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The Role of Microorganisms in the Degradation of Pesticides: A Sustainable Approach to Soil Remediation

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ABSTRACT: The widespread use of pesticides in agriculture, aquaculture, and public health has led to severe environmental and public health concerns due to their overapplication and persistence in ecosystems. Pesticide residues accumulate in soil, degrade its fertility, pollute groundwater, and harm non-target organisms, including beneficial insects and aquatic life. This persistent contamination poses a significant threat to biodiversity, food safety, and ecosystem resilience. The aim of this review is to examine microbial bioremediation as a sustainable and effective strategy for remediating pesticide-contaminated soils. The paper evaluates the mechanisms by which microorganisms degrade or transform hazardous pesticide compounds into less toxic or non-toxic forms and assesses the advantages and limitations of bioremediation technologies. Notably, bioremediation is recognized for its environmental compatibility, cost-effectiveness, and potential to restore soil health without undermining agricultural productivity. Recent studies highlight promising microbial strains capable of degrading diverse classes of pesticides under varying environmental conditions. However, challenges remain, including the scalability of microbial technologies, the complexity of mixed-contaminant sites, and the influence of abiotic factors on microbial efficacy. Future research should focus on optimizing microbial consortia, integrating genetic and metabolic engineering approaches, and developing field-scale applications tailored to specific agroecosystems. Advancing these areas will be critical for establishing bioremediation as a central pillar in sustainable pesticide management and environmental restoration strategies.

KEYWORDS: Pesticides; bioremediation; impacts; challenges

1. Introduction

Chemical substances called pesticides are used to get rid of weeds, fungi, insects, and rodents. These substances consist of plant growth regulators, fungicides, insecticides, herbicides, nematicides, molluscicides, and rodenticides, among others. Their use is essential for a number of industrial processes, including aquaculture, agriculture, food processing, and storage, as well as for crop protection, food preservation, and disease prevention. They also serve as a defense against diseases transmitted by vectors. On the other hand, overuse and improper pesticide use have resulted in serious problems such as food contamination, environmental harm, and pollution of aquatic and agricultural ecosystems. Humans can contract a variety of diseases from eating fruits, vegetables, meat, milk, and crops polluted with pesticides [1]. Pesticides can enter a person's body by skin contact, inhalation, or ingestion. The possible health impacts can be influenced by various factors, including the type of pesticide used, the exposure pathway and time frame, and the individual's health condition. Pesticides can be digested, eliminated, stored, or bioaccumulated in adipose tissues once they are within the body [2]. Growing populations and changing climatic patterns have resulted in an increased global dependence on pesticides, raising food production requirements and pest infestation rates [3]. Pesticide use in agriculture is rapidly increasing in emerging countries, especially in Southeast Asia. The number of pesticides used worldwide grew from 2.27 billion to 2.36 billion kilos between 2000 and 2007 [4]. Both freshwater and marine ecosystems are now heavily dependent on the widespread use of pesticides. Even though pesticides can increase crop yields and control pests, they can have disastrous impacts on the ecosystem [5]. Pesticide residues frequently linger in the soil, where they have an impact on microorganisms that are essential to the health of the soil. Therefore, steps must be taken to minimize the negative effects of residual pesticides and lower their concentrations. Bioremediation, an economical and environmentally sustainable technique that converts toxic pollutants into less harmful molecules through the aid of living organisms, is one possible remedy. The knowledge of the microbiological mechanisms underlying the chemical pesticides' biodegradation has garnered increasing attention in recent years [6]. Growing evidence points to bioremediation as an effective means of cleaning pesticide-contaminated soil and reducing the negative impacts of overuse. Pesticides are essential for agricultural and pest control, but they also have long-term effects on the environment and human health that need to be carefully managed and remedied using creative techniques. This essay aims to explore bioremediation strategies to mitigate the harmful effects of pesticide contamination and propose sustainable solutions for their management.

2. Categories of Pesticides

Based on where they came from, pesticides were typically classified into two main categories: chemical and biological. Chemical pesticides, which included synthetic and inorganic substances like sulfur, lime, and ferrous sulfate, were renowned for their ability to control pests quickly and efficiently. They were more effective and persistent in the environment because of their simple chemical structures, which also made them more soluble in water and easier for pests to absorb [1]. Furthermore, pesticides could be grouped according to a number of factors, including their level of toxicity, method of action, functional group, and chemical class. Fungicides, which targeted fungus, insecticides, which were used to kill insects, and herbicides, which were efficient at getting rid of weeds, were important categories [3]. Biological pesticides, often known as biopesticides, were made from natural organisms to reduce pests and increase crop yields. Microbial pesticides, for instance, protected plants from pests by using metabolites made by microbes. Choosing the right application methods, doses, and safety precautions required an understanding of these classes [7]. Organophosphates, organochlorines, carbamates, and pyrethroids were the four main types of organic compounds that made up the majority of synthetic pesticides [14]. Figure 1 showed the classification of chemical pesticides [34].

Biopesticides, on the other hand, were naturally occurring pesticides that originated from living things like fungi, bacteria, and plants. Pesticides used in agriculture comprised over 95% herbicides, fungicides, and insecticides. Around 2.66 million metric tons of agricultural pesticides were used globally in 2020, with herbicides making up almost half of that amount, according to data [8]. The majority of pesticides used in agriculture today were synthetic and contained a variety of organic and inorganic substances that could affect non-target species, including people, such as organochlorines, organophosphates, arsenic, lead, and mercury [8, 19]. Bioremediation processes may have been affected differently by different pesticide classes. Despite the potential of enzyme-based techniques, not all pesticide classes may have been appropriate for these uses [8].

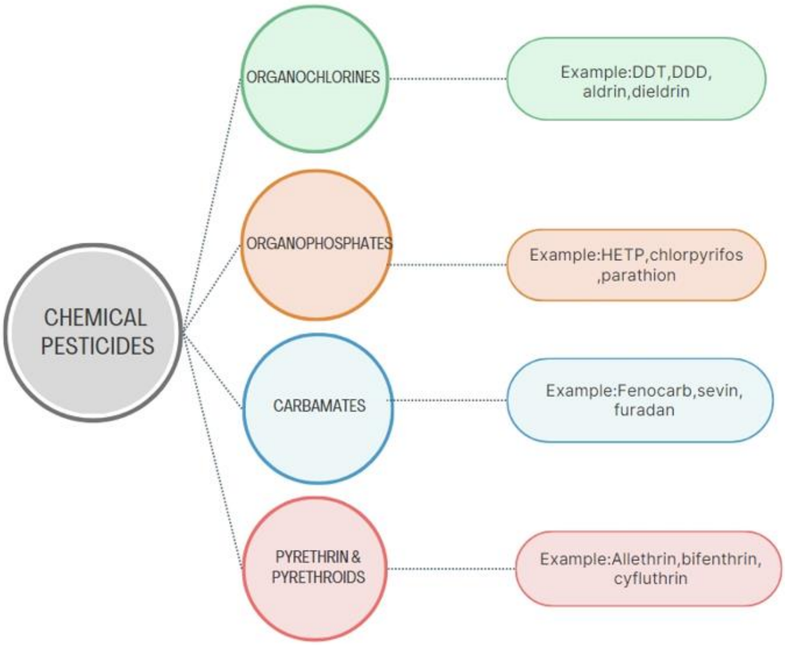

Figure 1. Classification of chemical pesticides.

3. Sources and Fate of Pesticides

Most pesticides applied in agriculture wound up in the land and atmosphere. The percentage of these compounds or their derivatives that were left as persistent residues in the soil ranged from 20 to 70 percent [9]. The main classification scheme for pesticides was based on where they were first introduced into the ecosystem. Point source pollution was contamination that came from a single, fixed source, such as chemical runoff from pesticides that were applied incorrectly, stored improperly, or disposed of improperly near water bodies. One frequent instance was the direct entry of pesticides into groundwater, which could contaminate wells and was frequently caused by spills or inappropriate disposal. Another example of point source pesticide pollution in surface waters was the usage of urban insecticides [11]. Through outlets including industrial sites, livestock farms, municipal wastewater treatment plants, and aquaculture activities, point sources of pesticide contamination (PSPC) emitted pesticides directly into aquatic habitats [10]. Farmers applied a lot of pesticides to preserve crops and boost harvests, making them major consumers. In addition, large amounts of pesticides were used in the wood treatment business to treat raw materials [11]. Chemical compounds from treated items could contaminate soil and water by leaking into them, depending on the pesticide's qualities. Industrial activities were a potential source of pesticide pollution, as chemical fertilizers and pesticides used in agriculture could seep into the soil and groundwater, compromising the ecosystem's equilibrium and the health of the soil [38, 39-41]. Furthermore, using home pesticides to maintain gardens and lawns released these chemicals into the soil, where they could linger and have a detrimental impact on nutrient cycling and soil organisms [40]. Conversely, non-point source pollution occurred when pesticides were dispersed widely from bigger areas throughout watersheds, eventually finding their way into bodies of water. Non-point sources, as opposed to point sources, derived from agricultural areas where pesticides gradually seeped into surface and groundwater due to erosion and runoff events [11]. Usually, when pesticides were sprayed on crops, they drifted into the soil or washed off of the treated plants and seeds. Pesticides were released into the environment due to a variety of factors, including planting dates, pesticide application techniques, amounts applied, and irrigation schedules [9].

Understanding the dispersion of pesticides throughout the biosphere required research on their behavior and mobility [11]. Pesticide residues persisted in spreading throughout the environment, despite current efforts to reduce application rates and their negative effects on the environment through improved pesticide formulations [12]. Upon initial application, pesticides stuck to plant leaves, stems, and fruits. On the other hand, systemic pesticides were absorbed by the plant and might have spread throughout its vascular system, impacting various sections. Plant enzymes played a crucial role in the metabolic transformation of some herbicides within plants, hence mitigating their toxicity. High vapor pressure pesticides had the ability to evaporate into the atmosphere, causing off-target drift and possibly damaging unintentional plants. Pesticide molecules broke down at different rates when exposed to sunlight, with some degrading rapidly and others building up over time. This process was known as photodegradation. Broader ecological effects could result from the use of pesticides since they could also harm non-target creatures, such as aquatic species and beneficial insects. Reducing environmental harm and advancing sustainable farming required an understanding of these processes. Surface runoff, evaporation, leakage, and microbial degradation were the ways in which pesticides got inside plants [13]. Furthermore, because of their strong affinity to soil particles, which could be modified by organic matter and texture, pesticides could linger in the soil for a long time, harming the ecosystem as well as the soil [14]. Through reactions like hydrolysis, oxidation, and reduction, microorganisms in contaminated soil could change the chemical structure of pesticides [21]. Microbial enzymes aided in the bioremediation of contaminated soils by dissolving complex pesticide molecules into less hazardous, simpler forms. Pesticides' chemical bonds were broken by adding water during a process called hydrolysis, which was frequently aided by enzymes like hydrolases and esterases [21]. Furthermore, pesticides could be oxidized by enzymes such as laccases, which added oxygen to their structure and increased their solubility, decreasing their toxicity [41]. Sources and environmental fate of pesticides were summarized in Table 1.

Table 1. Sources and environmental fate of pesticides.

Source/Process	Description	Environmental Impact	Reference
Soil Residues	20–70% of applied pesticides persist in soil.	Long-term soil contamination and disruption of soil ecosystems.	[9]
Point Source Pollution	Contamination from fixed locations (e.g., spills, improper disposal).	Direct pollution of surface and groundwater.	[10, 11]
Industrial and Agricultural Activities	Use of pesticides in farming and wood treatment industries.	Leaching into soil and water, affecting soil health and ecosystems.	[38, 39–41]
Urban and Household Use	Use of pesticides in gardens and lawns.	Soil contamination, disrupted nutrient cycling.	[40]
Non-Point Source Pollution	Pesticides dispersed over large areas via runoff and erosion.	Widespread water pollution, contamination of surface and groundwater.	[11]
Plant Absorption and Transformation	Pesticides absorbed and metabolized by plants (systemic pesticides).	Variable persistence and toxicity reduction depending on plant metabolism.	[9, 11]
Atmospheric Dispersion (Drift and Evaporation)	Evaporation and drift of volatile pesticides into the atmosphere.	Off-target effects; impact on non-target plants and species.	[12]
Photodegradation	Breakdown under sunlight exposure.	Reduces or sometimes increases pesticide persistence.	[12]
Soil Persistence and Microbial Degradation	Binding to soil particles, biotransformation by microbes through hydrolysis, oxidation, and reduction.	Long-term ecosystem harm; potential for bioremediation.	[14, 21, 41]

4. Pesticide Transport

Pesticide movement through the soil, availability to living things, and capability to reach water sources were all influenced by the sorption and desorption processes between soil particles and pesticide molecules. The length of time pesticides lasted and their toxicity within the hydrological system were mostly determined by their sorption characteristics. Certain pesticides that were sprayed on soil formed long-lasting bonds with soil colloids, whereas weakly bound pesticides separated into the soil solution and started to function biologically. Sorption lowered the danger of contamination by reducing the possibility of pesticide runoff, leaching, and uptake. Sorption potential was greatly impacted by variables such as soil texture, organic matter, pH, and the presence of certain minerals. Particularly when it came to clay particles and organic matter surfaces, soil pH in particular affected sorption by controlling the chemical form, mobility, and accessibility of pesticides [9]. Temperature had an effect on ammonium nitrogen adsorption, but soil moisture content also affected pesticide adsorption. Furthermore, the adsorption of pesticides like DDT was influenced by humic acid colloids in sediments, which could harm crops or leave dangerous residues [3]. Figure 2 shows the transport and fate of pesticides.

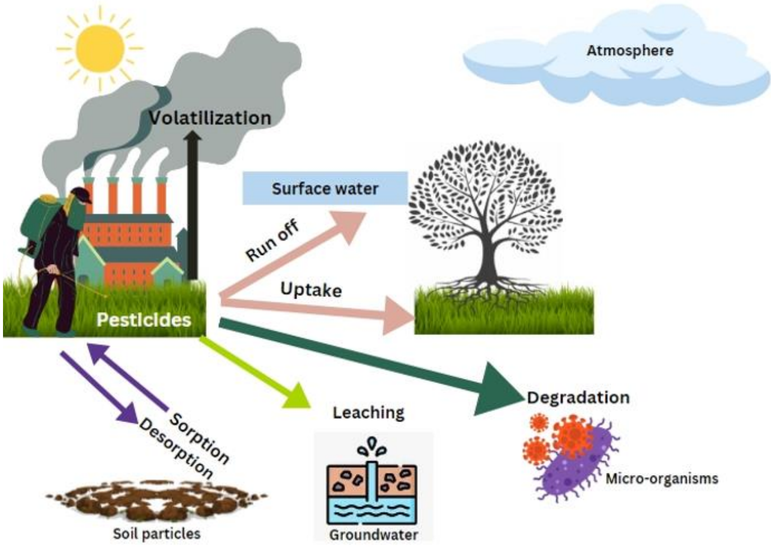

Figure 2. Fate of pesticides [Icon from Flaticon Basic License CC3.0 (Creative Commons)].

4.1.Leaching.

The main route by which these chemicals entered groundwater was soil leaching from pesticides [15]. Pesticides seeped through the soil layers and contaminated groundwater. The amount of leaching was influenced by a number of variables, such as the composition of the pesticide, the qualities of the soil, irrigation techniques, and hydrogeological processes. Less pesticide was left for leaching when more were eliminated via alternative routes [16]. The transport of pesticides from the topsoil layers to the deeper soil layers was influenced by soil density and porosity, as the transportation of pesticides was primarily controlled by macropore water flow. The texture of the soil was important for regulating the movement of pesticides and water [3]. The negative charge and vast surface area of clay-rich soils and sediments made them more apt to absorb pesticides; on the other hand, the role of clay as a pesticide sorbent was diminished in soils where organic matter was abundant [9]. By changing temperature and precipitation patterns, climate change could have a direct impact on pesticide leaching; alternatively, it could have an indirect impact through adjustments to land use, agricultural practices, and pest management strategies. Increased temperature could have hastened the decomposition of pesticides and lowered the risk of leaching, but it might also have improved desorption and increased the number of pesticides released from soil particles [17].

4.2.Volatization.

Pesticides from surfaces including soil, water, and plants underwent a process called volatilization that turned them into gas. Due to the phenomenon known as "drift," which occurred when pesticides escaped their original treatment areas and endangered surrounding crops, cattle, people, and other living things, this permitted pesticides to reach the atmosphere [15]. The chemical characteristics of the compounds, such as vapor pressure and water solubility, as well as environmental variables and agricultural methods, all had an impact on the rate of pesticide volatilization [18]. For example, during windy days, pesticides were more prone to evaporate. This process could be further improved by environmental factors like high temperatures, low humidity, and air movement. Compared to temperate locations, tropical regions had a higher probability of organochlorine pesticides (OCPs) leaking into the atmosphere. Furthermore, volatilization was less likely to occur for pesticides that were firmly bonded to soil particles [3].

4.3.Surface runoff.

Runoff was the overflow of water over the soil surface, usually caused by more precipitation than the soil could absorb. Through overland flow, this mechanism had the potential to introduce pesticides into adjacent surface water bodies. Pesticide runoff was typically viewed as harmful, even if some pesticide movement could help with pest management by promoting absorption into plant root zones. Pesticides were greatly reduced in effectiveness when runoff displaced them from their intended treatment regions. Moreover, contaminated surface water sources, including lakes, rivers, ponds, and streams, could be caused by pesticide-laden runoff, endangering aquatic life. Pesticide runoff was determined by a number of factors, including soil moisture levels, timing, amount, and period of irrigation and rainfall, and the physical and chemical makeup of the pesticides and the soil [15]. The likelihood that water would flow away from the treated area could be significantly increased by steeper slopes.

5. Challenges Faced by Pesticide Contamination

Because it can be challenging to store and dispose of pesticides safely, there are major environmental dangers involved. Overuse of them contaminates water and soil, damaging beneficial microbes and hindering plants' absorption of vital nutrients [19]. Many developing countries are using ineffective, outdated, hazardous, and ecologically persistent pesticides in an attempt to increase agricultural productivity and grow their economies. Cases of pesticide poisoning have increased dramatically during the past ten years. In Malaysia, pesticide poisoning has become a prevalent public health issue, with a reported rate of 3.8 cases per 100,000 individuals [13]. In countries like India, levels of organophosphate pesticides in certain water bodies have far surpassed safe environmental limits, contributing to an estimated 300,000 cases of organophosphate pesticide poisoning worldwide each year [20]. Challenges associated with pesticide contamination is shown in Table 2.

Table 2. Challenges associated with pesticide contamination.

Challenge Area	Description	Impact	Reference
Environmental contamination from pesticide storage and use	Unsafe storage and overuse contaminate water and soil, damaging microbes and nutrient absorption.	Environmental degradation; reduced agricultural productivity.	[19]
Use of hazardous pesticides in developing countries	Ineffective and persistent pesticides still widely used.	Increased cases of pesticide poisoning.	[13, 20]
Impact on Aquatic Organisms	Pesticides enter aquatic life via dermal contact, respiratory uptake, and ingestion.	Mortality, bioaccumulation, physiological and genetic damages.	[10, 21, 22]
Surface and Groundwater Contamination	Pesticides contaminate water via runoff, direct application, equipment cleaning, and percolation.	Deterioration of drinking water quality; ecosystem threats; costly remediation.	[3]
Soil Pollution	Pesticides harm soil microbes and affect nutrient cycling, humus formation, and soil structure.	Soil fertility decline; ecosystem imbalance.	[23, 24]
Human Exposure - Occupational and Non-occupational	Humans exposed via direct handling, consumption of residues, and inhalation.	Acute health issues (rashes, respiratory illnesses) and chronic diseases (cancer, neurological disorders).	[7, 14, 25, 26, 33]

5.1. Aquatic organisms.

Pesticides introduce hazardous substances that upset the equilibrium of aquatic life, mostly via industrial discharges and runoff from agriculture [21].These pesticides are absorbed by aquatic organisms through three main routes: (i) dermal contact, wherein they come into contact with contaminated water through their skin and experience harmful effects; (ii) respiratory contact, wherein they absorb pesticides through their gills during breathing; and (iii) ingestion, whereby they consume contaminated prey and may experience secondary poisoning ,for instance, if fish eat pesticide-exposed insects, they may experience negative effects if the insects contain a substantial quantity of toxins. Pesticides can have a direct or indirect effect on aquatic life. Significant increases in algal biomass as a result of less grazing pressure are examples of indirect effects, whereas physiological changes, such as higher mortality in water fleas exposed to pesticides, are examples of direct consequences [22]. Pesticides' unique chemical and physical characteristics, such as their stability against deterioration, bioaccumulation potential, and persistence in water, all affect how hazardous they are to aquatic creatures. Pesticides can either build up or be expelled from an organism based on how it uses energy. Aquatic life is susceptible to a range of health problems caused by these substances, including cancer, genetic abnormalities, neurological diseases, and changes in sexual behavior. Additional physiological consequences may appear as modifications to the liver, kidneys, and heart's anatomical structure [10].

5.2. Surface and groundwater contamination.

Both surface and groundwater have been discovered to contain a wide range of pollutants, including different pesticides. Pesticides are known to get into these water sources through a number of different routes, including direct application for controlling aquatic weeds and insects, runoff and percolation from fields used for agriculture, drift from agro-industrial wastewater, and the release from cleaning equipment used for pesticide application. Chemicals from treated fields, mixing areas, or trash disposal sites seep into the groundwater, contaminating it. A build-up of pesticides and other chemical pollutants is most likely to occur in surface water bodies like rivers, lakes, streams, reservoirs, and estuaries. Global freshwater and coastal ecosystems are facing serious and pressing issues as a result of pesticide-induced contamination of surface and groundwater. In addition, expensive treatment costs and advanced technological requirements make treating contaminated surface water—especially groundwater—more difficult. For example, pesticide pollution levels in Saskatchewan, Canada, have exceeded national guidelines, contaminating wetlands spanning between 37,000 and 500,000 square meters. In addition to having a direct negative impact on the quality of the drinking water in the area, pesticide contamination can also have unintended consequences by penetrating the soil and affecting other species up the food chain [3].

5.3. Soil pollution.

Agricultural crops treated with chemical pesticides have the potential to severely disturb the soil's microbial population, which includes important decomposers such as streptococcus species and nitrogen-fixing bacteria. Soil fertility is eventually affected by this disturbance because it has a detrimental effect on the humus, or organic matter, in the soil [23]. As such, the appropriate operation of biochemical pathways within soil biogeochemical processes may be hampered by these pesticides [24]. Furthermore, it has been demonstrated that the use of pesticides reduces the pH of the soil, which increases the dissolution of mineral-rich soil particles that are essential for the availability of nutrients. This procedure exacerbates soil compaction, which lowers drainage and air circulation. Microorganisms are essential for the nutrient cycling that plants require to thrive, and they help to maintain a healthy soil ecology.

5.4. Human exposure to pesticides.

There are two basic ways that pesticides might have been exposed to humans: actively, in the workplace, or passively, in non-workplace settings. Workplace exposure could have happened when pesticides were manufactured, transported, sold, and applied, including when exterminators were involved. Ingestion of pesticide residues via tainted food and water or inhalation of pesticide droplets drifting from treatment sites or fumigation operations were common forms of non-occupational exposure. Pesticides entered the body through the bloodstream and were then processed metabolically before being expelled from the body by the skin, urine, or breathing [25]. These routes of exposure had an impact on the toxicity levels of many pesticides as well. Because they were fat-soluble and could build up in the mother's blood, breast milk, and human adipose tissues, persistent organic pollutants (POPs) were especially worrisome [25]. Acute health problems such as eye irritation, rashes, blisters, skin irritations, blindness, nausea, dizziness, diarrhea, and, in extreme situations, death, resulted from brief exposure to pesticides. There were serious respiratory health hazards associated with agricultural work exposure, including asthma, bronchitis, impaired lung capacity, wheezing, persistent coughing, and shortness of breath. Workers at Costa Rican banana fields, Brazilian coffee plantations, and Ethiopian flower farms had been reported to experience similar respiratory problems [25]. The complex hormonal regulation that pesticides had the ability to disrupt could have resulted in a number of issues. For example, substances such as atrazine, cypermethrin, and ziram might have impacted the amounts of steroidogenic enzymes that were necessary for reproductive processes [33].

The most frequent kind of dementia in older persons was Alzheimer's disease (AD), which was becoming more common worldwide. Exposure to pesticides had been linked in numerous studies to a variety of neurological problems. Studies showed that men were generally exposed to more pesticides than women because of their work-related roles. Memory loss and problems processing sensory information were caused by damage to cholinergic neurons in the basal forebrain due to this exposure. Furthermore, a study showed that infants exposed to organochlorine pesticides during the prenatal and postnatal stages might have experienced cognitive deficits as well as indications of autism [26]. Although many pesticides had been linked to cancer, breast cancer was the most common form. This was especially the case for organophosphorus compounds such as parathion and malathion, which could interfere with the growth and multiplication of cells. Additional research indicated that exposure to organophosphorus might have lowered paraoxonase activity, which would have increased the possibility of coronary artery disease [14]. There were four primary ways that pesticides could have entered the human body: by ingestion, skin contact, ocular exposure, and inhalation. Whether a pesticide was inhaled orally, topically, or through the respiratory system, the degree of toxicity was dependent on the mode of exposure [7]. Extended exposure to pesticides could have resulted in cancer, endocrine system disruption, neurological and developmental impairments, reproductive problems, birth defects, and immunotoxic effects, among other major health problems. Neurotoxic effects, genotoxic and carcinogenic effects, and reproductive consequences were the three main categories into which these long-term health effects fell [25]. Figure 3 shows the negative effects of pesticides on human health [7].

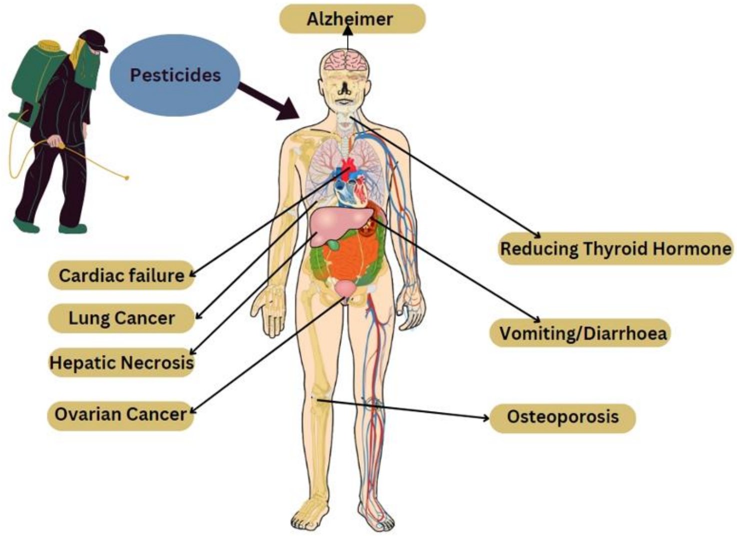

Figure 3. Negative effects of pesticides on human health Icon from Flaticon Basic License CC3.0 (Creative Commons)].

Numerous pesticides, such as sulfates and organochlorines, have been demonstrated in animal experiments to cause cancer; among these, DDT, lindane, and chlordane are especially linked to the development of tumors. Commercial pesticide formulations contain several compounds that are recognized carcinogens. Organophosphates have been associated with non-Hodgkin lymphoma and leukemia, while herbicides containing triazine have been associated with ovarian cancer [13].The infamous respiratory effects of DDT, an organochlorine insecticide that was once routinely employed in agriculture, are well known. According to recent studies, long-term exposure to these dangerous substances can cause chronic respiratory conditions including asthma. Through processes including irritation, inflammation, immunosuppression, and endocrine disruption, pesticide exposure may exacerbate asthma symptoms. Pesticide-related chemicals have the special ability to harm the bronchial mucosa, which increases the airways' sensitivity to allergens [27].

5.5. Impact of pesticides on terrestrial organisms and pollinators.

Despite the early belief that pesticides were less dangerous to beneficial bugs and other non-target species, recent events have demonstrated how poisonous they are to a variety of pollinators [39]. The ability of pollinators like bees, birds, and bats to forage and their general health can be adversely affected by pesticides, either directly or indirectly. For example, a number of studies have demonstrated the detrimental effects of neonicotinoids on bee populations, both acute and chronic, which may partially account for colony collapse disorder [38]. Bees frequently come into contact with pesticides while they forage and pollinate polluted crops. Similarly, exposure to pesticides has impacted a large number of insect-eating birds, resulting in a notable decrease in their biodiversity [2].

6. Remediation Technologies

One method that is emerging quickly and shows promise for treating pesticide contamination in contaminated areas is bioremediation. It entails the breakdown of environmental contaminants by use of naturally occurring biological processes, such as microbes and plants [8]. Since microbial bioremediation is a natural process, one of its main advantages is the public's acceptance of it. Furthermore, compared to alternative hazardous waste cleanup techniques, it is frequently more affordable. Both on-site (in situ) and off-site (ex situ) bioremediation techniques are possible. In contrast to other techniques that only change the form or location of toxins, bioremediation can remove organic pollutants entirely. However, there are certain disadvantages as well, such as the prolonged time needed to achieve treatment goals, the efficacy restrictions for all contaminants, the possibility of more hazardous or persistent byproducts forming, and the requirement for specialist knowledge to design and carry out the process [28]. Numerous technologies, including bioreactors, land farming, composting, soil washing improved by biological processes, and others, can be used in microbial bioremediation techniques. These methods can be used ex situ, where the materials are removed and treated in a controlled environment, or in situ, when contaminated materials are handled right there at the location. Both in situ and ex situ bioremediation were represented by the microbial remediation strategies in Figure 4.

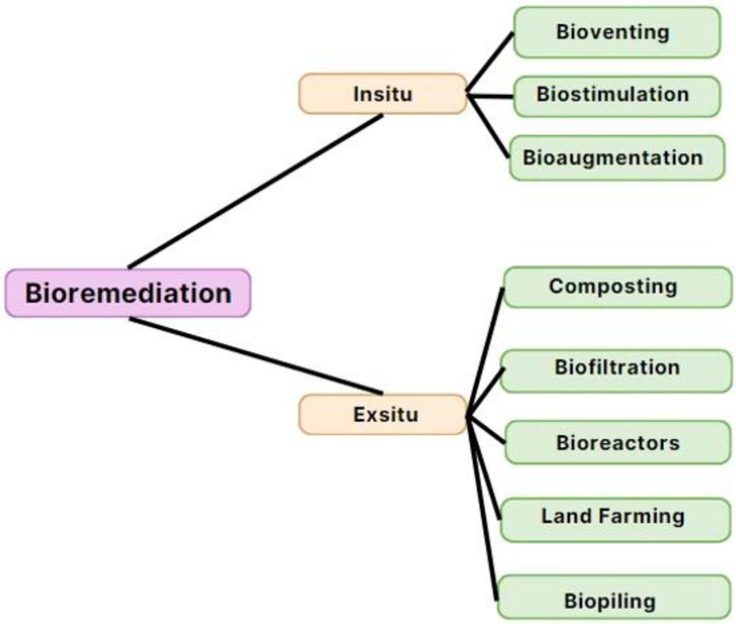

Figure 4. In situ and ex situ bioremediation.

Bioaugmentation introducing microorganisms into a contaminated site and biostimulation adding water, oxygen, and nutrients to stimulate microbial activity are two of the most effective bioremediation techniques [8]. Given their quick mutation and adaptability to changing environmental conditions, bacteria are essential to the bioremediation process. The enzymatic breakdown of pesticides results in the production of carbon dioxide and water, which are ultimately utilized by bacteria as a source of nutrition. Pesticides are initially absorbed by the microorganisms, and then they are progressively broken down into less dangerous or innocuous substances by metabolic enzymes [29]. Both aerobic and anaerobic microorganisms are employed in bioremediation processes. Complex compounds can be broken down by aerobic bacteria like Mycobacterium, Flavobacterium, and Nocardia. It has been demonstrated that these microbes break down many pollutants, including pesticides, hydrocarbons, alkanes, and polyaromatic chemicals, and they frequently use these pollutants as sources of energy and carbon. Anaerobic microorganisms, on the other hand, are used in bioremediation projects less frequently. Aerobic bacteria, on the other hand, are becoming more and more popular for their ability to dechlorinate solvents like trichloroethylene and chloroform and treat contaminants like polychlorinated biphenyls (PCBs) and chlorinated aromatic compounds (COCs) [30]. Since every bioremediation technique has been modified for a particular application, it has pros and cons of its own. Table 2 illustrates the advantages and restrictions of several bioremediation methods.

Table 1. Advantages and disadvantages of bioremediation.

Advantages	Disadvantages	References
Like treating contaminated soil, it's a natural process that takes some time. The pollutants are broken down by microbes, while their population gradually declines. In most cases, the outcome is innocuous and yields carbon dioxide, water, and cell biomass.	It is restricted to biodegradable substances since not all chemicals decompose fully or rapidly.	[30]
It doesn't take much work, can be completed on-site without disturbing microbes, and eliminates the need to transport waste, which lowers the hazards to human health and the environment.	Certain biodegradation byproducts may persist in the environment and be more hazardous than the parent substances.	[30]
When compared to more conventional methods of cleaning up oil-contaminated places, this strategy is more affordable. Pollutants are more easily disposed of when they are fully degraded, converting many poisonous substances into less hazardous products.	Ecologically benign and extremely specific, biological activities necessitate adequate nutrients and pollutants, healthy growing conditions, and active populations of microbes.	[30]
It makes no use of hazardous compounds. Fertilizers are used to promote microbial development, which fully destroys hazardous substances by converting them into water and harmless gasses.	It might be difficult to scale up from small lab testing to huge field operations. It's possible for contaminants to exist in the form of solids, liquids, or gasses, and bioremediation frequently requires more time than techniques like excavation or burning.	[30]
Its inherent environmental role makes it simple, low labor intensive, and economical.	To enhance bioremediation for sites with complex, unevenly dispersed pollutant mixes, more study is required.	[30]
Instead of being transported to another area of the environment, contaminants are entirely broken down.		[30]
Non-intrusive, potentially permitting continuous site usage. The current approach to cleaning up the environment from major pollutants provides chances for sustainable environmental improvement.		[30]

6.1. Composting.

One common biostimulation method for the sustainable repair of pesticide-contaminated areas is composting. In this process, organic material is broken down by microorganisms in an oxygen-rich environment to create compost, a stable byproduct that can be used as an organic fertilizer. The process of composting causes high temperatures, which in turn stimulate the activity of bacteria that break down pesticides, speeding up the breakdown of pesticides [31]. Biochar can be put to contaminated soils to accelerate their breakdown. Black carbon in the form of biochar is created by thermally converting biomass that has little to no oxygen by gasification or pyrolysis. Pesticides are effectively adsorbent because to its huge surface area and high porosity.

6.2. Biostimulation.

In order to promote the growth of local microorganisms, the biostimulation procedure entails supplying necessary nutrients like nitrogen, phosphorous, carbon, and oxygen. These nutrients are essential to microbial life because they boost microbial populations, supply the energy required for growth, and aid in the synthesis of enzymes that degrade contaminants. Many times, nutrients like phosphorus and nitrogen are supplied because they facilitate biodegradation and support a wide variety of microbes. Throughout the process, it is crucial to keep an eye on the levels of nutrients because both too little and too much can have a detrimental effect on the diversity and activity of microbes [34]. The proper organic elements and nutrients can be provided by biostimulation, which can hasten the breakdown of herbicides in the soil. It's critical to comprehend the redox cycle involved in the breakdown of these substances by bacteria for this strategy to work [37]. In contrast to bioaugmentation, biostimulation depends on boosting the activity of soil-dwelling microorganisms. Because native microorganisms are more competitive and usually more adapted to the local environment, this method is frequently chosen. Biostimulation can boost microbial metabolism by providing the required nutrients, which will accelerate and improve the breakdown of contaminants [36]. Nevertheless, if too many nutrients are added, eutrophication could happen, which could be a disadvantage of biostimulation. This may throw off the ecosystem's delicate balance, decreasing microbial diversity and harming the environment [36].

6.3. Bioaugmentation.

Contrarily, bioaugmentation involves adding particular microbial consortia or single strains to the soil in order to increase microbial diversity. This method uses special metabolic properties of microorganisms to speed up biodegradation. This process is greatly impacted by the amount of pesticides present in the soil; excessive pesticide concentrations might prevent soil microorganisms from performing their vital roles [34]. This approach is quick, inexpensive, and incredibly effective. There are primarily two approaches to bioaugmentation. One is introducing foreign microbes into the contaminated area to increase the activity of the native ones. This can be accomplished by either supplying nutrients to aid in the microorganisms' growth or by introducing them directly [36]. To improve their ability to break down contaminants, microorganisms from the contaminated site are genetically modified and then reintroduced to the same area. The ability of the new microbes to compete with the established ones and their degree of environmental adaptation determine how well bioaugmentation functions [36].

6.4. Bioventing.

In order to increase the activity of natural bacteria for bioremediation, a process known as "bioventing" entails introducing air to the unsaturated (vadose) zone under controlled conditions. Nutrients and moisture may also be added during this process which will speed up biodegradation and ultimately turn contaminants into innocuous materials. In contrast to other in-situ bioremediation techniques, bioventing has grown in popularity [34]. By introducing nutrients and air under controlled conditions through wells that are specifically constructed, bioventing increases the microbial activity in polluted soil [26]. The airflow is regulated to a minimum, just enough to provide the oxygen needed for microorganisms to flourish without evaporating dangerous substances. Depending on variables like the kind and quantity of pollutants, the pace of biodegradation, and the characteristics of the soil, such as its moisture content and air permeability, this procedure can take anywhere from six months to five years [26].

6.5. Biosparing.

In order to promote microbial activity, which helps remove pollutants from contaminated areas, air is injected into the subsurface soil using a process similar to bioventing. By pushing volatile organic chemicals upward into the unsaturated soil zone, this mechanism may promote the biodegradation of those substances. Two important variables determine the process's efficacy: (1) soil permeability, which influences the pollutants' accessibility to microorganisms, and (2) the pollutants' biodegradability [26]. On the other hand, by deliberately injecting air into the saturated zone, bioventing helps to accelerate the method of biodegradation by allowing volatile organic compounds to rise to the unsaturated zone [34].

6.6. Windrows.

In windrow bioremediation, contaminated soil piles are turned over on a regular basis to promote the activity of both permanent and migratory microorganisms that break down hydrocarbons, thus accelerating the biodegradation of pollutants. Through processes like acclimation, biotransformation, and mineralization, frequent aeration and water addition guarantee a uniform distribution of nutrients and contaminants, increasing microbial activity and quickening the bioremediation process. Windrow techniques have proven to remove hydrocarbons from soil at a faster rate than biopile treatment; nonetheless, the overall efficiency of windrows in this regard varies [34].

7. Future Research

Although it will be challenging to completely eradicate pesticides in the near future, using them wisely and carefully is still necessary. The majority of pesticides have the potential to be harmful to people and cause major health problems, such as cancer. According to epidemiological data, those who work as farmers or apply pesticides may be more susceptible to illnesses including leukemia, lymphoma, and other cancers. Furthermore, studies suggest that exposure to parents and exposure in childhood or adolescents may raise long-term health concerns [25]. Transitioning from batch and pilot research to large-scale field applications presents hurdles for bioremediation, a promising approach to remediating environmental contaminants. Additional investigation is required to create sophisticated bioremediation systems that can manage locations with intricate mixtures of pollutants, which are frequently dispersed unevenly across the ecosystem [31]. Since pesticide residues that have already gotten into the environment usually linger there for a long time, it is crucial to concentrate on both cleaning them up and keeping the law up to date. Chemical substances and manufactured pesticides are broken down by microbes and their enzymes, which is why microbial degradation techniques are so popular today. These techniques have limits even though they are eco-friendly. For example, extrinsic influences have a substantial impact on microbial metabolic pathways, thus more research is needed to enhance this strategy. International coordination of efforts is essential, particularly given the considerable variations in pesticide use regulations. Coordinating efforts and enhancing results can be achieved through cooperative research and the exchange of best practices [32]. Rich nations may have complex approval processes for pesticides and strict laws governing their use and sale, but many other nations might not follow these strict guidelines. Raising environmental knowledge is therefore the main preventive strategy in order to utilize pesticides in farming activities responsibly and minimize their influence on the environment [14]. Finally, ongoing monitoring of pesticide residues in agricultural fields, surrounding environments, agricultural commodities, and organisms is crucial to comprehend how pesticides enter and travel through the environment [9].

8. Conclusions

Though their widespread application has resulted in considerable soil contamination, pesticides are routinely used in agriculture to reduce losses caused by pests. Due to the significant health and environmental dangers posed by this contamination, dirty soils must be cleaned up and further deterioration must be stopped with efficient remediation techniques. The employment of microbes for bioremediation is one strategy that shows promise. It has a number of benefits, including low operating costs, economical approaches, and sustainability. To successfully remove dangerous compounds from the soil, however, one must comprehend the traits of the many microbial species that are employed in bioremediation. The success of bioremediation approaches depends on how well these bacteria adapt to various soil settings. Once pesticide residues have entered the environment, they typically stay there for a very long time and are quite resistant to breaking down in the natural world. As a result, it is crucial to concentrate on cleaning up these current pesticide residues and putting laws in place to control their effects. Before pesticides are discharged into the environment, they must be transformed into non-toxic chemicals using effective management techniques. In order to evaluate the consequences of broad pesticide usage on ecosystems, new approaches and techniques are needed. In order to develop solutions that protect the health of both humans and animals, ongoing research and collaboration are essential.In summary, in order to improve environmental and health outcomes, it will be required to address the problems posed by pesticide pollution and bioremediation through further study and partnerships.

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Author Contribution

Diya Merlin Varghese, Rubiyatno, Michael Lie, and Risky Ayu Kristanti contributed to conceptualization, methodology, data collection, formal analysis, and manuscript writing. Annisa Andarini Ruti, Gina Nadifah, and Ferdaus Mohd Altaf Hossain were involved in conceptualization and manuscript review. Md Abu Hanifa Jannat, Chayanee Chairattanawat, and Lucky Caesar Direstiyani contributed to manuscript review and final editing.

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Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

[1] Ayilara, M.S.; Adeleke, B.S.; Akinola, S.A.; Fayose, C.A.; Adeyemi, U.T.; Gbadegesin, L.A.; Omole, R.K.; Johnson, R.M.; Uthman, Q.O.; Babalola, O.O. (2023). Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides. *Frontiers in Microbiology*, *14*, 1040901. https://doi.org/10.3389/fmicb.2023.1040901.

[2] Nicolopoulou-Stamati, P.; Maipas, S.; Kotampasi, C.; Stamatis, P.; Hens, L. (2016). Chemical Pesticides and Human Health: The Urgent Need for a New Concept in Agriculture. *Frontiers in Public Health*, *4*, 148. https://doi.org/10.3389/fpubh.2016.00148.

[3] Tudi, M.; Ruan, H.D.; Wang, L.; Lyu, J.; Sadler, R.; Connell, D.; Chu, C.; Phung, D.T. (2021). Agriculture Development, Pesticide Application and Its Impact on the Environment. *International Journal of Environmental Research and Public Health*, *18*, 1112 https://doi.org/10.3390/ijerph18031112.

[4] Staley, Z.; Harwood, V.; Rohr, J. (2015). A synthesis of the effects of pesticides on microbial persistence in aquatic ecosystems. *Critical Reviews in Toxicology*, *45*, 813–836. https://doi.org/10.3109/10408444.2015.1065471.

[5] Kaur, T.; Sinha, A.K. (2019). Pesticides in Agricultural Run Offs Affecting Water Resources: A Study of Punjab (India). *Agricultural Sciences*, *10*, 1381–1395. https://doi.org/10.4236/as.2019.1010101.

[6] Huang, X.; Lu, G. (2021). Editorial: Bioremediation of Chemical Pesticides Polluted Soil. *Frontiers in Microbiology*, *12*, 682343. https://doi.org/10.3389/fmicb.2021.682343.

[7] Alengebawy, A.; Abdelkhalek, S.T.; Qureshi, S.R.; Wang, M. (2021). Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. *Toxics*, *9*, 42. https://doi.org/10.3390/toxics9030042.

[8] Chia, X.K.; Hadibarata, T.; Risky, A.K.; Jusoh, M.N.H.; Tan, I.S.; Foo, H.C.Y. (2024). The function of microbial enzymes in breaking down soil contaminated with pesticides: a review. *Bioprocess and Biosystems Engineering*, *47*, 597–620. https://doi.org/10.1007/s00449-024-02978-6.

[9] Rajan, S.; Parween, M.; Raju, N. (2023). Pesticides in the hydrogeo-environment: a review of contaminant prevalence, source and mobilisation in India. *Environmental Science and Pollution Research*, *45*, 5481–5513. https://doi.org/10.1007/s10653-023-01608-6.

[10] Siddiqui. S. (2019). Pesticide Sources, Their Fate, and Different Ways to Impact Aquatic Organisms. *Advances in Environmental Engineering and Green Technologies*, 20–40. https://doi.org/10.4018/978-1-5225-6111-8.ch002.

[11] Syafrudin, M.; Kristanti, R.A.; Yuniarto, A.; Hadibarata, T.; Rhee, J.; Al-onazi, W.A.; Algarni, T. S.; Almarri, A.H.; Al-Mohaimeed, A.M. (2021). Pesticides in Drinking Water—A Review. *International Journal of Environmental Research and Public Health*, *18*, 468 https://doi.org/10.3390/ijerph18020468.

[12] Dhuldhaj, U.; Singh, R.; Singh, V.K. (2022). Pesticide contamination in agro-ecosystems: toxicity, impacts, and bio-based management strategies. *Environmental Science and Pollution Research*, *30*, 9243–9270. https://doi.org/10.1007/s11356-022-24381-y.

[13] Oirdi, M.E.; Yaseen, M.; Farwa, U.; Raza, M.A.; Farhan, M.; Sandhu, Z.A.; Ali, F.; Aatif, M.; Khan, H.S.; Nahvi, I. (2024). Crops and people: the dangers and potential benefits of pesticides. *Cogent Food & Agriculture*, *10*, 1. https://doi.org/10.1080/23311932.2024.2334096.

[14] Pathak, V.; Verma, V.K.; Rawat, B.S.; Kaur, B.; Babu, N.; Sharma, A.; Dewali, S.; Yadav, M.; Kumari, R.; Singh, S.; Mohapatra, A.; Pandev, V.; Rana, N.; Cunill, J.M. (2022). Current status of pesticide effects on environment, human health and its eco-friendly management as bioremediation: A comprehensive review. *Frontiers in Microbiology*, *13*, 962619. https://doi.org/10.3389/fmicb.2022.962619.

[15] Rathore, H.S.; Nollet, L.M.L. (2012). Pesticides: Evaluation of environmental pollution. CRC Press : Boca Raton, USA. https://doi.org/10.1201/b11864.

[16] Rasool, S.; Rasool, T.; Gani, K.M. (2022). A review of interactions of pesticides within various interfaces of intrinsic and organic residue amended soil environment. *Chemical Engineering Journal Advances*, *11*, 100301. https://doi.org/10.1016/j.ceja.2022.100301.

[17] Ibrahim, H.M.; Al-Turki, A.M. (2020). Assessment of the Environmental Risk of Pesticides Leaching at the Watershed Scale under Arid Climatic Conditions and Low Recharge Rates. *Water*, *12*, 418. https://doi.org/10.3390/w12020418.

[18] Mamy, L.; Bonnot, K.; Benoit, P.; Bockstaller, C.; Latrille, E.; Rossard, V.; Servien, R.; Patureau, D.; Prevost, L.; Pierlot, F.; Bedos, C. (2021). Assessment of pesticides volatilization potential based on their molecular properties using the TyPol tool. *Journal of Hazardous Materials*, *415*, 125613. https://doi.org/10.1016/j.jhazmat.2021.125613.

[19] Sharma, A.; Kumar, V.; Shahzad, B.; Tanveer, M.; Sidhu, G.P.S.; Handa, N.; Kohli, S. K.; Yadav, P.; Bali, A.S.; Parihar, R.D.; Dar, O.I.; Singh, K.; Jasrotia, S.; Bakshi, P.; Ramakrishnan, M.; Kumar, S.; Bhardwaj, R.; Thukral, A.K. (2019). Worldwide pesticide usage and its impacts on ecosystem. *SN Applied Sciences*, *1*, 11. https://doi.org/10.1007/s42452-019-1485-1.

[20] Jiang, T.; Wang, M.; Zhang, W.; Zhu, C.; Wang, F. (2024). A Comprehensive Analysis of Agricultural Non-Point Source Pollution in China: Current Status, Risk Assessment and Management Strategies. *Sustainability*, *16*, *6*, 2515. https://doi.org/10.3390/su16062515.

[21] Maurya, P.K.; Malik, D.S.; Sharma, A. (2019). Impacts of pesticide application on aquatic environments and fish diversity. *Contaminants in Agriculture and Environment: Health Risks and Remediation*, 111–128. https://doi.org/10.26832/aesa-2019-cae-0162-09.

[22] Shefali; Kumar, R.; Sankhla, M.S.; Kumar, R.; Sonone, S.S. (2020). Impact of Pesticide Toxicity in Aquatic Environment. *Biointerface Research in Applied Chemistry*, *11*, *3*, 10131–10140. https://doi.org/10.33263/briac113.1013110140.

[23] Hassan Al-Taai, S. H. (2021). Soil Pollution - Causes and Effects. *IOP Conference Series: Earth and Environmental Science*, *790*, *1*, 012009. https://doi.org/10.1088/1755-1315/790/1/012009.

[24] Wołejko, E.; Jabłońska-Trypuć, A.; Wydro, U.; Butarewicz, A.; Łozowicka, B. (2020). Soil biological activity as an indicator of soil pollution with pesticides – A review. *Applied Soil Ecology*, *147*, 103356. https://doi.org/10.1016/j.apsoil.2019.09.006.

[25] Adám, B.; Cocco, P.; Godderis, L. (2024). Hazardous Effects of Pesticides on Human Health. *Toxics*, *12*, 186. https://doi.org/10.3390/toxics12030186.

[26] Ahmad, M.F.; Ahmad, F.A.; Alsayegh, A.A.; Zeyaullah, M.; Al Shahrani, A.M.; Muzammil, K.; Saati, A.A.; Wahab, S.; Elbendary, E.Y.; Kambal, N.; Abdelrahman, M.H.; Hussain, S. (2024). Pesticides impacts on human health and the environment with their mechanisms of action and possible countermeasures. *Heliyon*, *10*, *7*, e29128–e29128. https://doi.org/10.1016/j.heliyon.2024.e29128.

[27] Rajmohan, K.S.; Chandrasekaran, R.; Varjani, S. (2020). A Review on Occurrence of Pesticides in Environment and Current Technologies for Their Remediation and Management. *Indian Journal of Microbiology*, *60*, *2*, 125–138. https://doi.org/10.1007/s12088-019-00841-x.

[28] Tekere, M. (2019). Microbial Bioremediation and Different Bioreactors Designs Applied. *Biotechnology and Bioengineering*. https://doi.org/10.5772/intechopen.83661.

[29] Roy, A.; Roy, M.; Alghamdi, S.; Dablool, A.S.; Almakki, A.A.; Ali, I.H.; Yadav, K.K.; Islam, M.R.; Cabral-Pinto, M.M.S. (2022). Role of Microbes and Nanomaterials in the Removal of Pesticides from Wastewater. *International Journal of Photoenergy*, *2022*, 1–12. https://doi.org/10.1155/2022/2131583.

[30] Sharma, I. (2020). Bioremediation Techniques for Polluted Environment: Concept, Advantages, Limitations, and Prospects. *Trace Metals in the Environment - New Approaches and Recent Advances*. https://doi.org/10.5772/intechopen.90453.

[31] Ataikiru, T.L.; Ajuzieogu, C.A. (2023). Enhanced bioremediation of pesticides contaminated soil using organic (compost) and inorganic (NPK) fertilizers. *Heliyon*, *9*, e23133. https://doi.org/10.1016/j.heliyon.2023.e23133.

[32] Sun, S.; Sidhu, V.; Rong, Y.; Zheng, Y. (2018). Pesticide Pollution in Agricultural Soils and Sustainable Remediation Methods: a Review. *Current Pollution Reports*, *4*, 240–250. https://doi.org/10.1007/s40726-018-0092-x.

[33] Kalyabina, V.P.; Esimbekova, E.N.; Kopylova, K.V.; Kratasyuk, V.A. (2021). Pesticides: formulants, distribution pathways and effects on human health – a review. *Toxicology Reports*, *8*, 1179–1192. https://doi.org/10.1016/j.toxrep.2021.06.004.

[34] Raffa, C.M.; Chiampo, F. (2021). Bioremediation of Agricultural Soils Polluted with Pesticides: A Review. *Bioengineering*, *8*, 92. https://doi.org/10.3390/bioengineering8070092.

[35] World Health Organizations, Report 2022 - Pesticide residues in food. (accessed on 8 April 2025) Available online: https://books.google.com.my/books?hl=en&lr=&id=-YgOEQAAQBAJ&oi=fnd&pg=PR9&ots=qSTII-deHA&sig=NEpGBOAey1ABQwRKAFwYPNbwaew&redir_esc=y#v=onepage&q&f=false.

[36] Visvanathan, P.; Kirubakaran, D.; Rajkumar, M.; Selvam, K.; Manimegalai, P.; Vasantharaj, K. (2024). Recent Strategies for Natural Bioremediation of Emerging Pollutants: Development of a Green and Sustainable Environment. *ACS Symposium Series*, *2*, 1–19. https://doi.org/10.1021/bk-2024-1476.ch001.

[37] Kanissery, R.G.; Sims, G.K. (2011). Biostimulation for the Enhanced Degradation of Herbicides in Soil. *Applied and Environmental Soil Science*, *2011*, 1–10. https://doi.org/10.1155/2011/843450.

[38] Jactel, H.; Verheggen, F.; Thiéry, D.; Escobar-Gutiérrez, A.J.; Gachet, E.; Desneux, N. (2019). Pesticides and environmental health: The importance of public participation. *Environmental International*, *132*, 105068. https://doi.org/10.1016/j.envint.2019.105068.

[39] Wood, S.C.; Kozii, I.V.; Koziy, R.V.; Epp, T.; Simko, E. (2018). Comparative chronic toxicity of three neonicotinoids on New Zealand packaged honey bees. *PLOS ONE*, *13*(1), e0190517. https://doi.org/10.1371/journal.pone.0190517.

[40] Nath, A.; Bhuyan, P.; Gogoi, N.; Deka, P. (2023). Pesticides and Chemical Fertilizers: Role in Soil Degradation, Groundwater Contamination, and Human Health. Springer eBooks, pp. 131–160. https://doi.org/10.1007/978-3-031-35775-6_7.

[41] Kaur, R.; Singh, D.; Kumari, A.; Sharma, G.; Rajput, S.; Arora, S.; Kaur, R. (2021). Pesticide residues degradation strategies in soil and water: a review. *International Journal of Environmental Science and Technology*, *20*, 3537–3560. https://doi.org/10.1007/s13762-021-03696-2.