BIOREMEDIATION OF PESTICIDES AND PHARMACEUTICALS IN SOIL AND WATER: A REVIEW OF CURRENT STRATEGIES, MECHANISMS, AND FUTURE PROSPECTS

Pratibha Gumastha[1], Naresh Chandra Deshmukh [2*]
[1]Sai College, Sector 6, Bhilai, Chhattisgarh, India, 490006
[2*]Shaildevi Mahavidyalay, Anda, Durg, Chhattisgarh India

Abstract:
The contamination of soil and water with pesticides and pharmaceuticals is an increasing global concern, owing to their persistence in the environment, potential bioaccumulation, and adverse effects on human health and ecosystems. Bioremediation, utilizing microorganisms, plants, and enzymes, offers a promising solution for the degradation and removal of these contaminants. This research paper provides an in-depth review of the bioremediation techniques employed for pesticide and pharmaceutical degradation in soil and water. It covers the mechanisms of action, factors influencing biodegradation, microbial and plant species involved, and the challenges and future directions of this field. Through a synthesis of current knowledge, this paper aims to highlight the potential of bioremediation as a sustainable, cost-effective alternative to conventional methods of environmental detoxification.

1. Introduction:

Pesticides and pharmaceuticals are essential for agricultural and medicinal purposes, respectively. However, the improper disposal, overuse, or run off from agricultural lands and pharmaceutical waste have led to their accumulation in environmental matrices such as soil and water [1]. These pollutants, especially persistent organic pollutants (POPs), have long-term ecological and health impacts, including antimicrobial resistance, toxicity to aquatic life, and potential carcinogenicity [2]. Traditional remediation methods, such as chemical treatments and physical removal, are often costly, energy-intensive, and less environmentally friendly [3]. In contrast, bioremediation, the use of living organisms to remove or neutralize contaminants, is gaining traction as an eco-friendly and economically viable approach for addressing pesticide and pharmaceutical pollution [4].

The widespread use of pesticides in agriculture and pharmaceuticals in healthcare has undeniably brought about significant advancements in both sectors [5]. Pesticides have been instrumental in enhancing agricultural productivity by controlling pests, diseases, and weeds that affect crops, while pharmaceuticals have greatly contributed to the treatment and prevention of a wide range of diseases [6]. However, the benefits of these chemicals are often overshadowed by the adverse effects they have on the environment and public health when mismanaged [7]. The persistent nature of many pesticides and pharmaceutical compounds means they often remain in the environment for extended periods, making their removal and neutralization a challenging task [8].Improper application, excessive use, and the inadequate disposal of pharmaceutical and pesticide waste can lead to the leaching of these contaminants into the soil and water systems [9]. The continuous accumulation of these substances can result in significant contamination of groundwater, rivers, lakes, and other ecosystems [10]. This has far-reaching consequences not only for biodiversity but also for human health, as these pollutants may bioaccumulate in the food chain, leading to chronic exposure [11].Among the most concerning effects of pesticide and pharmaceutical pollution is the development of antimicrobial resistance (AMR), which is increasingly recognized as a global health crisis [12]. The release of antibiotics, antipyretics, and other pharmaceutical residues into the environment contributes to the evolution of resistant microbial strains, making infections harder to treat [7]. Additionally, aquatic life is highly susceptible to pesticide runoff, as many chemicals can cause developmental and reproductive issues in fish and other aquatic organisms, disrupting entire ecosystems [3].

In response to these environmental challenges, bioremediation has emerged as a promising and sustainable solution [4]. Bioremediation harnesses the natural abilities of microorganisms, plants, and even enzymes to break down or neutralize hazardous contaminants, turning harmful substances into non-toxic or less harmful compounds [9]. This method is considered to be cost-effective, less energy-consuming, and environmentally friendly compared to traditional remediation techniques, such as chemical treatments and physical removal [6].This research paper aims to explore the potential of bioremediation in the detoxification of pesticide and pharmaceutical pollutants in soil and water [10]. By reviewing the current strategies, microbial and plant-based degradation mechanisms, and the challenges associated with this approach, this paper seeks to highlight the role of bioremediation as a key tool in mitigating the harmful effects of pesticide and pharmaceutical contamination [8]. Furthermore, the paper will delve into the future prospects of bioremediation, focusing on novel technologies and approaches that could enhance its effectiveness and broaden its application across different environmental matrices [11].

2. Sources of Pesticides and Pharmaceuticals in Soil and Water

- **Pesticides**: The primary source of pesticide contamination is agricultural runoff, where pesticides are applied to crops to control pests and weeds [1]. Additionally, leaching from soil and the use of pesticides in urban settings contribute to pollution in groundwater and surface water bodies [2].
- **Pharmaceuticals**: Pharmaceutical pollution arises from improper disposal of unused medications, pharmaceutical manufacturing effluents, and the excretion of drug residues by humans and animals into the sewage system [3]. These residues often find their way into water bodies, where they persist for extended periods [4].

3. Bioremediation Mechanisms

Bioremediation relies on the metabolic activity of microorganisms, plants, and enzymes to degrade or transform harmful pollutants [5]. The main bioremediation mechanisms include:

- **Microbial Biodegradation**: Various bacteria, fungi, and actinomycetes possess the enzymatic machinery to break down pesticide and pharmaceutical molecules [6]. This includes hydrolysis, oxidation, reduction, and dehalogenation reactions that lead to the mineralization of these contaminants [7].
- **Plant-Mediated Remediation (Phytoremediation)**: Certain plant species have been found to accumulate, degrade, or transform contaminants from soil and water [8]. Plants such as

Cress (*Lepidium sativum*) and Poplar trees (*Populus spp.*) have demonstrated potential in degrading pesticide residues [9].

- **Enzyme-Mediated Bioremediation**: Enzymes such as cytochrome P450, laccases, and peroxidases play a critical role in the breakdown of pesticides and pharmaceuticals [10]. These enzymes, produced by microorganisms or plants, facilitate the degradation process by breaking down complex molecules into simpler, non-toxic forms [11].

4. Microbial Strains Used in Bioremediation of Pesticides and Pharmaceuticals

Microbial bioremediation is a promising and environmentally friendly strategy for the removal or degradation of pollutants such as pesticides and pharmaceuticals from contaminated environments [12]. Microorganisms, including bacteria, fungi, and algae, possess a wide range of metabolic pathways that allow them to degrade a variety of organic contaminants [13].

4.1. Bacteria Used in Bioremediation of Pesticides and Pharmaceuticals

- **Pseudomonas spp.**:

Pseudomonas species, particularly *Pseudomonas putida* and *Pseudomonas fluorescens*, are well-known for their ability to degrade a wide range of organic pollutants, including pesticides [14]. These bacteria possess various enzymes, such as dehydrogenases and hydrolases, that facilitate the breakdown of toxic compounds [15]. *P. putida* has been extensively studied for its ability to degrade organophosphates (e.g., chlorpyrifos) [16]. Additionally, some *Pseudomonas* strains degrade pharmaceutical contaminants, including antibiotics like tetracycline, through oxidation and reduction mechanisms [17].

- **Bacillus spp.**:

Bacillus subtilis and *Bacillus thuringiensis* are documented for their capacity to degrade pesticides, including organochlorines (e.g., DDT) and carbamates [18]. These bacteria use enzymes like esterases and oxidases to break down pesticide molecules [19]. Some *Bacillus* strains also degrade pharmaceutical contaminants, such as penicillin and sulfonamides, via enzymatic hydrolysis [20].

- **Arthrobacter spp.**:

Arthrobacter globiformis and *Arthrobacter chlorophenolicus* degrade chlorinated aromatic compounds commonly found in pesticides like hexachlorobenzene and DDT [21]. These bacteria utilize dechlorination pathways to break down persistent organic pollutants (POPs) [22]. They also degrade pharmaceutical compounds, including NSAIDs like ibuprofen [23].

- **Sphingomonas spp.**:

Sphingomonas aromaticivorans effectively degrades aromatic hydrocarbons, often found in pesticides like herbicides and insecticides [24]. They also degrade pharmaceutical contaminants like ibuprofen and acetaminophen [25]. These bacteria utilize monooxygenases and dioxygenases to break down pollutants into non-toxic forms [26].

4.2. Fungi Used in Bioremediation of Pesticides and Pharmaceuticals

- **White-Rot Fungi (e.g., Phanerochaete chrysosporium)**:

Phanerochaete chrysosporium produces extracellular enzymes such as lignin peroxidase and manganese peroxidase, enabling it to degrade organochlorines and PCBs [27]. It has also been shown to degrade pharmaceuticals like acetaminophen [28].

- **Aspergillus spp.**:

Species like *Aspergillus niger* and *Aspergillus terreus* break down pharmaceuticals, including ibuprofen and diclofenac, through oxidative reactions [29]. Their enzymes, such as laccases and cytochrome P450, play a critical role in degrading pesticide and pharmaceutical compounds into less toxic metabolites [30].

4.3. Algae in Bioremediation of Pesticides and Pharmaceuticals

Algae absorb and assimilate contaminants, including heavy metals, pesticides, and pharmaceutical residues [31]. Algal species such as *Chlorella vulgaris* and *Scenedesmus* absorb pesticides like atrazine and malathion from water and degrade pharmaceutical pollutants such as antibiotics [32]

4.4. Microbial Degradation Mechanisms

The mechanisms employed by microorganisms to degrade pesticides and pharmaceuticals are diverse and depend on the chemical structure of the pollutants. Common microbial degradation pathways include:

- **Hydrolysis**: The breakdown of pesticide and pharmaceutical compounds through the addition of water, leading to the cleavage of chemical bonds. Enzymes like esterases and hydrolases catalyze these reactions [3].
- **Oxidation and Reduction**: Microorganisms often employ oxidative and reductive processes to degrade contaminants. Enzymes such as cytochrome P450 monooxygenases, dehydrogenases, and reductases are involved in the introduction of oxygen atoms into pesticide and pharmaceutical molecules, making them more water-soluble and easier to degrade [4].
- **Dechlorination**: Chlorinated pesticides, such as DDT, undergo dechlorination in certain bacteria, including *Arthrobacter* and *Sphingomonas* species, leading to the removal of chlorine atoms from the pesticide molecule [9].
- **Ring Cleavage**: Many microorganisms degrade aromatic compounds, including herbicides and pharmaceuticals, by cleaving the aromatic ring. Fungi such as *Phanerochaete chrysosporium* are known for their ability to break down complex ring structures [10][11][12].

4.5. Advantages of Using Microbial Strains in Bioremediation

- **Cost-Effectiveness**: Microbial bioremediation is often cheaper than traditional methods, such as physical removal or chemical treatment, because it requires fewer resources and can be performed *in situ* (at the contamination site) [13][14][15].
- **Eco-Friendly**: Microbial degradation is a natural process, and the microorganisms involved in bioremediation often degrade pollutants into non-toxic or less toxic compounds, ensuring minimal environmental impact[18].
- **Versatility**: Microorganisms can degrade a wide range of pesticides and pharmaceutical contaminants, and they can be engineered to enhance their capabilities through genetic modification or selective adaptation [21].

5. Factors Influencing Bioremediation Efficiency

The effectiveness of bioremediation as a method for removing or neutralizing pesticides and pharmaceutical pollutants from soil and water is influenced by a range of environmental, biological, and chemical factors. These factors determine how well microorganisms (or other bioremediation agents, such as plants) can degrade, detoxify, or assimilate the contaminants. Understanding these factors is crucial for optimizing bioremediation processes and achieving the desired outcomes, particularly in complex and contaminated environments [22]

5.1. Environmental Factors

Environmental conditions play a significant role in determining the success of bioremediation. Since microorganisms and plants are highly sensitive to changes in their surroundings, several abiotic factors can either promote or hinder the bioremediation process [1][12].

5.1.1. Temperature

Temperature has a direct impact on the metabolic activity of microorganisms and the rate of bioremediation. Each microorganism has an optimal temperature range for growth and activity. At lower temperatures, the metabolic rate of microbes slows down, leading to reduced degradation rates of contaminants. Conversely, at high temperatures, microbial enzymes may denature, reducing the efficiency of bioremediation. Typically, mesophilic bacteria (those that thrive in moderate temperatures) are employed for bioremediation, with an optimal temperature range between 25°C and 35°C. However, thermophilic microorganisms (those that thrive in higher temperatures) can be used in certain cases where the contaminants are more persistent or difficult to degrade [7][25].

5.1.2. pH

The pH of the environment influences the solubility and bioavailability of contaminants as well as the growth and metabolic activity of microorganisms. Most microbes have a preferred pH range, typically between 6 and 8 for soil and water bioremediation. In highly acidic or alkaline conditions, the degradation process can slow down, as many microbes are unable to function efficiently outside their optimal pH range. Additionally, the ionization state of certain pollutants (e.g., pesticides and pharmaceuticals) can vary with pH, influencing their uptake and degradation by microorganisms. Therefore, maintaining a neutral to slightly alkaline pH is often crucial for maximizing bioremediation efficiency [3][19][34].

5.1.3. Oxygen Availability

Aerobic microorganisms, which require oxygen for respiration, are often more effective in degrading pollutants such as hydrocarbons and pesticides. In oxygen-rich environments, these microbes utilize oxygen to metabolize organic contaminants, breaking them down into less harmful substances [9][18]. However, in anaerobic (low-oxygen) environments, anaerobic bacteria may be more active in degrading certain pollutants through processes like reduction or fermentation [14][31]. For bioremediation, the oxygen availability must be managed based on the nature of the contaminants and the microbial community employed. In some cases, adding oxygen or promoting oxygen diffusion can enhance aerobic microbial activity, while in other cases, anaerobic conditions might be necessary to achieve optimal degradation [6][29].

5.1.4. Moisture Content

Water is essential for microbial growth and activity. Adequate moisture levels are required for the dissolution and transport of contaminants to microbial cells. In soil, the moisture content can affect the availability of both nutrients and pollutants to microbes. Too little moisture can lead to dehydration of microbial cells and a decline in microbial activity, while excessive moisture can create anaerobic conditions, hindering aerobic degradation processes [20][28]. The optimal moisture content depends on the microbial species and environmental conditions, but generally, a balanced, moist environment facilitates efficient bioremediation [10][22].

5.1.5. Nutrient Availability

Microorganisms require various nutrients, such as nitrogen, phosphorus, and sulfur, to grow and metabolize contaminants. The availability of these nutrients in the contaminated environment can influence microbial growth rates and their ability to degrade pollutants. If nutrients are deficient, bioremediation efficiency can be significantly reduced, as the microorganisms may not have the necessary resources for growth and enzyme production. In some cases, nutrient supplementation (e.g., nitrogen or phosphorus) can be used to enhance microbial activity and accelerate the degradation of contaminants. This process, known as nutrient biostimulation, has been widely applied in bioremediation projects [11][26][38].

5.1.6. Salinity

High salinity levels can stress microorganisms, particularly in marine and coastal environments, reducing their ability to perform bioremediation. High salt concentrations can affect the osmotic balance of microbial cells, leading to reduced growth rates and metabolic activity [5][15][30]. However, some halophilic (salt-loving) microorganisms have adapted to high-salinity conditions and can effectively degrade pollutants in saline environments [8][23]. In freshwater environments, it is important to control salinity levels, as high salt concentrations can limit the diversity and activity of microbes involved in bioremediation 36]

5.2. Chemical Factors

The chemical nature of the pollutants and the surrounding environment plays a pivotal role in bioremediation efficiency. The interactions between pollutants and microbial enzymes, as well as the chemical structure of the contaminants, can significantly impact the degradation process [15][19].

5.2.1. Pollutant Concentration

The concentration of pesticides and pharmaceutical pollutants in the environment influences the rate and extent of bioremediation. At low concentrations, pollutants may be rapidly degraded by microorganisms. However, at high concentrations, the contaminants can become toxic to the microbes, reducing their effectiveness. Additionally, high concentrations can lead to the accumulation of toxic intermediate metabolites that may inhibit microbial activity. Therefore, bioremediation processes are often more effective at moderate concentrations of contaminants, and the process must be adjusted to account for varying pollutant[25][32].

5.2.2. Bioavailability of Pollutants

The bioavailability of contaminants refers to the extent to which pollutants are accessible to microorganisms for degradation. Contaminants in soil or water may be bound to organic matter, sediment particles, or other substances, making them less available to microbial organisms. For efficient bioremediation, it is crucial that pollutants be in a form that microbes can readily access. The bioavailability of pollutants can be influenced by factors such as soil texture, particle size, organic matter content, and the chemical properties of the contaminants (e.g., hydrophobic or hydrophilic nature). Techniques such as surfactant addition or soil tilling can be used to increase the bioavailability of contaminants and promote microbial degradation [25].

5.2.3. Toxicity of Pollutants

Some pesticides and pharmaceutical compounds are highly toxic to microorganisms, which can inhibit the bioremediation process. For example, certain pesticides are designed to be highly toxic to pests and may also negatively affect the microorganisms used in bioremediation. Similarly, pharmaceuticals like antibiotics can inhibit microbial activity by disrupting microbial growth or inducing resistance. The toxicity of pollutants can be mitigated by introducing microbial strains that are resistant to these chemicals or by using bioremediation techniques that involve the breakdown of toxic compounds into less harmful intermediates [36].

5.2.4. Chemical Composition of Pollutants

The chemical structure of the contaminants determines how easily they can be degraded by microorganisms. Simple, small molecules are generally more readily metabolized, whereas large, complex molecules, such as persistent organic pollutants (POPs) like DDT or phthalates, are often more challenging to break down. The presence of functional groups, such as halogens, nitrates, or sulfates, can influence the reactivity and biodegradability of pollutants. Bioremediation efficiency can be enhanced by employing microbial strains with the specific enzymatic machinery required to degrade complex compounds [39].

5.3. Biological Factors

Biological factors, including the characteristics of the microbial community, microbial diversity, and the presence of microbial consortia, play a significant role in determining the success of bioremediation [17][22].

5.3.1. Microbial Diversity

A diverse microbial community can enhance the bioremediation process by providing a range of enzymatic activities capable of degrading different contaminants. In some cases, a consortium of microorganisms working together can achieve more efficient pollutant breakdown than a single species. For example, bacteria, fungi, and algae can all contribute to different stages of the degradation process, enhancing the overall efficiency of bioremediation [37].

5.3.2. Microbial Adaptation

Microorganisms that are naturally adapted to specific pollutants are more likely to thrive in contaminated environments and effectively degrade the pollutants. For example, certain bacteria have evolved to degrade organophosphates (commonly used pesticides) or pharmaceuticals like antibiotics. In addition to natural adaptation, microbial communities can be engineered or selected for enhanced degradation capabilities through selective pressure in laboratory settings, improving the overall efficiency of bioremediation [23][30][38].

5.3.3. Symbiotic Interactions

Acta Biomed 2020; Vol. 91, N. 1: ISSN: 0392-4203 | eISSN: 2531-6745

In some cases, microorganisms form symbiotic relationships with plants or other organisms to enhance the degradation of pollutants. For example, plants in phytoremediation processes may release root exudates that stimulate microbial activity, thereby enhancing pollutant degradation in the rhizosphere. Such interactions can be harnessed to increase the efficiency of bioremediation [24][33].

5.4. Management and Optimization of Bioremediation

To improve bioremediation efficiency, strategies such as biostimulation (adding nutrients or oxygen), bioaugmentation (introducing specific microbial strains), and maintaining optimal environmental conditions must be carefully planned and monitored[34].. Proper management of environmental parameters, such as temperature, pH, and moisture, can significantly enhance microbial activity and pollutant degradation [19]

In conclusion, bioremediation is a complex process influenced by multiple environmental, chemical, and biological factors. Understanding and managing these factors is essential for optimizing the efficiency of bioremediation processes for pesticides and pharmaceuticals. By manipulating these variables, bioremediation can be tailored to specific contaminants, improving both the speed and extent of pollutant removal from contaminated sites [15][27]

6. Case Studies on Bioremediation:

• **Degradation of Pesticides:** A study on the use of *Pseudomonas putida* in the bioremediation of organophosphate pesticide-contaminated soil showed significant pesticide degradation within 10 days of treatment, with a reduction in toxicity [25].

• **Pharmaceutical Pollutants:** *Bacillus subtilis* has been successfully employed in degrading pharmaceutical residues in wastewater, with a significant reduction in the levels of commonly found drugs such as paracetamol, ibuprofen, and carbamazepine [26][28].

7. Challenges in Bioremediation:

While bioremediation holds great promise, several challenges hinder its widespread application:

• **Limited Degradation Capacity:** Some pesticides and pharmaceuticals are highly persistent, requiring highly specialized or genetically engineered microorganisms for effective degradation [27].

• **Ecological Balance:** Introducing non-native species to degrade contaminants may disrupt the local ecosystem, leading to unforeseen consequences [29].

• **Slow Degradation Rate:** Bioremediation processes can be slow, especially in comparison to chemical or physical methods, and may require significant time for complete detoxification [30].

• **Contaminant Toxicity:** Some pollutants may inhibit the growth of bioremediating microorganisms or plants, leading to suboptimal performance [23][31].

8. Future Prospects and Innovations:

• **Genetically Engineered Microorganisms:** Genetic modification of microorganisms could enhance their ability to degrade a wider range of pesticides and pharmaceuticals, improving bioremediation efficiency [32].

• **Bioreactor Systems:** The development of bioreactors for large-scale treatment of contaminated water using microbial consortia or plant systems could facilitate the treatment of industrial wastewater [33].
• **Microbial Fuel Cells (MFCs):** Combining bioremediation with energy generation, microbial fuel cells could provide a sustainable approach for the simultaneous removal of contaminants and generation of electrical power [34].
• **Nanobioremediation:** Nanotechnology offers the potential to enhance bioremediation through the use of engineered nanoparticles that can adsorb, transport, or react with pollutants, facilitating their breakdown by microbes or plants [35].

9. Conclusion:

Bioremediation presents a sustainable and eco-friendly solution for addressing the contamination of soil and water by pesticides and pharmaceuticals. While challenges remain in optimizing degradation rates, improving microbial and plant-based strategies, and overcoming toxicity limitations, ongoing research holds promise for more effective and efficient bioremediation systems. Future advancements in genetic engineering, nanotechnology, and bioreactor design are expected to further enhance the capabilities of bioremediation, making it a key tool in mitigating environmental pollution and promoting ecosystem health

References :

1. Anjum, R., Rahman, M., Masood, F., & Malik, A. (2012). *Bioremediation of Pesticides from Soil and Wastewater*.
2. Raffa, C., & Chiampo, F. (2021). *Bioremediation of Agricultural Soils Polluted with Pesticides: A Review*. *Bioengineering*, 8.
3. Odukkathil, G., & Vasudevan, N. (2013). *Toxicity and bioremediation of pesticides in agricultural soil*. *Reviews in Environmental Science and Bio/Technology*, 12, 421-444.
4. Helbling, D. (2015). *Bioremediation of pesticide-contaminated water resources: the challenge of low concentrations*. *Current opinion in biotechnology*, 33, 142-148.
5. Geetha, M., & Fulekar, M. (2008). *Bioremediation of pesticides in surface soil treatment unit using microbial consortia*. *African Journal of Environmental Science and Technology*, 2, 036-045.
6. Giri, B., et al. (2020). *Progress in bioremediation of pesticide residues in the environment*. *Environmental Engineering Research*.
7. Ahemad, M., & Khan, M. S. (2011). *Pesticide Interactions with Soil Microflora: Importance in Bioremediation*.
8. Kuhad, R., et al. (2004). *Bioremediation of Pesticide-Contaminated Soils*.
9. Spina, F., et al. (2018). *Fungi as a toolbox for sustainable bioremediation of pesticides in soil and water*. *Plant Biosystems*, 152, 474-488
10. Sniegowski, K., et al. (2007). *Use of pesticide-primed agricultural soils for bioaugmentation of lab-scale on-farm bioremediation systems*.

11. Uqab, B., Mudasir, S., & Nazir, R. (2016). *Review on Bioremediation of Pesticides*. *Journal of Bioremediation and Biodegradation*, 2016, 1-5.

12. Chaudhari, M., & Solanki, K. (2023). *Role of CRISPR-Cas Technique in Bioremediation of Pesticides*. *International Journal of Current Microbiology and Applied Sciences*.

13. Chhaya, Raychoudhury, T., & Prajapati, S. K. (2020). *Bioremediation of Pharmaceuticals in Water and Wastewater*.

14. Bali, A. (2020). *Bioremediation of Pharmaceutical Wastes*. *Waste Management*. Das, M. P., Bashwant, M., Kumar, K., & Das, J. (2012). *Control of pharmaceutical effluent parameters through bioremediation*. *Journal of Chemical and Pharmaceutical Research*.

15. Mansour, H. B., et al. (2012). *Bioremediation of industrial pharmaceutical drugs*. *Drug and Chemical Toxicology*, 35, 235-240.

16. Qiu, R., Guérif, J., & Zhang, R. (2012). *Bioremediation of Contaminated Soil and Water*. *Pedosphere*, 22, 425.

17. Dasappa, S., & Loehr, R. (1991). *Toxicity reduction in contaminated soil bioremediation processes*. *Water Research*, 25, 1121-1130.

18. Aislabie, J., Saul, D., & Foght, J. (2006). *Bioremediation of hydrocarbon-contaminated polar soils*. *Extremophiles*, 10, 171-179.

19. Wu, C., Spongberg, A., Witter, J. D., Fang, M., & Czajkowski, K. (2010). *Uptake of pharmaceuticals by soybean plants from biosolids*. *Environmental Science & Technology*, 44, 6157-6161.

20. Gupta, P., & Gandhi, M. (2023). *Bioremediation of Organic Pollutants in Soil–Water System: A Review*. *BioTech*, 12.

21. Li, Y., Sallach, J., Zhang, W., Boyd, S., & Li, H. (2019). *Pharmaceuticals in soil-water-plant systems*. *Water Research*, 152, 38-46.

22. Ransing, S., et al. (2020). *Bioremediation of contaminated soils*. *International Journal of Chemical Studies*.

23. Chorom, M., Sharifi, H., & Motamedi, H. (2010). *Bioremediation of crude oil-polluted soil by fertilizers*. *Iranian Journal of Environmental Health Science & Engineering*, 7, 319-326.

24. Ajona, M., & Vasanthi, P. (2021). *Bioremediation of petroleum-contaminated soils – A review*. *Materials Today: Proceedings*.

25. Boopathy, R. (2000). *Factors limiting bioremediation technologies*. *Bioresource Technology*, 74, 63-67.

26. Garg, S. (2020). *Bioremediation of Agricultural, Municipal, and Industrial Wastes*. *Waste Management*.

27. Sheikhavandi, T. (2015). *Microbial Functional Activity in Bioremediation of Contaminated Soil and Water*.

28. Martínez-Hernández, V., et al. (2016). *Sorption and biodegradation in soil contact*. *The Science of the Total Environment*, 559, 232-241.

29. Braddock, J., et al. (1997). *Enhancement of microbial activity in hydrocarbon-contaminated soils*. *Environmental Science & Technology*, 31, 2078-2084.

30. **Lagadec, A. M., et al.** (2000). *Pilot-scale subcritical water remediation of polycyclic aromatic hydrocarbon- and pesticide-contaminated soil*. *Environmental Science & Technology*, 34, 1542-1548.
31. **Tumeo, M., & Guinn, D.** (1997). *Evaluation of Bioremediation in Cold Regions*. *Journal of Cold Regions Engineering*, 11, 221-231.
32. **Zhang, H., et al.** (2020). *Bioremediation of co-contaminated soil with heavy metals and pesticides*. *Chemical Engineering Journal*, 398, 125657.
33. **Randhawa, G., & Kullar, J. S.** (2011). *Bioremediation of Pharmaceuticals, Pesticides, and Petrochemicals with Gomeya/Cow Dung*. *ISRN Pharmacology*, 2011.
34. **Megharaj, M., et al.** (2011). *Bioremediation approaches for organic pollutants: a critical perspective*. *Environment International*, 37(8), 1362-1375.
35. **Ahemad, M., & Khan, M. S.** (2011). *Pesticide Interactions with Soil Microflora: Importance in Bioremediation*.
36. **De Wilde, T., et al.** (2007). *Overview of on-farm bioremediation systems to reduce point source contamination*. *Pest Management Science*, 63(2), 111-128.
37. **Baczynski, T. P., Pleissner, D., & Kryłów, M.** (2012). *Bioremediation of Chlorinated Pesticides in Field-Contaminated Soils*. *Clean-Soil Air Water*, 40, 864-869.
38. **Spina, F., et al.** (2018). *Fungi as a toolbox for sustainable bioremediation of pesticides*. *Plant Biosystems*, 152, 474-488.
39. **Giri, B., et al.** (2020). *Progress in bioremediation of pesticide residues in the environment*. *Environmental Engineering Research*.