one of the most environmentally feasible and cost-efficient technologies devised to manage pesticide contamination. Although a number of research groups around the world are working towards the evolution of biological remediation techniques for restoring severely polluted agricultural sites, but before these technologies can be commercialized, they must undergo rigorous field testing. The toxicity of the pesticide and its metabolites and numerous environmental conditions are the main reasons why a single technique fails to operate in the field. Therefore, it is necessary to create hybrid technologies that can adapt to the compounds' toxicity and ever-changing environmental conditions. Another factor to consider when choosing bioremediation methods is cost effectiveness. Apart from this, site categorization is an important stage in effective bioremediation that allows for selecting the most suitable and feasible remediation options among the *in-situ* and *ex-situ* methods. Numerous benefits associated with microbe-mediated bioremediation of pesticides, include minimal input costs, simple equipment and space requirements, and cost-effective ecosystem protection. Bioremediation holds the promise of reducing the possible damage that pesticides have brought about to the natural ecosystem while maintaining agricultural productivity and output. Every year, a significant number of pesticides are used in agricultural fields to control crop diseases and pests, but due to their heavy usage, pesticide residues have been detected, causing serious harm to both human health and the environment. Therefore, it is important to study microbial bioremediation of pesticides which provides an eco-friendly and sustainable alternative to other detoxification methods. It is also a versatile and less expensive method that can also be used in conjunction with other technologies. Unfortunately, there is limited knowledge about the variables in control of the deterioration process in the current environmental situation, which limits its applicability. Although a large number of microbial strains that have the capacity to degrade pesticides have been identified and microbial degradation of pesticide residues has made some initial headway, the actual use of microbial bioremediation in the field is yet to be implemented on a greater scale. Integration of advanced concepts of transcriptomics, proteomics, genomics, and metagenomics has led to an accelerated pace of discovery of potential genes, pathways and microbes that could be exploited in the future paving the way for more efficient bioremediation techniques. Some microbes have also been genetically altered to enhance their metabolic capabilities. There are, however, a large number of undiscovered bacteria waiting to be employed for pesticide detoxification. Therefore, it is crucial to investigate the unexplored potential microbes and to employ the already identified candidates to recover and restore value to the contaminated agricultural lands.

Acknowledgment

The authors gratefully acknowledge UGC for providing research funding under UGC-BSR project F. 30-461/2019(BSR).

Declarations

The authors declare that there is no conflict of interest.

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