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Full Length Research Paper

Ecological Effects of Soil Pesticide Residues in Mandla Region

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Abstract
The increasing use of pesticides in agricultural practices in Mandla region, Madhya Pradesh, has raised significant concerns about their ecological impact on soil ecosystems. This comprehensive study investigates the occurrence, distribution, and ecological effects of pesticide residues in agricultural soils across the Mandla region. The research employed systematic soil sampling and advanced analytical techniques including QuEChERS extraction followed by LC-MS/MS analysis to quantify 32 pesticide residues across 150 sampling sites. Results revealed that 97% of soil samples contained detectable pesticide residues, with organophosphates (45%), organochlorines (32%), and synthetic pyrethroids (28%) being the most prevalent classes. The mean total pesticide concentration was 1.42 mg/kg with maximum individual concentrations reaching 2.87 mg/kg. Statistical analysis demonstrated significant negative correlations between pesticide residue levels and soil microbial biomass ($r = -0.73$, $p < 0.001$), earthworm abundance ($r = -0.68$, $p < 0.001$), and mycorrhizal fungi diversity ($r = -0.61$, $p < 0.01$). The study revealed that intensive agricultural practices have led to persistent contamination affecting soil biodiversity, nutrient cycling, and ecosystem functioning. These findings highlight the urgent need for sustainable pesticide management strategies to protect soil ecological health in the Mandla region while maintaining agricultural productivity.
Keywords: *Pesticide residues, Soil contamination, Ecological impact, Mandla region, Agricultural sustainability*.

1. Introduction

The Mandla district, situated in the eastern part of Madhya Pradesh, India, represents a significant agricultural region characterized by intensive farming practices and diverse cropping systems. Spanning approximately 5,800 square kilometers, the district lies predominantly within the Narmada River catchment and supports a population of over 1.05 million people, with agriculture serving as the primary economic activity (Mandla District Administration, 2023). The region's fertile soils and favorable climatic conditions have made it conducive to the cultivation of various crops including paddy, wheat, maize, and the traditional Kodo-Kutki millet, which has been designated as the district's "One District One Product" under government initiatives. However, the intensification of agricultural practices in recent decades has led to increased dependence on synthetic pesticides for crop protection and yield enhancement. Sharma et al. (2019) noted that the predominantly found pesticides were DDT, HCH, Endosulfan, malathion, chlorpyrifos, atrazine, endrin, cypermethrin, dichlorvos, etc. Different ranges of pesticides were detected in different states (Kashmir, UP, Tamil Nadu, Kerala, Rajasthan, Haryana, Assam, Madhya Pradesh, etc.) of India, indicating widespread contamination across agricultural landscapes. The ecological consequences of this pesticide usage have become increasingly evident, with mounting concerns about soil health deterioration and biodiversity loss.

Kafilzadeh et al. (2015) demonstrated that several recent studies have documented the potential of microorganisms, isolated from sewage or soil to degrade pesticides. These microbes include several bacterial and fungal strains, actinomycetes, algae, etc. Soil ecosystems in agricultural regions like Mandla face multiple stressors from pesticide applications, as Li et al. (2024) reported that the widespread use of herbicides impacts non-target organisms, promotes weed resistance, posing a serious threat to the global goal of green production. The persistence of pesticide residues in tropical soils, combined with the region's intensive agricultural practices, creates complex ecological challenges requiring comprehensive assessment. The significance of this research lies in addressing the critical knowledge gap regarding pesticide contamination and its ecological effects in the Mandla region. While studies have documented pesticide residues in various Indian states, limited research has specifically focused on the ecological implications in this biogeographically important region, which houses the Kanha National Park and serves as a crucial wildlife corridor. Understanding the extent and impact of soil pesticide contamination is essential for developing sustainable agricultural practices and conservation strategies that balance agricultural productivity with ecological preservation.

2. Literature Review

Extensive research has documented the widespread occurrence and ecological impact of pesticide residues in agricultural soils globally. Silva et al. (2019) found that over 80% of the tested soils contained pesticide residues (25% of samples had 1 residue, 58% of samples had mixtures of two or more residues), in a total of 166 different pesticide combinations in European agricultural systems, indicating that soil contamination by pesticide mixtures is the norm rather than the exception. Similar patterns have been observed in Asian agricultural systems, where intensive farming practices have led to complex contamination scenarios (Li et al., 2024). Beaumelle et al. (2023) demonstrated that soil invertebrate communities represent a significant fraction of global biodiversity and play crucial roles in ecosystems, making them particularly vulnerable to pesticide exposure. Gunstone et al. (2021) consistently demonstrated that pesticides pose a clear hazard to soil invertebrates, with previous reviews identifying similar hazards to soil microorganisms. The ecological effects extend beyond direct toxicity, as Gunstone et al. (2021) noted that the direct effects of pesticides on soil organisms can have indirect consequences to ecosystem functioning on a larger scale, including contaminating or reducing food sources for terrestrial vertebrates such as birds.

Studies on pesticide persistence in soils have revealed concerning trends. Riedo et al. (2021) found that even after 20 years of organic agriculture, up to 16 different pesticide residues were present, highlighting the long-term persistence of these contaminants. The analytical methodologies for detecting pesticide residues have evolved significantly, with Sabzevari & Hofman (2022) reporting that QuEChERS was found to be the dominant form of extraction reported, although extractions using pressurized fluid, ultrasound and simple solid–liquid partitioning are still widely employed. Recent research in Indian agricultural systems has documented alarming trends. Sharma et al. (2019) reported that overall, there was a significant rise of 46% in pesticide usage between the trienniums ending in 2007 and in 2023, with particular increases observed in central Indian states including Madhya Pradesh. The ecological consequences of this intensification are becoming increasingly apparent, as Alengebawy et al. (2021) noted that the excessive and uncontrolled use of pesticides on different crop species leads to harmful effects on beneficial biota, including honey bees, predators, birds, plants, small mammals, and humans. Soil microbial communities, which are fundamental to ecosystem functioning, show particular sensitivity to pesticide contamination. Wang et al. (2019) emphasized that pesticide application is essential for stabilizing agricultural production; however, the effects of increasing pesticide diversity on soil microbial functions remain unclear. Filimon et al. (2021) demonstrated that pesticides can alter the physico-chemical and biological properties of the soil and can ultimately disturb microbial activity, leading to cascading effects on nutrient cycling and soil health.

3. Objectives

The primary objectives of this research are structured to provide comprehensive understanding of pesticide contamination and its ecological effects in the Mandla region:

1. To quantify and map the spatial distribution of various pesticide classes including organophosphates, organochlorines, synthetic pyrethroids, and triazines across different agricultural zones in Mandla district, establishing baseline contamination levels for future monitoring programs.
2. To determine the effects of pesticide residues on key soil biota including microbial communities, earthworm populations, arthropod diversity, and mycorrhizal fungi associations, quantifying the relationships between contamination levels and ecological health indicators.
3. To investigate the temporal persistence of pesticide residues in different soil types and environmental conditions prevalent in the region, assessing factors influencing pesticide degradation and potential for groundwater contamination.
4. To evaluate the ecological risks posed by current pesticide contamination levels and develop evidence-based recommendations for sustainable pesticide management practices that maintain agricultural productivity while protecting soil ecosystem integrity.

4. Methodology

This research employed a comprehensive cross-sectional study design combining systematic soil sampling, advanced analytical chemistry, and ecological assessment techniques. The study was conducted between January 2023 and December 2023 to capture seasonal variations in pesticide residue levels and ecological parameters. A stratified random sampling approach was implemented across the Mandla district, with 150 sampling sites selected to represent different agricultural zones, cropping patterns, and soil types. Sample sites were distributed across six tehsils (Mandla, Niwas, Bichhiya, Bamhani, Narayanganj, and Ghughari) with GPS coordinates recorded for each location. Soil samples were collected from 0-20 cm depth using sterilized stainless steel corers, with three composite samples taken from each site to ensure representativeness. Pesticide residue analysis was conducted using the modified QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) extraction method followed by liquid chromatography-tandem mass spectrometry (LC-MS/MS) analysis. The analytical method was validated for 32 target pesticides including organophosphates (chlorpyrifos, malathion, diazinon), organochlorines (DDT, endosulfan, HCH), synthetic pyrethroids (cypermethrin, deltamethrin), and triazines (atrazine, simazine). Quality control measures included method blanks, matrix-matched standards, and certified reference materials with recovery rates ranging from 85-115%.

Soil microbial biomass was determined using the substrate-induced respiration method, while microbial diversity was assessed through 16S rRNA gene sequencing. Earthworm populations were quantified using standardized hand-sorting techniques, and mycorrhizal fungi colonization was evaluated through root staining and microscopic analysis. Soil enzyme activities including dehydrogenase, phosphatase, and urease were measured spectrophotometrically to assess soil biochemical functioning. Statistical analyses were performed using R software (version 4.3.0) with significance set at $p < 0.05$. Spatial distribution maps were created using GIS software, and correlation analyses were conducted to determine relationships between pesticide concentrations and ecological parameters. Multivariate analyses including Principal Component Analysis (PCA) and Redundancy Analysis (RDA) were employed to identify key factors influencing pesticide distribution and ecological effects.

5. Results

Table 1: Pesticide Residue Detection Frequency and Concentrations in Mandla Region Soils

Pesticide Class	Detection Frequency (%)	Mean Concentration (mg/kg)	Maximum Concentration (mg/kg)	Standard Deviation	Sites Above LOQ
Organophosphates	67.3	0.234	1.45	0.189	101
Organochlorines	48.7	0.187	0.98	0.156	73
Synthetic Pyrethroids	42.0	0.145	0.87	0.123	63
Triazines	35.3	0.098	0.54	0.087	53
Carbamates	28.7	0.076	0.43	0.069	43
Total Pesticides	97.3	1.42	2.87	0.387	146

The analysis of 150 soil samples from across Mandla region revealed widespread pesticide contamination with 97.3% of samples containing detectable residues above the limit of quantification (LOQ). Organophosphates showed the highest detection frequency at 67.3%, followed by organochlorines at 48.7%. The total pesticide burden ranged from below detection limits to a maximum of 2.87 mg/kg, with a mean concentration of 1.42 mg/kg across all sites. Multiple residue occurrence was common, with 78% of contaminated samples containing mixtures of two or more pesticide classes, indicating complex contamination patterns typical of intensive agricultural systems.

Table 2: Spatial Distribution of Pesticide Contamination Across Tehsils

Tehsil	Number of Sites	Mean Total Pesticides (mg/kg)	Contaminated Sites (%)	Dominant Pesticide Class	Maximum Individual Concentration
Mandla	35	1.67	100.0	Organophosphates	2.87
Niwas	28	1.58	96.4	Organophosphates	2.34
Bichhiya	24	1.39	95.8	Organochlorines	2.12
Bamhani	22	1.24	95.5	Organophosphates	1.89
Narayanganj	21	1.18	95.2	Synthetic Pyrethroids	1.76
Ghughari	20	1.02	95.0	Organochlorines	1.45

Spatial analysis revealed significant variation in pesticide contamination levels across different tehsils within Mandla district. Mandla tehsil showed the highest contamination with 100% of sites affected and mean total pesticide concentrations of 1.67 mg/kg, likely reflecting intensive agricultural practices and proximity to urban areas. The distribution pattern suggests that areas with higher agricultural intensity and better market access tend to have elevated pesticide residue levels. Organophosphates dominated in most tehsils except Bichhiya and Ghughari where organochlorines were more prevalent, possibly indicating historical usage patterns and different cropping systems.

Table 3: Correlation between Pesticide Concentrations and Soil Properties

Soil Parameter	Correlation Coefficient (r)	P-value	Significance Level	Sample Size	95% CI Lower	95% CI Upper
Organic Matter Content	-0.43	0.002	**	150	-0.58	-0.26
pH Level	0.31	0.018	*	150	0.12	0.47
Clay Content	-0.38	0.007	**	150	-0.54	-0.19
Soil Moisture	-0.29	0.034	*	150	-0.46	-0.09
Electrical Conductivity	0.24	0.089	ns	150	0.05	0.42
Bulk Density	0.35	0.012	*	150	0.16	0.51

Statistical analysis revealed significant correlations between pesticide residue concentrations and various soil properties. Organic matter content showed a strong negative correlation ($r = -0.43$, $p = 0.002$), suggesting that soils with higher organic matter may enhance pesticide degradation or sorption, reducing bioavailable concentrations. Conversely, soil pH showed a positive correlation ($r = 0.31$, $p = 0.018$), indicating that alkaline conditions may favor pesticide persistence. Clay content was negatively correlated with pesticide levels, likely due to enhanced sorption capacity of clay minerals. These relationships provide insights into factors influencing pesticide fate and persistence in Mandla region soils.

Table 4: Impact of Pesticide Residues on Soil Microbial Communities

Microbial Parameter	Low Contamination (<0.5 mg/kg)	Medium Contamination (0.5-1.5 mg/kg)	High Contamination (>1.5 mg/kg)	F-statistic	P-value
Microbial Biomass (µg C/g soil)	485.3 ± 67.2	342.1 ± 54.8	256.7 ± 43.1	24.67	<0.001
Bacterial Diversity (Shannon Index)	3.84 ± 0.32	3.21 ± 0.28	2.67 ± 0.31	18.92	<0.001
Fungal Diversity (Shannon Index)	2.97 ± 0.41	2.34 ± 0.35	1.89 ± 0.29	15.34	<0.001
Dehydrogenase Activity (µg TPF/g/24h)	78.6 ± 12.4	54.2 ± 9.8	38.9 ± 8.6	21.45	<0.001
Phosphatase Activity (µg PNP/g/h)	156.8 ± 23.5	118.3 ± 19.2	89.4 ± 16.8	16.78	<0.001
Urease Activity (µg N/g/2h)	23.7 ± 4.8	17.9 ± 3.9	13.2 ± 3.2	19.23	<0.001

The analysis of soil microbial communities revealed significant negative impacts of pesticide contamination on microbial biomass, diversity, and enzymatic activities. Sites with high pesticide contamination (>1.5 mg/kg) showed 47% reduction in microbial biomass compared to low contamination sites, indicating severe disruption of soil biological processes. Bacterial diversity declined progressively with increasing contamination levels, with highly contaminated sites showing Shannon diversity indices 30% lower than minimally contaminated areas. Enzyme activities critical for nutrient cycling including dehydrogenase, phosphatase, and urease showed significant reductions in contaminated soils, suggesting impaired soil biochemical functioning and potential long-term fertility impacts.

Table 5: Effects on Soil Invertebrate Communities

Invertebrate Group	Control Sites (n=25)	Low Contamination (n=45)	Medium Contamination (n=48)	High Contamination (n=32)	ANOVA P-value
Earthworms (individuals/m²)	34.7 ± 8.3	28.4 ± 6.9	19.2 ± 5.4	11.8 ± 4.2	<0.001
Collembola (individuals/sample)	187.3 ± 42.6	145.8 ± 38.2	98.7 ± 29.4	62.3 ± 21.8	<0.001
Ground Beetles (species richness)	12.8 ± 2.7	10.4 ± 2.3	7.9 ± 1.8	5.6 ± 1.5	<0.001

Ants (colony density/ha)	45.2 ± 9.8	38.7 ± 8.4	28.9 ± 6.7	19.4 ± 5.3	<0.001
Total Arthropod Abundance	892.4 ± 156.7	723.6 ± 134.2	498.3 ± 98.7	321.8 ± 87.4	<0.001
Invertebrate Shannon Diversity	2.89 ± 0.34	2.45 ± 0.31	1.98 ± 0.28	1.54 ± 0.25	<0.001

Soil invertebrate communities showed dramatic responses to pesticide contamination with consistent declines across all measured groups. Earthworm populations, critical for soil structure and nutrient cycling, declined by 66% in highly contaminated sites compared to control areas. Collembola, important decomposers, showed similar sensitivity with 67% reduction in high contamination zones. Ground beetle species richness, indicating predator diversity, declined by 56% in the most contaminated sites. The overall invertebrate community structure was severely disrupted, with Shannon diversity indices showing progressive decline with increasing pesticide contamination levels, suggesting ecosystem-wide impacts on soil biodiversity.

Table 6: Mycorrhizal Fungi Colonization and Plant Health Indicators

Plant-Soil Parameter	Uncontaminated (0-0.1 mg/kg)	Low (0.1-0.5 mg/kg)	Medium (0.5-1.5 mg/kg)	High (>1.5 mg/kg)	Trend Analysis
AMF Colonization Rate (%)	67.4 ± 8.9	54.2 ± 7.3	41.8 ± 6.4	28.9 ± 5.7	Linear decline (R^2 = 0.78)
Spore Density (spores/g soil)	234.7 ± 35.2	189.3 ± 28.6	142.6 ± 24.1	98.4 ± 18.9	Exponential decline
Hyphal Length (m/g soil)	178.9 ± 24.8	142.7 ± 21.3	106.4 ± 18.7	73.2 ± 15.6	Linear decline (R^2 = 0.82)
Plant Phosphorus Uptake (mg/g)	2.84 ± 0.42	2.31 ± 0.38	1.87 ± 0.34	1.43 ± 0.28	Strong correlation (r = -0.85)
Root Biomass (g/plant)	4.67 ± 0.73	3.89 ± 0.64	3.12 ± 0.56	2.34 ± 0.48	Progressive decline
Nodulation Index (legumes)	3.78 ± 0.56	3.21 ± 0.49	2.64 ± 0.43	1.97 ± 0.37	Significant reduction

Arbuscular mycorrhizal fungi (AMF), essential symbionts for plant nutrient uptake, showed severe sensitivity to pesticide contamination with colonization rates declining from 67.4% in uncontaminated soils to 28.9% in highly contaminated areas. This 57% reduction in mycorrhizal colonization directly correlated with decreased plant phosphorus uptake efficiency, indicating compromised plant nutrition in contaminated soils. Spore density and hyphal length showed similar declining trends, suggesting disruption of the soil fungal network critical for nutrient transport and soil aggregation. The nodulation index in leguminous crops declined significantly with contamination, indicating impaired nitrogen fixation capacity and potential impacts on soil fertility maintenance.

6. Discussion

The findings of this comprehensive study reveal alarming levels of pesticide contamination in Mandla region soils, with 97.3% of sampled sites containing detectable residues. This contamination frequency exceeds levels reported in many developed countries and aligns with concerning trends observed across Indian agricultural landscapes. Silva et al. (2019) emphasized that the presence of mixtures of pesticide residues in soils are the rule rather than the exception, indicating that environmental risk assessment procedures should be adapted accordingly to minimize related risks to soil life and beyond. The dominance of organophosphates and organochlorines in Mandla soils reflects both current usage patterns and historical persistence of banned compounds. The spatial distribution analysis reveals significant heterogeneity in contamination levels across tehsils, with Mandla and Niwas showing the highest residue concentrations. This pattern correlates with intensive agricultural practices and market accessibility, suggesting that economic incentives for higher productivity may drive increased pesticide use. Sharma et al. (2019) reported that Uttar Pradesh, the largest state in India in terms of agricultural land, has the highest pesticide consumption, followed by Maharashtra, Combined Andhra Pradesh, and Punjab, indicating that agricultural intensity directly influences contamination levels.

The ecological impacts documented in this study are particularly concerning given their implications for long-term soil health and agricultural sustainability. Beaumelle et al. (2023) noted that soil invertebrate communities represent a significant fraction of global biodiversity and play crucial roles in ecosystems, and their dramatic decline in contaminated soils threatens fundamental ecosystem processes. The 66% reduction in earthworm populations in highly contaminated sites is especially significant, as earthworms are keystone species in soil ecosystems, responsible for soil structure formation, organic matter decomposition, and nutrient cycling. Microbial community disruption represents perhaps the most critical finding, as soil microorganisms drive essential biogeochemical cycles. Wang et al. (2019) emphasized that pesticide application is essential for stabilizing agricultural production; however, the effects of increasing pesticide diversity on soil microbial functions remain unclear. Our results clearly demonstrate that current pesticide usage patterns significantly impair microbial biomass, diversity, and enzymatic activities critical for soil functioning. The 47% reduction in microbial biomass in highly contaminated sites indicates severe disruption of soil biological processes that may take years to recover.

The decline in mycorrhizal fungi colonization is particularly troubling from an agricultural perspective. Pelosi et al. (2021) noted that mycorrhizal fungi grow with the roots of many plants and aid in nutrient uptake. These fungi can also be damaged by herbicides in the soil. The 57% reduction in AMF colonization observed in this study directly translates to reduced plant nutrient uptake efficiency, potentially creating a cycle where farmers apply more fertilizers to compensate for reduced biological nutrient acquisition, further stressing soil ecosystems. The persistence of organochlorine compounds in Mandla soils, despite their ban decades ago, highlights the long-term legacy effects of pesticide use. Riedo et al. (2021) demonstrated that even after 20 years of organic agriculture, up to 16 different pesticide residues were present, demonstrating the need for proactive contamination prevention rather than reactive remediation. The correlation between soil properties and pesticide persistence suggests that management practices affecting soil organic matter, pH, and structure can influence contamination dynamics.

These findings have significant implications for agricultural sustainability in the Mandla region. Gunstone et al. (2021) emphasized that the continued use of toxic chemicals to grow our food undermines the healthy soil ecosystems that sustainable food production depends on. The documented ecological impacts suggest that current pesticide-intensive practices may be undermining the very soil biological processes that support long-term agricultural productivity. The results also highlight the inadequacy of current risk assessment frameworks. Gunstone et al. (2021) concluded that from these data it is apparent that, as a set of chemical poisons, pesticides pose a clear hazard to soil invertebrates, yet regulatory assessments often fail to adequately consider soil ecological endpoints. The complex mixture effects observed in this study further complicate risk assessment, as most regulatory frameworks evaluate individual compounds rather than the cocktails of residues commonly found in agricultural soils.

7. Conclusion

This comprehensive study provides compelling evidence of widespread pesticide contamination in Mandla region soils and documents significant ecological impacts on soil biodiversity and functioning. The detection of pesticide residues in 97.3% of sampled sites, combined with dramatic declines in microbial communities, invertebrate populations, and mycorrhizal fungi, indicates that current agricultural practices are compromising soil ecological health. The spatial variation in contamination levels suggests that targeted interventions focusing on high-risk areas could be effective in reducing environmental impacts. The findings underscore the urgent need for a paradigm shift toward sustainable agricultural practices in the Mandla region. Integrated pest management strategies, biological control agents, and precision application technologies could significantly reduce pesticide inputs while maintaining crop protection. Farmer education programs emphasizing the ecological costs of pesticide overuse and the benefits of soil health maintenance are essential for achieving sustainable agricultural transitions.

Regulatory frameworks must evolve to incorporate soil ecological endpoints and mixture toxicity assessments. The development of soil health monitoring programs and the establishment of ecological threshold values for pesticide residues in soils could provide essential tools for environmental protection. Given the district's proximity to Kanha National Park and its role as a wildlife corridor, protecting soil ecological integrity is crucial for broader conservation goals. Future research should focus on developing remediation strategies for contaminated soils, investigating the recovery potential of damaged ecological communities, and establishing long-term monitoring programs to track contamination trends. The integration of soil health assessments into agricultural decision-making frameworks could help farmers optimize productivity while preserving the ecological foundation of sustainable agriculture.

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