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SOIL MICROBIAL COMMUNITIES AND FUNCTIONAL NETWORKS AS BIOINDICATORS OF PESTICIDE STRESS IN ECOSYSTEM MONITORING

Asli Bayer*, Esra Ersoy Omeroglu

Department of Biology, Basic and Industrial Microbiology Section, Faculty of Science, Ege
University, Bornova, 35100 Izmir, Türkiye

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Abstract

Pesticides are widely used in modern agriculture but exert significant pressure on soil microbial communities that sustain essential ecosystem functions. Evidence from both field experiments and meta-analyses indicates that pesticides alter microbial biomass, respiration, and enzyme activities, leading to long-term disruptions in soil functionality. Pesticide exposure has been reported to influence the structure and functioning of different soil microbial groups, leading to measurable changes in bacterial, fungal, and protist communities. These shifts, particularly under cumulative and multi-pesticide pressures, disrupt nutrient cycling and reduce the complexity of microbial interaction networks, ultimately weakening ecosystem resilience. The aim of this review is to provide an integrated evaluation of current studies addressing how pesticide exposure influences soil microbial communities and their functional interaction networks.

Special attention is given to the potential of microbial diversity, functional activity, and network-level responses as bioindicators for ecosystem monitoring and sustainable agricultural practices. However, sustainable practices such as compost application, biofertilizers, and microbial consortia may help to restore microbial diversity and activity. Advances in molecular and omics-based tools further strengthen the use of soil microbiota as bioindicators, offering valuable insights for sustainable agriculture and ecosystem monitoring [21].

Keywords: *Soil microbiota; Pesticide stress; Microbial interaction networks; Bioindicators; Sustainable agriculture*

1. Introduction

Pesticides are widely applied in modern agriculture, but their long-term presence in soils can affect microbial communities that are central to ecosystem functioning [1, 16]. The extent of these effects depends on the type of pesticide, the application rate, and the specific soil conditions. This review synthesizes current evidence on how pesticide-related chemical stressors influence soil microbial communities and their functional networks, with particular relevance for ecosystem monitoring.

Previous studies have demonstrated that pesticide effects on soil microorganisms are not uniformly negative but vary depending on pesticide chemistry, application rate, and soil properties. Different classes of pesticides may stimulate certain microbial processes while inhibiting others, resulting in complex and

*Corresponding author: Tel.: +90 232 311 54 98
E-mail address: aslibayer35@gmail.com

sometimes contrasting biological responses. For example, low concentrations of some herbicides have been reported to temporarily increase microbial activity, whereas higher doses often suppress enzyme activity and microbial growth. These findings highlight that pesticide–microbiome interactions are context dependent and should be evaluated using integrated biological indicators rather than single endpoints [8].

2. Soil Microbial Communities and Ecosystem Health

Soil microbial communities play a central role in maintaining ecosystem processes, making them particularly sensitive to disturbances caused by agricultural inputs.

Unintended pesticide effects can disrupt the organization and function of non-target biotic communities, posing significant risks to soil microorganisms that regulate essential ecosystem functions. Pesticides can cause unintended effects on non-target organisms, altering the structure and function of biotic communities. This issue is particularly critical for soil microbial communities, which play a central role in ecosystem processes. In a three-year study conducted in Swiss vineyards, the effects of herbicide application and increased soil copper content resulting from long-term use of copper-based fungicides were evaluated in relation to the diversity of bacteria, fungi, and protists, as well as soil respiration and decomposition. The findings showed that herbicides altered the microbial community composition, reduced species richness in fungi and protists, and decreased microbial biomass and respiration by 45% and 39%, respectively. Copper decreased bacterial and protist diversity in some years, although it did not significantly affect fungal richness. Overall, pesticide application influenced microbial diversity and certain soil functions in a group- and context-dependent manner, while decomposition rates remained largely unchanged. These results highlight the complex consequences of pesticide use on soil ecosystem balance and emphasize the need to reconcile agricultural productivity with environmental conservation [17].

3. Pesticide Impacts on Microbial Dynamics

Pesticide exposure influences soil microorganisms through multiple pathways, affecting both their activity and community structure.

3.1 Effects of different pesticide classes on soil microbial communities

The impacts of pesticides on soil microbial communities differ considerably among pesticide classes. Herbicides, insecticides, and fungicides target distinct biological processes and therefore influence microbial populations through different mechanisms. Herbicides have frequently been associated with changes in microbial biomass and enzyme activities, particularly those involved in carbon and nitrogen cycling. Insecticides may indirectly affect soil microorganisms by altering substrate availability following impacts on soil fauna, whereas fungicides can directly suppress fungal populations and shift bacterial–fungal balance in soils. Such class-specific responses underline the importance of evaluating pesticide effects beyond general toxicity and considering functional group sensitivity when assessing soil health [8].

Early studies highlighted that pesticide exposure can induce both structural and functional changes in soil microbial processes, providing initial evidence that different compounds may affect specific soil functions in distinct ways [7].

3.2 Effects on microbial biomass and activity

Changes in microbial biomass and activity are among the earliest detectable responses to pesticide stress and have been consistently reported across different soil types and experimental conditions [3]. The application of pesticides has measurable effects on microbial biomass, activity, and diversity. Endosulfan and quinalphos, for example, significantly reduced microbial biomass and metabolic activity under controlled conditions, even at environmentally acceptable concentrations [12]. Beyond immediate inhibitory effects, pesticide exposure can induce longer-term changes in soil microbial communities through tolerance development and community restructuring. Repeated or chronic exposure to pesticides may select for tolerant microbial populations, leading to shifts in dominant taxa without necessarily causing measurable reductions in total biomass or activity. While such adaptive responses may preserve certain soil functions in the short term, they can also alter microbial interaction patterns and reduce functional redundancy. These changes suggest that apparent recovery of microbial activity does not always indicate restoration of the original community structure or ecosystem resilience [5].

Broad-spectrum assessments examining multiple pesticides simultaneously have demonstrated that increasing chemical complexity can significantly impair microbial carbon-related functions and reshape soil microbial community composition [15]. Recent reviews synthesizing agrochemical impacts further indicate that pesticide exposure has been widely reported to alter microbial biomass, enzymatic activity, and functional processes across different soil systems, emphasizing the sensitivity of microbial functions to chemical disturbance [9].

Recent evidence suggests that the combined use of multiple pesticides may exert stronger functional stress on soil microbial communities than single-compound applications. Increasing pesticide diversity has been shown to alter microbial life-history strategies, promote genome streamlining, and intensify microbial-mediated nutrient cycling processes. These shifts can accelerate the consumption of soil carbon and nitrogen pools and destabilize microbial interaction networks, highlighting that cumulative pesticide pressure represents a critical driver of functional impairment in agricultural soils [10].

3.3 Impacts on nitrogen-cycling microorganisms

Nitrogen-transforming microorganisms are especially vulnerable to pesticide exposure due to their functional specialization. Similarly, meta-analysis studies have shown that pesticides exert inhibitory effects on ammonia-oxidizing microorganisms. These analyses revealed that herbicides and fungicides reduce the abundance of *amoA* genes, which serve as consistent biological indicators of pesticide exposure. Ammonia-oxidizing microorganisms (AOMs) have therefore been proposed as reliable bioindicators of pesticide-induced toxicity in soil ecosystems. Furthermore, the availability of standardized, high-resolution molecular methods for tracking the abundance and functional activity of these microorganisms enables more accurate evaluation of pesticide impacts on soil health. This approach contributes to the development of sustainable chemical innovation aligned with environmental protection and soil ecosystem resilience [18].

3.4 Disruption of microbial interaction networks

Beyond individual taxa, pesticide stress can alter the structure and stability of microbial interaction networks. Both synthetic fungicides and biopesticides can also decrease the complexity of microbial co-occurrence networks, though their effects vary across microbial groups [4]. These results indicate that pesticide stress affects not only community composition but also the stability of microbial interactions. Recent evidence shows that pesticide residues can reduce bacterial diversity while simultaneously increasing network stability through motif-level restructuring. This stability has been associated with a shift toward sparse, redundant interaction motifs that buffer microbial communities against cascading failures under chronic chemical stress [19-20].

4. Soil Microbial Communities as Bioindicators

The sensitivity of soil microorganisms to chemical stressors highlights their value as bioindicators of soil health. Changes in microbial biomass, enzyme activity, and diversity under pesticide exposure indicate that soil microbiota can be used as bioindicators of stress. Reduced enzyme activity and altered respiration rates reflect impairments in nutrient cycling and soil fertility [1]. Specific microbial groups show selective responses. For example, ammonia-oxidizing bacteria and archaea were particularly sensitive to pesticide application, and their reduced abundance signaled disruptions in nitrogen cycling [6]. Other studies confirmed that nitrifying communities are strongly affected by pesticide exposure [16]. Several review studies emphasize that microbial biomass, enzymatic activity, and community-related parameters together provide complementary information on soil responses to agrochemical inputs, supporting more comprehensive soil health assessments [9].

Conceptual frameworks on soil biomonitoring emphasize that biological indicators should reflect not only the presence of contaminants but also their ecological consequences. Soil microorganisms are particularly suitable bioindicators due to their rapid response to environmental disturbances and their central role in soil functioning. However, effective biomonitoring requires the integration of multiple microbial indicators, as no single parameter can adequately capture the complexity of soil ecosystem responses to chemical stressors such as pesticides. Foundational studies on soil health monitoring highlight the importance of combining biological, biochemical, and ecological perspectives to achieve reliable interpretation of bioindicator data [2].

Although soil microorganisms are widely recognized as sensitive indicators of pesticide-induced stress, their use as bioindicators is not without limitations. Microbial responses can be influenced by soil type, organic matter content, pH, and historical exposure to agrochemicals, complicating cross-site comparisons. In addition, tolerance development following repeated pesticide application may obscure early warning signals if only functional parameters are considered. These constraints highlight the importance of combining multiple microbial indicators and interpreting bioindicator data within an ecological context rather than relying on single-response metrics [5].

Recent reviews have emphasized that soil health assessment requires the integration of multiple biological indicators rather than reliance on single parameters. Microbial biomass, respiration, enzymatic activities, functional gene markers, and community-level analyses have all been shown to respond sensitively to a wide range of environmental stressors, including pesticide contamination. However, the effectiveness of these indicators can vary depending on soil type, land use history, and the nature of the applied agrochemicals. Consequently, the selection of appropriate microbial bioindicators should consider both functional responses and structural shifts within microbial communities to ensure ecologically meaningful interpretations [2]. Another important challenge in the use of microbial bioindicators is the influence of legacy effects resulting from long-term or repeated pesticide exposure. Microbial communities may develop tolerance or adaptive mechanisms that sustain certain soil functions while masking underlying compositional changes. As highlighted in recent synthesis studies, this functional redundancy can complicate the interpretation of soil health indicators if structural information is not simultaneously considered. Therefore, combining biochemical indicators with molecular and community-based approaches is increasingly recommended for robust assessment of pesticide-induced soil disturbance [2].

These considerations highlight the need for methodological frameworks that can capture both functional and structural dimensions of microbial responses to pesticide exposure.

5. Methodological Approaches

The literature discussed in this review was selected from widely used scientific literature focusing on soil microbial communities and pesticide-related disturbances. Both foundational studies and more recent research examining changes in microbial community structure, functional activity, and interaction networks in soil ecosystems were considered. A wide range of methodological approaches has been developed to assess pesticide effects on soil microbial communities. These approaches differ in their ability to capture functional responses, community composition, and long-term ecological effects.

Different approaches are available to study the effects of pesticides on soil microbiota. Early research relied on classical indicators such as microbial biomass, soil respiration, and enzyme activities to detect functional changes [1, 12]. These methods provided important baseline information but did not capture more detailed community-level dynamics. As a result, methodological developments increasingly shifted toward approaches capable of resolving microbial community structure.

Molecular techniques such as PCR-based analysis and 16S rRNA sequencing have enabled the identification of pesticide-sensitive microbial taxa [6, 16]. More advanced tools, including metagenomics and transcriptomics, have been applied to examine how pesticide exposure modifies microbial community composition and functional gene expression [4].

While these advanced techniques provide high-resolution insights into microbial responses, they are most informative when interpreted alongside conventional functional indicators. Molecular approaches have increasingly been used to complement traditional measurements of microbial biomass and enzyme activity in pesticide-exposed soils. Techniques such as PCR-based fingerprinting and community profiling allow detection of subtle shifts in microbial community structure that may not be captured by bulk functional indicators. However, molecular data require cautious interpretation, as changes in genetic fingerprints do not always translate directly into functional consequences. Combining molecular tools with functional assays therefore provides a more comprehensive understanding of pesticide-driven alterations in soil microbial communities [8].

Building on this integrative perspective, traditional indicators such as microbial biomass, soil respiration, and enzyme activities have been widely used to assess pesticide effects on soil microorganisms due to their simplicity and sensitivity. However, these bulk measurements often provide limited insight into underlying changes in microbial community structure. Similar functional outputs may be maintained by different microbial assemblages, masking shifts in community composition or tolerance development. As a result, reliance on single biological endpoints can lead to incomplete or misleading interpretations of pesticide-

induced stress. Integrating structural and functional indicators therefore represents a more robust approach for evaluating microbial responses to pesticide exposure across different soil environments [5].

Recent advances in soil health monitoring have promoted the classification of microbial bioindicators into physiological, biochemical, functional, and molecular categories. This integrative framework allows for a more comprehensive evaluation of soil responses to anthropogenic stressors, including pesticide inputs. In particular, molecular tools combined with conventional biochemical measurements have been shown to improve the sensitivity and reliability of soil health assessments across diverse ecosystems [2].

6. Future Perspectives and Knowledge Gaps

Despite substantial progress, several knowledge gaps remain in understanding pesticide–microbiome interactions. In addition, sustainable management practices such as compost addition, biofertilizers, and microbial consortia are being studied for their potential to counteract pesticide-driven losses of microbial diversity [4, 13]. Integrating these practices into agricultural monitoring programs could improve resilience and support ecosystem health.

Recent advances in high-throughput sequencing and network-based analyses have expanded the capacity to explore pesticide–microbiome interactions at higher resolution. Such approaches have been increasingly applied to investigate community-level responses, functional potential, and interaction patterns that are not detectable using conventional indicators alone. However, despite their analytical power, these methods remain underutilized in routine soil monitoring due to challenges related to data interpretation, comparability across studies, and integration with existing assessment frameworks [11, 14].

Recent conceptual advances in soil biomonitoring also underline the need for standardized frameworks that can link microbial bioindicators to long-term soil health assessment. Despite growing methodological sophistication, the lack of harmonized indicator selection and interpretation criteria remains a major challenge. Addressing these gaps will be essential for translating microbial bioindicator research into practical monitoring tools for sustainable soil management under pesticide pressure [2].

7. Conclusion

Pesticides exert diverse effects on soil microbial communities by decreasing biomass, altering enzyme activity, and disrupting nutrient cycling. Nitrogen-transforming microorganisms, including ammonia-oxidizing bacteria and archaea, are among the most sensitive groups to such disturbances. Both conventional and biopesticide applications can modify community composition and, in some cases, simplify microbial interaction networks, potentially reducing ecological stability. These findings emphasize the importance of microbial assemblages as sensitive indicators of soil stress. Recent developments in molecular and omics-based technologies are enhancing our capacity to evaluate these impacts more precisely, while sustainable agricultural practices such as compost enrichment and biofertilizer use are emerging as effective strategies to mitigate them. Strengthening the integration of microbial bioindicators into soil monitoring frameworks will be crucial for maintaining ecosystem health and advancing sustainable agriculture.

Taken together, the findings reviewed here indicate that pesticide-induced disturbances in soil microbial communities are multifaceted and context-dependent, involving both compositional shifts and functional reorganization. Apparent stability in microbial activity does not necessarily reflect ecological resilience, as underlying changes in community structure and interaction networks may persist. This highlights the need for assessment frameworks that move beyond single-response metrics and instead capture cumulative and combined pesticide pressures. Future research should prioritize integrative monitoring strategies that link microbial indicators with long-term soil health outcomes, thereby supporting evidence-based decision-making for sustainable agricultural management.

References

- [1] Arora S, Sahni, D. Pesticides effect on soil microbial ecology and enzyme activity: An overview. *Journal of Applied and Natural Science*, 2016, 8 (2), p 1126- 1132.
- [2] Bhaduri D, Sihi D, Bhowmik A, Verma B. C., Munda S, Dari B. A review on effective soil health bio-indicators for ecosystem restoration and sustainability. *Frontiers in Microbiology*, 2022, 13, 938481.

- [3] Dahiya UR, Das J, Bano S, Biological indicators of soil health and biomonitoring. In *Advances in Bioremediation and Phytoremediation for Sustainable Soil Management: Principles, Monitoring and Remediation* 2022, (pp. 327-347). Cham: Springer International Publishing.
- [4] Fournier B, Dos Santos S P, Gustavsen J A, Imfeld G, Lamy F, Mitchell EAD, Mota M, Noll D, Planchamp C, Heger T J. Impact of a synthetic fungicide (fosetyl-Al and propamocarb-hydrochloride) and a biopesticide (*Clonostachys rosea*) on soil bacterial, fungal, and protist communities, 2020, *Science of The Total Environment*, 738, 139635.
- [5] Imfeld G, Vuilleumier S. Measuring the effects of pesticides on bacterial communities in soil: a critical review. *European journal of soil biology*, 2012, 49, p 22-30.
- [6] Karas PA, Baguelin C, Papadopoulou ES, Nikolaidis N P, Tsiamis G. Assessment of the impact of three pesticides on microbial dynamics and functions in a lab-to-field experimental approach, *Science of The Total Environment*, 2018, 637, p 636-646.
- [7] Liebich J, Schäffer A, Burauel P. Structural and functional approach to studying pesticide side-effects on specific soil functions, *Environmental Toxicology and Chemistry*, 2003, 22(4), p 784-790.
- [8] Lo C C. Effect of pesticides on soil microbial community. *Journal of Environmental Science and Health Part B*, 2010, 45(5), p 348-359.
- [9] Meena RS, Kumar S, Datta R, Lal R, Vijayakumar V, Brtnicky M, et al. Impact of agrochemicals on soil microbiota and management: A review. *Land*, 2020, 9(2), p 34.
- [10] Ni B, Xiao L, Lin D, Zhang T L, Zhang Q, Liu Y, et al. Increasing pesticide diversity impairs soil microbial functions. *Proceedings of the National Academy of Sciences*, 2025, 122(2), e2419917122.
- [11] Nkongolo K K, Narendrula-Kotha R. Advances in monitoring soil microbial community dynamic and function, *Journal of applied genetics*, 2020, 61(2), p 249-263.
- [12] Pandey P, Chauhan U K. Effects of pesticides (endo sulfan and quinal phos) on microbial community under controlled conditions, *The FASEB Journal*, 2007, 21(6), A1000.
- [13] Papat R, Desmukh K. Mitigating Pesticide-Induced Soil Microbial Disruption Through Targeted Reclamation and Metagenomic Insights, *International Journal of Environmental Sciences*, 2025, 11(6), p 2563-2573.
- [14] Sibalekile A, Araya T, Castillo Hernandez J, Kotzé E. Glyphosate-microbial interactions: metagenomic insights and future directions, *Frontiers in Microbiology*, 2025, 16, 1570235.
- [15] Sim JX, Drigo B, Doolette C L, Vasileiadis S, Karpouzas D G, Lombi E. Impact of twenty pesticides on soil carbon microbial functions and community composition, *Chemosphere*, 2022a, 307, 135820.
- [16] Sim J X F, Doolette C L, Vasileiadis S, Drigo B, Wyrsh E R, Djordjevic S P, Donner E, Karpouzas D G, Lombi E. Pesticide effects on nitrogen cycle related microbial functions and community composition, *Science of the Total Environment*, 2022b, 807, 150734.
- [17] Steiner M, Falquet L, Fragnière A L, Brown A, Bacher S. Effects of pesticides on soil bacterial, fungal and protist communities, soil functions and grape quality in vineyards, *Ecological Solutions and Evidence*, 2024, 5(2), e12327.
- [18] Swaine M, Bergna A, Oyserman B, Vasileiadis S, Karas P A, Screpanti C, Karpouzas D G Impact of pesticides on soil health: identification of key soil microbial indicators for ecotoxicological assessment strategies through meta- analysis, *FEMS Microbiology Ecology*, 2025, 101(6), fiaf052.
- [19] Wang C, Wu R, Xue X, Li C, Long S, Xu F. Pesticide Residues Reduce Bacterial Diversity but Enhance Stability via Network Motif Restructuring, *Toxics*, 2025, 13(12), 1052.
- [20] Zheng C, Song J, Shan M, Qiu M, Cui M Huang C, et al. Key bacterial taxa with specific metabolisms and life history strategies sustain soil microbial network stability exposed to carbendazim and deoxynivalenol, *Science of The Total Environment*, 2024, 954, 176680.
- [21] Asli Bayer, Aisha Hitshika Kamba, Ersoy Omeroglu E. The role of microbial biosensors in promoting sustainable agriculture and ecological balance. *Baku State University Journal of Life Science & Biology*, 2024, v2,(1), p.45-49