



## Effects of Pesticides on Soil Microbial Activities

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Pesticides have become an integral component of modern agricultural systems due to their proven effectiveness in controlling a wide range of pests, including insects, weeds, fungi, rodents, and other harmful organisms (Streletsii et al., 2022). Their application has enabled farmers to protect crops from severe damage, reduce both pre- and post-harvest losses, and enhance overall agricultural productivity, thereby contributing significantly to global food security (Hughes et al., 2024). Despite these benefits, growing scientific evidence has raised serious concerns regarding the extensive and often indiscriminate use of pesticides and their adverse effects on soil ecosystems. Soil is a complex, living system in which microorganisms represent the most sensitive and functionally important biological components. These microorganisms play a central role in organic matter decomposition, nutrient mineralization, soil structure formation, and maintenance of soil fertility. As key drivers of biogeochemical cycles, soil microbes regulate enzymatic processes and nutrient transformations essential for plant growth (Raymond et al., 2022). Consequently, any disruption to microbial communities can adversely affect soil health and productivity. Several studies have reported that pesticide contamination alters microbial community composition, reduces microbial diversity, and inhibits crucial soil enzymes involved in organic matter turnover and nutrient cycling (Hamza et al., 2018; Fuchs et al., 2024). Astaykina et al. (2022) reported a pronounced, dose-dependent decline in soil microbial populations following pesticide application, with microbial abundance decreasing to about 63% under recommended doses and to nearly 35% under higher doses within 56 days. Additional studies have shown that increased pesticide concentrations adversely affect soil fauna, such as earthworms, by reducing gut microbial diversity, and inhibit key enzymes like microbial carbonic anhydrase, thereby disrupting soil respiration and carbon transformation processes (Nathan et al., 2020). Overall, these findings demonstrate that indiscriminate pesticide use undermines soil microbial communities, biochemical processes, and ecological balance. Adoption of sustainable practices, including Integrated Pest Management, use of pesticides at recommended doses, and appropriate safety measures, is essential to protect soil health while ensuring long-term agricultural sustainability.

**Keywords:** Pesticides, Soil Microbial Activity, IPM, Environmental Impact

### Brief Introduction About Pesticides

Pesticides are chemical or biological substances used to prevent, control, or eliminate harmful organisms such as insects, weeds, fungi, rodents, and microbes that damage crops, stored products, livestock, and public health systems (Hughes et al., 2024). They play a vital role in modern agriculture by protecting crops from pests and diseases, ensuring higher yields,

reducing post-harvest losses, and supporting global food security. However, the excessive or improper use of pesticides can lead to environmental pollution, soil and water contamination, residue buildup in food, development of resistant pest populations, and health risks to humans and animals. Therefore, their use requires careful management, adherence to safety guidelines, and adoption of integrated pest management (IPM) strategies to balance productivity with environmental safety.

### Types of Pesticides

Common types include insecticides, herbicides, fungicides, and rodenticides. Each type targets specific pests or unwanted organisms. The choice of pesticide depends on the crop, pest type, and environmental considerations.



### Key Characteristics of Pesticides

#### 1. Toxicity

Pesticides are inherently toxic substances designed to kill or suppress harmful organisms such as insects, weeds, fungi, and rodents. The degree of toxicity varies among pesticides and determines how dangerous they are not only to target pests but also to humans, beneficial organisms, animals, and the environment. Understanding toxicity levels is essential for safe handling, application, and risk assessment.

#### 2. Selectivity

Pesticides differ in their ability to target specific organisms. Selective pesticides act on particular pests while leaving other organisms relatively unharmed, making them useful in integrated pest management. Non-selective pesticides, by contrast, affect a broad range of living organisms and may disrupt ecological balance if not used carefully.

#### 3. Persistence

Persistence refers to how long a pesticide remains active in the environment after application. Persistent pesticides degrade very slowly, allowing them to remain in soil, water, or plant tissues for extended periods and sometimes leading to accumulation or long-term pollution. Non-persistent pesticides break down rapidly, reducing their environmental impact but sometimes requiring more frequent application.

## Benefits of Pesticides

### 1. Reduce Crop Losses and Improve Food Security

Pesticides protect crops from harmful insects, weeds, and diseases that can significantly reduce yield. By preventing such losses, pesticides help ensure stable agricultural production and contribute to global food security, especially in regions facing pest outbreaks or food shortages.

### 2. Enable Efficient Farming

With pesticides, farmers can manage pests quickly and effectively, allowing them to cultivate larger areas with fewer labor and time requirements. This improves overall farm efficiency, reduces production costs, and increases profitability.

### 3. Help in Managing Vector-Borne Diseases

In public health, pesticides are vital for controlling disease-transmitting vectors such as mosquitoes, ticks, and flies. Their use helps reduce the spread of diseases like malaria, dengue, chikungunya, and other vector-borne illnesses, protecting both human and animal health.

### 4. Conserving Natural Habitats

By improving yields on existing farmland, pesticides reduce the need to convert forests and natural ecosystems into agricultural land. This helps conserve biodiversity, protect wildlife, and maintain ecological balance.

## Positive Impact on Ecosystems

Although pesticides are often discussed for their harmful effects, they also provide several positive ecological benefits when used responsibly. These impacts help maintain ecosystem stability and support sustainable agriculture.

### 1. Prevent Pest Outbreaks

Pesticides help suppress destructive pest populations that can otherwise spread rapidly and damage natural vegetation. By preventing large-scale outbreaks, they protect plant communities and reduce ecological disruptions.

### 2. Protect Native Biodiversity

By controlling invasive pests and harmful organisms, pesticides help safeguard native plant and animal species. This protection supports balanced ecosystems and prevents the displacement of indigenous species.

### 3. Reduce Pressure on Natural Habitats

Higher crop yields achieved through effective pest control reduce the need to expand farmland into forests, wetlands, and grasslands. This indirectly conserves wildlife habitats and protects biodiversity-rich areas.

### 4. Support Public Health and Environmental Stability

Pesticides used to control vectors like mosquitoes and ticks reduce the spread of diseases. Healthy human and livestock populations exert less pressure on natural resources, contributing to better ecosystem management.

### 5. Maintain Agricultural Ecosystems

By preventing severe crop loss, pesticides help maintain plant cover, prevent soil erosion, and stabilize food chains for soil organisms, herbivores, and microorganisms that depend on vegetation.

## Harmful Effects of Pesticides on Ecosystems

Pesticides, when overused or misused, can disrupt ecological balance and negatively affect soil, water, air, plants, animals, and microorganisms. Their persistence and toxicity often lead to long-term environmental impacts.

### 1. Decline in Biodiversity

Pesticides can kill non-target organisms such as beneficial insects, pollinators (bees, butterflies), natural predators, soil fauna, birds, and aquatic species. Loss of these organisms disturbs food chains and weakens ecosystem resilience.

## 2. Soil Ecosystem Damage

Residues of pesticides in soil can kill beneficial microorganisms essential for nutrient cycling, organic matter decomposition, and soil fertility. Persistent chemicals reduce soil enzyme activity and disrupt microbial balance. Earthworms and other soil fauna are also adversely affected.

## 3. Water Pollution

Runoff and leaching carry pesticides into rivers, lakes, and groundwater. Contaminated water harms fish, amphibians, aquatic plants, and microorganisms. Bioaccumulation and biomagnification occur across aquatic food webs.

## 4. Impact on Non-target Species

Non-selective pesticides affect helpful organisms like predators (ladybird beetles, spiders), parasitoids, pollinators, and decomposers. Birds and mammals may ingest contaminated prey or plants, leading to poisoning or reproductive problems.

## 5. Development of Resistant Pest Populations

Continuous use of the same pesticide causes pests to develop resistance. Resistant pests multiply rapidly, leading to outbreaks and further ecosystem disturbance. This results in higher pesticide use, creating a harmful cycle.

## 6. Disruption of Ecological Balance

Reduction in predators and parasitoids leads to secondary pest outbreaks. Decline in pollinators affects plant reproduction and diversity. Imbalances in food webs weaken overall ecosystem stability.

## 7. Air Contamination

Volatile pesticides or spray drift can travel long distances. This affects nearby ecosystems, human settlements, and wildlife habitats.

## Impact of Pesticides on Biodiversity

Pesticides significantly influence biodiversity by altering population dynamics, species interactions, and ecosystem functions. Their effects extend across plants, animals, microorganisms, and entire ecological networks.

### 1. Reduction of Species Diversity

Pesticides often kill non-target organisms along with target pests. Beneficial insects, pollinators, soil fauna, birds, amphibians, and aquatic species are all susceptible. This widespread mortality reduces overall species richness and disrupts ecological balance.

### 2. Decline in Pollinators

Pollinators such as bees, butterflies, and hoverflies are highly sensitive to insecticides, especially neonicotinoids. Their decline leads to reduced pollination services, affecting crop yield and the reproduction of wild plants. Loss of pollinators weakens both agricultural and natural ecosystems.

### 3. Disruption of Food Chains

When predators, prey, or decomposers are affected by pesticides, food webs become unstable. For example, a decline in insect populations reduces food availability for birds, amphibians, and small mammals. Aquatic ecosystems also experience disruptions when pesticides contaminate water bodies, killing fish and plankton.

### 4. Harm to Soil Biodiversity

Soil organisms such as microbes, fungi, nematodes, and earthworms are essential for nutrient cycling, decomposition, and soil fertility. Many pesticides reduce microbial biomass and enzyme activities, causing long-term soil degradation and decreased biological activity.

### 5. Bioaccumulation and Biomagnification

Persistent pesticides can accumulate in tissues of organisms and magnify through the food chain. Top predators—such as birds of prey, fish-eating animals, and carnivorous mammals—often receive the highest concentrations, resulting in reproductive failures, deformities, and population declines.

## 6. Loss of Natural Pest Control

Natural enemies such as ladybird beetles, spiders, parasitoids, and predatory wasps regulate pest populations. Pesticides can kill or weaken these beneficial species, leading to pest resurgence and secondary pest outbreaks, further threatening biodiversity.

## 7. Threat to Aquatic Biodiversity

Pesticide runoff into rivers, lakes, and wetlands affects fish, amphibians, crustaceans, and aquatic plants. Sub-lethal exposure causes behavioral changes, weakened immunity, and impaired reproduction, while high concentrations lead to mass mortality.

## 8. Genetic Erosion

Long-term chemical exposure can reduce genetic variations within species. Low genetic diversity makes populations more vulnerable to diseases, environmental changes, and extinction.

## Resistance and Pest Outbreaks

Pesticides are essential for controlling harmful pests, but their repeated and excessive use can lead to the development of resistance in pest populations. When pests are frequently exposed to the same chemical, the most tolerant individuals survive and reproduce. Over time, this results in a population that no longer responds effectively to the pesticide, making pest control increasingly difficult.

As resistant pests multiply, they can trigger **severe outbreaks**, often more damaging than the initial infestation. Farmers respond by applying higher doses or more frequent sprays, which further accelerates resistance development and increases chemical load on the environment.

This creates a **harmful cycle**: increased pesticide use → stronger resistance → larger outbreaks → even more pesticide use. Such a feedback loop not only harms ecosystems by affecting non-target organisms but also raises production costs and reduces long-term sustainability for farmers. (Global Status of Commercialized Biotech/GM Crops: 2013).

## Strategies for Safe Pesticide Use (US EPA Suggested)

- Wearing personal protective equipment (PPE) such as gloves, masks, and protective clothing minimizes direct exposure to harmful chemicals.
- Ensuring proper storage and disposal of pesticides prevents accidental poisoning and environmental contamination.
- Regular maintenance and calibration of spraying equipment improve application accuracy and reduce pesticide wastage.



## Methodology for Analysis of the Effects of Pesticides on Soil Microbial Activity

Assessing the impact of pesticides on soil microbial activity requires a systematic and scientifically robust methodology. The process begins with sample collection, where soil is gathered from both pesticide-treated and untreated control sites. This comparison ensures that the effects of pesticides can be clearly distinguished from natural variations in microbial populations. Soil samples are collected from uniform depths and locations to maintain consistency and reliability across treatments.

Once collected, the samples undergo sample preparation, which involves aseptic handling to avoid contamination. The soil is homogenized to ensure uniformity and then stored at 4°C until further analysis. Proper storage preserves microbial integrity and prevents shifts in biological activity that could interfere with accurate assessment.

The next key step is the extraction and analysis of microbial activity. A range of standardized laboratory assays is employed to quantify microbial functions. These include soil respiration tests to measure metabolic activity, enzyme assays (such as dehydrogenase, amylase, or urease) to evaluate biochemical functioning, and microbial biomass estimation to determine overall microbial abundance. Together, these assays provide a comprehensive understanding of how pesticide exposure affects microbial health, diversity, and functional capacity.

Finally, the data generated from these assays undergo detailed pesticide exposure analysis. This process utilizes flow charts or analytical frameworks that guide data normalization, statistical evaluation, and interpretation. Key comparisons are made between treated and untreated samples to identify significant reductions or shifts in microbial activity attributable to pesticide stress. Statistical tools help detect trends, correlations, and dose-dependent responses. The outcome of this analysis offers insights into the resilience or vulnerability of soil microbial communities when exposed to agricultural chemicals.

Overall, this methodology provides a structured approach to evaluating pesticide impacts on soil ecosystems, ensuring accurate, reproducible, and meaningful results that contribute to environmental monitoring and sustainable agricultural management.

## Results and discussion

The results clearly demonstrate a progressive decline in soil bacterial count following pesticide application, with the magnitude of reduction varying across treatments. In the control soil, bacterial populations remained stable at 100% throughout the 40-day period, confirming that natural environmental factors did not contribute to microbial loss. This stability highlights that all observed reductions in the treated soils were solely due to pesticide exposure. In Treatment B (lower dose), a gradual decline was observed, with bacterial count decreasing from 100% at Day 0 to 85%, 70%, 60%, and finally 55% by Day 40. Although this reduction is moderate, it indicates that even low pesticide concentrations adversely affect microbial activity over time.

Treatment C (moderate dose) exhibited a sharper and more consistent decline. Bacterial counts reduced from 100% to 80% at Day 10, 60% at Day 20, 45% at Day 30, and 40% at Day 40. This pattern shows that increasing pesticide dosage enhances microbial toxicity, leading to accelerated population loss. The most severe impact was observed in Treatment D (highest dose). Bacterial population dropped drastically from 100% at Day 0 to 70% by Day 10, falling further to 50%, 35%, and 30% by Day 40. This represents the strongest inhibitory effect on microbial communities, demonstrating that high pesticide doses significantly disrupt soil biological functioning.

Overall, the results indicate a clear dose-dependent microbial decline, with higher pesticide concentrations causing more rapid and profound reductions in bacterial populations. This decline suggests adverse effects on soil health, as bacteria play crucial roles in nutrient cycling, organic matter decomposition, and maintaining soil fertility. The findings underscore the sensitivity of soil microorganisms to chemical stress and highlight the need for responsible pesticide use to avoid long-term ecological degradation.

## Salient Findings

- ❖ Pesticide application caused a consistent decline in culturable bacterial counts over 40 days, showing that microbial functional diversity is sensitive to pesticide stress.
- ❖ Control soils maintained stable microbial numbers, indicating that reductions in treated soils are directly attributable to pesticide exposure rather than natural fluctuations.

## Material and Methodology

To evaluate the impact of selected pesticides on microbial carbonic anhydrase (CA) activity, soil samples treated with 2,4-D, glyphosate, and dichlorvos were collected from controlled microcosm experiments. Microbial abundance was measured using viable plate counts. Enzyme activity was quantified through carbonic anhydrase assays, which involved specific reagents and spectrophotometric measurements. The percentage inhibition of CA activity was calculated relative to untreated soil samples. The relationship between pesticide concentration, microbial count, and CA inhibition was assessed to determine how pesticide exposure interferes with soil microbial respiration and CO<sub>2</sub> conversion processes. Statistical tools were used to evaluate treatment differences and confirm pesticide toxicity. These findings reveal that while some pesticides exert mild effects, others significantly reduce microbial abundance, potentially impairing soil biological activity and nutrient-cycling processes.

## Salient Findings

- ❖ Pesticides inhibited microbial carbonic anhydrase enzyme activity, demonstrating interference with CO<sub>2</sub> transformation and soil respiration functions.
- ❖ Microbial abundance and total microbial count declined under pesticide exposure, confirming toxicity to both microbial biomass and metabolic activity.

## Summary

- Pesticide application consistently reduced soil microbial population compared to untreated control soils.
- Higher pesticide doses caused greater and faster declines in microbial counts and diversity.
- Soil enzyme activities (e.g., amylase, carbonic anhydrase) were significantly inhibited after pesticide exposure.
- Gut microbial diversity of earthworms decreased, indicating adverse effects on soil fauna and ecosystem health.
- Overall, pesticides disrupted soil biological functions, organic carbon levels, and microbial balance across all studies.

## Conclusion

- ❖ Pesticides significantly reduce microbial abundance, with stronger reductions observed under highly toxic pesticides such as Paraquat, Glyphosate, and Dichlorvos, while mild declines occur under lower-toxicity chemicals like 2,4-D and Carbofuran.
- ❖ Microbial diversity and richness decline with increasing pesticide concentration, as seen through decreased Shannon Index values and reduced genera counts, indicating disruption of soil ecological balance.
- ❖ Functional microbial groups respond differently, with nitrifiers and phosphate solubilizers sometimes showing temporary increases, whereas fungi, actinomycetes, and bacteria often decline or fluctuate depending on pesticide type and exposure duration.
- ❖ Soil biochemical activities (e.g., amylase) are adversely affected, showing reduced enzyme activity under pesticide treatments except in some cases where compensatory microbial activity temporarily increases.
- ❖ Overall soil health deteriorates under continuous pesticide exposure, reflected through reduced organic carbon, suppressed beneficial microbes, and weakened nutrient cycling, highlighting the need for safer pesticide management and integrated pest management practices.

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