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Review

Pesticide residues degradation in soil: an overview

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Abstract

This review summarizes the recent developments observed in the degradation of pesticide residues through biotransformation, chemical degradation, and photodegradation. The systematic review was performed in 2025 by searching for keywords like "pesticide biotransformation," "pesticide toxicity," and "pest management practices" in the PubMed, Scopus, and Web of Science scientific databases, without any time restrictions. The findings of this research indicate that the biotransformation of pesticides by microorganisms represents a pivotal process governing the fate of these chemicals in the environment, occurring mainly through three pathways: enzymatic degradation, co-metabolism, and complete mineralization. Plants generally have a much lower capacity to degrade pesticide residues than microorganisms; thus, their primary strategy is to detoxify and sequester pesticides within their cells instead of achieving full mineralization. The degradation of pesticides in the natural environment can also be accomplished through chemical degradation and photodegradation. Crucial chemical pathways involved in pesticide degradation include hydrolysis, along with oxidation and reduction reactions. In light of the escalating concerns regarding pesticide toxicity, it is important to implement sustainable management practices in the agricultural sector that focus on reducing pesticide toxicity in the soil. The first step in reducing the toxicity of pesticides in soils is to decrease their use by maximizing treatment effectiveness, minimizing the number of interventions, and lowering application rates. Applying agricultural practices like crop rotation, intercropping, organic farming, habitat management, and regular monitoring of pest populations substantially contributes to reducing pesticide toxicity in the soil. These practices not only mitigate pesticide-related soil contamination but also improve sustainable agricultural output and ecosystem resilience.

Keywords: chemical degradation, microbial degradation, photodegradation, pesticide mineralization, pest management, soil microbiome

Introduction

The soil serves as the most important natural resource essential for food production and ecosystem sustainability. Simultaneously, it is the most fragile natural resource, vulnerable to numerous degradation processes that can swiftly impair or considerably lessen its biological function (Futa *et al.* 2024). The main anthropogenic factors contributing to soil degradation include industrialization, deforestation, and agrochemicals. The accompanying manifestation of soil degradation, particularly those caused by industrialization and uncontrolled agricultural activities, is the contamination of soil with various pollutants, including mineral fertilizers and pesticides. The pollutants identified are potential threats not just to soil but also to underground water and waterways, which jeopardize many ecosystems in both direct and indirect ways (Li *et al.* 2024).

Pesticides are substances, either organic or inorganic, utilized to control pests, diseases, and weeds in agricultural and urban environments. Inorganic pesticides include lime, copper, sulfur, ferrous sulfate, copper sulfate, and lime-sulfur, whereas organic pesticides are characterized by the presence of carbon in their chemical composition. Organic pesticides can be further classified into four major groups: organochlorines, organophosphates, carbamates, and pyrethroids (Parra-Arroyo *et al.* 2022). The pesticides that are most frequently used worldwide are organophosphates and carbamates. Although pesticides are key to contemporary agriculture, their extensive use can adversely affect soil fertility. Pesticide usage suppresses the activity of key soil enzymes for nutrient cycling, such as dehydrogenase, phosphatase, and urease, which adversely affects soil quality and subsequent plant growth (Yasir *et al.* 2025). Among pesticides, herbicides are the primary contaminants of soil because the toxic chemical substances they contain degrade slowly and poorly, leading to their accumulation over time in both the soil and in plants and their consumers (Parven *et al.* 2025).

Toxic substances present in pesticides can be absorbed by plants through either their underground or above-ground parts. The amount absorbed is determined by the concentration of the toxic substances in the pesticides, the developmental stage of the plant, and its interaction with environmental factors at the time of pesticide use and effectiveness (Lushchak *et al.* 2018). Numerous studies have demonstrated that toxic substances, once absorbed by plants, disrupt physiological processes and metabolic reactions within the plant (Jan *et al.* 2020; Jabłońska-Trypuć and Wiater 2022; Liu *et al.* 2024; Gruss *et al.* 2025).

Plants have evolved numerous mechanisms to protect themselves from the harmful effects of pesticide active substances. The majority of these mechanisms rely on the sequestration of active pesticide substances or their detoxification through a series of enzymatic reactions.

However, the effectiveness of these mechanisms is relatively low, particularly in scenarios where the plant has been treated with pesticides inappropriately multiple times. Contrary to plants, soil microorganisms exhibit a considerably higher potential to break down active pesticide compounds, attributed to their ability to easily change their genomes and adapt to new environments (Chowdhury *et al.* 2025). A large number of soil microorganisms use pesticide residues and other contaminants in the soil as food sources, transforming them through various enzymatic mechanisms into basic elements such as carbon dioxide, water, and ammonia (Khan 2025). Partial breakdown of toxic pesticide ingredients into less harmful metabolites may also occur, indicating incomplete degradation (Shehata and Gehan 2010; Hua *et al.* 2022).

However, the microbial degradation of pesticide active ingredients in soil is often limited by slow degradation kinetics. Additionally, complex soil properties create challenges that laboratory tests evaluating microbial efficacy in pesticide degradation cannot fully replicate. Consequently, microorganisms exhibit significantly higher degradation efficacy in controlled laboratory settings than in pesticide-impacted soils (Ewere *et al.* 2024).

This review provides basic scientific information about the impact of pesticides on plant growth and development, along with the mechanisms that soil microorganisms and plants utilize to transform toxic pesticide ingredients into less harmful substances. Specific attention is given to the key pathways that facilitate the degradation of the active pesticide compounds. A deeper understanding of the interactions between pesticides and the plants' and soil microbes' defense mechanisms against pesticide toxicity is essential for developing strategies to mitigate the environmental and health consequences of pesticide use. This review also summarizes the recent developments observed in the degradation of pesticides through chemical degradation and photodegradation.

Methodology

This review highlights recent findings concerning the degradation of pesticide residues in soil. The data were obtained from ScienceDirect, PubMed, Web of Science, and the Scopus database, per publication details as of December 2025. Studies were selected based on their focus on the key pathways that facilitate the degradation of the active pesticide compounds in the soil. Relevant keywords such as pesticide OR herbicide, AND soil, AND degradation OR sorption, AND pest management practices were incorporated into the search strategy. Boolean operators (AND, OR) were employed to refine and expand search queries. Articles written in languages other than English (unless an English translation was present) and studies not directly related to pesticide transformation, pesticide toxicity, and sustainable management of pesticides

in agriculture were disregarded. Editorials and conference abstracts were not included in the selection. The study's findings were organized and summarized using a narrative-based methodology.

Effects of pesticides on plants and soil microbes

It is widely recognized that responsible pesticide use is an essential component of sustainable agriculture, as it helps minimize the loss of crops, particularly in monoculture farming. Without the application of pesticides, losses in fruits, vegetables, and cereals from pests and diseases would be exceptionally high (Tudi *et al.* 2021). However, improper or excessive pesticide use can affect non-target plants by reducing generative development, restricting both shoot and root length, and impairing photosynthesis (Alengebawy *et al.* 2021). It's also important to note that pesticide drift and runoff can lead to nearby sensitive plant species being exposed to sublethal concentrations, which may interfere with biodiversity and ecosystem stability (Verdadero *et al.* 2025).

Pesticides may indirectly harm plants. Abay *et al.* (2023) reported that pesticides affect honeybees, thereby indirectly limiting plant pollination. In this context, a multitude of studies has indicated the collapse of honeybee colonies during the past several years, primarily due to the extensive application of pesticides on agricultural crops (Quandahor *et al.* 2024; Ahsan *et al.* 2025; Bütüner and Susurluk 2025). Additionally, the excessive and improper application of pesticides may lead to a decrease in populations of beneficial soil microorganisms. As an illustration, herbicides with triclopyr as an active ingredient hinder soil bacteria responsible for converting ammonia into nitrite (Widhiastuti *et al.* 2023), while glyphosate inhibits the activity of free-living nitrogen-fixing bacteria present in the soil (Singh *et al.* 2020). Mycorrhizal fungi that grow with the roots of many plants can also be adversely affected by herbicides, particularly when these are applied directly to a host plant (Druille *et al.* 2013; Wilkes *et al.* 2020).

The extent of damage in plants caused by each pesticide varies among pesticides, which primarily depends on the pesticide's active ingredient properties and applied dose. A highly toxic substance in pesticides causes severe toxicity symptoms even in small amounts, while a pesticide's active ingredient with lower toxicity usually demands higher doses to elicit mild symptoms (Garud *et al.* 2024). Pesticide toxicity also depends on the persistence of pesticides in the environment, the level and duration of exposure to pesticides, soil properties, and plant characteristics. Generally, the more stable and persistent a pesticide is, the greater its negative impact on the environment (Muñoz-Bautista *et al.* 2025). Of the plant characteristics, the cuticle's structure, the growth rate and developmental stage, and the plant's overall condition

seem most important in pesticide toxicity evaluation (Staiger *et al.* 2019). In terms of soil properties, organic matter content, clay content, pH value, and soil microbial composition exert the greatest influence (Mishra *et al.* 2023). Several studies have demonstrated that an increase in clay and/or organic matter content in soil enhances the adsorption of pesticide ingredients onto soil particles, affecting their bioavailability and mobility in the soil ecosystem (Rasool *et al.* 2022; Sarker *et al.* 2024; Ayenew and Getu 2025).

The response of soil microbial communities to pesticide exposure is inconsistent and depends on various factors, including the specific characteristics of the pesticide, its application rate, and the frequency of its use. The chemical structure, mode of action, and persistence of pesticides in the environment largely determine their impact on soil microbes (Swaine *et al.* 2025). As an illustration, organochlorine pesticides, acknowledged for their high levels of environmental persistence, can produce prolonged toxic effects on soil microbes (Jayaraj *et al.* 2016), while organophosphates, which degrade at a faster rate, may only induce temporary disturbances (Kilonzi and Otieno 2024). Frequent pesticide application and higher usage rates can enhance the negative repercussions on microbial diversity. Moreover, long-term pesticide application may favor resistant strains, potentially reducing overall microbial diversity. The loss of sensitive beneficial microbial species poses a risk to the soil ecosystem, negatively affecting nutrient cycling, plant-microbe interactions, and the maintenance of soil structure (Gruss *et al.* 2018; Ni *et al.* 2025).

Pesticide biotransformation pathways

Biotransformation refers to the process in which a substance is structurally modified through a series of enzymatic reactions within living organisms. This process plays a crucial role in the natural attenuation of environmental pollutants, including pesticides (Valentová 2023). Through biotransformation, hydrophobic and chemically stable pesticides can be transformed into more hydrophilic and typically less toxic metabolites, which enhance their eventual removal from the environment. The time required for biotransformation can vary from hours to days, or even years, based on the pesticide's chemical properties, biotransformation pathways, and environmental conditions (Aljabri 2025).

All living organisms, including microorganisms and plants, possess the capacity for biotransformation, using distinct enzymatic systems tailored to their specific ecological contexts. In microbial systems, the biotransformation of pesticide active ingredients often results in full mineralization, where they are converted into inorganic constituents such as CO₂, H₂O, and NH₃ (Kumar *et al.* 2025). Plants generally have a much lower capacity to degrade

pesticide components than microorganisms; thus, their primary strategy is to detoxify and sequester pesticides within their cells instead of achieving full mineralization (Zhang and Yang 2021).

Pesticide biotransformation pathways in plants

Plants have evolved sophisticated mechanisms to transform toxic pesticide ingredients into less toxic metabolites. These mechanisms rely on the plant's ability to take up, transform, and store pesticide ingredients within its cells, thereby preventing the release of metabolites with uncertain toxicity into the environment (Li *et al.* 2022). The detoxification of pesticides in plants is typically outlined as a three-phase process, often called the "green liver" model, drawing parallels to the metabolic functions of the liver in animals (Sandermann 1994).

Phase I refers to the activation of pesticide compounds through hydrolysis, oxidation or reduction. These metabolic reactions are mainly catalyzed by carboxylesterases, peroxidases, and cytochrome P450 monooxygenases, leading to the formation of reactive groups within the structure of pesticides. Carboxylesterases cleave ester bonds within pesticide molecules, resulting in the formation of more polar metabolites, thereby increasing the hydrophilicity and reactivity of the pesticides. Peroxidases catalyze the oxidation of a broad range of pesticide ingredients using hydrogen peroxide as the oxidant, whereas cytochrome P450 monooxygenases catalyze the insertion of an oxygen atom into C-H and N-H bonds within pesticide molecules, thereby increasing the reactivity of the pesticide and priming it for later conjugation reactions (Valdiviezo *et al.* 2022).

During Phase II, the activated pesticide metabolites are conjugated with naturally occurring hydrophilic molecules in plant cells, which decrease their toxicity and increase their solubility in water. Plant metabolites involved in conjugation reactions include glutathione, glucose, and amino acids (Vicidomini *et al.* 2024).

The conjugation of glutathione with activated pesticide molecules, facilitated by glutathione S-transferases, is a significant and common reaction for the transformation of pesticides in plant cells during Phase II. This reaction is typical for detoxifying toxic herbicides like atrazine and alachlor, facilitating their sequestration within plant cells (Garbaly *et al.* 2025). In the presence of UDP-glucosyltransferases, numerous pesticide metabolites are capable of attaching to the sugar component, primarily glucose, thereby increasing their water solubility and easing their storage in the vacuole (Gharabli *et al.* 2023). Some pesticides, such as the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D), can be conjugated with amino acids (Eyer *et al.* 2016).

The third and, at the same time, final phase of detoxifying pesticides in plant cells involves the sequestration of conjugated metabolites into vacuoles or their binding to cell wall components, primarily lignin. This phase efficiently immobilizes pesticide residues, ensuring that they do not interfere with cellular functions (Zhang *et al.* 2024). A simplified diagram of the three-step pesticide biotransformation pathway in plants is illustrated in Figure 1.

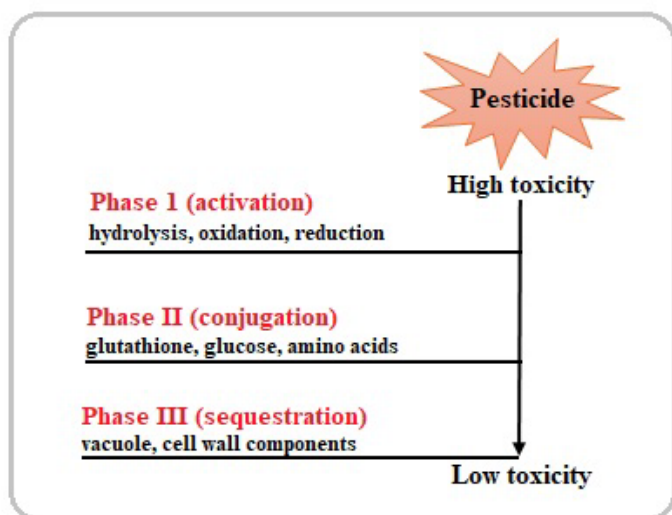


Figure 1. Simplified diagram of three-step pesticide biotransformation pathway in plants

For a better understanding of pesticide detoxification in plant cells, it is important to note that not all reactions that facilitate the detoxification of pesticides in plant cells are enzyme-mediated; some are the result of interactions with plant metabolites through non-enzymatic pathways, while others are generated through photochemical mechanisms. Additionally, it should be acknowledged that some pesticide residues still exhibit toxicity after undergoing biotransformation, indicating that their conversion does not guarantee complete detoxification.

Pesticide biotransformation pathways in soil microorganisms

Soil microbes are known for their impressive adaptability, which allows them to convert a wide range of toxic substances into non-toxic or less toxic forms (Maqsood *et al.* 2023). However, the effectiveness of pesticide transformation by soil microbes is difficult to predict, as it relies not just on specific microbial taxa but frequently arises from synergistic interactions among microbial communities. Additionally, soil biochemistry, current weather conditions, the toxicity levels of pesticides, and their modes of action have a significant impact on the microbial response to toxic pesticides in their surroundings (Shahid and Khan 2022).

The pesticides in the soil can be transformed via different microbial metabolic processes including enzymatic degradation, co-metabolism, and complete mineralization. These metabolic processes are largely influenced by intrinsic microbial factors, pesticide properties, and extrinsic environmental conditions. Understanding this is crucial for predicting the fate of pesticides and, consequently, for creating successful bioremediation techniques in pesticide-polluted soils (Chia *et al.* 2024).

Microbial enzymatic degradation

Many soil microorganisms, including bacteria and fungi, have evolved the ability to produce enzymes that degrade active pesticide ingredients. Nevertheless, bacteria play a leading role in the enzymatic breakdown of pesticides. This dominance stems from their rapid reproductive and evolutionary abilities, coupled with their capacity to perform horizontal gene transfers that facilitate pesticide degradation (Książek-Trela *et al.* 2025). Although the degradation pathways of pesticides are unique to each pesticide and its related microorganisms, the process of pesticide degradation by microorganisms can be broadly divided into three phases: Phase 1: The transformation of pesticide compounds into more water-soluble and less toxic products via oxidation, reduction, or hydrolysis reactions; Phase 2: The conversion of modified pesticide compounds from the first phase into less toxic products through conjugation with sugars and amino acids; Phase 3: The conversion of metabolites from Phase II into secondary conjugates that show lower toxicity than those produced earlier (Raffa and Chiampo 2021).

The first phase, known as initial biotransformation, includes the oxidation, reduction, or hydrolysis of the pesticide parent compound. These reactions make pesticide compounds more polar and more susceptible to further metabolism (Kosimov *et al.* 2025). The oxidative transformations of parent pesticides represent the most prevalent reactions during this phase, especially under aerobic conditions. For example, cytochrome P450 monooxygenases facilitate the addition of hydroxyl groups to the structure of pesticides, which is essential for the initial degradation of hydrophobic pesticide compounds like atrazine (Szewczyk *et al.* 2020). On the other hand, dioxygenases incorporate both atoms of molecular oxygen into a pesticide compound, making them essential for the cleavage of aromatic rings in the structure of many otherwise stable pesticide compounds (Dai *et al.* 2015). Reductive transformations commonly occur in anaerobic environments and play a crucial role in breaking down halogenated pesticides, which are notably resistant because of the stability provided by halogen atoms. In reductive dehalogenation, halogen atoms in a pesticide molecule, particularly chlorine, are

replaced by hydrogen atoms through the catalytic action of reductive dehalogenases. This reaction reduces the electronegativity of the pesticide parent compound, making it more prone to subsequent degradation (Li and Mitch 2018). Hydrolysis represents a key microbial degradation pathway for pesticides that contain ester, amide, carbamate, and phosphoric acid ester bonds. By adding a water molecule, hydrolytic enzymes cleave these bonds, producing a more soluble and usually less toxic product (Jayasekara *et al.* 2025). For example, phosphotriesterases catalyze the hydrolysis of organophosphate pesticides like parathion and malathion, producing less toxic diethyl phosphates and thiols (Bigley and Raushel 2013).

Table 1 summarizes key enzymes participating in microbial pesticide degradation.

Table 1. Key enzymes participating in pesticide degradation

Group of enzymes	Enzymes	Pathway	Target contaminants	References
Oxidoreductases	Oxygenases	catalyze the oxidation reaction by adding oxygen molecules	aromatic compounds, organochlorines, neonicotinoids, pyrethroids	(Xu <i>et al.</i> 2021; Cheng <i>et al.</i> 2022)
	Peroxidases	catalyze reduction reaction in the presence of H ₂ O ₂	polychlorinated biphenyls, organochlorines, organophosphates	(Li <i>et al.</i> 2016; Alneyadi <i>et al.</i> 2017; Senani <i>et al.</i> 2023)
	Laccases	catalyze the oxidation of aromatic rings	chlorpyrifos, atrazine, aldicarb, chlorothalonil, metolachlor, spinosad	(Jin <i>et al.</i> 2016; Siddiqui <i>et al.</i> 2022; Vaithyanathan <i>et al.</i> 2022)
	Aldo-keto reductases	catalyze redox transformations	glyphosate, butachlor	Agrawal <i>et al.</i> 2015; Li <i>et al.</i> 2022)
	Nitro-reductases	catalyze nitroreduction and demethylation	diphenyl ethers, neonicotinoids	Gautam and Dubey 2023; Tian <i>et al.</i> 2023)
Hydrolases	Phosphotriesterases	catalyze the hydrolysis of P-O bonds	chlorpyrifos, diazinon, methyl parathion	(Aswathi <i>et al.</i> 2019; Xu <i>et al.</i> 2022; Pashirova <i>et al.</i> 2024)
	Carboxyl-esterases	catalyze the hydrolysis of carboxyl ester bond	organophosphates, pyrethroids	Wang <i>et al.</i> 2022; Hlihor and Cozma 2023; Dutta <i>et al.</i> 2024)
	Haloalkane dehalogenases	catalyze the cleavage of carbon-halogen bonds	halogenated aliphatic compounds	Chen <i>et al.</i> 2023; Gelfand and Warshel 2025)

In the second phase, the modified pesticide compounds from the first phase are subjected to additional modifications through conjugation with endogenous molecules like glutathione, amino acids, sugars, etc. Consequently, these compounds are more water-soluble and, in general, less toxic than the original pesticide material. In the third phase, the additional conjugation of metabolites from the second phase takes place, resulting in the production of metabolites that show lower toxicity than those produced earlier (Papade *et al.* 2025). The occurrence of one, two, or all three phases of microbial pesticide degradation is contingent upon the enzymatic capabilities of each microbial species, the chemical structure of the pesticide compound, and environmental conditions. Ultimately, products resulting from the microbial degradation of pesticides, along with soil organic matter, serve as energy sources for both the same and other soil microorganisms (Ray *et al.* 2024).

Microbial pesticide biotransformation via co-metabolism

Co-metabolism involves the microbial biotransformation of pesticide compounds that are neither utilized as an energy source nor as a fundamental component of the organism. This process occurs accidentally while microorganisms obtain energy from other, more readily degradable carbon sources (Datta *et al.* 2024). For example, in the presence of glucose, which serves as an easily metabolizable carbon source, *Pseudomonas putida* demonstrates high efficiency in degrading the carbamate insecticide carbofuran (Gong *et al.* 2016). A further example of pesticide biotransformation via co-metabolism is the degradation of trichloroethylene by *Methylosinus trichosporium* in the presence of methane as a carbon source (Wu *et al.* 2022). Degradation of halogenated pesticides by methane-oxidizing bacteria via co-metabolism pathways has also been observed (Benner *et al.* 2015). Mqambalala *et al.* (2025) reported that co-metabolism plays a vital role in the degradation of highly resistant pesticides like atrazine, and that the availability of easily degradable organic materials can enhance these processes. Within this framework, co-metabolism could be a promising mechanism for the biodegradation of pesticides in soil if extra sources of carbon are added, which would enhance the co-metabolic activity of soil microorganisms.

Pesticide mineralization

Pesticide mineralization involves the complete degradation of the pesticide active ingredients to inorganic compounds like CO₂, NH₃, and H₂O. It is undoubtedly the most effective pesticide biotransformation pathway, as it completely eliminates pesticide toxicity (Ruomeng *et al.*

2023). However, it is important to note that the two previously described biotransformation pathways for pesticide degradation, microbial degradation and co-metabolism, should not be viewed separately from mineralization, as both pathways can represent preliminary steps in the complete breakdown of pesticides. Additionally, full pesticide mineralization is generally not accomplished by just one microorganism; it often requires a group of microorganisms, with each one able to break down the intermediates created by the others. A multitude of studies has illustrated that a broad spectrum of bacterial species contributes to pesticide mineralization, highlighting notable genera such as *Bacillus*, *Klebsiella*, *Acinetobacter*, *Aerobacter*, *Micrococcus*, *Neisseria*, *Pseudomonas*, and *Arthrobacter* (Zuo *et al.* 2015; Doolotkeldieva *et al.* 2018; Onwona-Kwakye *et al.* 2020). These bacteria utilize various oxidative and hydrolytic enzymes, such as oxygenases, esterases, and hydrolases, to effectively degrade pesticide molecules (Abu-Tahon *et al.* 2025). Table 2 presents a list of important microbial genera and species that play a role in pesticide degradation.

Table 2. A list of key microbial genus/species involved in the degradation of pesticides

Microbial Genus/Species	Target pesticides	References
<i>Pseudomonas</i>	organophosphates (e.g., chlorpyrifos, diazinon, methyl parathion), organochlorines (e.g., γ -hexachlorocyclohexane)	(Gilani <i>et al.</i> 2016; Gong <i>et al.</i> 2016; Levchuk <i>et al.</i> 2022; Mansouri <i>et al.</i> 2025)
<i>Acinetobacter</i>	organophosphates (e.g., profenofos, diazinon), neonicotinoids	(Kumar <i>et al.</i> 2021; Mahalle <i>et al.</i> 2025)
<i>Arthrobacter aureus</i> TCI	chlorinated triazines (e.g., atrazine, terbutylazine)	(Li <i>et al.</i> 2008; Silva <i>et al.</i> 2015)
<i>Bacillus</i>	pyrethroids, carbamates, diphenyl ethers	(Xiao <i>et al.</i> 2020; Gangola <i>et al.</i> 2022; Liaqat <i>et al.</i> 2023)
<i>Rhodococcus</i>	organophosphates, pyrethroids, organochlorines	(Ito <i>et al.</i> 2016; Egorova <i>et al.</i> 2017; Huang <i>et al.</i> 2023)
<i>Klebsiella</i>	neonicotinoids, organophosphates	(Pang <i>et al.</i> 2020; Ahmad <i>et al.</i> 2021; Elshikh <i>et al.</i> 2022)
<i>Streptomyces</i>	organochlorines, (e.g., endosulfan, dichloro-diphenyl-trichloroethane), organophosphates (e.g., chlorpyrifos)	(Fuentes <i>et al.</i> 2013; Naveena <i>et al.</i> 2013; Briceño <i>et al.</i> 2018)
<i>Flavobacterium</i>	organophosphates	(Ortiz-Hernández <i>et al.</i> 2003; Lopes <i>et al.</i> 2022)
<i>Stenotrophomonas maltophilia</i>	organochlorines (e.g., endosulfan), organophosphates (e.g., monocrotophos)	(Zaffar <i>et al.</i> 2018; Harshitha <i>et al.</i> 2024)

<i>Burkholderia</i>	organophosphates (e.g., methyl parathion, acephate)	(Liu <i>et al.</i> 2014; Wu <i>et al.</i> 2023)
<i>Sphingomonas</i>	organophosphates (e.g., chlorpyrifos), phenylureas (e.g., isoproturon)	(Li <i>et al.</i> 2007; Duc 2022)
<i>Achromobacter</i>	chlorinated triazines (e.g., atrazine)	(Cycon and Piotrowska-Seget 2016; Tonelli Fernandes <i>et al.</i> 2018)

Factors affecting microbial biotransformation of pesticides in soils

The biotransformation of pesticides by soil microbes is contingent upon multiple factors, with the soil's physico-chemical characteristics and the properties of the pesticides being the most significant (Shultana *et al.* 2025). Soil physico-chemical characteristics, such as moisture, temperature, aeration, pH, and organic matter content, have a profound effect on the rate of pesticide degradation by microbes, as they directly affect microbial growth and activity (Liu *et al.* 2025). A decrease in soil water content reduces the probability of soil microbes coming into contact with pesticide compounds, which results in lower microbial activity, a decline in the number of microorganisms present in the soil, and less microbial movement through the soil. In contrast, at high moisture levels (close to the soil's maximum water retention), the growth of microbes is restricted by the slow transfer of oxygen, which also limits their effectiveness in degrading pesticides (Kaur *et al.* 2023).

The relationship between pesticide degradation rate and both soil pH and temperature has been shown in numerous studies (Muskus *et al.* 2019; Materu *et al.* 2021; Meftaul *et al.* 2023). Typically, elevated soil temperatures enhance the breakdown of pesticides by microorganisms, as they boost the kinetic energy of pesticide compounds and the activity of microbial enzymes. However, extremely high temperatures (above 50°C) may denature microbial enzymes, limiting their ability to degrade pesticides (Doolotkeldieva *et al.* 2025). Soil pH also has a strong impact on the activity of microbial enzymes present in the soil, subsequently influencing the rate of pesticide degradation. Several studies have illustrated that microbial enzymes display specific pH optima that determine their performance in pesticide degradation (Huang *et al.* 2018; Banu *et al.* 2024). For instance, organophosphorus hydrolases and esterases that break down pyrethroids are most effective in alkaline conditions (Zong *et al.* 2022), whereas laccases, which are among the most crucial enzymes in the detoxification of polycyclic aromatic hydrocarbons, typically exhibit their optimum activity at low soil pH values (Younus *et al.* 2025).

Soil organic matter regulates pesticide retention and thus degradation rate by influencing sorption dynamics and microbial degradation potential. In general terms, the rise in pesticide adsorption correlates with an increase in soil organic matter content. This is due to organic matter having both electropositive and electronegative adsorption sites, which facilitate interactions with a broad spectrum of ingredients present in pesticides (Nandi *et al.* 2025). Additionally, increasing levels of organic matter in the soil support microbial growth and activity, thereby facilitating potential microbial pesticide biotransformation, especially via co-metabolism (Khan *et al.* 2023).

Pesticide properties that strongly affect microbial degradation of pesticides are composition, solubility, and adsorption/desorption properties. Pesticide composition dictates its physical and chemical properties, along with its inherent biodegradability (Pathak *et al.* 2022). For instance, polar groups like -OH and -COOH present in pesticides can serve as targets for microbial attack, thereby enhancing pesticide degradation (Pal *et al.* 2006). Conversely, the presence of halogen or alkyl groups on the aromatic rings of pesticide compounds has been demonstrated to enhance pesticide resistance against microbial biodegradation (Häggblom 1992).

Numerous studies have demonstrated that pesticide compounds with low water solubility experience more limited microbial degradation than those with higher water solubility (Székács *et al.* 2015; Gopal *et al.* 2025; Rodríguez-Seijo *et al.* 2025). Pesticides with polar functional groups in their structure tend to be more water-soluble and mobile in soil, increasing their potential for biodegradation. In contrast, nonpolar pesticides, such as organochlorines, are more likely to adsorb onto soil particles, reducing their bioavailability for degradation (Cheng *et al.* 2014).

Pesticides in soils exist either in a free state in the soil solution or are adsorbed onto soil particles via physical, electrostatic, and chemical bonds. Microorganisms can degrade only the dissolved fraction of the pesticide compound in the soil solution; therefore, the rate of dissolution of pesticides governs the rate of their microbial degradation (Otalvaro and Brigante 2018).

The fate and degradation of pesticides at application sites are also influenced by climatic factors, including rainfall, wind, humidity, and temperature. To illustrate, extreme precipitation can lead to the leaching of pesticides into groundwater, compromising its quality and stability (Li *et al.* 2020). Furthermore, the degradation patterns of pesticides are not the same in controlled growing environments compared to open fields, even with the same pesticide, as the climatic conditions in open fields cannot be managed as they are in greenhouses (Heo *et al.* 2023). Human actions associated with pesticide use, including application frequency, pesticide rate, and timing, also greatly influence the fate of pesticides in the soil (Commelin *et al.* 2022).

Figure 2 summarizes major factors affecting the fate and degradation patterns of pesticides in the soil.

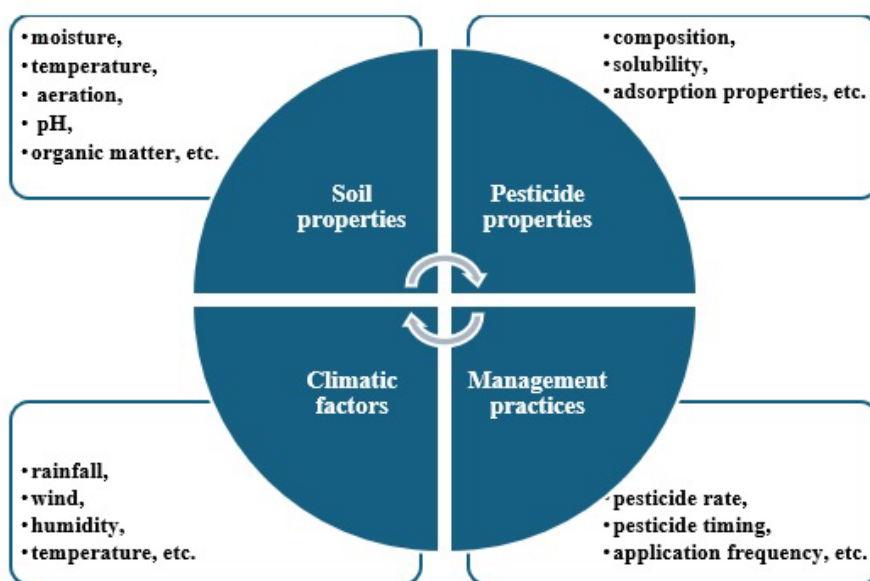


Figure 2. Major factors affecting the fate of pesticides in the soil

Existing strategies and future perspectives on pesticide microbial biodegradation

Since microbes are the key degraders of pesticides in contaminated areas, it is vital to understand the microbial processes occurring at each site to determine the best strategy for the remediation of soils polluted by pesticides. Pesticide microbial degradation may occur via three strategies: natural attenuation, biostimulation, and bioaugmentation. Natural attenuation refers to processes that diminish pesticide toxicity without human intervention; biostimulation is the practice of supplying nutrients to the affected site to boost microbial degradation efficiency, whereas bioaugmentation means adding specific microorganisms capable of breaking down pesticides. Presently, there is a deficiency of tools designed to support practitioners in selecting the optimal remediation strategy. There is also a lack of a holistic understanding of the complex interactions between microbial taxonomy, function and environmental variables in each specific habitat. Therefore, creating a predictive approach based on genomic analysis of soil microbial communities and an understanding of microbial composition and their degradation potential is vital for the efficient remediation of pesticide-contaminated soils. In this context, metagenomic approaches present a powerful framework for assessing the properties of both individual microbes and microbial communities as a whole, along with examining their interactions with pesticide compounds. Recent progress in genomics, transcriptomics,

proteomics, and metabolomics has considerably broadened the understanding of the molecular underpinnings of pesticide residue biotransformation. These advancements offer new possibilities for creating genetically modified microorganisms that possess improved pesticide biotransformation abilities (Basapuram *et al.* 2025).

Chemical degradation of pesticides in the soil

The breakdown of pesticides in the natural environment can also be accomplished through chemical degradation. Chemical degradation refers to the breakdown of pesticides via hydrolysis, oxidation, reduction, or other chemical reactions that are independent of living organisms (Teja and Kumar 2025). Soil pH, temperature, moisture, and adsorption properties, together with the pesticide's chemical and physical properties, govern the chemical reactions that occur and their rate (Navarro *et al.* 2007).

Hydrolysis

One of the most common pesticide chemical degradation reactions in the soil is hydrolysis. It refers to any chemical reaction in which a molecule of water interacts with one or more chemical bonds within the pesticide structure (Meng *et al.* 2022). Although hydrolysis can take place in any area of the environment where the pesticide molecule interacts with water, such as the soil surface and root zone, it is particularly significant in humid soils and aquatic habitats (Katagi 2002).

Pesticides that contain hydrolysable functional groups, such as ester, amide, carbonyl, and carboxyl groups, are particularly susceptible to hydrolysis, especially under alkaline conditions (Dyguda-Kazimierowicz *et al.* 2014). Aside from pH, the key factors influencing pesticide degradation through hydrolysis include the organic matter content and clay content with a significant surface area, both of which facilitate the hydrolytic breakdown of pesticides (Acharya *et al.* 2025). Elevated soil temperatures also accelerate the hydrolysis reaction (Shi *et al.* 2023), resulting in faster hydrolysis near the soil surface, where water is warmer. In contrast, in the deeper soil layers, hydrolysis reactions proceed much more slowly (Hugo *et al.* 2014).

Oxidation and reduction

Crucial chemical pathways for the breakdown of pesticides encompass oxidation and reduction reactions. Oxidative transformations are typically the most commonly observed pathways for

the chemical breakdown of pesticides in all environments, except for those that are the most oxygen-deprived. Molecular oxygen, along with its more reactive forms such as superoxide anion radicals and hydroxyl radicals, can interact with numerous pesticides, leading to the formation of various products that typically exhibit lower toxicity than the original pesticide substance (Dagneu *et al.* 2025).

Specific oxidant reactions of significance in pesticide degradation are ring hydroxylation, side-chain oxidation, and sulfoxidation. Ring hydroxylation occurs on aromatic rings in pesticides when hydroxyl radicals ($\cdot\text{OH}$) interact with the aromatic structure, resulting in the formation of hydroxylated intermediates. An example is the transformation of the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) into 2,4-dichlorophenol (2,4-DCP). In this reaction, the $\cdot\text{OH}$ attacks the C1-O bond of the aromatic ring, leading to the release of an alkoxy radical, which results in the formation of 2,4-DCP and glycolic acid (Xiong *et al.* 2025).

Side-chain oxidations refer to the oxidation of the alkyl side chains connected to the benzene rings, which are basic structural components in a wide range of pesticides. Consequently, the side chains connected to the benzene ring are removed, typically occurring before the benzene ring undergoes degradation. Side-chain oxidations are often mediated by oxidizing agents like $\cdot\text{OH}$. An example of this is the degradation of 4-(4-Chloro-2-methylphenoxy) butanoic acid (MCPB) into 2-methyl-4-chlorophenoxyacetic acid (MCPA) (Ren *et al.* 2012).

Sulfoxidation refers to the process of oxidizing thioethers (sulfides) into sulfoxides, which can subsequently be oxidized to form sulfones (Mączka *et al.* 2018). To illustrate, the highly toxic carbamate insecticide aldicarb can be oxidized via sulfoxidation to form aldicarb sulfoxide, which can then be further oxidized to aldicarb sulfone (Malhotra *et al.* 2021). In the same manner, the organophosphate fenamiphos can be converted to fenamiphos sulfoxide and eventually to fenamiphos sulfone (Cáceres *et al.* 2008).

Although oxidative transformations are generally the most commonly recognized routes for the chemical breakdown of pesticides, these compounds can also be transformed into smaller and often less toxic substances through reduction reactions. Specific reduction reactions of significance in pesticide chemical transformation are reductive dehalogenation, reduction of a nitro group (NO_2) to an amino group (NH_2), and reduction of a sulfoxide (Chung 2000).

Reductive halogenation refers to the process in which one ring-substituted halogen is replaced by a hydrogen atom. A wide variety of compounds, including halogen-containing pesticides, can be degraded via the reductive removal of halogen atoms, such as chlorine and fluorine. An example is the transformation of DDT (2,2-bis-p-chlorophenyl-1,1,1-trichloroethane) into DDD (2,2-bis-p-chlorophenyl-1,1,1-dichloroethane) (Gryglewicz and Piechocki 2010).

Pesticide compounds that contain a nitro group (NO_2) can be reduced to the corresponding amines, which is a common occurrence in flooded soil. An illustration of this is the conversion of the organophosphate pesticides, specifically parathion and methyl parathion, into their respective amino derivatives (Yang *et al.* 2007). It has also been observed that the nitro group of pentachloronitrobenzene can be reduced to an amino group, forming pentachloroaniline (Okutman Tas and Pavlostathis 2010).

Pesticides containing the sulfinyl functional group (sulfoxide) can be reduced back to sulfide in flooded soils under anaerobic conditions. An example is the transformation of phorate sulfoxide to phorate (Singh *et al.* 2003).

Photodegradation of pesticides on plant and soil surfaces

Photodegradation of pesticides by sunlight radiation might be regarded as one of the most important pathways for the breakdown of pesticides after their release into the environment. The phenomenon of pesticide photodegradation occurs via two pathways: direct photodegradation and indirect photodegradation. Direct photodegradation refers to the conversion of pesticide compounds that occurs due to the direct absorption of a solar photon (Cui *et al.* 2021). Accordingly, direct photodegradation can be an important degradation pathway for pesticide ingredients that have the ability to absorb solar radiation that reaches the surface of the Earth. The pesticide photolysis-relevant wavelength range of sunlight reaching Earth's surface is very often reported as 290–800 nm (Fan *et al.* 2023).

The extent of pesticide degradation via direct sunlight degradation is highly dependent on the UV-visible (UV-vis) absorption profiles of the pesticide, the surrounding medium, and the solar photon radiation to which the pesticide compound is exposed (Mitrović *et al.* 2025). Photocatalytic degradation reactions may involve isomerization, substitution, or oxidation, largely influenced by the pesticide's chemical structure, environmental conditions, and reactants. For instance, when exposed to light, pyrethroids may experience isomerization, which is then followed by changes such as the formation of 3,3-dimethacrylate, the cleavage of ester bonds resulting in carboxylic acid derivatives, as well as reductive decarboxylation and dehalogenation. These photochemical reactions play a crucial role in the degradation of pyrethroids, thereby diminishing their toxicity and adverse effects on the ecosystem (Sibanda *et al.* 2011).

Indirect photodegradation occurs when pesticides interact with short-lived reactive intermediates like hydroxyl radicals ($\cdot\text{OH}$), the excited triplet states of dissolved organic matter ($^3\text{DOM}^*$), and singlet oxygen ($^1\text{O}_2$) (Remucal 2014). These intermediates are formed

photochemically through the interaction of UV light with various environmental components. For example, nitrate photolysis produces $\cdot\text{OH}$ that can react with pesticides on the soil's surface (Bu *et al.* 2021). On the other hand, the absorption of light by dissolved organic matter leads to the generation of $^3\text{DOM}^*$, which can act as a precursor for $^1\text{O}_2$. Both $^3\text{DOM}^*$ and $^1\text{O}_2$ can interact with pesticides, resulting in a range of transformation products. For example, $^3\text{DOM}^*$ and $^1\text{O}_2$ are critical for the indirect photodegradation of the insecticide imidacloprid (Borsuah *et al.* 2024), while $\cdot\text{OH}$ contributes to the indirect photodegradation of the organochlorine acaricide dicofol (Ren *et al.* 2011).

Sustainable management of pesticides in agriculture

Pesticides are widely used in agriculture as plant protection agents; however, their use raises concerns regarding potential health risks for human health and the environment. Therefore, it is imperative to use advanced approaches aimed at minimizing pesticide contamination in the soil and promoting sustainable agricultural practices, such as crop rotation, intercropping, organic farming, habitat management, and regular monitoring of pest populations. These approaches not only reduce soil contamination from pesticides but also enhance sustainable agricultural productivity and ecosystem stability (Al-Ahmadi and Subr 2025; Topa *et al.* 2025). Pests and pathogens often form host-specific associations with particular crops. In this context, growing the same crop in the same field year after year enables these harmful organisms to create a permanent presence in the soil, which can escalate to damaging population levels. This happens as pests generally find it easier to reproduce when their preferred food source is available for a prolonged time. Furthermore, agricultural monoculture leads to nutrient depletion in the soil and disturbs the natural soil balance. Crop rotation and intercropping can assist in breaking pest cycles and reducing pest population buildup in agricultural fields while simultaneously allowing nutrients in the soil to regenerate naturally. The need for the use of pesticides under these conditions is considerably lower (Liang *et al.* 2025).

Organic farming also avoids using synthetically produced pesticides, instead focusing on natural methods for pest, disease, and weed management, directly contributing to reducing soil pollution. Pesticides utilized in organic farming are usually derived from natural sources and are typically less harmful than their synthetic counterparts used in conventional farming (Benbrook *et al.* 2021).

Habitat management is defined as the practice of creating habitat diversity and safe spaces for beneficial organisms, enhancing natural pest control and reducing reliance on pesticides. In the realm of habitat management, cover cropping and the development of buffer strips serve as

essential tools to bolster populations of beneficial insects and microorganisms. Regular monitoring of pest populations is yet another approach that aids in minimizing the need for chemical pesticides. It can assist in identifying the presence of pests and evaluating the need for pest control measures, thereby aiding in decision-making and optimizing pesticide use (Pearsons and Tooker 2017).

Optimizing application methods, timing, and rates can also help reduce pesticide use, thereby minimizing environmental contamination and lowering the risks associated with pesticide exposure. Key strategies for reducing pesticide use include precision application, the use of both reduced-risk pesticides with lower toxicity to non-target organisms and pesticides derived from natural sources, as well as proper pesticide storage and disposal (Leskovac and Petrović 2023).

Conclusions

The biotransformation of pesticides by microorganisms represents a pivotal process governing the fate of these chemicals in the environment. The key pathways responsible for pesticide biotransformation by soil microbes are microbial degradation, co-metabolism, and mineralization. Among these, microbial biodegradation is seen as the key mechanism for pesticide biotransformation in soil.

Plants generally have a much lower capacity to degrade pesticide components than microorganisms; thus, their primary strategy is to detoxify and sequester pesticides within their cells instead of achieving full mineralization. However, the intricate complexity of these biotransformation processes points to the requirement for detailed scientific exploration and stringent regulatory oversight.

The degradation of pesticides in the natural environment can also be accomplished through chemical degradation and photodegradation. Crucial chemical pathways involved in pesticide degradation include hydrolysis, along with oxidation and reduction reactions. Pesticide degradation by sunlight radiation occurs via two pathways: direct photodegradation and indirect photodegradation. Direct photodegradation refers to the process by which pesticide compounds are converted through the direct absorption of solar photons. In contrast, indirect photodegradation involves pesticides reacting with other photochemically generated species, leading to their degradation and the formation of various products.

In light of the escalating concerns regarding pesticide toxicity, it is important to implement sustainable management practices in the agricultural sector that focus on reducing pesticide pollution in the soil and fostering sustainable agriculture. The primary steps in fulfilling that

aim are to decrease pesticide use by maximizing treatment effectiveness, minimizing the number of interventions, and lowering application rates. Techniques such as crop rotation, intercropping, organic farming, habitat management, and consistent pest population monitoring also effectively reduce pesticide toxicity in the soil. These practices not only mitigate pesticide-related soil contamination but also improve sustainable agricultural output and ecosystem resilience. Additionally, advancements in biotechnology and genetic engineering are also important for enhancing the abilities of microorganisms to degrade pesticides. Such advancements provide innovative opportunities for the creation of genetically modified microorganisms with enhanced pesticide biotransformation capabilities.

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