

# Innovations

## Microbial Revolution for Pesticide Bioremediation

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**Abstract:** Pesticides are primarily used to prevent and control the damage caused by noxious weeds, fungus, and insects to crops, property, and human health but the widespread application of pesticides in agriculture has resulted in significant damage of the environment, endangering both human health and ecosystems. Through biodegradation, microorganisms such as bacteria, fungi, and algae present a viable and environmentally sustainable way to reduce pesticide contamination. These microorganisms have metabolic pathways that allow them to detoxify and metabolize a variety of pesticides, changing dangerous substances into less hazardous or non-toxic forms. Microbial degradation of pesticides encourages the repair of contaminated sites while also lessening the persistence of pesticides in soil and water. The efficiency of microbial breakdown depends on numerous factors, including the chemical composition of pesticides, ambient circumstances, and the microbial species involved. The variety of microorganisms such as Actinobacteria, Proteobacteria, Firmicutes, Fungi and Cyanobacteria involved in pesticide breakdown and their mode of action are discussed in this paper along with their role in environment. Technological developments in biotechnology and genetic engineering have significantly improved microorganisms' capacity to more efficiently degrade persistent insecticides.

**Keywords:** Pesticides, Biodegradation, Microbial communities, Actinobacteria, Fungi, Detoxification.

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### Introduction

Pesticides are chemical compounds or substances that are applied to crops, plants and animals in order to control or eradicate different types of pests. These pests can include fungi, insects, weeds, nematodes, rodents, and even unwanted plant growth. Under perfect circumstances, a pesticide kills just the target pest and not any other species, not even humans. However, these perfect circumstances and pesticide specificity are uncommon or unattainable and therefore these pesticides can indeed cause harm in various ways, including harm to human health and the environment and especially the farmers (Abhilash

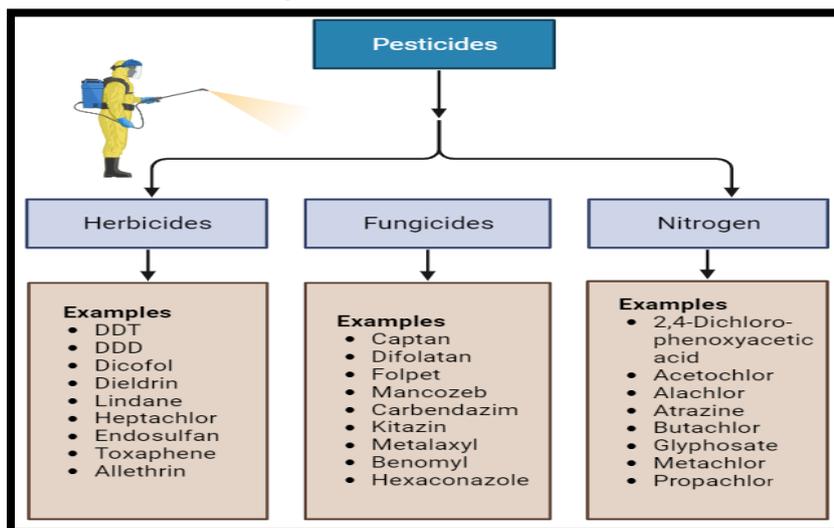
&Singh, 2009). When farmers were exposed to dangerous pesticides in different parts of the country, an evaluation of the association between pesticide use and the emergence of sickness signs and symptoms revealed a significant impact (Karunamoorthiet al., 2012). Leaks at pesticide disposal sites, improper cleaning of pesticide storage containers, improper field application of pesticide spills, and the release of pesticide-containing industrial effluent from manufacturing facilities are some of the primary causes of pesticide-induced environmental contamination (Sharma et al., 2019). Overuse of pesticides can eventually contaminate surface water bodies like lakes, ponds, and rivers by leaking into groundwater. In addition to lowering water quality, pesticide contamination causes a biological imbalance by affecting aquatic plants and animals (Mehmood et al., 2021). Public health issues are raised by the persistent and bioaccumulative characteristics of most pesticides since their active ingredients may be toxic and lethal to creatures that are not their intended targets (Eapen et al., 2007).

Pesticides are broken down and metabolized by microorganisms like bacteria and fungi, which results in their conversion into less toxic compounds or their full mineralization into other harmless substances like carbon dioxide and water. This process is known as microbial degradation of pesticides. This process is being researched extensively since it may have uses in bioremediation and sustainable agriculture. Since bioremediation offers a sustainable mechanism for detoxifying the hazardous compounds in soil systems, it is considered an innovative and developing method among the many pesticide detoxification treatment techniques for cleaning pesticide-contaminated sites (Pailanet al., 2020). This article reviews advances in biodegradation, focusing on degradation of pesticides by various group of microorganisms. It explores the toxic effects of pesticides, microbial mechanisms, strategies, and pathways for their degradation. The review highlights research on identifying efficient microbial strains for pesticide breakdown. Emphasis is placed on understanding and utilizing microorganisms for environmental remediation.

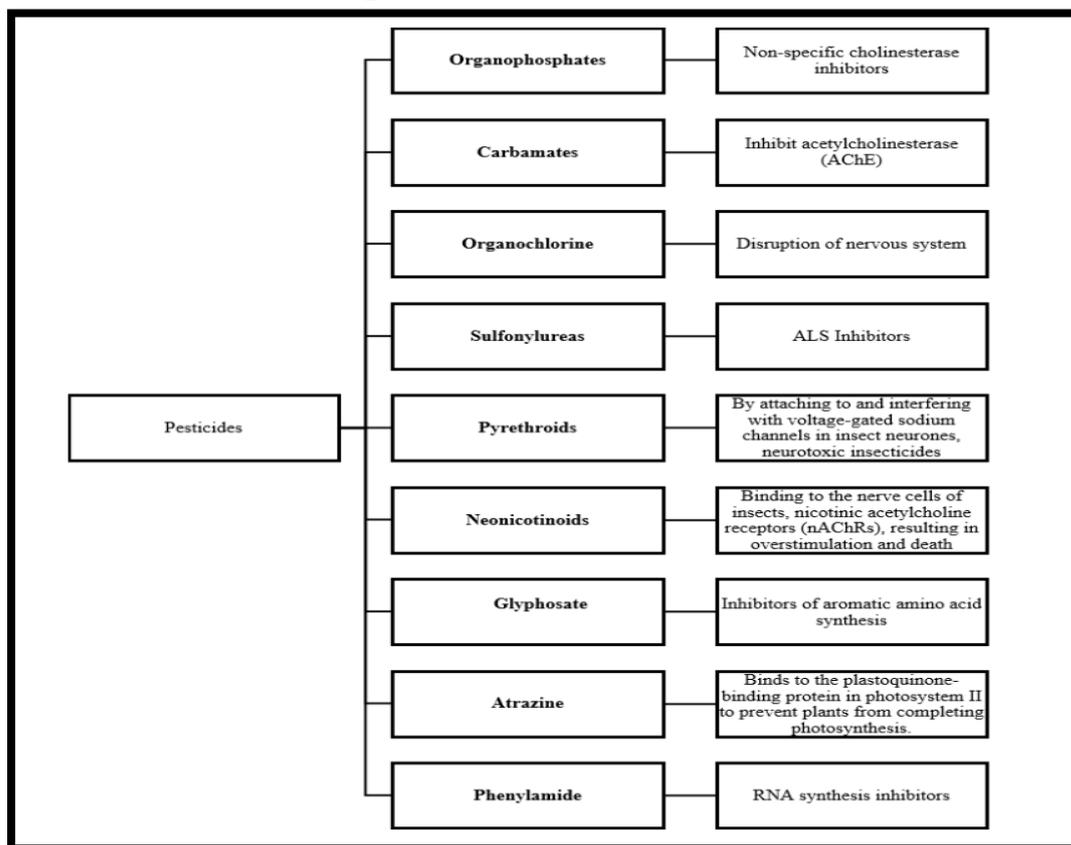
### **Classification of pesticides:**

Pesticides can be classified according to action mechanism, affecting the particular biochemical or physiological processes they target in pests. The nervous system of pests is disrupted by neurotoxins like pyrethroids (like permethrin) and organophosphates (like malathion); insects' normal development or reproduction is interfered by use of insect growth regulators (IGRs), like Methoprene; and mitochondrial inhibitors, like rotenone, interfere with the electron transport chain in mitochondria, disrupting cellular respiration in pests (Zhichkinaet al., 2020). Figure 1 shows a few typical chemical components and examples of herbicides, fungicides, and nitrogen compounds. Depending on their nature and mode of action, pesticides use a variety of strategies to control pests. Some inflict physical harm, such dehydrating pests by shattering their exoskeletons, while others interfere with the nervous system by preventing

enzymes or nerve signal transmission. Various group of pesticides and their mode of actions are summarized in figure 2.



**Figure 1: Classification of pesticides**

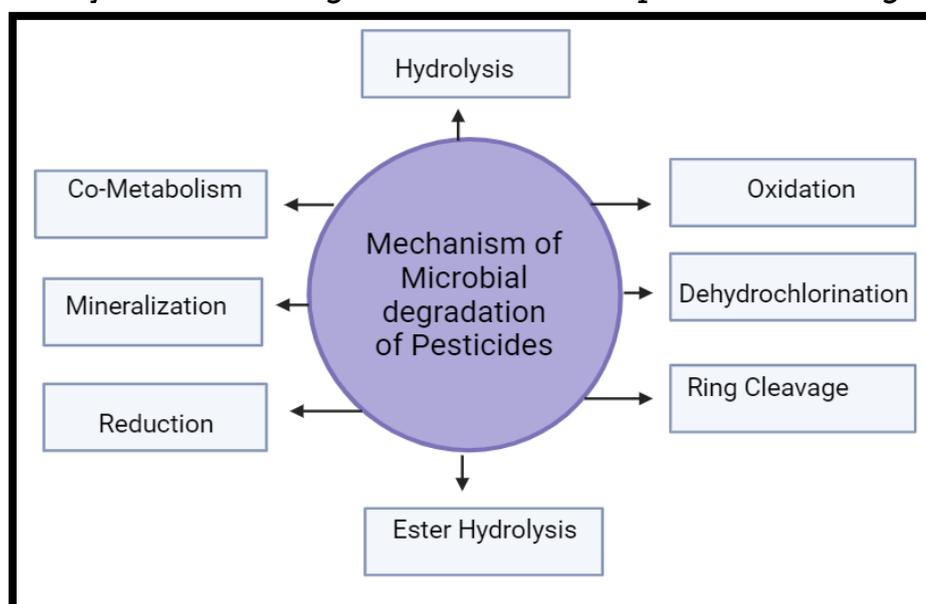


**Figure 2: Types of Pesticides and their mechanism of action**

**Microbial degradation of pesticides:**

Although pesticides have been crucial in boosting crop yields and shielding crops from pests, worries over their excessive and extensive usage and potential effects on the environment like, imbalance in microbial assemblage, nutrient dynamics and human health have been raised (Kumar et al., 2021). Pesticide

molecules are broken down into simpler and less hazardous chemicals by a variety of enzymatic processes that microorganisms carry out throughout the microbial degradation process. As they break down the pesticides into inorganic substances like carbon dioxide and water, the microorganisms use them as a nutritional medium for growth (Huang et al., 2018). There are several stages involved in the microbial breakdown of pesticide residues. Oxidation, reduction, hydrolysis, dehydrogenation, dehalogenation, decarboxylation, rearrangements, conjugations, and isomerization are the primary mechanisms by which degradation occurs. The four kinds of enzymes that are primarily in charge of biotransforming pesticide compounds are hydrolases, translocases, oxidoreductases, and transferases (Bansal 2012). In Figure 3, some of the mechanisms by which microorganisms break down pesticides are highlighted.



**Figure 3: Mechanisms of pesticides biodegradation**

#### **Microorganisms involved in degradation of pesticides:**

One natural process that lessens the impact of pesticides on the environment is their microbial breakdown. The microbial strains, their capacity to endure and flourish in the contaminated environment, and the environmental parameters (such as pH, temperature, and nutrient availability) would all play a role in the biodegradation technique's eventual effectiveness (Fuentes et al., 2016). Furthermore, the success of the biodegradation or bioremediation process depends on the monitoring and optimization of the microbial activity conditions. The main organisms that break down pesticides include bacteria, fungus, and actinomycetes. Byproducts of the degradation process can occasionally be further broken down by processes like co-metabolism and mineralization (Figure 3). Some of the important group of microorganisms involved in degradation of pesticides, firmicutes, proteobacteria, fungus actinobacteria and blue green algae are discussed hereunder.

**Actinobacteria**

Actinomycetes are a group of Gram-positive bacteria known for their high GC (guanine-cytosine) content in their DNA. They are widely distributed in various terrestrial and aquatic environments, and play important roles in ecological processes and biotechnology. Actinobacteria have a variety of metabolic capacities that support ecological processes, and they are well-known for being essential to the recycling of materials in the environment and involved in processes like improving soil health and nutrient cycling, decomposition of complex polymers, production of bioactive metabolites, bioremediation and symbiotic relationships (Mitra et al., 2022).

Since Actinobacteria can degrade a variety of organic contaminants, they have drawn attention for their ability to biodegrade a variety of chemical pesticides, like carbamates, sulfonylureas, organochlorines, s-triazines, acetanilides, triazinones, and organophosphates. Actinobacteria includes several species that are members of the pesticide-degrading classes, such as, *Arthrobacter*, *Microbacterium*, *Micrococcus*, *Nocardioides*, *Rhodococcus*, and *Streptomyces* (Fuentes et al., 2016). A novel method for bioremediation of chlordane degradation was suggested, utilizing groups of actinobacterial strains as consortium that degrade chlordane (Fuentes et al., 2023). Table 1 enlists the potential Actinobacteria involved in pesticide degradation and their mechanism of action.

**Table 1: Pesticide degrading Actinobacteria and Cyanobacteria**

Organism	Degrading pesticide	Mechanism of action	References
<i>Aulosirafertilissima</i> ARM 68 and <i>Nostoc muscorum</i> ARM 221	Malathion, Dichlorovos and Phosphomidon	Co-metabolism	Subramanian et al., (1994)
<i>Anabaena fertilissima</i> , <i>Aulosirafertilissima</i> and <i>Westiellopsisprolifca</i>	2,4-D ethyl ester	Biotransformation	Kumar et al., (2013)
<i>Anabaena</i> sp. PCC7120	Lindane	Co-metabolism	Guio et al., (2023)
<i>Arthrobacter</i> sp. AK-YN10	Atrazine	Co-metabolism	Sagarkaret al., (2015)
<i>Streptomyces</i> sp. M7	Lindane	Co-metabolism	Fuentes et al., (2011)
<i>Frankia alni</i> ACN14a	Atrazine	Genes for dealkylation and	Rehan et al., (2014)

		dichlorination.	
<i>N. muscorum</i>	Malathion (organophosphorus)	Co-metabolism	Ibrahim et al., (2014)
<i>Nostoc</i>	Dimethoate	Co-metabolism	Sahu and Gothalwal (2020)
<i>Spirulina platensis</i>	Chlorpyrifos	Enzymatic activity of alkaline phosphatase	Thengodkar and Sivakami (2010)
<i>Fischerella sp.</i>	Organophosphorus pesticide methyl parathion	Biosorption and Co-metabolism.	Tiwari et al., (2017)

**Blue green algae:**

Cyanobacteria are a diverse group of photosynthetic bacteria that can adapt to various environments, including those contaminated with pesticides. It has been studied how cyanobacterial biofertilizers might help with pest management and other agricultural issues like, inducing systemic resistance in plants, altering plant chemistry, enhanced plant growth, synergistic effects with some pesticides and reduction in chemical pesticides dependency (Vijayan et al., 2020).

Common blue-green algae involved in biodegradation of pesticides are like, *Aulosira*, *Nostoc*, *Anabaena*, *Synechocystis* and *Microcystis* (Sharma et al., 2011) Many cyanobacterial strains have been reported to degrade organophosphate pesticides like, quinolphos, dichlorophos, malathion, phosphomidon and monocrotophos (table 1). Although cyanobacteria may be beneficial in detoxifying pesticides, the practical implementation of this strategy necessitates careful consideration of a number of elements, including the particular cyanobacterial species used, the surrounding environment, and the bioremediation process' overall efficacy (Vijayan et al., 2024).

**Firmicutes:**

The majority of the bacteria in the firmicutes group have Gram positive cell walls and are low in G+C content. But there are few species of firmicutes that are Gram negative strains due to their perforated cell outer membrane, like *Pectinatus*, *Selenomonas*, *Megasphaera*, and *Zymophilus* (Onunga et al., 2015). Although they are not commonly classified as extremophiles and have ability to form endospores, certain organisms this phylum can demonstrate tolerance to diverse abiotic stressors and possess the ability to decompose a range of pesticides.

*Bacillus pumilus*, *Bacillus cereus*, *Bacillus licheniformis*, *Bacillus subtilis*, *Bacillus thuringiensis*, and *Paenibacillus polymyxa*—belong to the phylum Firmicutes and

have been reported for breakdown of pesticides (Regar et al., 2019). *Bacillus pumilis* and *Bacillus licheniformis* have been reported many times for their ability to degrade chlorpyrifos and utilize it as sole carbon and energy source. Quinalphos, which is widely and extensively used in agricultural fields, which persists and deteriorates crop health and soil fertility is degraded by bacteria of firmicutes group (Gangireddygarriet al., 2017).

**Proteobacteria:**

Proteobacteria are a diverse group of bacteria that play essential roles in various ecological and environmental processes, including the degradation of pesticides and other environmental contaminants. Several species of proteobacteria belonging to different classes have been identified as key players in the biodegradation of pesticides, like  $\alpha$ -proteobacteria (*Mesorhizobium*, *Methylobacterium*, *Pseudaminobacter* and *Rhizobium*),  $\beta$ -proteobacteria (*Achromobacter*, *Burkholderia* and *Alcaligenes*) and  $\gamma$ -proteobacteria (*Pseudomonas*, *Klebsiella*, *Xanthomonas*, and *Serratia*) (Maharana et al., 2024)

A fascinating example of microbial pesticide biodegradation is the breakdown of a foliar insecticide Acephate by proteobacteria like *Methylobacterium* (Kumar et al., 2021). Acephate is an organophosphate sprayed on fields to prevent aphid attacks on decorative plants and various vegetable crops. Different species of *Pseudomonas* present in agricultural soils are reported to be involved in degradation of a nematicide oxamyl and some chlorpyrifos (Osborn, 2005). Some of the important bacteria involved in pesticide degradation along with their mechanism of degradation are listed in table 2.

**Table 2: Pesticide degrading Bacteria**

Name of Organism	Degrading Pesticide	Mechanism of Degradation	Reference
<i>A. nicotinovorans</i>	Atrazine	Atrazine degrading genes (atzABC gene)	Aislabieet al., (2005)
<i>Eubacterium limosum</i>	Mythoxychlor and DDT	Reductive dichlorination	Yim et al., (2008)
<i>Alcaligenes faecalis</i> JBW4	Organochlorine pesticide endosulfan	Degradation using a non-oxidative pathway.	Kong et al., (2013)
<i>B. amyloliquefaciens</i>	Organophosphorus pesticides	Enhances the solubility of phosphorus, synthesize siderophores	Ngalimatet al., (2019)

		and Indole-3-acetic acid (IAA).	
<i>Bacillus licheniformis</i>	B-cypermethrine ( $\beta$ -CY)	Mineralization and co-metabolism	Zhao et al., (2019)
<i>Raoultella ornithinolytica</i> -ZK4	Pyrethroids	Ester bond hydrolysis	Zhang et al., (2019)
<i>Bacillus sp.</i>	Mixture of pesticides (cypermethrin, fi pronil, imidacloprid and sulfosulfuron)	Enzymatic action (laccase and aldehyde dehydrogenase)	Gangola et al., (2022)
<i>Serratia marcescens</i>	Organophosphorus insecticides dimethoate	Possess gene (organophosphorus degrading MLB fold metallohydrolase gene)	Xia et al., (2023)
<i>Raoultellaplanticola</i>	n-hexadecane	Production of biosurfactant lipopeptides.	Li et al., (2024)
<i>Pseudomonas aeruginosa</i> PAO1	Pyrethroid insecticides (etofenprox, bifenthrin, tetramethrin)	EstaraseEstA gene	Liu et al., (2025)

**Fungus:**

In the environment, fungi are renowned for their capacity to metabolize and decompose a wide range of organic substances, including numerous manmade pesticides. It has been discovered that some fungus possesses diverse range of enzymes that break down or modify specific pesticides, changing their chemical structures and lowering their toxicity (Chia et al., 2024). Several species of fungal communities such as white rote fungi, brown rot fungi, and endophytic fungi belonging to different classes have been identified for their role in biodegradation of pesticides like, Ascomycetes (*Lipomyces*, *Penicillium*, *Aspergillus* and *Verticillium*) and Basidiomycetes (*Dichotomitus*, *Ganoderma*, *Phanerochaete* and *Setreum*). (Rigas et al., 2007). These fungal communities are reported for degrading hazardous pesticides like, atrazine, chlorpyrifos, DDT, endosulfan, metalaxyl, terbuthylazine and xenobiotic compounds. Additionally, several fungi have the ability to associate with plant roots to develop symbiotic partnerships that could affect the rhizosphere's fate for pesticides (Ramakrishnan

et al., 2021). Table 3 summarizes the role of fungi involved in pesticide degradation.

**Table 3: Pesticide degrading Fungi**

Name of Organism	Degrading Pesticide	Mechanism of Degradation	Reference
<i>Penicillium citrinum</i>	2-aminoethylphosphonic and 2-oxoalkylphosphonic acids	Co metabolism	Zboinskae et al., (1992)
<i>Phanerochaete chrysosporium</i>	Chlorpyrifos, fonofos, and terbufos	Mineralization	Bumpus et al., (1993)
<i>Trichoderma harzianum</i>	Endosulfan	Co-metabolism	Katayama and Matsumura (1993)
<i>Aspergillus flavus</i> and <i>Aspergillus sydowii</i>	Pyrazophos and melathion	Hydrolysis by phosphatases and Mineralization	Hasan, (1999)
<i>Phanerochaete chrysosporium</i>	MPCA and benzoton.	Hydrolysing activity of laccase and lignin peroxidase	Castillo et al., (2001)
<i>Fusarium</i>	Organophosphorus pesticides	Co metabolism	Castro jr. et al., (2007)
<i>Lipomyces kononenkoae</i>	picloram	Co metabolism	Sadowsky et al., (2009)
<i>A.niger</i>	Endosulfan	Co-metabolism and desulfurization	Hussaini et al., (2013)
<i>L. edodes</i> EL1	Terbutylazine, difenoconazole, diflufenican and pendimethalin	Mineralization	Pinto et al., (2016)

<i>Fusarium proliferatum</i> CF2	Allethrin	Ester bond hydrolysis followed by cleavage of 5 carbon ring.	Bhatt et al., (2020)
<i>Trametes versicolor</i>	Acetamiprid and imidacloprid	Transformation	Hu et al., 2022

**Approaches for improving biodegradation**

Numerous strategies that increase the efficacy and efficiency of microbial and enzymatic activities can be used to improve biodegradation. To achieve the best circumstances for biodegradation, these include adjusting environmental factors like pH, temperature, and nutrient availability. Degradation rates can be greatly increased by using genetically engineered microbes (GEMs) designed for certain pollutants (Nag et al., 2024). To break down the xenobiotic more effectively, some methods enhance the rate of biodegradation. Three approaches are typically used, and they have been covered here. First method is bioaugmentation, which means to increase the catabolic activity at the contaminated site by adding microbial species at a particular site (Nzila et al., 2016). Second method is bioattenuation, Perelo(2010)explained the term "bioattenuation" that describes the innate ability of microorganisms to break down the residues of pesticides and xenobiotics. The complexity of the chemicals determines how long it takes to degrade them. The methods used in this process—biodegradation, sorption, and volatilization—transform the target compounds into less hazardous ones. The third method is biostimulation, which involves boosting the enzymatic activity and microbial activity by increasing the nutrient supply to the contamination site (Ortiz et al., 2013).

**Conclusion& future prospectives:**

While the environmental impact of pesticides is mostly mitigated by the microbial decomposition of these compounds, it is imperative to take into account the unique properties and circumstances of each pesticide as well as the environment in which it is applied.The field of bioremediation is changing as a result of continuous research into and identification of novel microbial species with the ability to degrade pesticides. The presence of microbial communities with pesticide degradation capabilities has wide-ranging implications for the environment, agriculture, and biotechnology. New pesticide-degrading microbes and mechanisms are being found because of genomic and metagenomic research, opening the door to more focused and effective degradation techniques. The development of microorganisms with improved metabolic capacities to degrade intricate and persistent poisons is possible through genetic engineering and synthetic biology. In order to increase efficiency and sustainability, bioreactor technologies and immobilized cell systems are being

developed for large-scale applications. Harnessing and conception these capabilities can help attenuate the negative impacts of pesticides, reduce pollution, and promote more sustainable and environmentally friendly practices.

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