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REVIEW ARTICLE

Recent Advances in the Microbial based biodegradation of Pesticides

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ABSTRACT
The use of pesticides in agriculture to prevent the spread of disease and pests has the potential to endanger both human and environmental health. In addition to endangering animals and contaminating soil, water, and air, they can cause respiratory illnesses, cancer, and difficulties related to reproduction. Degradation of pesticides is an efficient method for reducing the adverse effects of pesticides, such as their persistence and toxicity, and preventing the evolution of pests that are resistant to pesticides at the same time. Practices such as crop rotation, habitat alteration, and the use of natural enemies are examples of alternative means of pest control. Integrated pest management, which employs several different pest control strategies while minimizing the negative impact of each, is one example of an alternative method of pest control.
KEYWORDS: *Pesticides, Degradation, Ecosystem, Photocatalysis.*

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INTRODUCTION

Chemicals known as pesticides are used to prevent or get rid of pests like weeds, fungus, and insect. They play a crucial role in modern agriculture by protecting crops from damage and increasing food production. Pesticides help prevent crop losses caused by pests and diseases, ensuring higher yields, and maintaining food security. The agricultural industry relies heavily on pesticides to protect crops from pests and illnesses and to boost yield and production. However, their usage should be carefully regulated to minimize environmental impact and potential hazards to human health. Use of pesticides is not without risk, even though these chemicals have several desirable effects. One main cause for worry is the effect that they have on human health. Pesticides have the potential to be hazardous and have been associated with a numerous health condition, including those affecting the respiratory system, cancer, and reproductive health. Another concern is their impact on the environment. Pesticides can contaminate soil, water, and air, leading to environmental damage and harming wildlife. They may also result in the creation of pests that are difficult to control because they are resistant to pesticides [1]. This review will look at the history of pesticide usage in farming, as well as the pros and cons of this practice. Various pesticides can be classified based on their chemical composition and mode of action. Common classes include organophosphates, pyrethroids, neonicotinoids, and herbicides. Organophosphates, such as malathion, target the nervous system of insects, while pyrethroids like permethrin affect their sodium channels. Neonicotinoids, including imidacloprid, act on insect nicotinic acetylcholine receptors. Herbicides like glyphosate target plant-specific processes. These classifications provide a framework for understanding pesticide properties and help in developing effective pest management strategies. Pesticides, while effective in controlling pests and increasing crop yields, have significant negative impacts on crops, humans, and other organisms. Studies have shown that pesticide residues can accumulate in crops, posing risks to human health through consumption. Additionally, these chemicals can harm beneficial insects, pollinators, and aquatic organisms, disrupting ecosystems and biodiversity. A publication by Pesticide Action Network highlights the detrimental effects of pesticides, urging the

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adoption of sustainable and integrated pest management strategies to mitigate these harmful consequences. Integrated pest management (IPM) combines various pest control techniques to minimize the reliance on chemical pesticides. It focuses on monitoring pest populations, implementing cultural practices, using resistant crop varieties, and employing biological controls to suppress pests while minimizing environmental harm [2]. Biological control methods, such as the use of beneficial insects like ladybugs or parasitic wasps, offer a sustainable alternative to chemical pesticides. These natural enemies prey on pests, reducing their populations and providing long-term control without the need for synthetic chemicals [3]. Degradation of pesticides is essential to reducing the dangers to the environment and human health that originated with their use. Environmental degradation of pesticides can lead to contamination of soil, water, and air, causing adverse effects on ecosystems and human health. Various methods have been developed to degrade pesticides, including biological degradation through microbial activity, chemical degradation using oxidants or reducing agents, and physical degradation through photolysis or adsorption. These methods play a vital role in reducing pesticide residues, ensuring sustainable agricultural practices, and protecting the environment [4]. Bacterial approaches have emerged as the most impressive for effective pesticide degradation. Bacterial methods utilize the enzymatic potential of microorganisms to break down pesticides into harmless compounds. Studies have highlighted the efficiency of bacterial strains such as Pseudomonas, Bacillus, and Arthrobacter in degrading a wide range of pesticides [5]. These microbial-based strategies offer promising prospects for sustainable and eco-friendly pesticide remediation. Bacteria possess remarkable capabilities when it comes to the degradation and breakdown of pesticides. They exhibit specialized enzymatic systems that allow them to metabolize and neutralize a wide range of toxic compounds. One prominent mechanism involves the production of pesticide-degrading enzymes, such as hydrolases, oxidases, and dehydrogenases, which can break down the chemical structure of pesticides into less harmful components. For example, studies have shown that certain bacterial species, like *Pseudomonas* and *Bacillus*, play a crucial role in pesticide biodegradation through the production of specific enzymes, offering a potential eco-friendly solution to pesticide pollution. A recent study investigated the mineralization of pesticides in agricultural soils. The researchers examined five commonly used pesticides and measured their degradation rates over time. The study found that the majority of the pesticides showed significant mineralization within a six-month period, indicating their potential to break down and reduce their environmental impact [6]. In a study six different pesticides were studied for their mineralization potential in soil samples. The researchers assessed the degradation rates and identified the key factors influencing pesticide breakdown. The study demonstrated that soil pH, moisture content, and microbial activity significantly affected the mineralization rates, highlighting the importance of understanding soil characteristics for effective pesticide management. The researchers measured the pesticide degradation rates under different environmental conditions and found variations in mineralization kinetics among the tested compounds. The study emphasized the need for tailored approaches to pesticide management based on specific chemical characteristics [6]. Pesticides are commonly used in agriculture to provide protection to crops against various pests, diseases, and weeds. However, their widespread use has led to serious environmental problems, including contamination of soil and water resources. Therefore, it is essential to find effective and eco-friendly ways to mitigate pesticide contamination. Biodegradation is a promising technique that utilizes microorganisms to degrade and detoxify pesticides. Several studies have investigated the potential of microorganisms for pesticide biodegradation. For example, studies have stated the use of bacteria, fungi, and algae for the biodegradation of pesticides such as chlorpyrifos, glyphosate, and atrazine [6,7]. In addition, genetic engineering techniques have been used to enhance the biodegradation capabilities of microorganisms. For instance, researchers have developed genetically modified bacteria that can degrade pesticides more efficiently [7]. Moreover, the use of co-cultures of microorganisms has been proposed to enhance the degradation of complex pesticide mixtures [6]. Overall, biodegradation has shown great potential for the effective and eco-friendly management of pesticide contamination.

TABLE 1: Potential benefits and risks of pesticide use in agriculture.

Benefits	Risks	References
Control pests and diseases	Human health effects	[8]
Improve crop quality and appearance	Environmental damage	[5]
Increase productivity and yield	Development of pesticide-resistant pests	[4]

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SIDE EFFECTS OF EXCESS USE OF PESTICIDES IN AGRICULTURE:

Pesticides are regularly used in agriculture to control pests and enhance the crop production. However, Overuse of pesticides can have detrimental impacts on the environment and human health. In this review, we will examine the side effects and uses of excess amounts of pesticides in agriculture. One of the most concerning effects of pesticides is their potential impact on human health. Exposure to pesticides has been associated to an increased risk of various health issues, like cancer, birth abnormalities, and neurological illnesses [9]. In addition, many pesticides are known to be toxic to other beneficial insects, which can have a substantial effect on the state of ecosystems [10]. The usage of excessive amounts of pesticides in agriculture can also lead to environmental problems. Pesticides can contaminate soil, air and water, which adversely affects to wildlife and aquatic ecosystems [11]. In addition, excessive use can also generate pesticide-resistant pests, which cannot be control and can result in decreased crop yields [12]. Despite the potential risks associated with pesticide use, many farmers continue to rely on them as a primary means of pest control. This is partly due to the fact that pesticides are often seen as a quick and easy solution to pest problems [13]. However, alternative pest control strategies, including integrated pest management, can be effective while reducing the detrimental effects on human health and the environment [14].

TABLE 2: Summary of effects of pesticides on health & environment

Pesticides	Potential Health Effects	Potential Environmental Effects	References
Glyphosate	Cancer, birth defects	Soil & water contamination	[9]
Chlorpyrifos	Neurological disorders	Toxic to bees & other insects	[10]
Atrazine	Hormone disruption	Water contamination	[11]
DDT	Cancer, reproductive problems	Toxic to fish & wildlife	[10]

PURPOSE TO DEGRADE THE PESTICIDES:

Pesticides overuse and improper disposal can lead to environmental contamination, posing a significant threat to human health and the ecosystem. Degrading pesticides is an effective method to mitigate their adverse effects on the environment. In this review, we discuss the purpose of degrading pesticides and highlight five references that support this approach. One of the main reasons for degrading pesticides is to reduce their persistence in the environment as they persist in the soil, air, and for extensive periods, causing long-term damage to the ecosystem. The degradation of chlorpyrifos, a commonly used pesticide, reduced its persistence in soil and water. This finding emphasizes the importance of degrading pesticides to prevent their accumulation in the environment [15]. Another purpose of degrading pesticides is to reduce their toxicity. Pesticides can have harmful effects on non-target organisms, including humans. For example, organophosphate pesticides can cause acute and chronic health effects, such as neurotoxicity and carcinogenicity. The degradation of these pesticides can reduce their toxicity and minimize their adverse effects on human health. Degrading organophosphate pesticides can reduce their toxicity, making them less harmful to humans and the environment [16]. Degrading pesticides can also improve soil quality and promote sustainable agriculture. Pesticides can alter the soil microbiome, reducing soil fertility and productivity. The degradation of pesticides can restore the balance of the soil microbiome, promoting healthy soil and sustainable agriculture. degradation of pesticides increased soil microbial activity and nutrient availability, leading to improved soil quality and crop yield [17]. Furthermore, degrading pesticides can prevent the development of pesticide-resistant pests. Excessive use of pesticides responsible for the emergence of pesticide-resistant pests, which cause significant damage to crops. Degrading pesticides can reduce their effectiveness, making it less likely for pests to develop resistance. Degrading pesticides reduced the development of pesticide-resistant pests, highlighting the importance of this approach in sustainable pest management [18]. Lastly, degrading pesticides can reduce the cost of pesticide clean-up and disposal. Improper disposal of pesticides can lead to environmental contamination and high clean-up costs. Degrading pesticides on-site can reduce the need for expensive clean-up and disposal methods. On-site degradation of pesticides was a cost-effective and sustainable method for pesticide management [19].

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TABLE 3: The purpose of degrading pesticides

PURPOSE	REFERENCES
Reduce persistence in the environment	[15]
Reduce toxicity	[16]
Improve soil quality & promote sustainable agriculture	[17]
Prevent development of pesticide-resistant pests	[18]
Reduce cost of cleanup & disposal	[19]

DIFFERENT TECHNIQUE TO DEGRADATION OF PESTICIDES:

The widespread use of pesticides has raised concerns about their potential impact on human health and the environment. Therefore, researchers have been investigating various techniques to degrade pesticides and reduce their harmful effects. In this review, we will discuss five different techniques for pesticide degradation: biological degradation, chemical oxidation, photocatalysis, electrochemical degradation, and adsorption. Biological degradation, also known as biodegradation, involves the use of microorganisms to break down pesticides into less harmful compounds. This technique has revealed promising results in degrading a wide variety of pesticides, such as organochlorines, organophosphates, and carbamates [20]. Chemical oxidation, on the other hand, involves the use of strong oxidizing agents such as hydrogen peroxide or ozone to degrade pesticides [21]. This technique is highly effective in breaking down persistent organic pollutants (POPs) such as DDT and its metabolites. Photocatalysis is another promising technique for pesticide degradation that involves the use of semiconductor materials such as titanium dioxide (TiO_2) to degrade pesticides under UV irradiation [22]. The photocatalytic process generates highly reactive species that can break down pesticides into harmless compounds. Electrochemical degradation, on the other hand, involves the use of an electric current to degrade pesticides. This technique has shown good results in degrading herbicides and insecticides [23]. Finally, adsorption is a technique that involves the use of adsorbents to trap and remove pesticides from contaminated water or soil. Activated carbon, zeolites, and clay minerals are commonly used as adsorbents [24].

TABLE 4: Different techniques for pesticides degradation

TECHNIQUES	ADVANTAGES	DISADVANTAGES	REFERENCES
Biological degradation	Effective for wide range of pesticides	Slower degradation compared to other techniques	[21]
Chemical oxidation	Highly effective for persistent organic pollutants (POPs)	Require high energy consumption	[22], [24]
Photocatalysis	Generates highly reactive species	Efficiency may decrease with prolonged uses	[23]

POTENTIAL MICROBES-BASED BIOREMEDIATION OF PESTICIDES:

The excessive use of pesticides led to deposition in air, soil and water, posing a hazard to human health as well as an environment. Microbial degradation is a promising approach to alleviate the antagonistic effects of pesticides. In this review, we discuss the best microbes for degrading pesticides based on their efficiency and specificity. One of the most efficient pesticide-degrading microbes is *Pseudomonas putida*. This bacterium is recognized for its capability to degrade a vast range of pesticides, including atrazine and chlorpyrifos, through various metabolic pathways [25]. Similarly, *Bacillus thuringiensis* is a potent pesticide-degrading bacterium, especially for organophosphate and carbamate pesticides [20]. Another important group of pesticide-degrading microbes are fungi, including *Trichoderma* species. It is reported that, *Trichoderm*a species can degrade a variety of pesticides, including carbofuran and chlorpyrifos, through enzymatic degradation [27]. In addition, *Aspergillus* species have shown promising results in degrading organochlorine pesticides such as DDT [28]. The efficiency and specificity of pesticide-degrading microbes are often dependent on environmental conditions such as temperature, pH, and the presence of co-substrates. For instance, *Arthrobacter* species have been found to degrade atrazine efficiently under low-temperature conditions [29].

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TABLE 5: Best microbes for degrading different types of pesticides

PESTICIDE	MICROBE	REFERENCE
Atrazine	*Pseudomonas putida, Arthrobacter sp.*	[25]
Chlorpyrifos	*Pseudomonas putida, Trichoderma species*	[30], [31]
Organophosphates	*Bacillus thuringiensis*	[28]
Carbamates	*Bacillus thuringiensis*	[29]
DDT	*Aspergillus species*	[28]

Bacterial species and pesticide degradation:

Numerous bacterial species have demonstrated their ability to degrade pesticides, providing promising alternatives for pesticide remediation. One such example is *Pseudomonas putida*, a gram-negative bacterium renowned for its exceptional metabolic versatility. Studies have shown that *P. putida* can degrade a wide range of pesticides, including organophosphates, carbamates, and chlorinated compounds. The bacterium achieves this through its potent enzymatic machinery, such as esterase, amidases, and dehalogenases, which facilitate the breakdown of pesticide molecules [32]. Another noteworthy bacterial species is *Bacillus thuringiensis*, widely used as a biological pesticide for its insecticidal properties. Interestingly, *B. thuringiensis* also possesses the ability to degrade pesticides. For instance, it has been found to degrade pyrethroids, a common class of insecticide. This bacterium achieves pesticide degradation through the production of esterase, which cleave ester bonds in the pesticide molecules, rendering them harmless [33]. Studies have explored the potential of the bacterium *Agrobacterium radiobacter* in degrading herbicides*. A. radiobacter* possesses enzymes, such as 2,4-dichlorophenoxyacetic acid (2,4-D) monooxygenase, which facilitate the degradation of herbicides like 2,4-D, a commonly used compound for weed control [34].

Pesticide degradation by fungal species:

Fungal species have demonstrated remarkable abilities to degrade various classes of pesticides, including insecticides, herbicides, and fungicides. One notable example is the degradation of the insecticide chlorpyrifos by the fungus *Trichoderma atroviride*. A study by Kwon *et al.* 2020, [35] showed that *T. atroviride* effectively degraded chlorpyrifos through enzymatic processes, offering a promising approach for the remediation of this commonly used insecticide. The herbicide glyphosate has also been successfully degraded by fungal species. It was found that the fungus *Aspergillus niger* efficiently degraded glyphosate through the production of specific enzymes. This finding provides evidence for the potential of fungal species in mitigating the environmental persistence of glyphosate and its associated risks. Fungicides, which are designed to control fungal pathogens, can also be targeted for degradation by certain fungal species. For instance, a study by demonstrated the degradation of the fungicide carbendazim by the *fungus Trametes versicolor*. The researchers observed significant degradation of carbendazim in the presence of *T. versicolor*, indicating its potential application in the detoxification of fungicide-contaminated environments [35].

DEGRADATION OF PESTICIDES BY USING MICRO-ORGANISMS PROS AND CONS:

Persistent nature of pesticides leads to environmental pollution and adverse health effects. Therefore, the development of safe and effective methods for the degradation of pesticides is of great importance. One promising approach is the use of microorganisms, which have the ability to degrade pesticides through enzymatic reactions. In this review, we will discuss the pros and cons of using microorganisms for pesticide degradation. One advantage of using microorganisms is that they are natural and non-toxic. The use of microorganisms for the degradation of pesticides can help reduce the harmful effects of these chemicals on the environment and human health. Microorganisms can degrade pesticides into harmless compounds through various mechanisms such as hydrolysis, oxidation, and reduction [36]. Another advantage is that the use of microorganisms is cost-effective. The use of microorganisms for the degradation of pesticides can be an economical and environmentally friendly approach. Microorganisms are readily available in nature, and their cultivation and maintenance are relatively simple and inexpensive [37]. However, the use of microorganisms also has some limitations. One major drawback is that the effectiveness of microorganisms for pesticide degradation can be influenced by various factors such as temperature, pH, and nutrient availability. The efficacy of microorganisms for pesticide degradation can be affected by the type and concentration of the pesticide, as well as the microbial community structure and diversity [38]. Another limitation is the limited knowledge of microbial degradation pathways and mechanisms. The exact pathways and mechanisms of microbial degradation of pesticides are not fully understood, which limits the ability to predict the efficacy of microbial degradation in different environmental conditions [39]. Additionally, there is a potential for the release of harmful metabolites during the degradation process. Some microbial degradation products can be more toxic than the parent compound, posing a risk to human health and the environment [40]. Despite these limitations, the use of microorganisms for pesticide degradation is a promising approach that has gained attention in recent years. Future research should focus on developing standardized microbial testing protocols, improving our understanding of microbial degradation pathways and mechanisms, and evaluating the potential risks associated with the release of microbial degradation products.

MECHANISMS INVOLVED IN THE BIODEGRADATION OF PESTICIDES

Different pathways have been reported for microbial degradation of pesticides, which vary depending on the type of pesticide and the microbial species involved. One of the common pathways used by microbes to degrade pesticides is the hydrolytic pathway. This pathway involves the breakdown of the pesticide into simpler compounds by the addition of water molecules. For example, the hydrolysis of organophosphate pesticides involves the cleavage of the P-O bond, leading to the formation of an alcohol and an organic acid. This pathway is carried out by different microbial species, including bacteria and fungi [41]. Another pathway used by microbes to degrade pesticides is the oxidative pathway. This pathway involves the oxidation of the pesticide molecule by enzymes, resulting in the formation of various products such as alcohols, aldehydes, and carboxylic acids. Some examples of pesticides that are degraded via oxidative pathways include pyrethroids and carbamates. Microbial species such as *Pseudomonas, Bacillus*, and *Aspergillus* have been reported to use this pathway [42],[43]. In addition to the hydrolytic and oxidative pathways, some microbes use the reductive pathway to degrade pesticides. This pathway involves the reduction of the pesticide molecule by enzymes, leading to the formation of simpler compounds such as alcohols and amines. The reductive pathway is commonly used by anaerobic bacteria such as *Desulfovibrio* and *Clostridium* to degrade halogenated pesticides [44]. Microbial degradation of pesticides can also occur via the conjugation pathway. This pathway involves the addition of a polar group, such as a sugar or an amino acid, to the pesticide molecule, resulting in its inactivation or detoxification. Some examples of pesticides that are degraded via the conjugation pathway include atrazine and glyphosate. Microbial species such as *Rhizobium* and *Bacillus* have been reported to use this pathway [45].

TABLE 6: different pathways used by microbes to degrade pesticides

PATHWAY	MICROBIAL SPECIES	PESTICIDES DEGRADED	REFERENCES
Hydrolytic	Bacteria & fungi	Organophosphates	[41]
Oxidative	*Pseudomonas, Bacillus*, & *Aspergillus*	Pyrethroids & Carbamates	[42]
Reductive	*Desulfovibrio* & *Clostridium*	Halogenated pesticides	[43]
Conjugation	*Rhizobium* & *Bacillus*	Atrazine & Glyphosate	[44]

CONCLUSION

Recent advances in the microbial-based biodegradation of pesticides from natural sources have provided promising strategies for the environmentally friendly removal of these harmful chemicals. Microorganisms, including bacteria, fungi, and algae, have demonstrated their ability to metabolize and degrade a wide range of pesticides, transforming them into non-toxic compounds or mineralizing them into harmless substances. Recent studies have focused on isolating and characterizing pesticide-degrading microorganisms from diverse environments such as soil, water, and plant rhizosphere. Furthermore, advances in genomic and metagenomic technologies have enabled the identification and manipulation of key enzymes and metabolic pathways involved in pesticide degradation, leading to the development of genetically modified microorganisms with enhanced degradation capabilities. These microbial-based approaches offer a sustainable and efficient solution for the removal of pesticide residues, reducing their environmental impact and promoting the conservation of ecosystems.

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