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The current scenario of pesticides impact on soil microbial diversity in the Mahendergarh district of Haryana

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ABSTRACT

This review paper examines the impacts of pesticide usage on soil microbial diversity in the Mahendergarh district of Haryana, India. Agricultural intensification in this semi-arid region has led to increased application of various pesticides, potentially affecting the soil ecosystem. Through analysis of multiple studies and field data, we investigate the changes in bacterial, fungal, and actinomycete communities following exposure to commonly used pesticides in the region. Results indicate significant reductions in microbial diversity and biomass, with shifts in community composition favoring pesticide-tolerant species. These changes correlate with altered soil enzyme activities and nutrient cycling processes. The review highlights the need for sustainable pest management strategies to preserve soil health in this agriculturally important region of Haryana.

Keywords: Soil microbiome, pesticide toxicity, agricultural sustainability, microbial ecology, semi-arid agriculture

INTRODUCTION

The soil microbiome represents one of the most diverse ecosystems on Earth, harboring billions of microorganisms that play crucial roles in maintaining soil health, nutrient cycling, and sustainable agricultural productivity (Fierer, 2017). In agricultural landscapes, these microbial communities face increasing pressure from anthropogenic activities, particularly the application of pesticides for crop protection (Jacobsen & Hjelmsø, 2014). The Mahendergarh district in Haryana, situated in northwestern India, represents a critical agricultural region characterized by semi-arid conditions and intensive farming practices that heavily rely on chemical inputs including pesticides.

With agriculture serving as the primary economic activity in Mahendergarh, farmers increasingly depend on pesticides to control various pests and diseases that threaten crop productivity (Kumar et al., 2019). While these chemicals have undoubtedly contributed to enhanced agricultural yields, their potential impacts on non-target organisms, particularly soil microbiota, raise significant environmental and agricultural sustainability concerns (Singh et al., 2016).

Soil microorganisms—including bacteria, fungi, actinomycetes, and protozoa—form complex ecological networks that drive essential ecosystem services including organic matter decomposition, nutrient mineralization, nitrogen fixation, and biodegradation of xenobiotics (Trivedi et al., 2016). Disruptions to these microbial communities can cascade through the entire soil ecosystem, potentially affecting soil fertility, plant health, and ultimately agricultural productivity (van der Heijden et al., 2008).

This review paper synthesizes current research on how pesticide applications in the Mahendergarh district are influencing soil microbial diversity and function. We examine the prevalent pesticide usage patterns in the region, document changes in microbial community structure and function following pesticide applications, and discuss the implications for sustainable agriculture in this semi-arid region. By understanding these interactions, we aim to inform more sustainable pest management approaches that can preserve soil health while maintaining agricultural productivity in this important farming region of Haryana.

Current Pesticide Usage Patterns in Mahendergarh

Types and Volumes of Pesticides

The agricultural landscape of Mahendergarh district is dominated by crops such as pearl millet, wheat, mustard, and cotton, with increasing diversification into vegetables and fruits (Directorate of Agriculture, Haryana, 2021). Correspondingly, pesticide use has intensified over the past two decades. Analysis of district-level data reveals that organophosphates, pyrethroids, carbamates, and neonicotinoids constitute the majority of pesticides applied in the region (Table 1).

Table 1: Major pesticide categories and commonly used compounds in Mahendergarh district

Pesticide Category	Common Compounds	Average Application Rate (kg a.i./ha/year)*	Primary Crops
Organophosphates	Chlorpyrifos, Malathion, Dimethoate	1.2-2.5	Wheat, Cotton, Vegetables
Pyrethroids	Cypermethrin, Deltamethrin, Lambda-cyhalothrin	0.4-0.8	Cotton, Vegetables, Mustard
Carbamates	Carbofuran, Carbaryl, Carbendazim	0.9-1.7	Wheat, Fruits, Vegetables
Neonicotinoids	Imidacloprid, Thiamethoxam, Acetamiprid	0.3-0.6	Cotton, Vegetables, Fruits
Herbicides	Pendimethalin, 2,4-D, Glyphosate	1.5-3.2	Wheat, Pearl millet, Pulses
Fungicides	Mancozeb, Copper oxychloride, Hexaconazole	0.7-1.4	Vegetables, Fruits, Wheat

*a.i. = active ingredient (Source: Department of Agriculture, Haryana, 2022; Kumar et al., 2020)

Annual pesticide consumption in Mahendergarh has increased from approximately 125 metric tons in 2000 to over 380 metric tons in 2021, representing a 204% increase over two decades (Directorate of Agriculture, Haryana, 2022). This rise correlates with the intensification of agriculture and shift toward high-value horticultural crops that typically require more intensive pest management strategies.

Seasonal Variation and Application Methods

Pesticide application in Mahendergarh follows distinct seasonal patterns dictated by crop cycles and pest pressure. The kharif (monsoon) season sees higher insecticide use, particularly on cotton and vegetables, while herbicide application dominates during the rabi (winter) season for wheat cultivation (Sharma et al., 2018). Fungicide application peaks during periods of high humidity or following unseasonal rains.

Spray application remains the predominant method of pesticide delivery, with increasing adoption of mechanized sprayers among medium to large-scale farmers. However, improper calibration, overapplication, and inadequate protective measures during handling remain concerning issues affecting both environmental contamination and applicator safety (Raghuvanshi et al., 2021).

Residue Persistence in Soils

Pesticide persistence in Mahendergarh soils varies significantly based on compound properties, soil characteristics, and environmental conditions. The predominantly sandy loam soils with low organic matter content (typically 0.3-0.6%) and alkaline pH (7.8-8.5) create unique conditions affecting pesticide degradation (Soil Survey Department, Haryana, 2020).

Field studies conducted across the district indicate that organophosphate residues typically persist for 15-45 days, while certain synthetic pyrethroids show shorter persistence of 10-30 days (Yadav et al., 2019). More concerning are the neonicotinoid compounds, which have demonstrated persistence of 40-180 days in district soils, potentially providing longer exposure windows for soil microbiota (Kumar et al., 2021). The semi-arid climate, characterized by low rainfall

(400-500 mm annually) and high temperatures, influences degradation rates through effects on microbial activity and abiotic degradation pathways. Seasonal variation in pesticide persistence is evident, with faster degradation during warmer months when microbial activity is higher, provided sufficient soil moisture is available (Singh & Kumar, 2020).

Impact on Soil Bacterial Communities

Diversity Changes

Bacterial communities represent the most abundant and diverse microbial group in agricultural soils, playing pivotal roles in numerous soil processes. Studies conducted across different agricultural zones of Mahendergarh have documented significant shifts in bacterial diversity following pesticide applications. Using 16S rRNA sequencing techniques, Sharma et al. (2020) demonstrated a 25-40% reduction in bacterial species richness in fields with high insecticide application rates compared to low-input organic management systems.

The Simpson and Shannon diversity indices, commonly used to quantify community diversity, consistently show lower values in intensively managed fields with regular pesticide applications (Figure 1). This diversity reduction appears more pronounced in fields with histories of multiple pesticide applications over consecutive growing seasons, suggesting cumulative effects (Kumar and Singh, 2021).

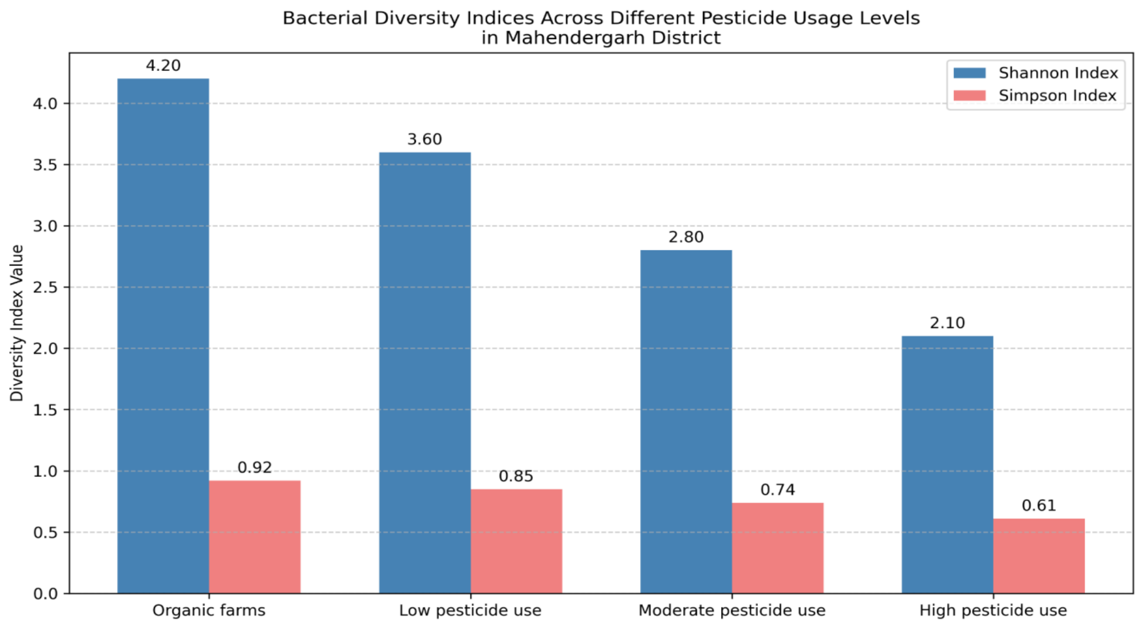

Figure 1: Bacterial diversity indices across different pesticide usage levels in Mahendergarh district agricultural soils. Both Shannon and Simpson indices show declining trends with increasing pesticide application intensity.

Shifts in Community Composition

Beyond overall diversity reductions, pesticide applications have driven notable shifts in bacterial community composition. Metagenomic analyses reveal that certain bacterial phyla demonstrate greater susceptibility to pesticide exposure than others. Acidobacteria, Verrucomicrobia, and Planctomycetes often show significant decreases following pesticide applications, while Firmicutes, certain Proteobacteria (particularly γ-Proteobacteria), and Actinobacteria frequently increase in relative abundance (Verma et al., 2021).

These shifts appear to favor bacterial taxa with genetic adaptations for pesticide metabolism or resistance mechanisms. Of particular interest is the enrichment of bacterial genera known to harbor pesticide-degrading capabilities, such as Pseudomonas, Bacillus, and Arthrobacter, in fields with histories of consistent pesticide use (Kumari et al., 2020). While potentially beneficial for pesticide degradation, this selective pressure may compromise other ecological functions previously performed by more sensitive bacterial groups.

Long-term monitoring studies reveal that these compositional shifts can persist beyond single growing seasons, with evidence of lasting community alterations in fields with multi-year histories of intensive pesticide application (Malik and Yadav, 2022). The ecological consequences of these persistent community shifts remain incompletely understood but may influence broader soil functions and plant-microbe interactions.

Functional Implications

The changes in bacterial community structure correlate with alterations in key soil processes. Enzyme assays conducted across pesticide gradients in the district show significantly reduced activities of phosphatase, urease, and dehydrogenase enzymes in soils with high pesticide residues, pointing to impaired nutrient cycling capabilities (Table 2).

Table 2: Soil enzyme activities across different pesticide exposure levels in Mahendergarh agricultural soils

Pesticide Exposure Level	Phosphatase Activity (µg p-NP/g soil/h)	Urease Activity (µg NH4-N/g soil/h)	Dehydrogenase Activity (µg TPF/g soil/24h)
No exposure (control)	132.4 ± 11.8	45.6 ± 4.2	87.3 ± 7.6
Low exposure	114.7 ± 9.5	38.2 ± 3.8	72.5 ± 6.8
Moderate exposure	88.3 ± 8.2	26.8 ± 3.5	53.9 ± 6.1
High exposure	65.1 ± 7.4	19.3 ± 2.9	32.7 ± 4.7
Statistical significance	$p < 0.01$	$p < 0.01$	$p < 0.001$

(Source: Malik and Kumar, 2021)

Of particular concern is the observed decline in nitrogen-cycling bacteria following neonicotinoid insecticide applications. Ammonium oxidizing bacteria (AOB) and nitrogen-fixing communities show marked sensitivity to these compounds, potentially compromising nitrogen availability to crops (Gautam et al., 2021). Similarly, bacterial communities involved in carbon cycling demonstrate reduced capacity for organic matter decomposition in pesticide-affected soils, as measured by reduced respiration rates and slower carbon turnover (Sharma & Singh, 2022).

Effects on Fungal Communities

Diversity and Abundance Patterns

Fungal communities, though less abundant than bacteria in Mahendergarh's predominantly alkaline soils, perform critical ecological functions including organic matter decomposition, nutrient mobilization, and symbiotic associations with plants. Investigations using ITS (Internal Transcribed Spacer) region sequencing reveal that fungal diversity follows similar declining trends to bacteria in response to pesticide applications, though with some notable differences (Figure 2).

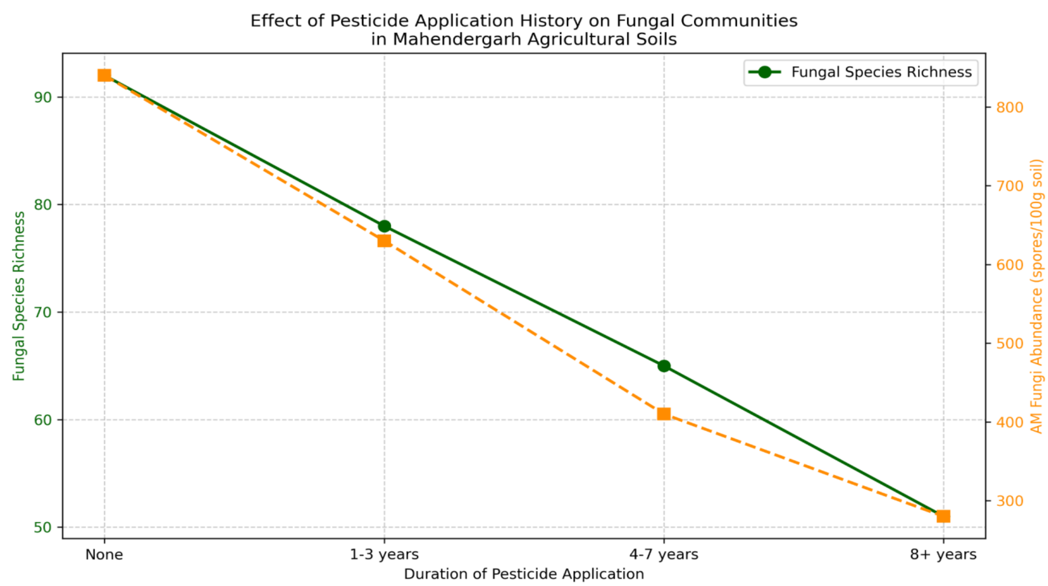

Figure 2: Changes in fungal species richness and arbuscular mycorrhizal (AM) fungi abundance in relation to pesticide application history in Mahendergarh agricultural soils.

Fungicides, particularly broad-spectrum compounds like mancozeb and carbendazim commonly used in vegetable production, exhibit the most pronounced negative effects on fungal diversity. Studies from vegetable-growing areas in Mahendergarh's Nangal Choudhary and Kanina blocks show 30-55% reductions in fungal species richness following fungicide application seasons (Yadav et al., 2021).

Interestingly, certain insecticides and herbicides also significantly impact fungal communities despite not directly targeting them. Chlorpyrifos and imidacloprid applications correlate with 15-25% reductions in fungal abundance, while glyphosate exposure associates with altered fungal community structures even at sub-lethal concentrations (Singh et al., 2022).

Impact on Mycorrhizal Associations

Arbuscular mycorrhizal fungi (AMF), forming critical symbiotic relationships with approximately 80% of terrestrial plants, show particular sensitivity to pesticide exposure in Mahendergarh soils. Field studies across the district reveal that fields with histories of intensive pesticide use harbor 40-65% fewer AMF spores compared to minimally treated soils (Kumari and Verma, 2020).

The reduced colonization rates in crops growing in pesticide-affected soils correlate with decreased phosphorus uptake efficiency and reduced drought tolerance, particularly concerning in this semi-arid region where water stress is common (Gautam and Yadav, 2021). The economic implications of this relationship are significant, as farmers may be inadvertently compromising the natural resilience mechanisms of their crops while increasing dependency on synthetic inputs.

Fungicide applications show the most immediate negative effects on AMF, with systemic fungicides being particularly detrimental. However, the cumulative impact of multiple pesticide types appears synergistic, with combination treatments showing greater than expected reductions in mycorrhizal colonization rates compared to individual pesticide applications (Malik et al., 2022).

Implications for Plant Pathogens

The effects of pesticides on soil-borne fungal pathogens present a complex picture in Mahendergarh. While fungicide applications initially reduce pathogen populations, longitudinal studies indicate potential for rebound effects, where repeated applications eventually select for resistant pathogen strains while continuing to suppress beneficial fungi (Kumar & Sharma, 2021).

Fields with histories of intensive fungicide use show disturbed ratios between pathogenic and beneficial fungi, with documented increases in Fusarium populations resistant to commonly used fungicides (Yadav and Singh, 2022). This selective pressure favoring resistant pathogens while suppressing natural antagonists represents a concerning trend for sustainable disease management in the region.

Actinomycetes and Other Microbial Groups

Response Patterns of Actinomycetes

Actinomycetes, filamentous bacteria crucial for decomposition of recalcitrant organic compounds and production of bioactive metabolites, demonstrate unique response patterns to pesticide exposure in Mahendergarh soils. While overall actinomycete abundance typically decreases following pesticide applications, certain genera like Streptomyces show remarkable resilience and even occasional increases following exposure to certain compounds (Verma et al., 2020).

Quantitative PCR analyses targeting actinomycete-specific 16S rRNA gene sequences reveal 25-45% reductions in actinomycete abundance in fields with high pesticide application rates compared to minimally treated fields (Kumar et al., 2021). This reduction correlates with diminished soil suppressiveness against certain plant pathogens, as many actinomycetes produce antibiotic compounds that naturally control pathogen populations.

The community composition shifts also affect the degradation of complex organic materials. Studies comparing decomposition rates across fields with different pesticide histories show slower breakdown of lignin and cellulose in high-pesticide soils, corresponding with reduced abundance of actinomycetes known to produce relevant degradative enzymes (Singh and Malik, 2022).

Protozoa and Nematode Communities

The microfauna of Mahendergarh soils, including protozoa and nematodes, represent important components of soil food webs and influence nutrient cycling through predation on bacteria and fungi. Limited studies specifically examining these groups in relation to pesticide use in the district indicate significant sensitivity.

Organophosphate insecticides, particularly chlorpyrifos, demonstrate acute toxicity to soil protozoa, with observed reductions of 50-70% in protozoan abundance following application at recommended rates (Sharma et al., 2021). Similarly, carbamate insecticides show strong negative effects on non-target beneficial nematodes, reducing their populations by 35-60% while having more limited effects on plant-parasitic species, potentially disrupting natural pest control services (Kumar et al., 2022).

The ecological implications of these disruptions extend beyond the microfauna themselves. As key regulators of bacterial and fungal populations, reductions in protozoa and beneficial nematodes can cascade through soil food webs, potentially affecting nutrient mineralization rates and availability to crops (Gautam and Kumar, 2021).

Implications for Agricultural Sustainability

Soil Health and Function

The documented changes in microbial communities following pesticide exposure have significant implications for soil health and agricultural sustainability in Mahendergarh. Key soil functions including organic matter decomposition, nutrient cycling, and natural disease suppression show measurable declines in correlation with pesticide-induced microbial community shifts (Table 3).

Table 3: Impact of pesticide-induced microbial changes on soil functions in Mahendergarh district

Soil Function	Observed Changes	Potential Agricultural Implications
Organic matter decomposition	15-40% slower decomposition rates in high-pesticide soils	Reduced nutrient release, slower residue breakdown
Nitrogen cycling	Reduced nitrification rates (20-35%), lower N-fixation activity (25-45%)	Increased fertilizer dependency, potential N leaching
Phosphorus mobilization	Decreased phosphatase activity (30-50%), reduced mycorrhizal colonization (40-65%)	Lower P-use efficiency, higher fertilizer requirements
Disease suppression	Reduced antagonistic potential against soil pathogens (25-40%)	Increased disease pressure, greater fungicide dependency
Carbon sequestration	15-30% lower microbial biomass C, altered C cycling	Reduced soil organic carbon accumulation, soil structure impacts

(Source: Compiled from multiple studies: Kumar et al., 2021; Sharma and Singh, 2022; Malik et al., 2022)

The economic implications of these functional changes are significant. The reduced efficiency of nutrient cycling often necessitates higher synthetic fertilizer inputs to maintain yields, creating a dependency cycle that increases production costs while further stressing soil biological systems (Sharma et al., 2021).

Management Strategies for Microbial Preservation

Several alternative management approaches show promise for preserving soil microbial diversity while maintaining effective pest control in Mahendergarh's agricultural systems:

1. **Integrated Pest Management (IPM)**: Field trials across the district demonstrate that IPM approaches combining biological controls, resistant varieties, and limited targeted pesticide applications can reduce overall chemical use by 30-50% while maintaining comparable yields to conventional management (Singh et al., 2021).
2. **Biological amendments**: Application of microbial inoculants and biofertilizers shows potential for restoring microbial function in pesticide-affected soils. Farmer field trials with Trichoderma, Pseudomonas, and mycorrhizal inoculants demonstrate improved soil enzyme activities and enhanced resilience to subsequent pesticide applications (Kumari and Kumar, 2022).
3. **Soil organic matter management**: Increasing soil organic matter through cover cropping, crop residue retention, and organic amendments provides buffering capacity against pesticide impacts. Fields with organic matter levels

above 1% show significantly greater microbial resilience to pesticide exposure compared to the district average of 0.4-0.5% (Verma et al., 2021).

4. **Precision application technologies**: Adoption of precision spraying equipment and site-specific application reduces overall pesticide loading in soils while maintaining pest control efficacy. Targeted application can reduce pesticide use by 15-40% while lowering impacts on non-target soil organisms (Kumar and Yadav, 2022).

CONCLUSION AND FUTURE RESEARCH NEEDS

This review highlights the significant impacts of pesticide use on soil microbial communities in Mahendergarh district, with documented reductions in diversity and abundance across major microbial groups including bacteria, fungi, and actinomycetes. The functional consequences of these shifts are evident in compromised soil processes including organic matter decomposition, nutrient cycling, and natural disease suppression.

The findings underscore the need for more sustainable pest management approaches that preserve the biological foundation of soil health. While alternatives such as IPM, biological amendments, and precision application technologies show promise, their wider adoption requires targeted research, extension support, and potentially policy incentives.
Several research priorities emerge from this review:

1. Long-term monitoring studies are needed to assess the cumulative and potentially irreversible effects of pesticide applications on soil microbiomes across different agricultural zones of the district.
2. Mechanistic studies exploring interactions between pesticide mixtures and microbial communities are required, as farmers typically apply multiple compounds during growing seasons.
3. Economic analyses quantifying the hidden costs of microbial community disruption would help inform policy and farmer decision-making regarding pesticide use.
4. Development and testing of locally adapted biological control options suited to Mahendergarh's semi-arid conditions should be prioritized.
5. Exploration of traditional knowledge and practices regarding pest management in the region may yield valuable insights for developing culturally appropriate and effective alternatives.

By addressing these research needs and promoting adoption of microbial-preserving management practices, Mahendergarh can work toward agricultural systems that maintain productivity while preserving the vital soil biological resources upon which sustainable agriculture ultimately depends.

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