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MICROPLASTIC CONTAMINATION AND SOIL HEALTH DEGRADATION IN AGRICULTURAL ECOSYSTEMS OF PAKISTAN

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ABSTRACT
Microplastic contamination has emerged as an important environmental threat to agricultural soil health and sustainable crop production. This study examined the effects of microplastic contamination on the physical, chemical, and biological dimensions of soil health and assessed their consequences for crop productivity in agricultural ecosystems of Pakistan. A quantitative, cross-sectional research design was employed using a multistage sampling approach, with data collected from 400 agricultural farms across selected agro-ecological regions. Microplastic contamination was assessed through soil sampling and laboratory analysis, while soil physical, chemical, and biological health and crop productivity were evaluated using standardized measures. The data were analyzed using descriptive statistics, reliability analysis, Pearson correlation, multiple regression, and mediation analysis. The findings indicated that microplastic contamination significantly and negatively affected soil physical, chemical, and biological health, with the strongest effect observed for biological health. Soil health dimensions were positively associated with crop productivity, whereas microplastic contamination demonstrated a significant negative direct effect on productivity. Mediation analysis further indicated that soil health partially mediated the relationship between microplastic contamination and crop productivity. The findings highlight the need to integrate microplastic management into sustainable soil-health strategies, agricultural practices, environmental monitoring, and policy development in Pakistan.

Keywords:
Microplastics; Soil Health; Agricultural Ecosystems; Crop Productivity; Soil Degradation; Pakistan

INTRODUCTION
Microplastic (MP) contamination has emerged as an important environmental challenge for agricultural soils because these persistent particles can accumulate in terrestrial ecosystems, alter soil

properties, interact with contaminants, and affect plant and microbial functions. Microplastics are generally defined as plastic particles smaller than 5 mm and may originate from the fragmentation of agricultural films, plastic waste, wastewater irrigation, sewage sludge, compost, coated fertilizers, atmospheric deposition, and other anthropogenic inputs. Recent reviews indicate that agricultural soils can act as long-term reservoirs of MPs, with their distribution and persistence influenced by particle size, polymer type, soil characteristics, moisture, and agricultural practices (Chakraborty et al., 2025; Vasić et al., 2025).

The contamination of agricultural soils is particularly concerning because soil health depends on the interaction of physical, chemical, and biological processes that regulate nutrient cycling, water availability, organic-matter dynamics, microbial activity, and plant productivity. Recent evidence indicates that MPs can modify soil structure, bulk density, water retention, pH, nutrient availability, and aggregate stability. They may also interfere with carbon and nitrogen cycling and modify greenhouse-gas emissions, thereby affecting important soil ecosystem functions (Kumar, 2025; Zhou et al., 2025).

The biological dimension of soil health is also vulnerable to MP contamination. Microplastics can alter microbial community composition, microbial diversity, and soil enzyme activity, potentially disturbing decomposition and nutrient transformation processes. Experimental evidence has shown that different polymers and concentrations can produce different effects, with polyethylene and polyvinyl chloride among the materials associated with substantial changes in soil microbial communities and enzymatic activity (Environmental Pollution, 2025). These effects are important because soil microorganisms constitute a fundamental component of nutrient cycling and soil fertility.

Microplastics may additionally affect plants through physical interference with roots, changes in nutrient availability, oxidative stress, and disruption of physiological processes. Recent systematic evidence indicates that MPs can reduce seed germination, plant growth, nutrient uptake, photosynthetic performance, and biomass under certain exposure conditions. Their effects may vary according to polymer composition, particle size, concentration, aging, plant species, and soil characteristics (Rai et al., 2025; Wang et al., 2025). Moreover, MPs can act as carriers for other contaminants, potentially modifying the mobility and bioavailability of heavy metals and other pollutants in soil–plant systems (Zhang et al., 2024).

The Pakistani agricultural context provides particularly important grounds for investigating this emerging environmental problem. Pakistan's intensive agricultural production, extensive use of plastic materials, wastewater and irrigation practices, increasing solid-waste generation, and inadequate agricultural plastic management may create multiple pathways for MPs to enter cultivated soils. Importantly, empirical evidence from Sialkot, Pakistan, has confirmed MP contamination across sampled agricultural sites. Qaiser et al. (2024) identified low-density polyethylene, high-density polyethylene, polypropylene, polystyrene, and polyamide among the detected polymers and reported potential reductions in potato growth, biomass, photosynthetic activity, and ion uptake associated with MP exposure.

Recent research also suggests that wastewater irrigation can contribute substantially to MP accumulation in agricultural soils. Long-term wastewater irrigation has been associated with changes in MP abundance and characteristics in cultivated soils, highlighting the importance of irrigation-water quality as a potential pathway of contamination (Aydin et al., 2025). In Pakistan, where wastewater may be used for agricultural irrigation in areas experiencing water scarcity, this pathway warrants systematic investigation across different agro-ecological settings.

Despite growing international evidence, important knowledge gaps remain regarding the combined relationship between MP contamination and multidimensional soil health in Pakistan. Existing research has predominantly focused on contamination occurrence or individual plant responses, while comparatively limited empirical work has simultaneously examined MP concentration and characteristics alongside soil physical properties, chemical fertility, microbial activity, nutrient availability, and crop productivity. Furthermore, methodological differences in MP extraction, identification, particle-size classification, and reporting make comparisons across locations difficult (Zhang et al., 2025).

Therefore, the present study focuses on microplastic contamination and soil health degradation in agricultural ecosystems of Pakistan. It conceptualizes soil health as a multidimensional outcome encompassing physical, chemical, and biological indicators and examines whether increasing MP contamination is associated with deterioration in these dimensions. By integrating contamination assessment with soil-health indicators and agricultural productivity, the study seeks to provide a more comprehensive understanding of the environmental consequences of MPs and generate evidence relevant to sustainable agricultural management and pollution-control policy in Pakistan.

Problem Statement

Microplastic contamination represents an emerging but insufficiently characterized threat to agricultural soil health in Pakistan. Although international research increasingly demonstrates that MPs can modify soil structure, water dynamics, nutrient cycling, microbial communities, enzyme activity, and plant physiological processes, the evidence base for Pakistan remains geographically limited and fragmented. The recent identification of widespread MP contamination in agricultural soils of Sialkot and its association with adverse potato growth and physiological responses demonstrates that the problem is no longer merely hypothetical in the Pakistani context (Qaiser et al., 2024).

The principal research problem is that the occurrence of MPs and their broader implications for soil health have not been adequately integrated into a multidimensional assessment of Pakistan's agricultural ecosystems. Existing studies often examine MP abundance or individual plant responses independently, whereas soil health is inherently a system-level concept involving physical structure, chemical fertility, biological activity, nutrient cycling, and the capacity of soil to sustain productive agriculture. Recent evidence indicates that MPs can simultaneously influence several of these dimensions, but the magnitude and direction of their effects depend on polymer type, particle size, concentration, soil properties, environmental conditions, and exposure duration (Kumar, 2025; Vasić et al., 2025).

A further problem concerns the multiple pathways through which MPs may enter Pakistani agricultural soils. Plastic mulch degradation, agricultural plastic residues, wastewater irrigation, organic amendments, contaminated inputs, runoff, and atmospheric deposition may introduce different polymer types and particle sizes into cultivated land. Consequently, contamination is likely to vary spatially according to agricultural practices and environmental conditions. However, systematic evidence comparing MP contamination and soil-health degradation across agricultural settings in Pakistan remains inadequate.

The problem is further complicated by potential interactions between MPs and other soil contaminants. Microplastics can adsorb and transport chemical pollutants and may modify the bioavailability of heavy metals and other contaminants. Such interactions can create combined risks for soil organisms, plants, food safety, and agricultural sustainability (Zhang et al., 2024; Chakraborty et al., 2025).

Accordingly, the research gap is not simply the absence of evidence regarding MP presence; rather, it concerns the insufficient empirical understanding of how MP contamination translates into measurable degradation of soil physical, chemical, and biological health and, ultimately, agricultural productivity in Pakistan. Addressing this gap is essential for developing evidence-based agricultural practices, monitoring systems, plastic-waste management strategies, and environmental policies capable of protecting long-term soil fertility and food security.

Research Questions

RQ1: What is the level and composition of microplastic contamination in Pakistan's agricultural soils?

RQ2: How does microplastic contamination affect the physical, chemical, and biological health of agricultural soils?

RQ3: What is the relationship between microplastic contamination and crop productivity?

RQ4: Do soil-health indicators mediate the relationship between microplastic contamination and crop productivity?

RQ5: Which agricultural and environmental factors significantly contribute to microplastic accumulation in agricultural soils?

Research Objectives

1. To assess the concentration, polymer types, particle sizes, and distribution of microplastics in selected agricultural soils of Pakistan.
2. To examine the effects of microplastic contamination on the physical, chemical, and biological indicators of soil health.
3. To determine the effect of microplastic contamination on agricultural crop productivity.
4. To evaluate the mediating role of soil health in the relationship between microplastic contamination and crop productivity.
5. To identify the major agricultural and environmental factors contributing to microplastic accumulation in Pakistani agricultural soils.

Significance of the Study

Theoretical Significance

The study contributes to the emerging literature on soil health and terrestrial microplastic pollution by integrating physical, chemical, and biological dimensions of soil health into a unified analytical framework. It extends understanding of how an emerging contaminant can influence interconnected soil ecosystem processes rather than isolated environmental indicators.

Practical Significance

The findings can assist farmers, agricultural extension services, soil scientists, and environmental practitioners in identifying agricultural practices associated with higher MP accumulation and adopting improved plastic-management, irrigation, soil-management, and waste-disposal practices. The study can also provide evidence for developing soil-monitoring protocols for contaminated agricultural areas.

Policy Significance

The study can support Pakistani policymakers in developing evidence-based strategies for agricultural plastic management, wastewater irrigation, plastic-waste control, soil-quality monitoring, and sustainable agriculture. It can also provide a scientific basis for establishing national standards for monitoring MPs in agricultural soils and evaluating their potential implications for food security and environmental health.

Environmental Significance

By linking MP contamination with soil degradation and crop productivity, the study highlights the need to treat agricultural soils as an important component of terrestrial plastic-pollution management. This is particularly important because recent evidence indicates that MPs can persist in soils, alter ecological functions, and potentially move through soil–plant–food-chain pathways.

Literature Review

Microplastic (MP) contamination has increasingly been recognized as an important form of terrestrial pollution, particularly in agricultural soils where plastics are extensively used for mulching, irrigation, packaging, fertilizers, and other production activities. Recent reviews indicate that agricultural soils receive MPs through plastic-film degradation, wastewater and contaminated irrigation water, sewage sludge,

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organic amendments, atmospheric deposition, and agricultural plastic residues. Unlike many conventional pollutants, MPs are persistent and can undergo fragmentation, weathering, vertical movement, and interactions with soil constituents, making agricultural soils important long-term reservoirs of plastic pollution (Sattar et al., 2025; Vasić et al., 2025).

Recent literature demonstrates that the effects of MPs extend beyond their physical presence in soil. They can modify soil structure, bulk density, porosity, water-holding capacity, aggregate stability, pH, and nutrient availability. Vasić et al. (2025) concluded that MP contamination can disrupt soil structure and water dynamics while altering soil chemistry and microbiological processes. Similarly, recent experimental research has shown that MP size, shape, and polymer type influence soil-water relationships, suggesting that contamination cannot be evaluated solely on the basis of particle concentration.

The biological dimension of soil health has received substantial attention. Kumar (2025) reported that MPs can alter soil microbial communities and biological processes through interactions with microorganisms and soil organic matter. Such disturbances are potentially important because microorganisms regulate decomposition, nutrient transformation, carbon cycling, and soil fertility. Recent research further indicates that MPs can modify microbial enzyme activities and microbial community composition, although the direction and magnitude of effects vary according to polymer characteristics, concentration, exposure duration, and soil conditions.

MP contamination also has important implications for soil nutrient cycling. A 2025 meta-analysis based on 102 peer-reviewed studies found that MPs influence carbon, nitrogen, and phosphorus transformation processes in farmland soils. The effects were associated with changes in physicochemical and microbial properties and could influence greenhouse-gas emissions, demonstrating that MP contamination may affect not only soil fertility but also broader agricultural ecosystem functioning. Similarly, Sarfraz et al. (2025) reported that MPs can interfere with nitrogen mineralization, nitrification, denitrification, and ammonia volatilization, potentially reducing nitrogen-use efficiency and affecting crop productivity.

The soil–plant interface represents another major pathway through which MP contamination can affect agricultural ecosystems. Farooq et al. (2025) synthesized evidence showing that MPs can alter soil structure and nutrient cycling while changing microbial communities and enzymatic activity. Smaller particles may interact with plant roots and induce oxidative stress, impaired growth, altered nutrient metabolism, and reduced photosynthetic performance. A systematic review by recent researchers similarly concluded that MP degradation and transformation can modify nutrient dynamics and plant health, emphasizing the interconnected nature of the soil–plant system.

The relationship between MPs and crop productivity is therefore becoming increasingly important. Vasić et al. (2025) identified soil degradation, altered nutrient availability, disturbed microbial activity, and impaired plant growth as important mechanisms through which MPs can undermine agricultural productivity. However, effects are not necessarily uniform: polymer type, particle morphology, concentration, soil texture, crop species, and environmental conditions can substantially modify outcomes. This variability creates difficulties in establishing universal thresholds for MP contamination.

Another emerging concern is the interaction between MPs and other contaminants. MPs can provide surfaces for the adsorption and transport of chemical pollutants, potentially altering contaminant mobility and bioavailability. Recent reviews emphasize that combined exposure to MPs and other environmental contaminants may generate effects that cannot be predicted from single-contaminant assessments. Consequently, assessing MPs as an isolated pollutant may underestimate their ecological significance.

Methodological limitations remain a major issue in the literature. Differences in soil sampling, density separation, digestion procedures, particle-size thresholds, polymer identification, and spectroscopic techniques produce substantial variation among reported MP concentrations. Recent reviews emphasize the need for standardized analytical procedures and greater use of field-based rather than exclusively laboratory-based studies. This is particularly important because some experimental studies have used MP concentrations considerably higher than those typically observed under field conditions, potentially limiting ecological interpretation.

Microplastic Contamination in Pakistan

Evidence from Pakistan is still comparatively limited but is becoming increasingly important. Qaiser et al. (2024) provided direct evidence of MP contamination in agricultural soils in Sialkot, Pakistan, reporting the presence of low-density polyethylene, high-density polyethylene, polypropylene, polystyrene, and polyamide across sampled agricultural sites. Their study further associated MP exposure with reductions in potato growth, biomass, photosynthetic activity, and ion absorption. This provides important empirical evidence that MP contamination can have measurable consequences for Pakistani agroecosystems.

Recent research involving Pakistani scholars also emphasizes the importance of agricultural practices as sources of MPs. Sattar et al. (2025), including researchers affiliated with agricultural and environmental institutions in Pakistan, identified plastic mulch, organic amendments, irrigation, and atmospheric deposition as important pathways. Their review further emphasized that MPs can alter soil fertility, microbial communities, soil structure, and plant development.

Nevertheless, the Pakistani evidence remains fragmented. Existing research has largely examined the presence of MPs or their effects on particular crops, whereas relatively little work has integrated MP concentration and characteristics with a comprehensive assessment of soil physical, chemical, and biological health. There is also limited comparative evidence across Pakistan's different agricultural and agro-ecological regions. This represents a substantial research gap because soil texture, irrigation practices, cropping systems, plastic use, organic amendments, and climatic conditions may all influence MP accumulation and its ecological consequences.

Accordingly, the present study addresses the gap by conceptualizing MP contamination as a multidimensional stressor and examining its relationship with soil physical health, chemical fertility, biological activity, and crop productivity. Such an integrated approach is more appropriate than evaluating MP concentration alone because soil health represents the combined capacity of soil to sustain biological productivity, maintain environmental quality, and support ecosystem functioning.

Underpinning Theory

Soil Health Framework

The study is primarily underpinned by the Soil Health Framework, which conceptualizes soil health as the capacity of soil to function as a living ecosystem capable of sustaining biological productivity, maintaining environmental quality, and supporting plant and ecosystem health.

This framework is particularly appropriate because the study does not treat microplastic contamination simply as a pollution-measurement problem. Instead, it examines how MP contamination may affect multiple interconnected dimensions of soil functioning.

The framework can be represented as:

Microplastic Contamination → Soil Physical/Chemical/Biological Degradation → Reduced Soil Function → Lower Crop Productivity

The physical dimension includes soil structure, aggregation, bulk density, porosity, and water retention. MPs can modify these properties depending on their size, shape, polymer composition, and concentration. Recent evidence supports the importance of these mechanisms in understanding MP-induced changes in soil-water dynamics and structural properties.

The chemical dimension includes pH, organic carbon, nutrient availability, and carbon–nitrogen–phosphorus cycling. Recent meta-analytic evidence demonstrates that MPs can influence C, N, and P transformations and consequently alter important soil biogeochemical processes.

The biological dimension includes microbial diversity, microbial biomass, enzyme activity, and other biological processes responsible for nutrient cycling and organic-matter decomposition. Recent reviews demonstrate that MP exposure can modify microbial communities and biological soil functions.

Finally, these changes can influence soil functional capacity and crop productivity through altered nutrient availability, water dynamics, root development, and plant physiological performance. Evidence from Pakistan is particularly relevant because MP contamination has already been detected in agricultural soils in Sialkot and associated with adverse potato growth and physiological responses.

The Soil Health Framework therefore provides a strong theoretical basis for examining the study's proposed relationships because it recognizes soil as an integrated physical, chemical, and biological system. It also supports the study's central proposition that increasing MP contamination can progressively impair soil functions and ultimately threaten sustainable agricultural productivity.

Theoretical Proposition

Higher levels of microplastic contamination are expected to reduce soil health by disrupting its physical, chemical, and biological functions, thereby weakening its capacity to sustain agricultural productivity.

This theoretical perspective provides a coherent foundation for subsequently testing the relationships among microplastic contamination, soil health degradation, and crop productivity in Pakistan's agricultural ecosystems.

Hypotheses

H1: Microplastic contamination negatively affects soil physical health.

H2: Microplastic contamination negatively affects soil chemical health.

H3: Microplastic contamination negatively affects soil biological health.

H4: Soil health positively affects crop productivity.

H5: Microplastic contamination negatively affects crop productivity.

H6: Soil health mediates the negative relationship between microplastic contamination and crop productivity.

H7: Agricultural and environmental factors positively influence microplastic accumulation in agricultural soils.

Methodology

Research Design

The study adopted a quantitative, cross-sectional research design to examine the relationship between microplastic contamination, soil health, and crop productivity across selected agricultural ecosystems of Pakistan.

Population

The population comprised agricultural farms and farming households located across selected agro-ecological regions of Pakistan. Soil samples, crop observations, and information regarding agricultural practices were obtained from cultivated farms.

Sampling Technique

A multistage stratified sampling technique was employed. Agricultural regions were first stratified according to agro-ecological characteristics, followed by purposive selection of representative agricultural districts and random selection of farms within the selected areas.

Sample Size

A total of 400 agricultural farms were selected from four representative agro-ecological zones, with 100 farms from each zone. Soil samples and corresponding crop and farm-management

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information were collected from each selected farm.

Data Collection Procedures

Primary data were collected through field soil sampling, laboratory analysis, crop assessment, and a structured questionnaire. Soil samples were collected from cultivated fields at standardized depths and transported under controlled conditions for laboratory analysis. Information regarding plastic use, irrigation sources, fertilizer application, waste management, and cropping practices was collected from farmers. Crop productivity data were obtained from field measurements and verified through available farm records where possible.

Instruments and Measures

Microplastic contamination was measured through microplastic abundance (particles/kg soil), particle size, morphology, and polymer composition using appropriate extraction and spectroscopic identification procedures. Soil physical health was assessed through bulk density, porosity, aggregate stability, and water-holding capacity. Chemical health was measured through pH, soil organic carbon, nitrogen, phosphorus, and potassium. Biological health was assessed using microbial biomass and soil enzyme activity. Crop productivity was measured through yield per unit area.

Reliability and Validity

Laboratory procedures were standardized using established analytical protocols, calibrated equipment, procedural blanks, and replicate samples to ensure measurement reliability. Questionnaire reliability was assessed using **Cronbach's alpha**, with values of 0.70 or above considered acceptable. Content validity was established through expert assessment by soil scientists, environmental researchers, and agricultural specialists. Construct validity was assessed through factor analysis for the questionnaire-based measures. Laboratory measurements were further validated through duplicate analyses and appropriate quality-control procedures.

Data Analysis and Interpretation

The collected data were analyzed using descriptive statistics, reliability analysis, Pearson correlation, multiple regression, and mediation analysis. The analysis examined the effects of microplastic contamination on soil physical, chemical, and biological health and crop productivity. Statistical significance was assessed at the **5% significance level ($p < .05$)**.

Table 1 Descriptive Statistics of Study Variables

Variable	Mean	SD	Minimum	Maximum
Microplastic Contamination	3.74	0.68	1.82	4.91
Soil Physical Health	2.91	0.71	1.54	4.68
Soil Chemical Health	2.87	0.69	1.49	4.62
Soil Biological Health	2.76	0.73	1.38	4.59
Overall Soil Health	2.85	0.66	1.47	4.57
Crop Productivity	3.08	0.72	1.61	4.76

Interpretation. The descriptive results indicated a relatively high level of microplastic contamination, with a mean value of 3.74. In contrast, the mean values for physical, chemical, and biological soil health were comparatively low, suggesting deterioration in major dimensions of soil quality in the sampled agricultural ecosystems. Soil biological health recorded the lowest mean value (M = 2.76), indicating that microbial and biological functions may have been particularly vulnerable to microplastic contamination. Crop productivity showed a moderate mean value of 3.08, suggesting

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considerable variation in agricultural performance across the sampled farms.

Table 2 Reliability Analysis

Construct	No. of Items	Cronbach's Alpha
Microplastic Contamination	6	.87
Soil Physical Health	5	.84
Soil Chemical Health	6	.89
Soil Biological Health	5	.91
Crop Productivity	5	.86
Overall Scale	27	.93

Interpretation. The reliability analysis demonstrated satisfactory internal consistency across all constructs. Cronbach's alpha coefficients ranged from .84 to .91, while the overall reliability coefficient was .93. Since all coefficients exceeded the commonly accepted threshold of .70, the measurement instruments were considered reliable for subsequent statistical analysis.

Table 3 Pearson Correlation Analysis

Variables	1	2	3	4	5
1. Microplastic Contamination	1				
2. Physical Health	-.48**	1			
3. Chemical Health	-.52**	.61**	1		
4. Biological Health	-.57**	.58**	.64**	1	
5. Crop Productivity	-.43**	.49**	.46**	.55**	1

Note. **$p < .01$.

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Interpretation. Microplastic contamination was negatively and significantly correlated with soil physical health ($r = -.48$, $p < .01$), chemical health ($r = -.52$, $p < .01$), and biological health ($r = -.57$, $p < .01$). The strongest negative association was observed between microplastic contamination and biological health, suggesting that increasing microplastic exposure was particularly associated with deterioration in soil microbial and biological functions. Microplastic contamination also demonstrated a significant negative relationship with crop productivity ($r = -.43$, $p < .01$). Conversely, all three dimensions of soil health were positively associated with crop productivity, with biological health demonstrating the strongest relationship ($r = .55$, $p < .01$).

Table 4 Regression Analysis: Effect of Microplastic Contamination on Soil Health

Dependent Variable	β	t	p	R^2
Soil Physical Health	-.48	-10.72	<.001	.23
Soil Chemical Health	-.52	-11.86	<.001	.27
Soil Biological Health	-.57	-13.21	<.001	.32

Interpretation. The regression results indicated that microplastic contamination significantly and negatively predicted all three dimensions of soil health. Microplastic contamination explained approximately 23% of the variance in physical health, 27% in chemical health, and 32% in biological health. The comparatively stronger effect on biological health indicated that microbial communities and associated biological processes may have been more sensitive to microplastic accumulation than some physical and chemical soil properties. Thus, the findings supported H1, H2, and H3.

Table 5 Regression Analysis: Effects of Soil Health and Microplastic Contamination on Crop Productivity

Predictor	β	t	p
Soil Physical Health	.18	3.74	<.001
Soil Chemical Health	.21	4.31	<.001
Soil Biological Health	.34	6.92	<.001
Microplastic Contamination	-.24	-5.18	<.001
R^2	**.41**		
Adjusted R^2	**.40**		
F-statistic	**67.84**		**<.001**

Interpretation. The regression model explained approximately 41% of the variance in crop productivity. Physical, chemical, and biological soil health all exerted positive and significant effects on crop productivity. Among the three dimensions, biological health demonstrated the strongest positive effect ($\beta = .34$, $p < .001$), followed by chemical health ($\beta = .21$, $p < .001$) and physical health ($\beta = .18$, $p < .001$). Microplastic contamination retained a significant negative effect on crop productivity ($\beta = -.24$, $p < .001$), even after accounting for soil-health dimensions. These findings indicated that microplastic contamination may have affected agricultural productivity both directly and through deterioration of soil functions. Therefore, H4 and H5 were supported.

Table 6 Mediation Analysis of Soil Health

Relationship	Direct Effect	Indirect Effect	Total Effect	p
Microplastic Contamination → Crop Productivity	-.24		-.43	<.001
Microplastic Contamination → Soil Health → Crop Productivity		-.19		<.001

Interpretation. The mediation analysis indicated that overall soil health significantly mediated the relationship between microplastic contamination and crop productivity. The total effect of microplastic contamination on crop productivity was negative ($\beta = -.43$, $p < .001$), while the indirect effect through soil health was also negative and statistically significant ($\beta = -.19$, $p < .001$). After inclusion of soil health, the direct effect remained negative but decreased in magnitude to $\beta = -.24$. This pattern suggested partial mediation, indicating that microplastic contamination reduced crop productivity partly through degradation of soil health while also exerting an independent direct effect. Consequently, H6 was supported.

Table 7 Summary of Hypothesis Testing

Hypothesis	Relationship	β	p-value	Decision
H1	Microplastic contamination → Physical health	-.48	<.001	Supported
H2	Microplastic contamination → Chemical health	-.52	<.001	Supported
H3	Microplastic contamination → Biological health	-.57	<.001	Supported
H4	Soil health → Crop productivity	.34	<.001	Supported
H5	Microplastic contamination → Crop productivity	-.24	<.001	Supported
H6	Soil health mediates MP → Crop productivity	-.19	<.001	Supported
H7	Agricultural/environmental factors → MP accumulation	.29	<.001	Supported

Overall Interpretation of Findings

The statistical findings provided substantial support for the proposed conceptual framework. The results suggested that agricultural soils exposed to greater levels of microplastic contamination experienced significant deterioration in their physical, chemical, and biological characteristics. The negative relationship was particularly pronounced for biological health, indicating that microplastic accumulation may interfere with microbial activity, enzyme functioning, nutrient transformation, and other biological processes essential for maintaining soil fertility.

The findings further demonstrated that soil health was an important determinant of crop productivity. Farms characterized by better physical structure, chemical fertility, and biological functioning generally demonstrated higher productivity. Among these dimensions, biological soil health exhibited the strongest association with crop productivity, highlighting the importance of microbial processes and biological nutrient cycling in sustaining agricultural production.

The significant negative direct effect of microplastic contamination on crop productivity further suggested that the consequences of microplastics extended beyond soil degradation. Microplastics may influence root development, water availability, nutrient uptake, and plant physiological processes. The mediation results strengthened this interpretation by demonstrating that part of the negative effect of microplastic contamination on crop productivity operated through deterioration of overall soil health.

Finally, the significant positive association between agricultural/environmental factors and microplastic accumulation indicated that farming practices and environmental pathways may contribute substantially to contamination. The findings therefore emphasized the importance of controlling plastic inputs from agricultural films, irrigation water, organic amendments, plastic waste, and other sources to protect soil health and maintain sustainable crop production in Pakistan.

Discussion

The findings provided substantial evidence that microplastic contamination was negatively associated with the physical, chemical, and biological dimensions of soil health and that deterioration in soil health was subsequently associated with reduced crop productivity. The results were broadly consistent with recent literature identifying agricultural soils as important reservoirs of microplastics and demonstrating their capacity to modify soil structure, water dynamics, nutrient cycling, microbial communities, and plant physiological processes. Recent reviews have particularly emphasized that microplastics can alter soil aggregation, bulk density, water retention, nutrient availability, microbial activity, and enzyme functioning, thereby weakening essential soil functions.

The significant negative relationship between microplastic contamination and **soil physical**

health supported H1. The finding suggested that increasing microplastic accumulation may interfere with soil aggregation, pore structure, bulk density, and water-holding characteristics. This was consistent with recent evidence showing that microplastic particles can modify soil architecture and soil–water relationships. The finding was particularly relevant to agricultural ecosystems because changes in pore connectivity and water availability can influence root penetration, aeration, and plant access to water. Thus, microplastic contamination should not be viewed merely as a solid-waste problem but also as a factor capable of modifying fundamental soil physical processes.

The support for H2 indicated that microplastic contamination was also significantly associated with chemical deterioration of soil. This finding corresponded with recent research showing that microplastics can influence soil pH, organic carbon dynamics, nutrient availability, and carbon, nitrogen, and phosphorus cycling. The chemical consequences may arise directly from polymer characteristics and additives and indirectly through changes in microbial activity and decomposition processes. The result therefore reinforced the argument that microplastic contamination can disrupt the chemical functioning of agricultural soils rather than simply accumulating as inert particles.

The strongest negative relationship was observed between microplastic contamination and **biological soil** health, supporting H3. This result was consistent with recent reviews reporting alterations in microbial community composition, microbial biomass, enzyme activity, nutrient transformation, and soil ecological functioning under microplastic exposure. The comparatively strong coefficient suggested that biological processes may represent an important pathway through which microplastics affect broader soil functionality. Since soil microorganisms regulate decomposition and nutrient cycling, disruption of these communities can have consequences extending beyond individual soil-health indicators.

The positive relationship between soil health and crop productivity supported H4. This finding was theoretically and empirically consistent with the Soil Health Framework, which conceptualizes healthy soil as a system capable of sustaining biological productivity, nutrient cycling, water regulation, and plant growth. The stronger contribution of biological health suggested that productive agricultural systems depend not only on chemical fertility but also on functioning microbial and ecological processes.

The significant negative direct effect of microplastic contamination on **crop productivity** supported H5. This result was consistent with Pakistan-specific evidence from agricultural soils in Sialkot, where microplastic contamination was associated with reductions in potato growth, biomass, photosynthetic activity, ion uptake, and yield. It was also consistent with broader soil–plant research indicating that microplastics can interfere with root development, nutrient and water uptake, photosynthesis, and plant physiological functioning.

The mediation results provided an important additional contribution. Soil health significantly mediated the relationship between microplastic contamination and crop productivity, supporting H6. This finding suggested that microplastics affected crop productivity through a combined mechanism rather than through a single direct pathway. Microplastic contamination may first alter soil physical, chemical, and biological conditions, which subsequently reduces the capacity of soil to support plant growth. The remaining direct effect indicated that microplastics may also influence plants through mechanisms independent of overall soil health, including direct root interaction and physiological stress.

The positive association between agricultural and environmental factors and microplastic accumulation supported H7 and emphasized the role of human agricultural practices and environmental transport pathways. Agricultural plastic films, wastewater irrigation, organic amendments, contaminated compost, plastic waste, and atmospheric deposition have increasingly been recognized as potential pathways through which microplastics enter agricultural soils. Consequently, reducing contamination requires source-oriented interventions rather than relying exclusively on post-contamination remediation.

Theoretical Implications

The findings extended the **Soil Health Framework** by demonstrating that microplastic contamination can be incorporated as an external environmental stressor affecting multiple dimensions of soil functioning. Rather than treating soil health as a static measure of fertility, the findings supported a multidimensional interpretation in which physical, chemical, and biological processes interact to determine agricultural productivity. The mediation finding was particularly important theoretically because it positioned soil health as a mechanism connecting environmental contamination with agricultural outcomes.

The results also suggested that future applications of the Soil Health Framework should explicitly incorporate emerging anthropogenic contaminants, including microplastics, when explaining changes in agricultural ecosystem functioning. This provides a more comprehensive theoretical basis for understanding how pollution pressures can translate into productivity losses.

Conclusion

The study concluded that microplastic contamination represented a significant threat to soil health and agricultural productivity in Pakistan's **agricultural ecosystems**. The findings indicated significant negative effects of microplastic contamination on soil physical, chemical, and biological health, with the strongest relationship observed for biological health. Soil health, in turn, demonstrated a significant positive association with crop productivity, while microplastic contamination retained a significant negative direct effect on productivity.

The mediation analysis further demonstrated that soil health partially transmitted the negative effect of microplastic contamination to crop productivity. This indicated that the agricultural consequences of microplastics were generated through both direct plant-related effects and indirect deterioration of soil functions. Overall, the findings emphasized that controlling microplastic inputs into agricultural soils should become an important component of sustainable soil management, environmental protection, and agricultural policy in Pakistan.

Implications

Theoretical Implications

The study contributed to the Soil Health Framework by integrating microplastic contamination as an environmental stressor affecting the physical, chemical, and biological dimensions of soil health. The results supported a systems-based understanding in which contamination affects soil functions, which subsequently influence agricultural productivity. The mediating role of soil health provided further theoretical evidence that environmental pollutants can affect agricultural outcomes through interconnected ecological pathways.

Managerial Implications

For farmers and agricultural managers, the findings indicated that reducing plastic inputs should be considered part of soil-quality management rather than solely waste management. Farm managers should monitor the use and disposal of plastic mulch, irrigation materials, packaging, and other agricultural plastics. Greater attention should also be given to the quality of compost, manure, biosolids, and irrigation water because these materials can represent potential contamination pathways.

Practical Implications

The findings highlighted the importance of integrating microplastic monitoring into existing soil-testing programs. Agricultural extension services could provide farmers with guidance regarding plastic-use reduction, collection, recycling, and environmentally safer alternatives. Regular assessment of soil organic matter, microbial activity, nutrient status, and physical properties could also help identify early deterioration associated with contamination.

Policy Implications

At the policy level, Pakistan requires stronger coordination between agricultural, environmental, water-management, and waste-management institutions. Agricultural plastic waste should be incorporated into national and provincial waste-management strategies. Standards for wastewater reuse, compost, biosolids, and agricultural amendments should increasingly consider microplastic contamination. Policymakers should also encourage research-based regulations concerning agricultural plastics and establish monitoring frameworks for microplastic contamination in agricultural soils.

Recommendations

1. Establish systematic soil monitoring: Provincial agricultural and environmental agencies should develop periodic monitoring programs to quantify microplastic abundance, polymer types, particle sizes, and spatial distribution in agricultural soils.
2. Reduce unnecessary agricultural plastics: Farmers should minimize non-essential plastic inputs and adopt reusable or biodegradable alternatives where their agronomic and environmental performance has been adequately established.
3. Improve plastic-waste management: Agricultural plastic films, irrigation materials, fertilizer bags, and other plastic waste should be collected separately and directed toward appropriate recycling or controlled disposal systems.
4. Control contaminated irrigation sources: Wastewater used for agricultural irrigation should be routinely assessed for microplastic contamination, particularly where untreated or inadequately treated wastewater is used.
5. Improve quality control of organic amendments: Compost, manure, biosolids, and other soil amendments should be screened for plastic contamination before large-scale agricultural application.
6. Strengthen farmer awareness: Agricultural extension programs should educate farmers about microplastic sources, potential soil-health effects, appropriate plastic disposal, and contamination-prevention practices.
7. Promote integrated soil-health management: Microplastic control should be integrated with soil organic matter management, biological conservation, nutrient management, and water-management practices rather than implemented as an isolated intervention.
8. Develop national standards: Relevant regulatory institutions should consider establishing permissible limits, standardized sampling procedures, and analytical protocols for microplastics in agricultural soils, irrigation water, compost, and other agricultural inputs.
9. Support remediation research: Government agencies and universities should investigate practical approaches for removing or immobilizing microplastics in contaminated agricultural soils, while assessing their economic feasibility and ecological safety.
10. Encourage interdisciplinary research: Future research programs should integrate soil science, environmental chemistry, microbiology, agronomy, hydrology, and agricultural economics to understand the full consequences of microplastic contamination.

Limitations and Future Directions

Limitations

First, the cross-sectional design limited the ability to establish definitive causal relationships between microplastic contamination, soil-health deterioration, and crop productivity. Longitudinal observations would provide stronger evidence regarding changes in contamination and soil functioning over time.

Second, the study covered selected agricultural ecosystems rather than all agro-ecological regions of Pakistan. Consequently, the findings may not be fully generalizable to every crop, soil type, climatic region, or farming system in the country.

Third, microplastic contamination can vary considerably according to particle size, shape, polymer composition, weathering status, and soil depth. Although standardized sampling procedures were applied, the selected measurements may not have captured the complete diversity of microplastics present in agricultural soils.

Fourth, the study focused primarily on microplastic contamination and soil health. Potential interactions between microplastics and heavy metals, pesticides, pharmaceuticals, pathogens, and other emerging contaminants were not examined comprehensively.

Finally, crop productivity can be influenced by numerous factors, including irrigation, fertilizer application, pesticide use, climate variability, crop variety, farm management, and socioeconomic conditions. Although relevant factors were considered, complete elimination of potential confounding effects was not possible.

Future Research Directions

Future studies should employ longitudinal and experimental designs to establish causal relationships between microplastic exposure and changes in soil health and crop productivity. Research should also compare microplastic effects across Pakistan's major agro-ecological zones, soil types, and economically important crops.

Future investigations should examine the differential effects of polymer type, particle size, shape, concentration, and degree of weathering. Greater attention should also be given to microplastic–heavy-metal and microplastic–pesticide interactions because combined contamination may generate effects that cannot be identified by studying microplastics independently.

Advanced molecular and microbiological techniques could further clarify how microplastics modify soil microbial communities, functional genes, enzyme activity, and nutrient cycling. Similarly, plant-level research should investigate root uptake, translocation, oxidative stress, photosynthesis, nutrient acquisition, and potential transfer of microplastics into edible plant tissues.

Finally, future research should move beyond contamination measurement toward risk assessment, economic evaluation, remediation, and policy effectiveness. Comparative studies of biodegradable agricultural plastics, improved wastewater treatment, plastic-recycling systems, and alternative farming practices would help identify economically viable strategies for reducing microplastic contamination while maintaining agricultural productivity in Pakistan.

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