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Herbicides Effects on Soil Functions: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

This review explores the impact of herbicides on soil functions, offering a detailed analysis of how these chemicals influence soil health. Herbicides, commonly used for controlling unwanted plants,

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often disturb the balance of soil ecosystems by altering microbial diversity, disrupting nutrient cycling, and affecting organic matter breakdown. The findings show that herbicides can either inhibit or stimulate soil microbial activities, depending on their type, concentration, and environmental conditions. While some herbicides have minimal short-term effects on soil respiration and microbial activity, others significantly reduce soil enzyme activities, slow down nitrogen mineralization, and disrupt beneficial microbial relationships, such as those involving mycorrhizal fungi. The persistence of herbicide residues in soil presents further challenges, with potential risks of contaminating soil and groundwater. It highlights the importance of using herbicides carefully, considering both their effectiveness in weed control and their long-term effects on soil health. However, the paper concludes with an evaluation of the ecological and evolutionary impacts of herbicides on soil microbial communities, calling for further research to fully understand these complex interactions.

Keywords: Herbicides; soil microbial communities; nutrient cycling; soil contamination; organic matter decomposition; environmental impact.

1. INTRODUCTION

Herbicides, though effective in controlling unwanted plants, can significantly impact soil functions and processes. They often reduce the diversity and abundance of crucial soil microorganisms like bacteria, fungi, and protozoa, which play essential roles in nutrient cycling and organic matter decomposition. However, in recent years, the agrochemical industry has seen a surge in the production of various herbicides designed to target and eliminate specific weeds at different stages of their growth [1]. By 2016, over 2,000 herbicides, categorized into 15 different modes of action, had been introduced to the global market [2]. The effectiveness of these herbicides in controlling weeds has led to their widespread adoption among farmers. However, excessive use of these chemicals can disrupt natural processes and harm non-target organisms [3]. Soil, which serves as a repository for agricultural contaminants, is a major habitat for microbial communities like bacteria, fungi, and actinomycetes. These microorganisms play crucial roles in maintaining soil fertility through the degradation of organic material, decomposition, and nutrient cycling [4]. In modern agriculture, the microbial population in soil is considered a key indicator of agricultural health and productivity. Soil microorganisms are essential in linking the soil, plant, herbicide, fauna and human relationships, particularly through their role in herbicide degradation [5]. The application of herbicides can lead to significant changes in the soil microbial population, both quantitatively and qualitatively, potentially affecting plant growth. The impact of herbicides on microbial growth whether stimulating or inhibiting depends on the type and concentration of the chemicals, the species of microorganisms present, and environmental conditions. This review aims to assess the effects of herbicide use on soil function and processes and how it affects soil microbes.

2. DATA SOURCING

The data and information presented in this manuscript were gathered from secondary sources, including reputable scientific publications and research institutions such as Google Scholar, ResearchGate, Scopus, and Web of Science. Key search terms and phrases used to identify relevant resources included “herbicides effects on soil function and processes,” “herbicide effects on soil microorganisms,” and “impacts of herbicides residue.” The selected materials were thoroughly reviewed, downloaded, and cited to ensure they were relevant and aligned with the focus of the manuscript.

3. SOIL AS A REPOSITORY FOR HERBICIDES

The soil acts as a repository for agricultural contaminants such as herbicides and serves as a major habitat for microbial communities, including bacteria, fungi, and actinomycetes. These microorganisms play a critical role in soil fertility through organic material degradation, organic matter decomposition, and nutrient cycling [6,7,8]. However, excessive application of herbicides can inhibit these natural processes and decrease the performance of non-target organisms [3]. Some soil organisms, however, utilize these herbicides as a carbon energy source for their metabolic activities. The extent of soil contamination with herbicides depends on several factors, including the persistence of the herbicides in the soil environment, the quantity and frequency of application, and the toxicity of the chemicals. Herbicides are often designed to persist long enough to effectively control weeds [9,10,11]. The fate of herbicides in the soil is influenced by two major processes: transfer and degradation. The transfer process includes percolation, runoff, uptake by flora and fauna, and sorption and desorption, which allows the chemicals to remain physically intact in the soil. The degradation processes encompass microbial decomposition, plant detoxification, rhizosphere chemical breakdown, and photodecomposition, which are chemically engineered. These processes determine the persistence of herbicides, their efficacy against weeds, and their potential for soil and groundwater contamination [3].

4. EFFECT OF HERBICIDES ON SOIL FUNCTIONS

Herbicide application impacts not only target organisms but also soil microorganisms, often adversely affecting key soil functions. A significant side effect of herbicides is their disruption of soil biochemical processes. These chemicals can hinder biochemical reactions by interfering with soil enzymatic activity and microbial growth [12]. Herbicides can be toxic to microbial populations, leading to reduced microbial biomass, soil heterotrophic respiration, and the activity of organic matter-decomposing and nutrient-cycling microbes [13]. However, microbial populations and enzyme activities may recover after an initial period of inhibition, potentially due to microbial adaptation to the herbicides or the degradation of the chemicals. Additionally, plant debris from herbicide-killed plants can increase nutrient availability, supporting microbial growth and activity [14]. For example, an increase in soil dehydrogenase (DH) activity from the 7th to the 28th day after herbicide application may be attributed to a rise in microbial communities that utilize herbicides as a carbon source [11], whereas protease activity is influenced by proteolytic bacteria distribution [15].

Specific herbicides have varied effects on soil functions:

- Glyphosate, applied at recommended rates, does not significantly affect soil respiration [13].
- Pretilachlor enhances respiration activity and microbial biomass [16].
- Conventional rates of alachlor, metolachlor, and butachlor do not affect soil dehydrogenase activity [17]. However, butachlor (5 to 100 mg/kg) significantly reduces methane production in alluvial-rich soil [18].
- Sulfonylurea herbicides, applied at recommended rates, do not significantly impact respiration [13].
- A mixture of nicosulfuron, atrazine, and dimethenamide does not significantly alter soil methane oxidation rate or the abundance of methane oxidizers [19].

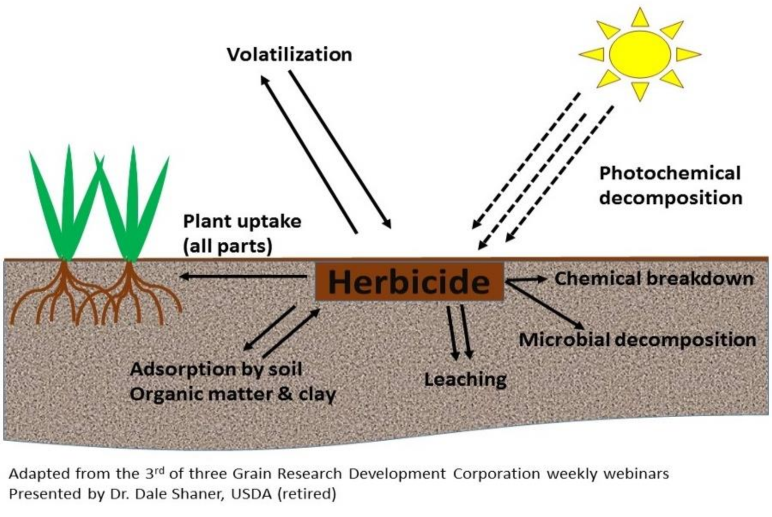

Fig. 1. Fate of herbicide after field application

- Imazaquin (0.14 kg/ha) applied to field-grown soybean has no effect on soil microbial biomass, dehydrogenase, or hydrolase activity [20].
- Atrazine application at rates greater than 100 mg/kg increases soil microbial activity, such as respiration and dehydrogenase activity [21], whereas application at recommended rates (5 mg/kg) shows no significant effect on β-glucosidase activity [22].

4.1 Selected Herbicides Impacts on Soil Function

The impacts of various herbicides on soil functions have been extensively studied. Zhang *et al.* [23] found that Chlorimuron-ethyl significantly reduces the number and diversity of N-fixing bacteria in soil. Zabaloy and Gomez [24], along with Zabaloy *et al.* [25], observed that 2,4-Dichlorophenoxyacetic acid has minor and transient effects on microbial respiration at low rates [26], but at higher rates, it inhibits hydrolase and stimulates dehydrogenase activities. Wang *et al.* [24], Han *et al.* [27], Chang *et al.* [28], and Astaykina *et al.* [29] reported that Atrazine exposure leads to adaptive changes in animal-host gut microbiomes, decreasing earthworm gut microbiome diversity and exerting selective pressure on host genomes. Perucci *et al.* [30] noted a decline in acid and alkaline phosphatase activity at lower concentrations of Butachlor, but an increase in alkaline phosphatase activity at higher concentrations. Damin *et al.* [31] showed that Glyphosate slows down N-mineralization and reduces N uptake by subsequent crops. Kumari *et al.* [32] and Angelini *et al.* [33] observed that Butachlor, Metolachlor, and Alachlor reduce N-fixation by cyanobacterial mats, decrease cyanobacterial diversity, and lower diazotroph numbers in aerobic soils. Casabe´ *et al.* [34], Zaller *et al.* [35], and Druille *et al.* [36] found that Glyphosate alters ecological interactions between earthworms, mycorrhizal fungi, and plants, reduces mycorrhizal spore counts, and causes *E. fetida* to exhibit avoidance behavior. Finally, Omotayo and Okoro [37] documented that Paraquat reduces the bacterial population, particularly *Luteimonas* and *Pseudo-propionibacterium*, within 14 days.

5. CONSEQUENCES OF HERBICIDE RESIDUES FOR SOIL PROCESSES

The impact of herbicide residues on soil processes is influenced by the chemical composition of the herbicides, their mode of action, the susceptibility of soil microbes, and various edaphic and climatic factors. Predicting the fate and legacy of herbicides in soil is challenging due to the interplay of multiple factors: herbicides affect microbial communities, and microbes can degrade these herbicides. The interactions between these processes are shaped by the physical and chemical properties of the soil, agricultural management practices, and climatic conditions, leading to variable findings on herbicide effects on soil microbiomes [38,39]. For instance, glyphosate disrupts the shikimate pathway in most microbes, but genetic resistance to glyphosate varies among microbial communities [40]. Consequently, glyphosate-degrading microbes that use glyphosate as a nutrient source may become more prevalent in the microbial community [41]. Similarly, while atrazine may not impact the overall microbial community in some environments, it can reduce soil microbial biomass or promote atrazine-degrading bacteria in other settings, leading to enhanced atrazine degradation [42,43].

5.1 Effects of Herbicide Residues on Soil

The presence of herbicide residues in soil raises significant concerns due to their potential direct impacts on plants and soil microorganisms. While herbicides applied at recommended field rates are generally considered to have minimal long-term effects on microbial populations, their presence can still influence soil functions and health. An ideal herbicide should effectively target pests while quickly breaking down into non-toxic substances [44]. Herbicides such as glyphosate residing in soil not only affect rhizosphere microbiota but also aerial plant endophyte functionality, which emphasizes the destructive effects of such herbicides on plant symbiotic microbes, here with cascading effects on plant-pest insect interactions [45]. This means, herbicides can either inhibit or stimulate microbial activities, affecting crucial processes such as nitrogen fixation, nitrification, and denitrification. This can lead to alterations in nutrient availability for plants. Additionally, soil enzymes, which are essential for organic matter decomposition and nutrient cycling, can be inhibited by herbicides, resulting in slowed decomposition and reduced nutrient availability as noted by [30,23]. The type and concentration of herbicides can disrupt soil enzyme profiles, creating imbalances in soil biochemical processes. Their effects on the decomposition rate of organic matter can either accelerate or decelerate, further influencing soil structure and

Table 1. Identified ecological and evolutionary impacts of herbicides on soil and microbial communities from the study

Impact Category	Details
Microbial Diversity Reduction	Herbicides can reduce the diversity of soil microbial communities, leading to a decline in beneficial microorganisms that play key roles in nutrient cycling, organic matter decomposition, and soil fertility maintenance.
Alteration of Microbial Functions	Certain herbicides inhibit critical microbial functions, such as nitrogen fixation, phosphorus solubilization, and organic matter decomposition, leading to disruptions in nutrient availability and soil health.
Soil Enzyme Activity Inhibition	Herbicides can decrease the activity of soil enzymes involved in essential processes like decomposition of organic matter, nitrogen mineralization, and carbon cycling, which can impair soil fertility and plant growth.
Development of Herbicide-Resistant Microbes	Continuous exposure to herbicides may drive the evolution of resistant microbial strains, leading to a shift in microbial community composition and potentially reducing the efficacy of herbicides over time.
Disruption of Symbiotic Relationships	Herbicides can negatively impact symbiotic relationships, such as those between plants and mycorrhizal fungi, reducing the ability of plants to uptake nutrients and affecting overall plant health and growth.
Soil Contamination and Residue Persistence	Herbicide residues can persist in the soil, leading to long-term contamination that affects soil structure, microbial health, and the overall ecosystem, with potential risks of bioaccumulation and groundwater contamination.
Alteration of Soil Physical Properties	Herbicides may indirectly affect soil physical properties by altering microbial activity, leading to changes in soil structure, porosity, and water retention, which can impact plant root growth and soil erosion.
Evolutionary Pressure on Microbial Communities	The selective pressure exerted by herbicides can lead to an evolutionary shift in microbial communities, favoring the survival of resistant or adaptable species, which may alter the natural balance of soil ecosystems.

Source: Author's Compilation

fertility. Moreover, some herbicides negatively impact mycorrhizal associations, which are crucial for nutrient and water uptake. Certain microorganisms are capable of degrading herbicides, while others may be adversely affected, depending on the application rates and the specific herbicide used [1]. The ecological and evolutionary impacts of glyphosate and other herbicides on microbial soil communities are not yet fully understood [46]. Recent studies suggest a negative correlation between pesticide use and beneficial soil and root-associated microbes, as well as disturbances in herbicide-modulated nutrient cycling [47]. For example, glyphosate, which contains phosphorus, can contribute to increased phosphorus loads in the ecosystem [48].

6. CONCLUSION

Herbicides, though vital for modern agricultural practices, pose significant risks to soil health and function. The disruption of soil microbial communities and the inhibition of key soil processes can lead to reduced soil fertility, impacting crop productivity and environmental sustainability. The persistence of herbicide residues in soil and their potential to contaminate groundwater further exacerbates these concerns. Therefore, while herbicides are effective in weed control, their long-term ecological impacts need to be carefully managed.

7. RECOMMENDATIONS

1. **Integrated Weed Management:** Adopt integrated weed management practices that reduce reliance on chemical herbicides by incorporating mechanical, cultural, and biological control methods.
2. **Use of Biodegradable Herbicides:** Encourage the development and use of herbicides that degrade quickly in the environment to minimize long-term soil contamination. Examples of biodegradable herbicides include acetic acid (vinegar-based

herbicides), pelargonic acid, soap-based herbicides etc.

3. **Monitoring and Regulation:** Implement strict monitoring and regulation of herbicide application rates and frequencies to prevent excessive buildup in soil.
4. **Soil Health Programs:** Promote soil health programs that focus on maintaining and enhancing microbial diversity and activity through the use of organic amendments and conservation tillage.
5. **Research and Development:** Support research into the ecological impacts of herbicides and the development of alternative weed control methods that are less harmful to soil ecosystems.
6. **Farmer Education:** Educate farmers on the potential risks associated with herbicide use and the benefits of adopting sustainable agricultural practices.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Sebiomo A, Ogundero VW, Bankole SA. Effect of four herbicides on microbial population, soil organic matter, and dehydrogenase activity. African Journal of Biotechnology. 2011;10:770–778.
2. Choudhury PP, Singh R, Ghosh D, Sharma AR. Herbicide use in Indian agriculture (p. 110). ICAR-Directorate of Weed Research, Jabalpur, Madhya Pradesh; 2016.
3. Subhani A, El-ghamry AM, Huang C, Xu J. Effect of pesticides (herbicides) on soil microbial biomass – A review. Pakistan Journal of Biological Sciences. 2000; 3(5):705–709.
4. Zain MMM, Rosli BM, Kamaruzaman S, NurMasirah M, Yahya A. Effects of selected herbicides on soil microbial populations in oil palm plantation of Malaysia: A microcosm experiment. African Journal of Microbiology Research. 2013;7(5):367–374.
5. Raj SK, Syriac EK. Herbicidal effects on the bio-indicators of soil health - A review. Journal of Applied and Natural Science. 2017;9:2438–2448.
6. Hutsch BW. Methane oxidation in non-flooded soils as affected by crop production. European Journal of Agronomy. 2001;14:237–260.
7. De-Lorenzo ME, Scott GI, Ross PE. Toxicity of pesticides to aquatic microorganisms: A review. Environmental Toxicology and Chemistry. 2001;20:84–98.
8. Rosli BM, Kamaruzaman S, Nur Masirah M, Zain MMM, Yahya A. Effects of selected herbicides on soil microbial populations in oil palm plantation of Malaysia: A microcosm experiment. African Journal of Microbiology Research. 2013;7(5):367–374.
9. Greer CW, Hawari J, Samson R. Influence of environmental factors on 2,4-dichlorophenoxyacetic acid degradation by *Pseudomonas cepacia* isolated from peat. Archives of Microbiology. 1990;154:317–322.
10. Wang QK, Wang SL, Liu YX. Responses to N and P fertilization in a young Eucalyptus dunnii plantation; microbial properties, enzyme activities, and dissolved organic carbon. Applied Soil Ecology. 2008;40:484–490.
11. Vandana LJ, Rao PC, Padmaja G. Effect of herbicides and nutrient management on soil enzyme activity. Journal of Rice Research. 2012;5:1–2.
12. Maheswari ST, Ramesh A. Fate and persistence of herbicide residues in India. In Herbicide residue research in India. 2019;1–28.
13. Rose MT, Cavagnaro TR, Scanlan CA, Rose TJ, Vancov T, Kimber S, Kennedy IR, Kookana RS, Zwieten LV. Impact of herbicides on soil biology and function. Advances in Agronomy. 2016;136:133–220.
14. Sondhia S, Waseem U, Varma RK. Fungal degradation of an acetolactate synthase (ALS) inhibitor pyrazosulfuron ethyl in soil. Chemosphere. 2013;93:2140–2147.
15. Subrahmanyam G, Archana G, Chamyal LS. Soil microbial activity and its relation to soil indigenous properties in semi-arid alluvial and estuarine soils of Mahi river basin, Western India. International Journal of Soil Science. 2011;6:224–237.

16. Kumar A, Nayak AK, Shukla AK, Panda BB, Raja R, Shahid M, Tripathi R, Mohanty S, Rath PC. Microbial biomass and carbon mineralization in agricultural soils as affected by pesticide addition. Bulletin of Environmental Contamination and Toxicology. 2012;88:538–542.
17. Subhani A, Liao M, Huang CY, Xie ZM. Alteration of certain soil microbiological and biochemical indices of a paddy soil under anthropogenic stress. Journal of Zhejiang University Science. 2002;3:467–474.
18. Mohanty SR, Nayak DR, Babu YJ, Adhya TK. Butachlor inhibits production and oxidation of methane in tropical rice soils under flooded condition. Microbiological Research. 2004;159:193–201.
19. Seghers D, Siciliano SD, Top EM, Verstraete W. Combined effect of fertilizer and herbicide applications on the abundance, community structure, and performance of the soil methanotrophic community. Soil Biology and Biochemistry. 2005;37:187–193.
20. Seifert S, Shaw DR, Zablotowicz RM, Wesley RA, Kingery WL. Effect of tillage on microbial characteristics and herbicide degradation in a Sharkey clay soil. Weed Science. 2001;49:685–693.
21. Moreno JL, Aliaga A, Navarro S, Hernández T, García C. Effects of atrazine on microbial activity in semiarid soil. Applied Soil Ecology. 2007;35:120–127.
22. Mahía J, González-Prieto SJ, Martín A, Bååth E, Díaz-Raviña M. Biochemical properties and microbial community structure of five different soils after atrazine addition. Biology and Fertility of Soils, 47, 577–589.23.
23. Zhang X, Li X, Zhang C, Zhang H. Responses of soil nitrogen-fixing, ammonia-oxidizing, and denitrifying bacterial communities to long-term chlorimuron-ethyl stress in a continuously cropped soybean field in Northeast China. Ann Microbiol. 2013;63:1619–1627.
24. Zabaloy MC, Garland JL, Gómez MA. An integrated approach to evaluate the impacts of the herbicides glyphosate, 2,4-D and metsulfuron-methyl on soil microbial communities in the Pampas region, Argentina. Applied Soil Ecology. 2008;40:1–12.
25. Zabaloy MC, Gómez MA. Microbial respiration in soils of the argentine pampas after metsulfuron methyl, 2,4-D, and glyphosate treatments. Communications in Soil Science and Plant Analysis. 2008; 39:370–385.
26. Wang GH, Zhang L, Wang J, Jin Z, Fan Y, Guo M, Guo R, Yu X, Shi Z. Changes in microbiome confer multigenerational host resistance after sub-toxic pesticide exposure. Cell Host & Microbe. 2020;27: 213–224.e7.
27. Han L, Zhou Y, Shi J, Pan L, Zhang X, Wang J, Jin Y, Li L, Wang R. Earthworms accelerated the degradation of the highly toxic acetochlor S-enantiomer by stimulating soil microbiota in repeatedly treated soils. Journal of Hazardous Materials. 2021;420:126669.
28. Chang X, Zhao J, Wang Y, Zhou Q, Shi X, Xue C, Gao Y. Exposure to fomesafen alters the gut microbiota and the physiology of the earthworm *Pheretima guillelmi*. Chemosphere. 2021;284:131290.
29. Astaykina A, Ostrovska Y, Nadirova O, Ivantsiv A, Serkiz Y. Effects of three pesticides on the earthworm *Lumbricus terrestris* gut microbiota. Frontiers in Microbiology. 2022;13:853535.
30. Perucci P, Dumontet S, Bufo SA, Mazzatura A, Casucci C. Effects of organic amendment and herbicide treatment on soil microbial biomass. Biology and Fertility of Soils. 2000;32:17–23.
31. Damin V, Trivelin PCO, Barbosa TG, Carvalho SJP, Moraes MF. Mineralization and corn recovery of 15 Nitrogen from black oats residues treated with herbicides. Journal of Plant Nutrition. 2012;35:1830–1842.
32. Fuchs B, Krischke M, Mueller MJ, Krauss J. Glyphosate-modulated biosynthesis driving plant defense and species interactions. Trends in Plant Science. 2021;26:312–323.
33. Kumari N, Narayan OP, Rai LC. Cyanobacterial diversity shifts induced by butachlor in selected Indian rice fields in Eastern Uttar Pradesh and Western Bihar analyzed with PCR and DGGE. Journal of Microbiology and Biotechnology. 2012; 22:1–12.
34. Casabé N, Piola L, Fuchs J, Oneto ML, Pamparato L, Basack S, Giménez R, Massaro R, Papa JC, Kesten E. Ecotoxicological assessment of the effects of glyphosate and chlorpyrifos in an Argentine soya field. Journal of Soils and Sediments. 2007; 7:232–239.

35. Zaller JG, Heigl F, Ruess L, Grabmaier A. Glyphosate herbicide affects belowground interactions between earthworms and symbiotic mycorrhizal fungi in a model ecosystem. Scientific Reports. 2014;4: 5634.
36. Druille M, Cabello MN, Omacini M, Golluscio RA. Glyphosate reduces spore viability and root colonization of arbuscular mycorrhizal fungi. Applied Soil Ecology. 2013;64:99–103.
37. Omotayo A, Okoro G. Toxicity of agricultural pesticides to soil bacteria. Egyptian Academic Journal of Biological Sciences G Microbiology. 2022;14:29-36.
38. Nguyen NK, Hiradate S, Fujie K, Kosugi Y. Large variation in glyphosate mineralization in 21 different agricultural soils explained by soil properties. Science of the Total Environment. 2018;627:544–552.
39. Zabaloy MC, Gómez E, Pedrini S, Torres L. Microbiomes and glyphosate biodegradation in edaphic and aquatic environments: Recent issues and trends. World Journal of Microbiology and Biotechnology. 2022;28:98.
40. Leino L, Niemelä M, Yli-Mattila T. Classification of the glyphosate target enzyme (5-enolpyruvylshikimate-3-phosphate synthase) for assessing sensitivity of organisms to the herbicide. Journal of Hazardous Materials. 2021; 408:124556.
41. Chávez-Ortiz P, Paradelo M, Gil-Sotres F, Trasar-Cepeda C. Glyphosate-based herbicides alter soil carbon and phosphorus dynamics and microbial activity. Applied Soil Ecology. 2022;169: 104256.
42. Yale RL, Purdy LH, Jiménez-Gasco MM. Microbial changes linked to the accelerated degradation of the herbicide atrazine in a range of temperate soils. Environmental Science and Pollution Research International. 2017;24:7359–7374.
43. Fernandes AFT *et al.* Impact of atrazine exposure on the microbial community structure in a Brazilian tropical latosol soil. Microbes and Environments. 2020;35: ME19143.
44. Stanley HO, Maduike EM, Okerentugba P. Effect of herbicide (atrazine and paraquat) application on soil bacterial population. Sky Journal of Soil Science and Environmental Management. 2013;2:101–105.
45. Fuchs B, Krischke M, Mueller MJ, Krauss J. Glyphosate-modulated biosynthesis driving plant defense and species interactions. Trends in Plant Science. 2021;26:312–323.
46. Nguyen DB, Rose MT, Rose TJ. Impact of glyphosate on soil microbial biomass and respiration: A meta-analysis. Soil Biology and Biochemistry. 2016;92:50–57.
47. Riedo J, Stamm C. Widespread occurrence of pesticides in organically managed agricultural soils – The ghost of a conventional agricultural past? Environmental Science & Technology. 2021;55:2919–2928.
48. Hébert MP, Loecke TD. The overlooked impact of rising glyphosate use on phosphorus loading in agricultural watersheds. Frontiers in Ecology and the Environment. 2019;17:48–56.

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