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Research Paper

Effect of New Generation Herbicides on Soil Nutrients: A Review

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Abstract
New generation herbicides represent a significant advancement in weed management strategies, yet their effects on soil nutrient dynamics and soil health remain an important area of investigation. This review synthesizes current knowledge on how contemporary herbicides impact soil chemical properties, nutrient availability, microbial communities, and enzyme activities that govern nutrient cycling. Emerging evidence suggests that while new generation herbicides used at recommended doses generally have minimal adverse effects on overall soil health, certain active ingredients and formulations can negatively impact ammonia-oxidizing microorganisms, nutrient cycling processes, and mycorrhizal associations. The review examines the mechanisms by which herbicides alter soil nutrient dynamics, discusses herbicide residues and persistence, and evaluates sustainable alternatives for maintaining soil health in agricultural systems. Understanding these interactions is crucial for developing management strategies that balance effective weed control with soil nutrient preservation and long-term agricultural sustainability.
Keywords: *herbicides, soil nutrients, nitrogen cycling, microbial communities, soil health, enzyme activity, sustainable agriculture*

I. Introduction

Herbicides have become essential tools in modern agriculture, playing a key role in effective weed control to ensure high crop yields. The ongoing development of agricultural practices and the rise of herbicide-resistant weed species have prompted the creation and adoption of new-generation herbicides that offer better effectiveness, lower environmental impact, and adherence to strict regulatory standards (Panneerselvam et al., 2021). Worldwide, herbicides make up a significant share of the agrochemical inputs used in cropping systems, where their application directly affects crop production and the efficiency of mechanized farming (Keystone BioAg, 2024). Despite these advantages, herbicide use raises concerns about environmental contamination, especially through residues leaching into soil and groundwater, which can threaten non-target organisms and soil ecosystem functions (Keystone BioAg, 2024; Villaverde et al., 2008).

Soil microorganisms are fundamental to maintaining soil health and fertility as they regulate key processes such as organic matter decomposition, nutrient cycling, and symbiotic associations critical for plant nutrient acquisition (Cropnuts, 2024). These microbial communities, including nitrogen-fixing bacteria, mycorrhizal fungi, and decomposers, facilitate the conversion of complex organic compounds into forms readily available for plant uptake, thus sustaining long-term soil productivity (Cropnuts, 2024). However, herbicides, particularly those targeting specific plant biochemical pathways such as acetolactate synthase (ALS)-inhibiting herbicides (e.g., penoxsulam, flucetosulfuron, ethoxysulfuron), may inadvertently affect soil microbial populations and functions by inhibiting enzymes shared across plants and soil microorganisms (Panneerselvam et al., 2021).

The persistence and behavior of herbicides in soil depend on their chemical properties and soil characteristics such as organic matter content, clay composition, and pH, which influence herbicide adsorption, availability, and degradation rates (Villaverde et al., 2008; Iowa State University, 2025). Adsorption to soil colloids reduces the bioavailability of herbicides but also determines their effectiveness and environmental mobility, necessitating a balance between efficient weed control and minimal soil ecosystem disruption (Villaverde et al., 2008). New generation herbicides like bispyribac sodium, flucetosulfuron, ethoxysulfuron, and penoxsulam have been reported to variably impact soil enzyme activities, microbial biomass, and beneficial fungi like arbuscular mycorrhizal fungi (AMF) that improve nutrient uptake and soil structure (Raj et al., 2017; Panneerselvam et al., 2021).

Studies highlight that although some herbicides can temporarily suppress microbial populations or enzymatic activity, these effects may be transient, with microbial communities adapting or recovering over time (Tyagi et al., 2018). In particular, combinations of certain herbicides may mitigate negative impacts compared to their individual application, showing the importance of integrated weed and soil health management strategies (Panneerselvam et al., 2021). Given the central role of soil microorganisms in nutrient cycling and plant health, understanding the nuanced interactions between new generation herbicides and soil nutrient dynamics is imperative for developing sustainable agricultural practices that safeguard soil fertility while achieving effective weed control.

This review synthesizes current knowledge on the effects of contemporary herbicides on soil chemical properties, nutrient availability, microbial communities, and enzyme activities. By examining herbicide persistence, modes of action, and impact on soil nutrient cycling processes, the study aims to provide a comprehensive understanding of the implications of new generation herbicides on soil health, emphasizing the need for environmentally responsible usage and alternative weed management approaches.

II. Classification and Characteristics of New Generation Herbicides

2.1 Herbicide Categories and Modes of Action

The classification of new generation herbicides is centered on their mode of action, chemical structure, and the physiological timing of their application. This approach not only aids in the management of herbicide-resistant weed populations but also informs best practices for minimizing off-target impacts on soil and environmental health (Kudsk&Streibig, 2013; Heap, 2014).

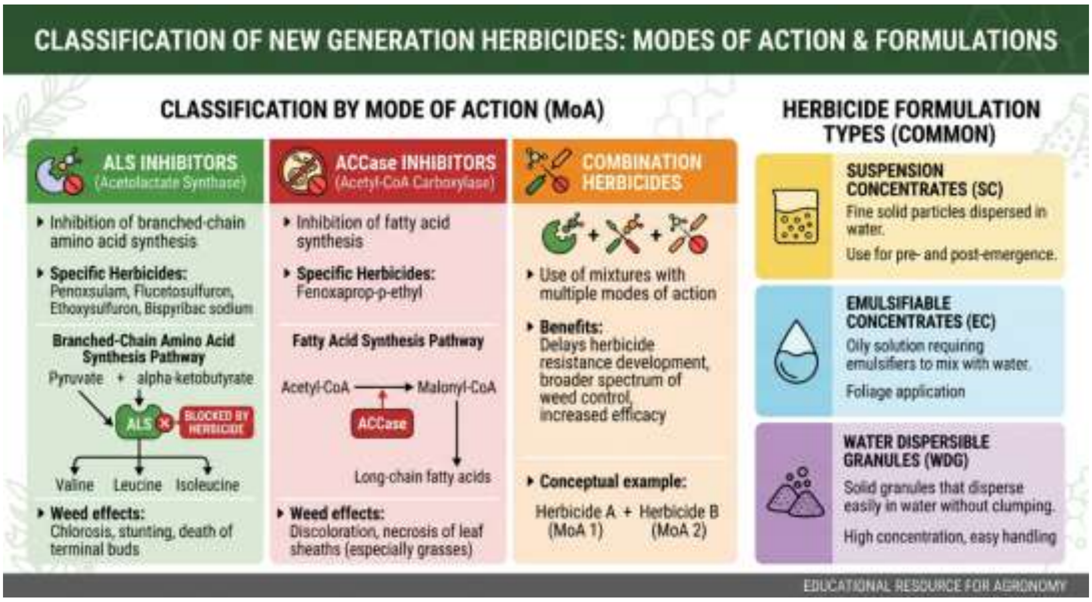
Herbicide / Group	Effect on Soil Nutrients	Mechanism of Interaction	Impact on Soil Fertility
Glyphosate	Can reduce the availability of micronutrients like Fe, Mn, Zn	Chelation (binds micronutrients in soil)	May temporarily reduce micronutrient uptake by plants
Atrazine	May influence the nitrogen cycle	Affects soil microbial activity responsible for nitrification	It can alter nitrogen transformation in soil
Paraquat	Minimal direct nutrient interaction	Strong adsorption to soil particles	Little effect on nutrient availability
2,4-D	Slight effect on soil microorganisms	Temporary microbial disturbance	Minor short-term changes in nutrient mineralization
Pendimethalin	Limited nutrient interaction	Binds strongly to soil organic matter	Generally, no major impact on nutrient levels
Imazethapyr	May affect phosphorus availability indirectly	Alters microbial population involved in P cycling	Slight changes in P mineralization possible

Acetolactate Synthase (ALS) Inhibitors comprise a substantial proportion of post-emergence herbicides used for selective and efficient weed management, notably including penoxsulam, flucetosulfuron, and ethoxysulfuron. The ALS enzyme, targeted by these herbicides, is critical in the biosynthesis of the essential branched-chain amino acids—valine, leucine, and isoleucine. This enzyme exists in both weed species and a range of soil microorganisms, such as ammonia-oxidizing bacteria, which means ALS inhibitors can disrupt soil nitrogen cycling and alter microbial community composition if residues persist or enter the microbial environment (Tranel& Wright, 2002; Swaine et al., 2025; Panneerselvam et al., 2021).

Aryloxyphenoxypropionate (APP) Herbicides, such as fenoxaprop-p-ethyl, act by inhibiting acetyl-CoA carboxylase (ACCase), a key enzyme in fatty acid synthesis crucial for membrane formation in plants. While this enzyme is also present in various bacteria and fungi, APP herbicides can adversely affect certain non-target soil microbes, thereby impacting soil health and possibly leading to shifts in microbial community diversity and function (Xu et al., 2016; Raj et al., 2017).

Bispyribac Sodium, representing the pyrimidinone class, is distinguished by its multiple-site disruption of plant metabolic processes, mainly via inhibition of ALS. Empirical evidence shows that bispyribac sodium formulated as a suspension concentrate (SC) generally demonstrates lower toxicity to beneficial soil microorganisms and less negative impact on microbial biomass and enzyme activities compared to other ALS inhibitors (Raj et al., 2017; Panneerselvam et al., 2021). This makes it a potential candidate for use in integrated weed and soil management systems aiming for sustainability.

Combination Herbicides have been developed to both broaden the weed control spectrum and delay the evolution of herbicide-resistant weed biotypes. Examples like penoxsulam plus cyhalofop-butyl and fenoxaprop-p-ethyl plus ethoxysulfuron allow simultaneous targeting of multiple metabolic pathways in weeds and are commonly applied in intensive cropping systems. However, research indicates that such combinations may produce either synergistic toxicity or unexpected antagonistic effects on soil microorganisms, underscoring the importance of studying ecological interactions before deployment (Carriquiry et al., 2024; Shaner, 2014).



2.2 Formulation Types and Adjuvants

Modern commercial herbicides are formulated in a variety of forms—including suspension concentrates (SC), emulsifiable concentrates (EC), and water dispersible granules (WDG)—to enhance ease of application, improve spray coverage, and optimize the biological availability of the active ingredient. These formulations typically contain not just the active herbicide molecule but a diverse set of adjuvants such as surfactants, emulsifiers, solvents, and stabilizers that can significantly alter the efficacy and environmental profile of the final product (Green &Beestman, 2007).

Adjuvants such as surfactants are intended to increase herbicide uptake by leaves; however, their chemical composition may also influence the toxicity of the formulation independently of the active ingredient. For instance, polyoxyethylene tallow amine (commonly used as a surfactant in many glyphosate-based products) has been shown to produce substantial cytotoxic effects on non-target soil organisms, while alternative adjuvants like polyethylene glycol (PEG 300), propylene glycol (PG), and monoethylene glycol (MEG) are generally less toxic (Panneerselvam et al., 2021; Mesnage et al., 2013).

Formulation additives can also modify herbicide sorption, mobility, and degradation in soils. For example, certain surfactants may enhance the leaching of herbicides into subsoil layers and water tables, with potential for groundwater contamination and altered microbial ecology (Villaverde et al., 2008; Green &Beestman, 2007). Thus, the composition and concentration of adjuvants require careful consideration during herbicide development, registration, and practical application in the field.

Overall, understanding both the active chemical and the roles of co-formulants is essential for predicting herbicide behavior in agricultural environments and implementing practices that protect soil health while ensuring effective weed control.

2.2 Formulation Types and Adjuvants

Commercial herbicide formulations are engineered using a variety of carrier systems—such as suspension concentrates (SC), emulsifiable concentrates (EC), and water dispersible granules (WDG)—that optimize handling, application, and biological activity of the active ingredients. The choice of formulation directly influences herbicide stability, absorption by plant foliage, movement in soil, and consequently, the environmental and ecological footprint of the product (Green &Beestman, 2007; Mesnage et al., 2013).

In addition to the active molecules, these formulations include diverse auxiliary components or adjuvants: surfactants, emulsifiers, dispersants, solvents, and stabilizers. Adjuvants are added to improve spray retention, droplet spread, and penetration of the herbicide into plant tissues. However, their chemical nature and concentration markedly alter the interaction of herbicides with soil, affecting sorption, microbial toxicity, and runoff potential (Green &Beestman, 2007).

Surfactants are a notable class of adjuvants. While enhancing herbicide efficacy on target weeds, they can also pose independent risks to soil health. For example, polyoxyethylene tallow amine (TN-20) is known for high cytotoxicity toward soil microorganisms and aquatic fauna, sometimes exhibiting greater toxicity than some active herbicide compounds themselves (Mesnage et al., 2013; Panneerselvam et al., 2021). In contrast, surfactants like polyethylene glycol (PEG 300), propylene glycol (PG), and monoethylene glycol (MEG) are generally regarded as less harmful to non-target organisms, thus preferred for minimizing adverse environmental effects (Panneerselvam et al., 2021).

The concentration and combinations of adjuvants within a formulation also impact herbicide persistence—the duration a compound remains active in the soil—and its biodegradation rate. Surfactants can accelerate or inhibit herbicide leaching and microbial breakdown, altering the exposure duration for soil microorganisms and risk of contamination of water bodies (Villaverde et al., 2008; Green &Beestman, 2007).

Given these findings, the selection of both active ingredients and adjuvant systems is crucial. Eco-toxicological assessment of all components—not just the herbicide—should be incorporated into product registration and sustainable field use. Strategies such as integrating less toxic surfactants, precision application methods, and routine monitoring of soil health indicators are recommended to manage herbicidal impacts on non-target soil biota and agricultural sustainability (Mesnage et al., 2013; Green &Beestman, 2007).

III. Soil pH and Electrical Conductivity

New generation herbicides applied at recommended rates generally exert minimal direct effects on fundamental soil chemical properties such as soil pH and electrical conductivity (EC). However, factors like herbicide persistence, repeated application, and specific soil physicochemical characteristics can cause subtle but important modifications to these parameters over time (Sondhia, 2014; Green &Beestman, 2007).

Soil pH plays a critical role in governing herbicide behavior, influencing both the chemical stability of the herbicide molecule and its bioavailability to plants and soil microorganisms (Oklahoma State University Extension, 2018). For example, herbicides belonging to triazine and sulfonylurea chemical families degrade faster in acidic or neutral soils but persist longer under alkaline (high pH) conditions. Conversely, imidazolinone herbicides tend to have increased persistence in acidic soils (WeedSmart, 2023; Oklahoma State University Extension, 2018). Such differential degradation impacts residual herbicide levels in soil, which may accumulate in specific pH contexts and modulate soil microbial activity and nutrient transformations (Swaine et al., 2025).

Electrical conductivity—a measure of soluble salts in the soil solution—can also be influenced by herbicide applications. Some herbicides, such as glyphosate, have been shown to increase soil EC by altering ionic concentrations and soil chemistry through microbial community changes or decomposition byproducts (Patel, 2008; Old Historicity, 2023). Elevated EC levels may indicate salt accumulation, which can adversely affect soil structure, water availability, and nutrient uptake by crops (KrishiBazaar, 2024). For instance, glyphosate-treated fields have exhibited increases in soil EC values by 0.3 to 0.5 dS/m relative to untreated controls in some studies (Patel, 2008).

The persistence of herbicides in soil—often quantified as half-life—varies widely due to soil moisture, temperature, organic matter, and microbial activity (Colquhoun, 2006; Chen et al., 2016). Dimethachlor, for example, exhibits a half-life that ranges from as low as 2 days to beyond 50 days depending on environmental and soil conditions, with longer persistence correlating to slower degradation and potential chronic soil interactions (ISWS, 2014; Chen et al., 2016). Such persistence can extend the period during which herbicides interact with soil chemical properties and biota, with implications for soil nutrient cycling and ecosystem functioning (Keerthi, 2025).

In summary, while new generation herbicides generally cause limited immediate shifts in soil pH and EC within recommended dosing, their long-term environmental behavior and accumulation under varying soil conditions necessitate careful management. Monitoring and adaptive management practices—considering soil pH, EC, and herbicide half-life—are essential to prevent undesirable alterations to soil chemistry and maintain sustainable agroecosystem health.

3.1 Soil Organic Carbon and Nutrient Reserves

Soil organic matter serves as the primary reservoir of essential plant nutrients, including carbon, nitrogen, phosphorus, and sulfur. Over 95% of organic sulfur and 20ΓÇô80% of organic phosphorus in soil are contained within organic matter reserves. Microorganisms are responsible for mobilizing these nutrients through decomposition and organic matter turnover processes.

Meta-analytic evidence demonstrates that herbicide applications, particularly fungicides and herbicides, result in negative responses in plant nutrient cycling functional groups. When aggregated across multiple pesticide treatments, significant overall negative effects emerge on nutrient cycling indicators (log response ratio [LRR] = ΓêÆ0.11 ┬▒ 0.03, P Γëñ 0.001). For fungicide-treated soils, plant nutrient cycling functional groups demonstrated negative responses (LRR = ΓêÆ0.34 ┬▒ 0.18, P Γëñ 0.001), while herbicide-treated soils showed similar patterns (LRR = ΓêÆ0.21 ┬▒ 0.16, P = 0.08). These reductions in microbial endpoints responsible for organic matter decomposition suggest potential decreases in bioavailable soil nutrients, including nitrogen, phosphorus, and sulfur (Swaine et al., 2025).

IV. Microbial Biomass and Community Composition

Soil microbial biomass constitutes the living fraction of soil organic matter, serving as an active reservoir of nutrients such as carbon and nitrogen critical for plant growth and soil fertility. It reflects the overall metabolic potential and health of soil ecosystems, making it a sensitive indicator of soil disturbance, including herbicide application (Anderson, 1984; Panneerselvam et al., 2021).

Experimental application of dimethachlor at concentrations 100 times higher than field rates initially caused a significant transient increase in microbial biomass carbon (MBC), with an approximate rise of 100 µg/g within seven days post-application. This initial stimulation may represent microbial proliferation driven by labile carbon sources provided by herbicide degradation byproducts. However, by day 112, MBC values declined to levels comparable to untreated controls, indicating eventual microbial community adaptation or recovery (Medo et al., 2021). At recommended application doses, no significant impact on microbial biomass carbon was observed, consistent with findings that typical field use of new generation herbicides minimally disrupts microbial biomass (Panneerselvam et al., 2021; Medo et al., 2021).

Advancements in molecular techniques, particularly high-throughput 16S rRNA gene sequencing, allow characterization of soil microbial community composition and its shifts with precision. Studies indicate that new generation herbicides applied at recommended doses cause subtle and transient modifications primarily affecting the relative abundance of dominant bacterial phyla (Pertile et al., 2021). However, at elevated doses, significant changes emerge. For instance, dimethachlor applied at a 100-fold field rate shifts bacterial populations by increasing Proteobacteria—especially herbicide-degrading genera such as Pseudomonas and Achromobacter—while reducing the abundance of Acidobacteria, which are generally more sensitive to chemical disturbances (Pertile et al., 2021).

These differential responses among microbial taxa suggest varying degrees of herbicide sensitivity, metabolic capabilities for degradation, and resilience. The enrichment of degradative taxa reflects natural selection pressures favoring microbial communities adapted to use herbicides or their breakdown products as energy sources, a process critical for herbicide dissipation and soil detoxification (Silva et al., 2023; Medo et al., 2021). However, reduced diversity or declines in sensitive functional groups like Acidobacteria may impair ecosystem processes including nutrient cycling and organic matter turnover (Swaine et al., 2025).

In summary, while recommended use rates of new generation herbicides generally maintain soil microbial biomass and community stability, elevated doses cause more pronounced shifts indicating potential disruption to soil microbial ecosystems. These findings underscore the importance of careful dosage regulation and monitoring microbial indicators to safeguard soil biological health in agricultural systems.

4.1 Ammonia-Oxidizing Microorganisms as Sensitive Indicators

Recent meta-analytic evidence identifies ammonia-oxidizing archaea (AOA) and bacteria (AOB) harboring the ammonia monooxygenase gene (amoA) as the most consistent and sensitive indicators of herbicide toxicity to soil microbiota (Swaine et al., 2025). Across aggregated pesticide treatments, AOA amoA gene abundance demonstrated the most significant reduction compared to other microbial endpoints (LRR = -0.37 ± 0.2, P = 0.003), with effects primarily driven by fungicide treatments (LRR = -0.83 ± 0.33, $P \leq 0.001$) and similarly pronounced effects from herbicide applications (Swaine et al., 2025).

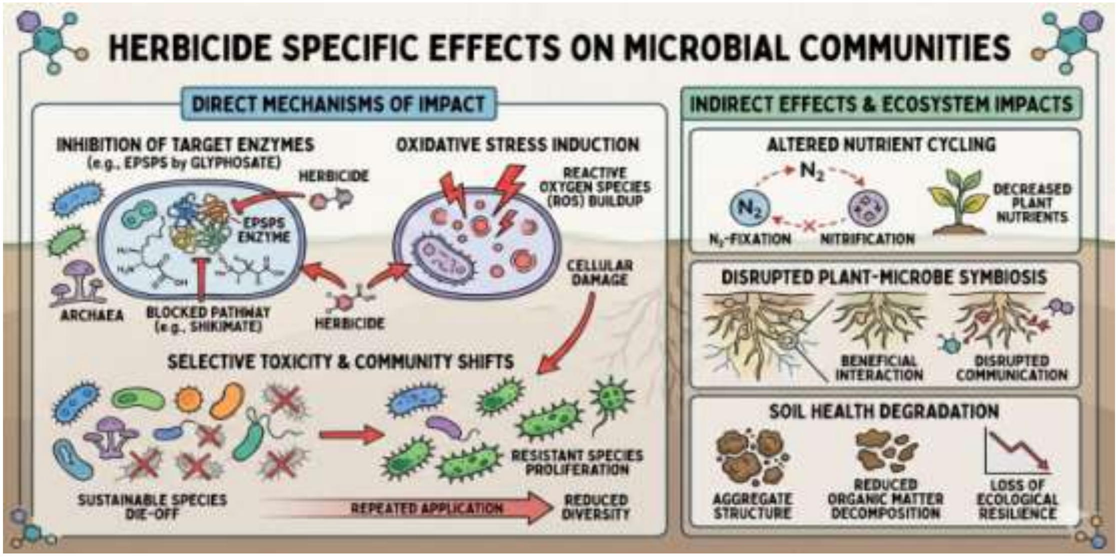
The pronounced sensitivity of ammonia-oxidizing microorganisms to herbicide exposure reflects both direct toxicity mechanisms and indirect effects mediated through alterations in microbial interactions (van Bruggen et al., 2021; Pester et al., 2012). Several herbicide classes, including sulfonylureas, triketones, and glyphosate-based compounds, inhibit plant enzymes with homologous bacterial targets, particularly within nitrifier genomes (van Bruggen et al., 2021). These shared biochemical pathways explain the herbicide toxicity observed in soil nitrifiers despite the absence of direct chemical interaction mechanisms in these non-target organisms (Wang et al., 2023; Limpiyakorn et al., 2011).

Tebuconazole, a triazole fungicide increasingly detected in European soils at concentrations exceeding predicted environmental concentrations, demonstrates significant effects on AOA amoA abundance even when analyzed among 65 individual active ingredients (Swaine et al., 2025; Han et al., 2021; Baćmaga et al., 2022). The mechanism of tebuconazole inhibition in AOA remains incompletely characterized, as sterol biosynthesis genes identified in archaea appear structurally distinct from fungicide binding sites (Baćmaga et al., 2022; Wang et al., 2016).

4.2 Herbicide-Specific Effects on Microbial Communities

Among new generation post-emergence herbicides evaluated in rice cultivation systems, differential effects on soil microbial communities emerge based on active ingredient and formulation type. Bispyribac sodium formulated as a suspension concentrate enhanced soil microbial properties compared to other herbicides, with microbial biomass carbon values reaching 549.10ΓÇô549.83 ┬╡ g/g soil/h and dehydrogenase activity values of 22.51ΓÇô23.17 ┬╡ g TPF/g soil/h. These enhancements in microbial parameters suggest that bispyribac sodium either exhibits minimal toxicity to soil microorganisms or stimulates microbial activity through alternative mechanisms.

Conversely, penoxsulam and flucetosulfuron demonstrated significant reductions in soil microbial properties. Penoxsulam treatment reduced microbial biomass carbon from control levels of 558.45ΓÇô558.63 ┬╡ g/g soil/h to 514.88ΓÇô484.87 ┬╡ g/g soil/h at recommended and double recommended doses respectively. Similarly, dehydrogenase activity declined from 23.06 ┬╡ g TPF/g soil/h in controls to 18.82ΓÇô20.03 ┬╡ g TPF/g soil/h in penoxsulam-treated soils. These reductions reflect acetolactate synthase inhibition affecting both plant and microbial targets.



V. Influence on Soil Enzyme Activities

5.1 Dehydrogenase Activity

Dehydrogenase enzymes represent strictly intracellular enzymes produced by living microbial cells and serve as sensitive markers of pesticide impacts on soil microorganisms. Their activity indicates the metabolic capacity of the soil microbial community and reflects the oxidation-reduction status of the soil environment. Herbicide applications at 100-fold field rates significantly decrease dehydrogenase activity, with reductions to 10ΓÇô40% of control values observed particularly around day 56 of incubation. At recommended field rates, herbicides do not significantly lower dehydrogenase activity compared to controls, suggesting that appropriate dosing preserves this critical enzyme activity.

Certain new-generation herbicides demonstrate dose-dependent effects on dehydrogenase activity. Penoxsulam at the recommended dose reduced dehydrogenase activity to 20.03 ┬╡ g TPF/g soil/h compared to controls at 23.06 ┬╡ g TPF/g soil/h. Double-dose penoxsulam further reduced activity to 18.82 ┬╡ g TPF/g soil/h, indicating progressive inhibition with increasing herbicide concentration.

5.2 Fluorescein Diacetate Hydrolysis

Fluorescein diacetate (FDA) hydrolysis represents a broad-spectrum measure of soil microbial activity, reflecting the action of non-specific extracellular enzymes, including esterases, proteases, and lipases involved in organic matter decomposition. Unlike dehydrogenase, FDA hydrolysis responds more variably to herbicide exposure, with some herbicides increasing activity while others reduce it. This differential response reflects the diverse enzyme systems contributing to FDA hydrolysis and the heterogeneous composition of the soil microbial community.

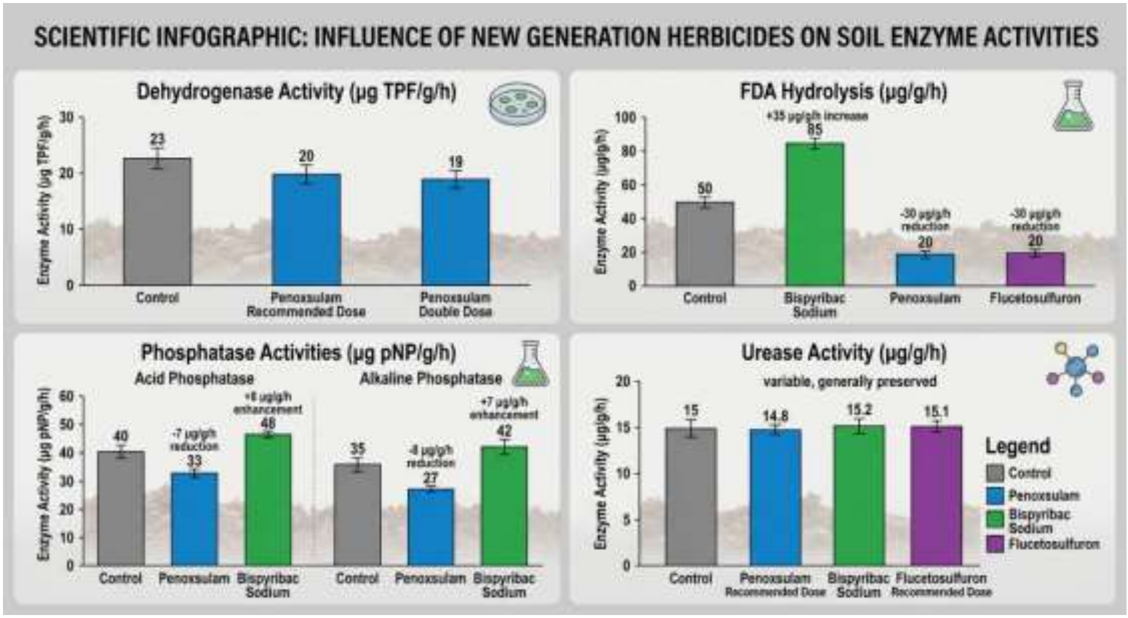
Meta-analytic assessment across 59 global studies identified FDA hydrolysis as exhibiting a significant reduction in fungicide-treated soils (LRR = ΓêÆ0.41 ┬▒ 0.24, P = 0.002), though responses in herbicide-treated soils were less consistent. For new generation post-emergence herbicides in rice, bispyribac sodium enhanced FDA activity (34.92ΓÇô36.46 ┬╡ g/g soil/h), while penoxsulam and flucetosulfuron reduced FDA activity to 28.92ΓÇô33.01 ┬╡ g/g soil/h.

5.3 Phosphatase and Urease Activities

Acid and alkaline phosphatases participate in the hydrolysis of organic phosphorus compounds, making these enzymes critical for phosphorus cycling and plant-available phosphorus maintenance. Urease catalyzes the hydrolysis of urea to ammonia and carbon dioxide, serving as an essential catalyst in the nitrogen cycle.

Herbicide applications produce variable effects on phosphatase activities. Penoxsulam treatment reduced both acid phosphatase activity from control values of 40.03ΓÇô40.30 ┬╡ g p-nitrophenol released/g soil/h to treatment values of 32.50ΓÇô33.80 ┬╡ g/g soil/h and alkaline phosphatase activity from 34.80ΓÇô35.83 ┬╡ g/g soil/h to 26.10ΓÇô28.13 ┬╡ g/g soil/h. Bispyribac sodium conversely enhanced both acid and alkaline phosphatase activities, suggesting enhancement of phosphorus cycling capabilities.

Urease activity demonstrated significant reduction in fungicide-treated soils (LRR = ΓêÆ0.37 ┬▒ 0.19, P = 0.002) but variable responses to herbicide exposure. The preservation of urease activity at recommended herbicide doses suggests minimal interference with nitrogen transformations at typical field application rates.



VI. Impact on Plant-Microbe Interactions

6.1 Arbuscular Mycorrhizal Fungal Associations

Arbuscular mycorrhizal fungi (AMF) establish obligate symbiotic associations with plant roots, enhancing nutrient acquisition, particularly for phosphorus and certain micronutrients, while receiving photosynthetically-fixed carbohydrates from host plants. These symbiotic relationships substantially improve plant nutrient uptake capacity and contribute to soil structure stability through hyphal networks.

Evaluation of new generation post-emergence herbicides reveals differential impacts on AMF root colonization and sporulation. Among herbicides tested in rice cultivation, penoxsulam significantly reduced AMF root colonization from control levels of 80.0% to 57.0% at the recommended dose and 42.3% at double the recommended dose. This reduction in mycorrhizal association reduces plant access to phosphorus and other immobile nutrients, potentially limiting plant growth and development even if soil nutrient concentrations remain adequate.

Bispyribac sodium formulated as a suspension concentrate enhanced AMF colonization to 82.0ΓÇô86.7% and increased sporulation to 1019ΓÇô1077 spores/100 g soil compared to control values of 860 spores/100 g soil. This enhancement suggests compatibility between bispyribac sodium and beneficial mycorrhizal associations. Flucetosulfuron reduced colonization to 65.7% and sporulation to 783ΓÇô822 spores/100 g soil, indicating herbicide-specific effects on AMF dynamics.

6.2 Rhizosphere Microbe Interactions

The rhizosphere represents the soil region immediately surrounding plant roots, where microbial populations respond to root exudates containing amino acids, carbohydrates, and other organic compounds. Root exudates shape rhizosphere microbiome composition and drive metabolic processes supporting plant nutrient acquisition. Herbicide-induced alterations in photosynthesis, as evidenced by reductions in chlorophyll accumulation with some herbicides, including glyphosate, reduce root exudation and thereby indirectly affect rhizosphere microbial communities and metabolic activity.

Plant-microbe signaling in the rhizosphere facilitates nutrient acquisition, pathogen suppression, and stress tolerance. Herbicide effects on root exudation quality and quantity consequently cascade through rhizosphere processes, affecting nutrient transformation rates and plant-available nutrient concentrations.

VII. Herbicide Residues and Persistence in Soil

7.1 Half-Life and Environmental Persistence

The persistence of herbicide residues in soil fundamentally determines the duration and intensity of herbicide-soil microorganism interactions. Contemporary herbicides demonstrate highly variable soil half-lives ranging from 2ΓÇô48 days to extended periods exceeding 50 days, depending on soil properties, climatic conditions, and microbial degradation rates.

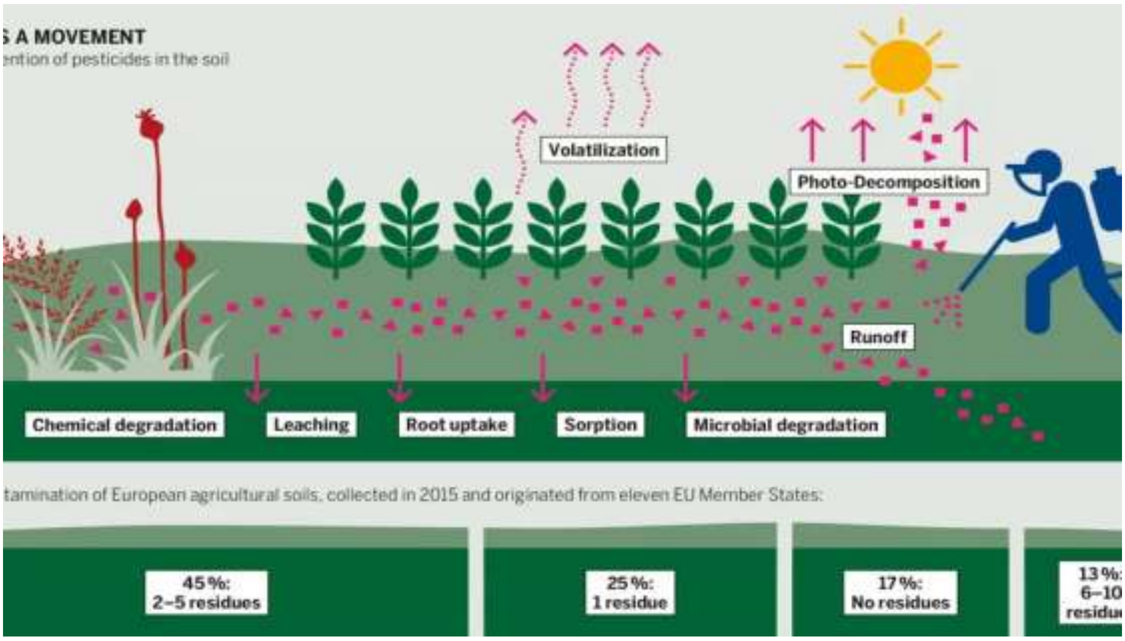
Dimethachlor, a chloroacetamide herbicide, typically demonstrates half-lives of 2ΓÇô16 days but can persist for extended periods in specific soil conditions. This variable persistence reflects the role of soil microorganisms in herbicide dissipation through metabolism and degradation. Linuron, a phenylurea herbicide, presents more extended persistence with field half-lives in the 10ΓÇô170 day range (median 48 days), reflecting slower soil microbial degradation rates and greater chemical stability.

7.2 Herbicide Accumulation and Soil Degradation

Repeated herbicide applications, particularly when applications exceed recommended intervals and dosages, can lead to herbicide accumulation in soil. Long-term field studies reveal that cumulative herbicide residue concentrations significantly exceed single application concentrations, extending the duration of microorganism-herbicide interactions. This accumulation pattern has important implications for soil health preservation and the sustainability of herbicide efficacy in field conditions.

7.3 Residue Degradation Pathways

Soil microorganisms possess diverse metabolic pathways enabling herbicide mineralization and degradation. Meta-analysis of predicted microbial gene expression reveals that dimethachlor application triggers upregulation of genes associated with xenobiotic degradation pathways, including caprolactam, styrene, benzoate, and polycyclic aromatic hydrocarbon degradation. This transcriptomic response identifies specific microbial groups adapted to herbicide degradation, primarily within the Proteobacteria phylum. Similarly, Pseudomonas and Achromobacter genera proliferate in dimethachlor-treated soils, reflecting their enhanced capacity for herbicide biodegradation compared to other bacterial groups.



VIII. Nitrification and Nitrogen Cycle Dynamics

8.1 Effects on Nitrification Rates

Nitrification, the oxidation of ammonia to nitrate mediated by specialized ammonia-oxidizing archaea and bacteria, represents a critical step in nitrogen cycling. Nitrification rates directly influence plant-available nitrogen concentrations and nitrogen loss through leaching and denitrification. Meta-analytic evidence demonstrates consistent reductions in nitrification activity following herbicide applications, with both fungicides (LRR = ΓêÆ0.34 ┬▒ 0.22, P Γëñ 0.001) and herbicides (LRR = ΓêÆ0.34 ┬▒ 0.28, P = 0.001) producing similar inhibitory effects.

Herbicides inhibit nitrification through multiple mechanisms. Direct toxicity mechanisms involve herbicide binding to nitrifier-specific enzymes or metabolic targets. Indirect mechanisms operate through herbicide-induced reductions in ammonia availability to nitrifiers due to decreased plant biomass and reduced organic matter inputs, or through competition between nitrifiers and other microbial groups for limiting resources. Additional indirect effects may operate through herbicide suppression of nitrifier predators including bacteriophages and protozoa.

8.2 Ammonia Accumulation and Toxicity

When nitrification rates decline, ammonia accumulates in soil to concentrations that can become toxic to plants and soil organisms. Excessive ammonia disturbs nutrient uptake balance, disrupts plant hormonal regulation, decreases soluble carbohydrate accumulation, and impairs photosynthesis and associated metabolic pathways. The inhibition of nitrification by certain herbicides may paradoxically increase soil ammonia concentrations, potentially exacerbating plant stress even though available nitrogen concentrations remain adequate.

8.3 Potential Nitrification Methodology

Potential nitrification assays represent standardized methods for assessing soil nitrification capacity but demonstrate significant limitations in detecting herbicide-induced nitrification inhibition. Despite standardized protocols (ISO-15685), potential nitrification does not account for differential physiologies of nitrifying organisms including substrate preferences, ammonia affinity, and cell-specific enzyme activity rates. This methodological limitation explains why potential nitrification frequently demonstrates insignificant responses to herbicide applications while more sensitive molecular indicators (amoA gene abundance) reveal substantial herbicide-induced inhibition of ammonia-oxidizing microorganisms.

IX. Sustainable Alternatives and Future Perspectives

9.1 Integrated Weed Management Approaches

Integrated weed management (IWM) combines multiple control strategies, including cultural, mechanical, biological, and chemical approaches, reducing reliance on single-herbicide control systems. IWM strategies, including crop rotation, tillage modification, mulching, and early-season weed control, reduce herbicide application frequency and rates while maintaining effective weed control. Implementation of IWM demonstrates reduced soil microbial disturbance compared to herbicide-only control systems, though requires increased management complexity.

9.2 Biorational and Bioherbicide Development

Biorational herbicides based on natural compounds or microbial metabolites represent promising alternatives to synthetic chemical herbicides. Natural phytotoxins, including fungal metabolites (radicinin, tenuazonic acid, thaxtomin A) and plant-derived compounds, demonstrate selectivity against problematic weeds and unique mechanisms of action differing from conventional herbicides. These characteristics enable effective control of herbicide-resistant weed populations.

However, most commercially available biorational herbicides target organic agriculture markets, typically requiring higher application rates, more frequent applications, and commanding premium prices compared to synthetic alternatives. Development of improved biorational formulations through enhanced production optimization, selective microbial strain selection, and advanced delivery systems could expand commercial viability for broader adoption in conventional agricultural systems.

9.3 Controlled-Release Formulations and Nanotechnology

Contemporary herbicide formulation research emphasizes controlled-release systems and nanotechnology-based delivery platforms to minimize environmental dispersal while maintaining herbicide efficacy. Polymer-based microencapsulation systems using materials including poly(3-hydroxybutyrate), polyurethane urea, and polyesters enable gradual herbicide release and reduced soil residence time. Laboratory and field evaluations demonstrate that controlled-release formulations maintain equivalent herbicide efficacy while reducing total active ingredient requirements and environmental persistence.

Nanotechnology-based herbicide formulations, including nanoemulsions and nanoparticles, demonstrate enhanced absorption and translocation in plants compared to conventional formulations. However, questions regarding long-term soil accumulation of nanomaterials and potential nano-specific toxicity to soil organisms remain inadequately characterized, requiring systematic investigation before widespread implementation in agricultural systems.

9.4 Selective Herbicide Combinations

Strategic combination of herbicides with divergent modes of action reduces selection pressure for herbicide-resistant weed populations while potentially moderating impacts on non-target soil organisms. Evidence from this review indicates that combination herbicides can substantially modify herbicide effects on soil microorganisms compared to individual active ingredients. For example, the combination of penoxsulam plus cyhalofop-butyl substantially reduced detrimental effects on arbuscular mycorrhizal associations compared to penoxsulam applied individually, while the combination of fenoxaprop-p-ethyl plus ethoxysulfuron demonstrated negative synergistic effects on soil microbial properties.

X. Regulatory Framework and Recommendations

10.1 Current Regulatory Limitations

Current regulatory frameworks assessing herbicide impacts on soil health rely primarily on the nitrogen transformation test (OECD 216), which has received substantial criticism for low resolution and erratic performance. Contemporary evidence demonstrates that standardized soil microbial endpoints, particularly ammonia-oxidizing microorganism abundance provides superior sensitivity to herbicide-induced soil disturbance compared to conventional regulatory tests. The regulatory framework inadequately addresses accumulated pesticide residues in soil and their cumulative effects on soil microbiota, despite widespread soil contamination with residue concentrations frequently exceeding predicted environmental concentrations.

10.2 Recommendations for Sustainable Herbicide Management

Based on this comprehensive review, the following recommendations emerge for herbicide management, balancing effective weed control with soil nutrient preservation:

1. Herbicide Selection Criteria: Agricultural practitioners should prioritize herbicides demonstrating minimal effects on ammonia-oxidizing microorganisms and soil enzyme activities at recommended application rates. Bispyribac sodium suspension concentrate formulations appear preferable to certain ALS-inhibitor class herbicides based on demonstrated compatibility with soil microbial communities.

2. Application Dose Adherence: Strict adherence to manufacturer-recommended application rates and intervals substantially preserves soil microbial function and nutrient cycling rates. Double-recommended-dose applications show pronounced negative effects on soil enzyme activities and ammonia-oxidizing organisms, suggesting that application dose optimization represents a critical management practice.

3. Formulation Consideration: Suspension concentrate formulations generally exhibit reduced toxicity to soil microorganisms compared to emulsifiable concentrate formulations, likely reflecting differences in surfactant toxicity. Selection of herbicide formulations incorporating non-toxic adjuvants (PEG 300, propylene glycol, monoethylene glycol) may reduce unintended soil microbial impacts.

4. Temporal Application Scheduling: Implementing herbicide-free intervals and rotating herbicide modes of action reduces cumulative soil residue concentrations and associated microbial disturbance. Reduced herbicide application frequency through improved cultural practices (mulching, cover crops, crop rotation) preserves soil health more substantially than chemical weed control alone.

5. Mycorrhizal Management: Herbicide selection should consider compatibility with beneficial mycorrhizal associations, as arbuscular mycorrhizal colonization substantially enhances plant nutrient acquisition capabilities. Selection of mycorrhizal-compatible herbicides or implementation of strategic herbicide combinations can substantially preserve these beneficial plant-microbe associations.

XI. Conclusion

New generation herbicides have substantially advanced weed management capabilities through enhanced selectivity, reduced environmental persistence, and novel modes of action. However, substantial evidence demonstrates that certain contemporary herbicides and formulations can negatively impact soil nutrient dynamics through effects on soil microbial communities, enzyme activities, and plant-microbe interactions. Most critically, ammonia-oxidizing microorganisms emerge as the most sensitive indicators of herbicide toxicity to soil microbiota, with consistent inhibition observed across fungicide and herbicide applications.

When applied at manufacturer-recommended rates, most new-generation herbicides demonstrate transient, minimal effects on soil nutrient cycling and microbial communities. However, application doses exceeding recommendations, repeated applications without adequate intervals, or selection of particularly sensitive herbicide active ingredients can substantially impair soil microbial function and nutrient availability. The observed compatibility between bispyribac sodium and soil microbial processes, contrasted with documented inhibitory effects of certain ALS-inhibitor class herbicides, demonstrates that herbicide active ingredient and formulation selection substantially influence soil health impacts.

Future advances in sustainable weed management require integrated approaches that combine herbicide selection optimization, adherence to appropriate application rates and intervals, implementation of crop management practices that reduce herbicide dependency, and regulatory framework modernization that incorporates sensitive soil microbial endpoints. Development of controlled-release formulations, biorational herbicides, and combination strategies represents promising directions for reducing herbicide impacts on soil health while maintaining effective weed control in agricultural systems.

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