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ENVIRONMENTAL FATE AND DEGRADATION KINETICS OF HERBICIDES IN SOIL–WATER SYSTEMS: GENOMIC INSIGHTS INTO MICROBIAL BIODEGRADATION

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ABSTRACT

Herbicides are extensively applied in modern agriculture to improve crop productivity and control weed infestations. However, their widespread use has resulted in increasing contamination of soil–water systems, posing significant environmental and ecological concerns. The persistence of herbicide residues can adversely affect non-target organisms, soil health, water quality, and ecosystem stability, necessitating a comprehensive understanding of their environmental fate and degradation mechanisms. This review aims to evaluate the environmental fate of herbicides in soil–water systems, examine degradation kinetics and influencing factors, and summarize recent genomic insights into microbial biodegradation and their implications for sustainable remediation.A comprehensive review of recent literature was conducted focusing on herbicide transport processes, degradation pathways, kinetic models, microbial degradation mechanisms, genomics, multi-omics technologies, and genomics-guided bioremediation strategies. Herbicide fate is controlled by adsorption, desorption, leaching, runoff, and degradation processes. Both abiotic and biotic mechanisms contribute to herbicide transformation, while degradation kinetics are commonly described using first-order, pseudo-first-order, and Michaelis–Menten models. Advances in genomics, metagenomics, transcriptomics, proteomics, and metabolomics have facilitated the identification of degradative microorganisms, functional genes, enzymes, and metabolic pathways. Emerging bioremediation approaches, including bioaugmentation, biostimulation, engineered microbial consortia, and synthetic biology-based interventions, have demonstrated significant potential for enhancing herbicide removal. Integrating degradation kinetics with genomics and multi-omics technologies offers new opportunities for improving herbicide risk assessment, remediation efficiency, and sustainable agricultural management while reducing environmental contamination.

KEYWORDS: Herbicides, Environmental fate, Degradation kinetics, Microbial biodegradation, Genomics-guided bioremediation.

1. INTRODUCTION

Herbicides have been widely applied in current agriculture to increase productivity and minimize weed pressure. The application of herbicides has greatly improved the efficiency of agriculture; yet worries have been raised about the environmental persistence of herbicide residues. A number of herbicides, especially triazine and sulfonylurea herbicides, are persistent in the environment and can pose dangers to non-target species, biodiversity, and ecosystem processes, indicating the requirement for detailed research into herbicide environmental behavior and degradation (Ahmad et al., 2023). Herbicides end up in the soil and water environment via several mechanisms including runoff, leaching, spray drift, and improper disposal. The behavior and persistence of herbicides in the environment are related to several physicochemical factors, such as water solubility, absorption capacity, and degradation rate. The presence of herbicide residues in soil-water ecosystems will change microbial populations, pollute underground water resources, and harm aquatic ecosystems, highlighting the urgency to control environmental contamination by herbicides (Bhende & Dafale, 2023). Degradation of herbicides is vital for assessing their environmental persistency and ecological hazards as well as their potential remediation. Information on degradation kinetics and metabolite toxicity obtained during studies provides the key to proper assessment of risk and application of sustainable methods of combating herbicide contamination (Basapuram et al., 2025). One of the most efficient and eco-friendly ways of herbicide elimination is biodegradation by microbial organisms. Many bacteria and fungi have special enzymatic mechanisms capable of breaking down different herbicides and transforming them into substances with lower toxicity or completely mineralizing them. The adaptability of microorganisms present in the environment helps to improve the efficiency of herbicide degradation and facilitates natural attenuation and bioremediation process (Ahmad et al., 2022). In recent years, it has been proven that microbial organisms can effectively detoxify various types of herbicides such as carbendazim and sulfosulfuron and contribute to soil recovery and ecological sustainability (Arya et al., 2025). Research into herbicide degradation has significantly increased due to studies focused on pesticide-degrading organisms and their applications in the environment (Bhatt et al., 2019). The recent developments in genomics, metagenomics, and environmental biotechnology have greatly contributed to our knowledge of the process of herbicide biodegradation. The use of new methods in herbicide degradation includes the biomass-based remediation technologies that have increased the possibilities of herbicide elimination sustainably (Al Salti et al., 2026). This review aims to analyze the environmental fate of herbicides in the soil-water system, identify degradation kinetics and influencing factors, provide information on microbial biodegradation processes, and assess genomic information about degradative pathways.

2. Physicochemical Properties and Environmental Fate of Herbicides

2.1 Classification of Major Herbicides

Herbicides are categorized on the basis of chemical structure, mechanism of actions, and weed targets. Some important classes are triazines, chloroacetanilides, phenoxy acids, sulfonylureas, and aryloxyphenoxypropionates. There are significant differences among these chemicals in terms of their environmental properties, toxicities, and biodegradation processes. Acetochlor is one example of a chloroacetanilide herbicide, which is used extensively in pre-emergent weed control but is known to cause environmental pollution owing to its persistence and mobility in agricultural soils (Chen et al., 2024).

2.2 Physicochemical Properties Governing Environmental Behavior

Environmental fate of herbicides depends on their physicochemical properties like water solubility, vapor pressure, adsorption coefficient (Koc), octanol-water partition coefficient (Kow), and chemical stability. Water-soluble herbicides generally exhibit higher mobility through soil layers compared to herbicides with strong adsorption capabilities. The former easily leaches through soil, while the latter get retained in the soil matrix. This ultimately defines the fate of the herbicide in the environment following their application in agriculture (Bhende et al., 2022).

2.3 Adsorption and Desorption Processes

Adsorption and desorption are two vital procedures involved in controlling herbicide retention and mobility within the soil. Adsorption refers to the process where the molecules attach themselves to soil particles, organic matter, or clay minerals; as a result, there is a decrease in their bioavailability. On the other hand, desorption describes the process where the bonded herbicides break off from the soil and dissolve in the soil solution. Various factors that control both adsorption and desorption are the soil properties such as organic carbon levels, soil texture, water content, and pH (Chavez Rodriguez et al., 2020).

2.4 Leaching, Runoff, and Transport in Soil–Water Systems

However, once used, herbicides can be transferred beyond their intended locations via processes such as leaching, surface runoff, and sub-surface transfer. Leaching contributes to the process of transferring herbicides downwards into the groundwater table, while surface runoff results in the transfer of herbicides to surface water during periods of precipitation or irrigation. This is an important issue due to its significance in environmental pollution and toxicity effects on the ecosystem. Transport of herbicides occurs depending on the climate, soil type, and chemical nature (Chen et al., 2024).

Figure 1. Major Transport Pathways of Herbicides in Soil–Water Systems

Figure 1 shows the main ways through which herbicides move once they are applied to soils in agriculture. The modes include surface runoff, whereby herbicides end up being washed off to bodies of water; leaching into groundwater; adsorption in the soil matrix; and finally vaporization to the air.

2.5 Factors Influencing Herbicide Persistence

The persistency of herbicides is dependent on both physical and biological elements such as temperature, water content of soil, pH value, nutrients present, as well as biological activity such as that of microorganisms. Further, the chemical composition of the herbicide also plays an influential role in its persistence, as certain compounds make these products vulnerable to biological breakdown. Fungi and bacteria have been found to play significant roles in breaking down herbicides using various biological methods (Carles et al., 2021; Bokade et al., 2021).

3. Degradation Processes of Herbicides in Soil–Water Systems

3.1 Abiotic Degradation Mechanisms

A description of abiotic degradation entails an explanation of how herbicides get broken down by non-living entities in the environment, such as soil and water bodies. This process plays a crucial role in determining the persistence, mobility, and toxicity of the herbicides. Various environmental conditions including light exposure, temperature, humidity, and oxidizing potential will dictate the rate and extent of this breakdown process. In some instances, abiotic processes not only eliminate herbicides from the ecosystem, but they create intermediary compounds with varied toxicology characteristics (Coleman et al., 2020).

3.1.1 Hydrolysis

Hydrolysis is one of the key mechanisms of abiotic decomposition where the molecules of the herbicides undergo reactions with water molecules leading to bond cleavage and formation of transformation products. The efficiency of hydrolysis is influenced by parameters like pH, temperature, moisture content in soils, and the structure of the molecule. Ester, amide, and carbamate groups are among those herbicide compounds that are highly susceptible to hydrolysis. It plays a significant role in herbicide dissipation in both aquatic and terrestrial ecosystems (Chowdhury et al., 2025).

3.1.2 Photodegradation

Photodegradation is the breaking down of herbicides due to the action of light energy from the sun. It can be direct photolysis or the indirect production of active oxygen species that catalyze the reactions of the herbicides. This is highly significant in water and on topsoil, where penetration by sunlight is relatively higher. Variables affecting photodegradation include light intensity, wavelength, presence of dissolved organic material, and the molecular structure of the herbicides themselves.

3.1.3 Oxidation–Reduction Reactions

Oxidation-reduction reactions have an important role in the breakdown of herbicides via electron transfer. This process is regulated by soil redox conditions, oxygen supply, microbial action, and metal ions. An oxidative reaction usually leads to the disintegration of complicated substances into smaller ones, while a reductive reaction causes a change in the nature of functional groups. This process is especially important in marshy environments, where variable redox states affect herbicide dynamics.

3.2 Biotic Degradation Mechanisms

Biological degradation refers to the decomposition of herbicides by living things, specifically microorganisms within soil and water environments. Microorganisms such as bacteria and fungi have various metabolic functions that allow them to modify or break down herbicides. Biodegradation is seen as the most efficient natural attenuation technique since it results in high levels of detoxification and degradation of herbicides. The effectiveness of biodegradation is influenced by microbial diversity, environment, nutrients, and the chemical structure of herbicides (Dhakal et al., 2025).

3.2.1 Microbial Metabolism

Herbicide biodegradation in nature can be attributed to microbial metabolism. The microorganisms use the herbicides as their source of carbon, nitrogen, phosphorus, or energy in the process where herbicides are converted using metabolic pathways like hydrolysis, oxidation, dehalogenation, and cleavage. It is easier to convert complex chemicals to simple chemicals that are less toxic through the above processes. There has been an increase in knowledge about microbial metabolism of pesticides and adaptation to polluted environments due to advancements in microbial ecology and molecular biology (Ghorab et al., 2026).

3.2.2 Co-metabolism

Co-metabolism refers to the degradation of herbicides by microbes that take place unintentionally when the microbes break down other organic substances. This is achieved by the use of general-purpose enzymes that result from the growth processes of the microorganisms involved, which act on herbicides without necessarily providing a metabolic advantage to the microbe itself. The importance of co-metabolism lies in the ability of this process to enable the degradation of herbicides that are unable to sustain the growth of any organisms on their own (Corredor et al., 2024).

3.2.3 Mineralization and Detoxification

Herbicide mineralization is the process of total decomposition of herbicides to non-toxic elements like carbon dioxide, water, and mineral nutrients. Herbicide detoxification, on the other hand, is the process of breaking down toxic substances to metabolically active but less toxic substances. Enzymes and metabolic systems within microbes play a major role in facilitating both processes. Studies using multi-omics techniques have shown how microbe physiology and enzymatic reactions are involved in herbicide degradation processes (Gao et al., 2024).

Table 1. Comparison of Abiotic and Biotic Herbicide Degradation Processes in Soil–Water Systems

Degradation Type	Mechanism	Key Factors	End Products	Reference
Abiotic	Hydrolysis	pH, temperature, moisture	Transformation products	Chowdhury et al. (2025)
Abiotic	Photodegradation	Solar radiation, wavelength	Photoproducts	Coleman et al. (2020)
Abiotic	Oxidation–Reduction	Redox potential, oxygen	Oxidized/reduced metabolites	Dhakal et al. (2025)
Biotic	Microbial Metabolism	Microbial activity, nutrients	Simpler metabolites	Ghorab et al. (2026)
Biotic	Co-metabolism	Co-substrate availability	Intermediate products	Corredor et al. (2024)
Biotic	Mineralization	Enzyme activity, environmental conditions	CO_2, H_2O, minerals	Gao et al. (2024)

Table 1 provides an overview of the different biotic and abiotic processes associated with the degradation of herbicides in the soil-water environment. Abiotic processes are hydrolysis, photolysis, and oxidation-reduction reactions while biotic processes are microbial degradation, co-metabolism, and mineralization.

4. Degradation Kinetics of Herbicides

4.1 Fundamentals of Herbicide Degradation Kinetics

The kinetic study of herbicide degradation refers to the process by which herbicides break down or decompose in the environment. It is important to have such knowledge about persistence, half-life, exposure, and risk. Kinetic research can give us quantitative data regarding herbicide degradation rates depending on different conditions of the environment. Degradation kinetics can be used to form certain management approaches and reduce herbicide concentrations within the environment (Havens et al., 2017).

4.2 Kinetic Models Applied in Environmental Studies

Kinetic models based on mathematical formulations have been frequently applied to characterize degradation kinetics and to calculate degradation rates for herbicides in different environmental matrices. Such models facilitate the comprehension of interactions between contaminants, microorganisms, and environmental components. The choice of kinetic model is largely determined by the mode of degradation and complexity of the system studied. The relevance of selecting an appropriate model cannot be underestimated because it enables an accurate prediction of herbicide persistence and assessment of remediation efficiency (Iqbal et al., 2026).

4.2.1 First-Order Kinetics

First-order kinetics represents the most widely used kinetic model when investigating herbicide degradation processes. The use of this model is based on the assumption that the rate of degradation is linearly related to the amount of herbicide in the environment. Hence, degradation takes place quickly when high concentrations of herbicides are observed and becomes slower when lower concentrations occur. First-order kinetics are considered especially important for predicting the half-lives of herbicides and their environmental persistence in nature (Hussain et al., 2016).

4.2.2 Pseudo-First-Order Kinetics

The pseudo-first-order rate expression can be used when there is one excess reactant, such as water, oxygen, or microbial cofactors, during the degrading process of the compound. In such cases, despite having several influences on the degradation process, the process seems to operate based on the principles of first-order kinetics due to having an excess of one compound. The pseudo-first-order analysis can be useful for analyzing the degradation processes of herbicides in soil and water under constant environmental conditions.

4.2.3 Michaelis–Menten and Monod Models

The Michaelis–Menten and Monod models are widely used to model enzyme reactions and microbial degradation mechanisms. These models take into consideration substrate consumption, growth of microorganisms, and enzyme reaction rate, hence their utility in biodegradation studies. They differ from first-order kinetics because they incorporate saturation phenomena that arise when the concentration of contaminants is high. These models offer a more accurate description of biological reactions and enable assessment of the efficiency of microbial action on herbicide biodegradation and bioremediation (Li et al., 2020).

4.3 Environmental Factors Affecting Degradation Rates

Environmental conditions play a key role in herbicide degradation kinetics because of their effects on the stability of herbicides, microbial life, and bioavailability. Differences in temperature, moisture, pH, nutrition content, and contaminant levels can have an impact on the rate of degradation. All these elements have complex interactions that make the behavior of herbicides site-specific in many cases. Knowledge of environmental control of degradation kinetics helps to predict persistence effectively (Kumar, 2023).

4.3.1 Temperature

Temperature is one of the major determinants that affect the rate at which herbicides degrade. High temperatures increase the rate of chemical reactions and metabolic activities of microbes, thus speeding up degradation. Low temperatures, on the other hand, cause decreased enzyme activity and slow down microbial metabolism, hence degradation processes. This means that changes in seasonal temperatures may play a role in how long herbicides remain active in the soil and water environment.

4.3.2 Soil Moisture

Water content in the soil can have a huge impact on the degradation process of herbicides due to its effect on microbial activity, chemical movement, and oxygen. If there is adequate moisture in the soil, then microbial growth will be favorable, and this will result in effective movement of soluble herbicides to microbes that degrade them. If the soil lacks moisture, then microbial activity and the degradation process will not be favorable.

4.3.3 pH and Nutrient Availability

Soil pH plays a vital role in the stability, solubility, adsorption properties, and microbial communities. Some herbicides are degraded faster under acid soil pH values, but there are other herbicides that undergo faster degradation under neutral or basic soil pH values. Nutrients also play a key role in the rate of degradation because they promote the growth and functioning of microorganisms involved in this process.

4.3.4 Herbicide Concentration and Bioavailability

Degradation efficiency is directly influenced by the concentration and bioavailability of herbicides. While high concentration will impair the performance of microorganisms or cause substrate inhibition, a low concentration may fail to sustain microorganisms in their degradation process. The bioavailability of herbicides refers to the amount available to be used by the microorganisms. Absorption on the soil surface decreases its bioavailability and, therefore, reduces its rate of degradation. Interactions between microorganisms improve the availability of the herbicide, resulting in improved degradation efficiency (Giwa et al., 2025).

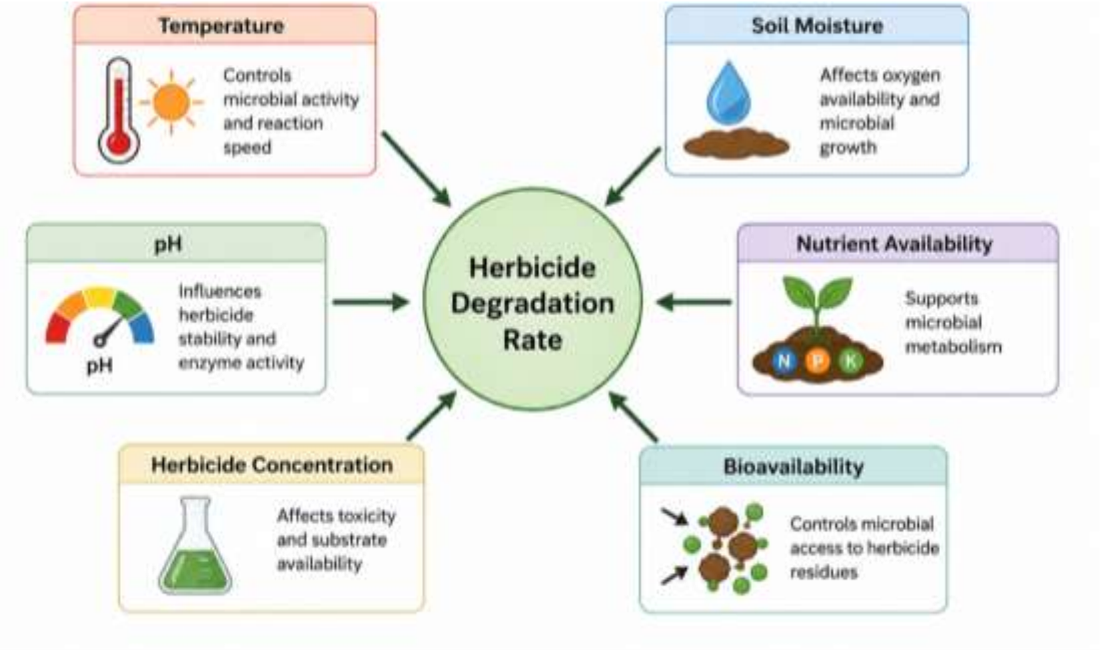

Figure 2. Environmental Factors Affecting Herbicide Degradation Rates

Figure 2 shows the important environmental conditions that affect herbicide degradation in the soil-water environment. The conditions including temperature, soil moisture, pH, nutrients, herbicide concentration, and bioavailability control microbial and enzymatic activities as well as herbicide availability and hence affect the efficiency of degradation, persistence, and environmental fate of herbicides.

5. Microbial Biodegradation of Herbicides

5.1 Diversity of Herbicide-Degrading Microorganisms

Biodegradation by microbes is one of the major pathways in the degradation of herbicides in a polluted environment. There are various types of bacteria, fungi, and microbes that contain enzymes that can degrade herbicides and turn them into less harmful chemicals. These microbes have developed survival techniques that help them live in such environments and consume foreign substances as sources of nutrition or energy. Diversity in the microbes involved in biodegradation helps keep the ecosystem healthy and assists in the natural degradation of herbicides in the environment (Lin et al., 2020).

5.1.1 Bacterial Degraders

Bacteria have been identified as one of the most efficient microorganisms for degradation of herbicides because of their metabolic diversity and quick reproduction rate. Genus Pseudomonas, Bacillus, Ochrobactrum, Arthrobacter, and Sphingomonas have been shown to be capable of degrading various types of herbicides and xenobiotics. The degradation process in bacteria involves catabolic pathways, which are coded using degradative genes. Development in genomic research has also enabled more insight into bacterial adaptations, chemotaxis, and metabolism concerning pesticide degradation (Nayak et al., 2019).

Table 2. Major Bacterial Genera Involved in Herbicide Biodegradation

Bacterial Genus	Herbicides Degraded	Major Mechanism	Reference
Pseudomonas	Sulfonylureas, Neonicotinoids	Oxidation, Hydrolysis	Li et al. (2020)
Ochrobactrum	Organophosphates	Hydrolysis	Nayak et al. (2019)
Bacillus	Various herbicides	Enzymatic degradation	Lin et al. (2020)
Arthrobacter	Triazines	Mineralization	Singh & Singh (2016)
Sphingomonas	Aromatic herbicides	Ring cleavage	Mohapatra & Phale (2021)

Table 2 highlights various bacterial genera that have been found to break down herbicides, together with the herbicides that they break down, as well as the mechanisms by which they do so. The different bacterial genera mentioned above have a variety of metabolic abilities which help them break down herbicides using biological mechanisms like oxidation, hydrolysis, mineralization, and ring cleavage.

5.1.2 Fungal Degraders

The presence of fungi helps in herbicide biodegradation due to their ability to secrete extracellular enzymes that can help degrade various organic molecules. The wide network of hyphae formed by fungi makes it possible for them to inhabit polluted environments and utilize pollutants not accessible by other microorganisms. Various fungal species show a high level of substrate tolerance and are able to metabolize herbicides of different structures. With oxidative and hydrolytic actions, fungi become crucial players in lowering environmental toxicity.

5.2 Metabolic Pathways of Herbicide Biodegradation

Herbicide biodegradation is achieved through various metabolic mechanisms that include hydrolytic, oxidative, reductive, dehalogenative, and cleavage reaction types. Through such metabolism, the complex herbicides are degraded to intermediates before further transformation to simple forms, which are finally assimilated into biological cycles. The variety of pathways followed during herbicide metabolism shows the structural variability of the compounds, as well as microbial adaptability. Various works investigating xenobiotic degradation have demonstrated wide metabolic diversity and identified the need for pathway understanding for bioremediation purposes (Mohapatra & Phale, 2021).

5.3 Key Enzymes Involved in Herbicide Transformation

The process of microbial degradation of herbicides involves enzymes which promote vital transformation reactions. Examples of such enzymes include hydrolases, oxygenases, dehydrogenases, reductases, and dehalogenases. The action of these enzymes includes processes such as bond breakage, oxidation, and detoxification to allow microbes to use herbicides as sources of nutrition. In the case of neonicotinoids, research has shown the existence of certain enzymes that help in the degradation process. Enzymes are important when creating remediation processes using enzymes (Pang et al., 2020a).

5.4 Microbial Consortia and Community Interactions

It is common for microbial consortia to degrade contaminants more efficiently than individual strains since there will be complementary metabolism carried out by various microorganisms. The interaction between bacteria and fungi allows the utilization of substrates, detoxification, and mineralization of the herbicides. The degradation of complex compounds requires cooperation among the microbes to allow for a series of metabolic processes to occur. The research on the degradation of imidacloprid shows that microbial interactions are essential in the rate and process of the transformation (Pang et al., 2020b).

6. Genomic Insights into Herbicide Biodegradation

6.1 Whole-Genome Sequencing of Herbicide-Degrading Microorganisms

Whole genome sequencing techniques have changed the course of investigation into biodegradation processes associated with herbicides. The genetic makeup of microbial degraders can be investigated using such genomics techniques. This allows for a more accurate analysis of how herbicides are metabolized. Novel mechanisms of degradation may also be discovered through such an analysis, thus giving insight into the adaptive capabilities of microbes exposed to such toxins. Genome-based research has become important in developing remediation techniques for herbicide-contaminated habitats (Singh & Singh, 2016).

6.2 Functional Genes Associated with Herbicide Degradation

Degradation of herbicides depends on various functional genes that encode the enzymes involved in hydrolytic, oxidoreductive, and cyclizing processes. Recent developments in the field of molecular biology and genomics allowed the discovery of many different genes involved in the process of degradation through the transformation of xenobiotics. Such genes are known to control the efficiency and specificity of the degradation processes. Knowledge of their structure, activity, and distribution helps to understand the mechanism of biodegradation and create gene-based remediation strategies (Shah et al., 2024).

6.3 Catabolic Gene Clusters and Regulatory Networks

The catabolic genes associated with herbicide degradation tend to be clustered as gene clusters for optimal gene expression. The regulatory networks are responsible for regulating the expression of these genes in response to changes in the environment. This regulation results in the increased adaptation capability of the microorganisms, allowing them to degrade herbicides more efficiently despite different environments. Advances in genome-wide analysis techniques such as genomics and transcriptomics along with computational modeling have considerably enhanced knowledge of these regulatory processes (Raj et al., 2026).

6.4 Horizontal Gene Transfer and Adaptive Evolution

Horizontal gene transfer is essential for the evolution of herbicide-degrading microorganisms since it allows for rapid spreading of degradative genes among different microbes. Mobilization of genetic material through plasmids, transposons, and integrons is important in the exchange of genes associated with degradation ability and adaptation of microbes in contaminated environment. Such evolutionary mechanisms result in creation of efficient degradative communities. Also, microbial metabolites may affect the expression of genes, pollutant availability and interaction among different microbial communities, making biodegradation more effective (Setiawardani et al., 2025). Studies of microbial communities revealed that horizontal gene transfer between different populations of bacteria along with cooperation were important factors in successful herbicide bioremediation (Pileggi et al., 2020).

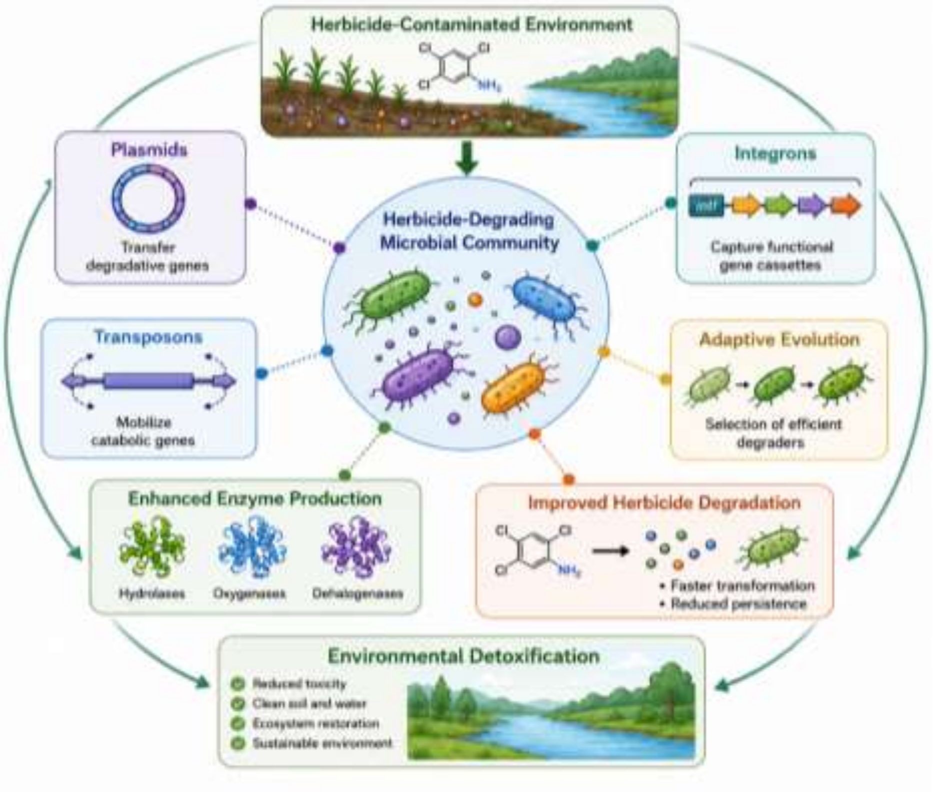

Figure 3. Role of Horizontal Gene Transfer in Herbicide Biodegradation

Figure 3 highlights the significance of horizontal gene transfer in improving the degradation of herbicides by microbes. Plasmids, transposons, and integrons serve as genetic material that contributes to the spread of such genes within microbial communities. Such activities ensure evolutionary adaptation, enhanced enzyme efficiency, rapid degradation of the herbicides, and detoxification of the environment.

7. Omics Approaches for Investigating Herbicide Degradation

7.1 Metagenomics

The metagenomics technique is now being used as an effective way to study the biodegradation of herbicides because it allows for the study of complete microbial populations without the necessity of cultivating them. The technique allows scientists to detect both degradative microorganisms and genes responsible for metabolism in the environment. Metagenomics helps to get important information about microbial populations and their role in the process of biodegradation. This data can be applied to develop more efficient bioremediation methods for contaminated soil and water (Souza et al., 2025).

7.2 Transcriptomics

Transcriptomics studies gene expression under certain environmental stimuli, giving an idea of the biological activities responsible for herbicide decomposition. Messenger RNA profiles allow scientists to study which genes are activated after herbicide exposure and understand how microorganisms react to stress due to contaminants. It allows better comprehension of the regulatory systems managing the biodegradation process and adaptation of microorganisms. Transcriptomic studies have gained greater prominence as they allow better insight into dynamic processes that control the efficiency of microbial degradation (Wageed et al., 2025).

7.3 Proteomics

The field of proteomics involves studying large numbers of proteins produced by microorganisms for herbicide degradation. Because the proteins themselves carry out the reactions that result in the breakdown of contaminants, proteomic studies have great potential in providing insights into enzymes involved in contaminant degradation. Proteomics allows for the analysis of degradative proteins, stress responses, and adaptations in response to exposure to contaminants. Protein profiling is an important component of understanding biodegradation processes and developing effective microbial systems (Uniyal et al., 2021).

7.4 Metabolomics

Metabolomics involves the study of all the metabolites generated from microbial degradation. Through metabolomics, intermediates and end products generated in the process of herbicide metabolism are studied in order to determine the mechanism of degradation. Metabolomics is beneficial in terms of determining the nature of reactions that take place in microbes, as well as how toxic certain metabolites may be. The use of metabolomics helps in studying how the metabolic fate of herbicides can be assessed (Singh & Saxena, 2022).

7.5 Integrated Multi-Omics Approaches

Multi-omics approaches integrate metagenomics, transcriptomics, proteomics, and metabolomics to offer an extensive insight into biodegradation mechanisms. The use of multi-omics is significant since it helps to unravel complicated interrelations of genetic capacity, expression of genes, proteins, and metabolism involved in the process of herbicide biodegradation. With such techniques, it becomes possible to find critical microbes, regulatory systems, and functional mechanisms associated with the biodegradation of contaminants. Recently, significant progress has been made due to developments in microbial engineering for the purpose (Srivastava et al., 2026).

Table 3. Applications of Omics Technologies in Herbicide Biodegradation

Omics Approach	Key Information	Application	Reference
Metagenomics	Microbial diversity and genes	Identifies degradative microbes and pathways	Souza et al. (2025)
Transcriptomics	Gene expression	Reveals microbial response to herbicides	Wageed et al. (2025)
Proteomics	Enzymes and proteins	Identifies degradative proteins	Uniyal et al. (2021)
Metabolomics	Metabolites	Tracks degradation products and pathways	Singh & Saxena (2022)
Multi-Omics	Integrated biological data	Comprehensive biodegradation analysis	Srivastava et al. (2026)

Table 3 highlights some important omic techniques utilized for biodegradation of herbicides. These omics tools offer additional information regarding microbial diversity, gene expressions, protein functions, and metabolic conversions. The combination of these techniques leads to better insights into biodegradation processes, which enable scientists to identify effective pathways for remediation.

8. Genomics-Guided Bioremediation Strategies

8.1 Bioaugmentation

Bioaugmentation refers to the addition of specially engineered microbes that are capable of breaking down herbicides into uncontaminated environments to promote their degradation faster. With genomics, it is now possible to identify efficient degrader organisms that have specific genes and metabolic pathways for effective catabolism. This helps understand the capabilities of such organisms with regard to adaptation, metabolism, and environment interaction, enabling researchers to select only the best candidates for bioaugmentation purposes. Moreover, genetic studies help track the performance of such introduced microbes in the environment. Therefore, genomics-based bioaugmentation appears to be a highly effective technique (Wei et al., 2025).

8.2 Biostimulation

The biostimulation technique stimulates the native microorganisms through alterations in the environmental conditions that promote herbicide degradation. The process is achieved by incorporating nutrient sources, organic matter, electron donors, or sorbing agents that aid microbial growth and increase bioavailability of the contaminants. Current literature shows that biochar incorporation significantly promotes the microbial community structure, sorption ability, and degradation capability of the herbicides in soil systems. Studies on genomic and microbial ecology have provided insights into the effects of biostimulation on stimulated microbial population in response to the altered environment. Therefore, biostimulation can be considered a sustainable method of remediation in herbicide-polluted ecosystems (Wu et al., 2025a).

8.3 Engineered Microbial Consortia

The concept of engineered microbial consortia involves the use of specifically chosen microbial species capable of complementing one another by undertaking different metabolic roles in the process of degrading herbicides. In contrast to the use of individual strains, microbial consortia benefit from synergies between their components, resulting in improved efficiency and wider substrate range in herbicide breakdown. Genomics can be used to screen and select for microbial strains that can interact beneficially in such microbial consortia. Thus, engineered microbial consortia are capable of overcoming metabolic constraints of individual strains and achieving complete mineralization of contaminants (Yang et al., 2025).

8.4 Synthetic Biology and CRISPR-Based Approaches

With the advent of synthetic biology and CRISPR technology, there have been advancements in enhancing microbial biodegradation properties. By genetically manipulating microorganisms, they are endowed with superior degradative enzymes, stress resistance, and efficient metabolic pathways. The application of genome editing using CRISPR helps modify the target functional genes responsible for transforming herbicides and enhance their ability to degrade such compounds. Additionally, synthetic biology makes it possible to design specific microorganisms that have the ability to degrade particular pollutants. Such advancements make it possible to develop future bioremediation approaches that address herbicide pollution problems (Wu et al., 2025b).

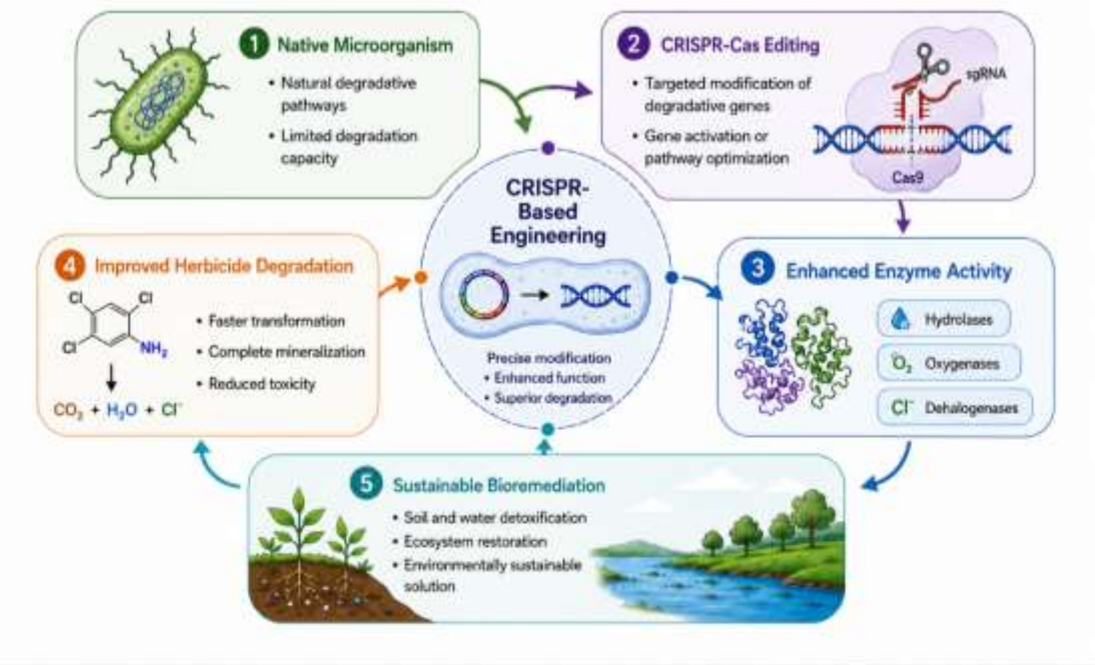

Figure 4. CRISPR-Based Enhancement of Herbicide Biodegradation

The role of CRISPR-Cas technology in the genetic modification of microbial metabolism for the enhancement of herbicide biodegradation is depicted in Figure 4. The manipulation of specific genes involved in degrading enzymes results in improved enzyme efficiency and metabolism; hence, herbicides are degraded quickly, and their mineralization occurs.

8.5 Challenges in Field-Scale Applications

Although substantial advances have been made in the application of genomic knowledge to bioremediation, some limitations hinder the successful use of bioremediation at a field scale. Variations within the environment, microbial competition, variability of contaminants, and changing climatic conditions can influence the survival and efficacy of added microorganisms. Moreover, the complexity of degradation processes and interaction between different contaminants could lower the efficacy of the process when applied under natural settings. However, the application of advanced analysis techniques like isotope fractionation and trace studies has enhanced the knowledge on in situ biodegradation processes and microbial activity (Wang et al., 2025).

9. Future Perspectives and Research Gaps

9.1 Limitations of Current Biodegradation Studies

Despite numerous achievements in the area of research on herbicide biodegradation, there still exist certain problems. The problem lies in the fact that most of the research is being performed in laboratory conditions where all the processes are easier to control. At the same time, the impact of soil characteristics, microorganisms, environment, and a combination of various pollutants can seriously affect the effectiveness of such processes. Another problem is associated with an analysis of individual contaminants instead of pollutant mixtures in general. It is necessary to know more about the long-term effects on ecology (Zabaloy et al., 2022).

9.2 Emerging Sequencing and Bioinformatics Technologies

The advances in next generation sequencing, metagenomics, metatranscriptomics, and bioinformatics are revolutionizing herbicide biodegradation studies. Modern techniques allow for the complete analysis of microbial communities, gene functions, metabolic pathways, and their interactions that take part in the degradation of contaminants. Next generation sequencing techniques provide unique opportunities for revealing new microbes with degradative capabilities and novel catabolic processes. At the same time, bioinformatics allows for integrating all biological data to facilitate its subsequent analysis. These technological advances will definitely contribute to a more rapid discovery of effective biodegradation systems (Zhou et al., 2018).

9.3 Artificial Intelligence and Predictive Modeling

Prediction of herbicide degradation and optimization of bioremediation strategies through machine learning techniques have received attention in recent times. Machine learning algorithms help in analyzing huge environmental data sets and discovering associations between the microorganisms and the environment, and their contribution to degradation. It helps in predicting degradation rates and identifying organisms that contribute to degradation. Integration of artificial intelligence in combination with omics-based data sets is anticipated to be beneficial for future decision-making processes in environmental management systems (Zhou et al., 2021).

9.4 Climate Change and Herbicide Fate

Climate change will play a very significant role in determining the degradation of herbicides in the environment. Climate-related changes in factors like temperature, precipitation, water availability, and other extreme weather conditions might have a considerable effect on the mobility of herbicides in the environment and their microbial degradation efficiency. Such modifications will cause a shift in the microbial communities and biochemical reactions taking place in the environment, which will eventually affect their degradation rate. In addition, climate-induced alterations in agricultural activities might enhance herbicide use and its presence in the environment (Zhang et al., 2020).

9.5 Toward Sustainable Herbicide Management

Sustainable management of herbicides can be realized by coupling high-performance biodegradation techniques with environmentally sound farming practices. The future research directions include microbial degradation systems, ecological risk evaluation, precision farming practices, and soil management systems. Biochar amendments have demonstrated promising results in terms of herbicide uptake and microbial activity toward herbicide breakdown. Integrating these sustainable measures with genomics-driven bioremediation and management approaches would ensure minimal environmental pollution without compromising agricultural output. Such an approach is crucial to ensuring ecosystem sustainability and environmental conservation (Zhang et al., 2018).

10. CONCLUSION

Herbicides have become a necessary part of agriculture, but their extensive usage has caused serious environmental problems due to their high persistence and mobility in the soil-water matrix. Fate and transport of herbicides occur through various processes, including adsorption, desorption, leaching, runoff, and degradation (abiotic/biotic). It is very important to have knowledge of these processes to estimate how contaminants behave in the environment and predict any ecological risk. Degradation kinetics is an important parameter that can help in predicting herbicide persistence in the environment and environmental exposure. Different kinetic models like first order, pseudo-first order, and Michaelis-Menten models can be useful in this regard. Moreover, these models help develop remediation strategies, by pointing out factors that affect degradation efficiency. Advancements in genomics and other omics techniques have increased our knowledge on herbicide degradation by microbes. Using metagenomics, transcriptomics, proteomics, and metabolomics, scientists have been able to identify degradative microorganisms, genes, enzymes, and pathways that transform herbicides. These developments have helped to fast-track the use of genomics-led bioremediation technologies, such as bio-augmentation, bio-stimulation, engineering microbial communities, and synthetic biology approaches. In the future, omics techniques together with bioinformatics and artificial intelligence are likely to play an important role in the evolution of herbicide management, especially by promoting environmental sustainability through bioremediation. This interdisciplinary approach would be helpful in minimizing contamination in the environment and practicing sustainable agriculture amid global climate changes and food production demands.

REFERENCES

1. Ahmad, S., Ahmad, H. W., & Bhatt, P. (2022). Microbial adaptation and impact into the pesticide's degradation. *Archives of Microbiology*, *204*(5), 288.
2. Ahmad, S., Chandrasekaran, M., & Ahmad, H. W. (2023). Investigation of the persistence, toxicological effects, and ecological issues of S-triazine herbicides and their biodegradation using emerging technologies: A Review. *Microorganisms*, *11*(10), 2558.
3. Al Salti, S., Rajamohan, N., & Joshi, S. (2026). Bacterial Biomass-based Remediation of Atrazine and Terbuthylazine–A Review on Pathways, Operating Conditions, and Toxicology. *Current Microbiology*, *83*(6), 327.
4. Arya, R., Gautam, B., Bharti, B., Negi, N., Kumar, A., & Mohan, J. (2025). Microbial biodegradation of carbendazim and sulfosulfuron: A sustainable approach for pesticide detoxification and soil restoration. *International Journal of Agricultural Invention*, *10*(2), 279-287.
5. Basapuram, G., Dutta, A., & Duttagupta, S. (2025). Biotransformation of Pesticides across Biological Systems: Molecular Mechanisms, Omics Insights, and Biotechnological Advances for Environmental Sustainability. *ACS omega*, *10*(43), 50709-50723.
6. Bhatt, P., Huang, Y., Zhan, H., & Chen, S. (2019). Insight into microbial applications for the biodegradation of pyrethroid insecticides. *Frontiers in Microbiology*, *10*, 1778.
7. Bhende, R. S., & Dafale, N. A. (2023). Insights into the ubiquity, persistence and microbial intervention of imidacloprid. *Archives of Microbiology*, *205*(5), 215.
8. Bhende, R. S., Jhariya, U., Srivastava, S., Bombaywala, S., Das, S., & Dafale, N. A. (2022). Environmental distribution, metabolic fate, and degradation mechanism of chlorpyrifos: recent and future perspectives. *Applied Biochemistry and Biotechnology*, *194*(5), 2301-2335.
9. Bokade, P., Purohit, H. J., & Bajaj, A. (2021). Myco-remediation of chlorinated pesticides: insights into fungal metabolic system. *Indian Journal of Microbiology*, *61*(3), 237-249.
10. Carles, L., Donnadieu, F., Wawrzyniak, I., Besse-Hoggan, P., & Batisson, I. (2021). Genomic analysis of the Bacillus megaterium Mes11: New insights into nitroreductase genes associated with the degradation of mesotrione. *International Biodeterioration & Biodegradation*, *162*, 105254.
11. Chavez Rodriguez, L., Ingalls, B., Schwarz, E., Streck, T., Uksa, M., & Pagel, H. (2020). Gene-centric model approaches for accurate prediction of pesticide biodegradation in soils. *Environmental science & technology*, *54*(21), 13638-13650.
12. Chen, S. F., Chen, W. J., Song, H., Liu, M., Mishra, S., Ghorab, M. A., ... & Chang, C. (2024). Microorganism-driven 2, 4-D biodegradation: Current status and emerging opportunities. *Molecules*, *29*(16), 3869.
13. Chen, W. J., Chen, S. F., Song, H., Li, Z., Luo, X., Zhang, X., & Zhou, X. (2024). Current insights into environmental acetochlor toxicity and remediation strategies. *Environmental Geochemistry and Health*, *46*(9), 356.
14. Chowdhury, I. F., Doran, G. S., Stodart, B. J., Chen, C., & Wu, H. (2025). Microbial Degradation of Herbicide Residues in Australian Soil: An Overview of Mechanistic Insights and Recent Advancements. *Toxics*, *13*(11), 949.
15. Coleman, N. V., Rich, D. J., Tang, F. H., Vervoort, R. W., & Maggi, F. (2020). Biodegradation and abiotic degradation of trifluralin: a commonly used herbicide with a poorly understood environmental fate. *Environmental science & technology*, *54*(17), 10399-10410.
16. Corredor, D., Duchicela, J., Flores, F. J., Maya, M., & Guerron, E. (2024). Review of explosive contamination and bioremediation: insights from microbial and bio-omic approaches. *Toxics*, *12*(4), 249.
17. Dhakal, G., Thapa Magar, S., & Fujino, T. (2025). Pesticide Degradation by Soil Bacteria: Mechanisms, Bioremediation Strategies, and Implications for Sustainable Agriculture. *Environments*, *12*(12), 492.
18. Gao, Z., Gu, C., Fan, X., Shen, L., Jin, Z., Wang, F., & Jiang, X. (2024). Biochemical insights into the biodegradation mechanism of typical sulfonylureas herbicides and association with active enzymes and physiological response of fungal microbes: A multi-omics approach. *Environment International*, *190*, 108906.
19. Ghorab, M. A., Khalil, M. S., El-Sayyad, G. S., Nada, H. G., Elfadil, D., El-Sherif, D. M., ... & Chen, S. (2026). Microbial degradation of organophosphorus pesticides: mechanisms, environmental impacts, and future perspectives. *World Journal of Microbiology and Biotechnology*, *42*(6), 325.
20. Giwa, A. S., Waheed, M., Khalid, H. V., Shafique, E., Rahman, S. U., & Ali, N. (2025). Mechanistic insights into fungal-bacterial synergy for DDT biotransformation. *Antonie Van Leeuwenhoek*, *118*(9), 137.

21. Havens, P. L., Sims, G. K., & Erhardt-Zabik, S. (2017). Fate of herbicides in the environment. *Handbook of weed management systems*, 245-278.
22. Hussain, S., Hartley, C. J., Shettigar, M., & Pandey, G. (2016). Bacterial biodegradation of neonicotinoid pesticides in soil and water systems. *Microbiology Letters*, *363*(23), fnw252.
23. Iqbal, N., Nauman, M., Ullah, S., Hussain, B., Vasudhevan, P., Riyazuddin, R., ... & Pu, S. (2026). Microbial Remediation of Lindane-Contaminated Soils: Unveiling Environmental Fate, Degradation Pathways, and Future Directions. *Land Degradation & Development*, *37*(6), 1942-1958.
24. KUMAR, P. (2023). Degradation of Xenobiotics by Bacteria and Fungi: An Overview. *Biopesticides International*, *19*(2).
25. Li, M., Song, J., Ma, Q., Kong, D., Zhou, Y., Jiang, X., ... & Zhang, Q. (2020). Insight into the characteristics and new mechanism of nicosulfuron biodegradation by a Pseudomonas sp. LAM1902. *Journal of agricultural and food chemistry*, *68*(3), 826-837.
26. Lin, Z., Zhang, W., Pang, S., Huang, Y., Mishra, S., Bhatt, P., & Chen, S. (2020). Current approaches to and future perspectives on methomyl degradation in contaminated soil/water environments. *Molecules*, *25*(3), 738.
27. Mohapatra, B., & Phale, P. S. (2021). Microbial degradation of naphthalene and substituted naphthalenes: metabolic diversity and genomic insight for bioremediation. *Frontiers in Bioengineering and Biotechnology*, *9*, 602445.
28. Nayak, T., Panda, A. N., Adhya, T. K., Das, B., & Raina, V. (2019). Biodegradation of Chlorpyrifos and 3, 5, 6-trichloro-2-pyridinol (TCP) by Ochrobactrum sp. CPD-03: insights from genome analysis on organophosphorus pesticides degradation, chemotaxis and PGPR activity. *BioRxiv*, 2019-12.
29. Pang, S., Lin, Z., Zhang, W., Mishra, S., Bhatt, P., & Chen, S. (2020). Insights into the microbial degradation and biochemical mechanisms of neonicotinoids. *Frontiers in microbiology*, *11*, 868.
30. Pang, S., Lin, Z., Zhang, Y., Zhang, W., Alansary, N., Mishra, S., ... & Chen, S. (2020). Insights into the toxicity and degradation mechanisms of imidacloprid via physicochemical and microbial approaches. *Toxics*, *8*(3), 65.
31. Pileggi, M., Pileggi, S. A., & Sadowsky, M. J. (2020). Herbicide bioremediation: from strains to bacterial communities. *Heliyon*, *6*(12).
32. Raj, A., Pant, A., Kumar, A., Kumar, A., Kalamdhad, A. S., & Khwairakpam, M. (2026). Systems-Level Insights Into Microbial Naphthalene Biodegradation: An Integrated In Silico and Omics Perspective. *Environmental Microbiology*, *28*(3), e70264.
33. Setiawardani, A., Putri, R. E., Hasan, W., Kristianto, S., Widodo, W. T., Rehman, M. T., & Zainal-Abidin, M. H. (2025). Role of microbial secondary metabolites in enhancing pesticide biodegradation: A critical review on solubility, mobility, and environmental risk of metabolites. *Water, Air, & Soil Pollution*, *236*(11), 722.
34. Shah, B. A., Malhotra, H., Papade, S. E., Dhamale, T., Ingale, O. P., Kasarlawar, S. T., & Phale, P. S. (2024). Microbial degradation of contaminants of emerging concern: metabolic, genetic and omics insights for enhanced bioremediation. *Frontiers in Bioengineering and Biotechnology*, *12*, 1470522.
35. Singh, B., & Singh, K. (2016). Microbial degradation of herbicides. *Critical reviews in microbiology*, *42*(2), 245-261.
36. Singh, Y., & Saxena, M. K. (2022). Insights into the recent advances in nano-bioremediation of pesticides from the contaminated soil. *Frontiers in microbiology*, *13*, 982611.
37. Souza, K. S., da Silva, M. R. F., Candido, M. A., Lins, H. T. S., de Lima Torres, G., da Silva Felix, K. C., ... & de Oliveira, M. B. M. (2025). Biodegradation potential of glyphosate by bacteria: a systematic review on metabolic mechanisms and application strategies. *Agronomy*, *15*(5), 1247.
38. Srivastava, S., Mir, R. A., Hussain, S. J., Mitra, S., Srivastava, S., Kumar, P., & Kaur, H. (2026). Microbial engineering for pesticide degradation: Current insights and future directions for sustainable agriculture. *Frontiers in Microbiology*, *17*, 1751932.
39. Uniyal, S., Sharma, R. K., & Kondakal, V. (2021). New insights into the biodegradation of chlorpyrifos by a novel bacterial consortium: process optimization using general factorial experimental design. *Ecotoxicology and Environmental Safety*, *209*, 111799.
40. Wageed, M., Mahdy, H. M., Kalaba, M. H., El-Moez, S. I. A., Kelany, M. A., & Soliman, M. (2025). Enhanced biodegradation of Diquat herbicide by Bacillus velezensis MW8SH: insights into Performance, degradative Pathways, and practical applications. *International Journal of Environmental Research*, *19*(6), 226.
41. Wang, Z., Fang, F., Xi, B., Zhang, H., Wang, Y., & Zhao, X. (2025). Revealing the Biodegradation Mechanism of Pesticides: Emphasizing the Role of Isotope Fractionation and Tracing. *Journal of Agricultural and Food Chemistry*, *73*(29), 18100-18118.
42. Wei, W., Wu, Y., Sha, Z., Lu, Z., & Wang, M. (2025). Ethiprole biodegradation by Pseudomonas sp. NC1: Insights into the mechanisms and pathways. *International Biodeterioration & Biodegradation*, *198*, 105985.
43. Wu, C., Wang, Y., Clarke, J. L., Su, H., Wang, L., Glazunova, O. A., ... & Liu, X. (2025). Biochar enhances the sorption and degradation of fluridone and its main metabolite in soil: insights into biodegradation potential and remediation of microbial communities. *Biochar*, *7*(1), 81.
44. Wu, J., Peng, H., Cheng, P., Liu, H., Zhang, Y., & Gong, M. (2025). Microbial degradation mechanisms, degradation pathways, and genetic engineering for pyrethroids: current knowledge and future perspectives. *Critical Reviews in Toxicology*, *55*(1), 80-104.

45. Yang, D., Dong, R., Fu, F., Zhao, L., Li, X., Ye, H., ... & Sun, Y. (2025). Biodegradable microplastics exert differential impacts from polyethylene on pesticide fate in soil-earthworm systems: insights into degradation selectivity and microbial mechanisms. *Environmental Pollution*, 127394.
46. Zabaloy, M. C., Allegrini, M., Hernandez Guijarro, K., Behrends Kraemer, F., Morrás, H., & Erijman, L. (2022). Microbiomes and glyphosate biodegradation in edaphic and aquatic environments: recent issues and trends. *World Journal of Microbiology and Biotechnology*, *38*(6), 98.
47. Zhang, P., Sun, H., Min, L., & Ren, C. (2018). Biochars change the sorption and degradation of thiacloprid in soil: insights into chemical and biological mechanisms. *Environmental pollution*, *236*, 158-167.
48. Zhang, W., Lin, Z., Pang, S., Bhatt, P., & Chen, S. (2020). Insights into the biodegradation of lindane (γ-hexachlorocyclohexane) using a microbial system. *Frontiers in microbiology*, *11*, 522.
49. Zhou, J., Liu, K., Xin, F., Ma, J., Xu, N., Zhang, W., ... & Dong, W. (2018). Recent insights into the microbial catabolism of aryloxyphenoxy-propionate herbicides: Microbial resources, metabolic pathways and catabolic enzymes. *World Journal of Microbiology and Biotechnology*, *34*(8), 117.
50. Zhou, Z., Wu, X., Lin, Z., Pang, S., Mishra, S., & Chen, S. (2021). Biodegradation of fipronil: current state of mechanisms of biodegradation and future perspectives. *Applied microbiology and biotechnology*, *105*(20), 7695-7708.