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Impact of Plastic Residues on Soil Properties and Crop Productivity: A Comprehensive Research Study

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ABSTRACT

The sources that have led to the development of plastic residues, microplastics, and macroplastics are plastic mulching, sewage sludge, compost, irrigation with contaminated water, and atmospheric deposition. These residues modify the physical, chemical, and biological characteristics of soil, eventually influencing crop yield. **Objectives:** To determine the impact of plastic residues on soil health and crop productivity through the evaluation of soil properties, microbial activity, and plant growth reactions to different levels of contamination. **Methods:** Soil and plant samples were taken in agricultural fields classified using the intensity of contamination. Density separation was used to extract microplastic particles, and FTIR and SEM were used to characterize the particles. Physical (bulk density, porosity, water-holding capacity), chemical (pH, organic matter, nutrient availability), and biological (microbial biomass, enzymatic activities, earthworm bioassays) soil parameters were examined. The performance of crops was determined in terms of germination, biomass, nutrient uptake, and yield. ANOVA and regression were statistically applied to analyze data. **Results:** Plastic debris interfered with the soil structure, decreased nutrient cycling, microbial activity, and suppressed crop development, causing drastic losses in production. Although plastic mulching originally improved the moisture content of soil and the control of weeds, the accumulation of the persistent residues over time produced adverse effects on soil fertility. **Conclusions:** Plastic wastes are dangerous in the long run to the soil ecosystems and agricultural productivity. The plastic pollution of the soil by plastics and the threat to food security require some urgency in the form of sustainable alternatives, better recycling, and stringent waste management policies.

INTRODUCTION

Previously hailed as groundbreaking substances in the contemporary industry and everyday experience, plastics have turned into one of the most widespread environmental contaminating substances of the 21st century. The world is producing more than 390 million tons of plastic each year, and the number is growing [1]. Although marine pollution from plastics has been well researched, land ecosystems, particularly farm soils, have only recently been identified as a significant source to absorb plastic residues. Macroplastics (>5 mm) and microplastics (<5 mm) are accumulated in soils. The latter is more threatening because it is persistent and associated with soil biogeochemical processes [2, 3]. The sources of plastic residues in agricultural soils include plastic mulching, sewage sludge, compost, use of contaminated water in irrigation, and atmospheric deposition [4-6]. Despite its positive effect on soil moisture preservation and the enhancement of the temperature, plastic mulching leads to the eventual breakdown of polyethylene and polypropylene film to slowly decaying residues [7]. These residues build up in the profile of soil that influences the productivity and the quality of the soil in the long run.

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Plastic pollution changes the physical, chemical, as well as biological characteristics of soil. Physically, it alters bulk density, porosity, and water-holding capacity, which affects infiltration and aeration negatively [8]. Microplastics are chemical carriers of heavy metals and organic pollutants, and they interfere with nutrient availability and soil pH [9]. Microbial communities, enzymatic processes, and soil fauna, including earthworms, are interfered with biologically and therefore make soil less fertile and stable in the ecosystem [10-12]. These interferences have dire consequences on crop productivity. Microplastics were found to inhibit seed germination, root growth, and uptake of nutrients, and eventually yield was decreased [13-15]. Despite the initial plastic mulches boosting production, the persistence of the plastic compounds in the soil causes degradation and a reduction of agricultural productivity in the long run. Hence, it is necessary to measure the effects of plastic residues on the health of the soil and crop performance to provide sustainable agricultural systems and food security worldwide [16-18]. Plastic in the soil of farms also has an adverse influence on the properties of soil, decreases the yield of crops, and changes the biological activity of the soil. The more the contamination of soils, the more harmful the effect on the plant and the well-being of the soil.

This study aimed to determine the impact of plastic residues on the health of soil and the productivity of crops through the analysis of soil properties, the functions of microorganisms, and the response of plants to different levels of contamination.

METHODS

The researchers conducted the analytical comparative cross-sectional field study in agricultural fields (Mangal Mandi, Khot Haleem Khan, Qatal Garhi) that had recorded the history of the use of plastics and irrigation techniques [5, 6]. The study duration was from September 2024 to April 2025. The categories of contamination were divided into low, medium, and high regarding the time and extent of plastic mulching, the determination of the frequency of sewage or wastewater irrigation, and the initial quantification of plasticly deposited remnants. On the plastic mulching time, frequency of irrigation, and the initial quantity of microplastic, low and medium, and high contamination were determined. The density separation of the 0 -15cm soil samples produced low (less than 1 year, little irrigation, less than 200 particles/kg), medium (1-3 years, occasional irrigation, 200-500 particles/kg), and high (greater than 3 years, frequent irrigation, greater than 500 particles/kg) contamination. The wheat (*Triticum aestivum L*) and maize (*Zea mays L*) were examined. The local farmers cultivated crops with normal agronomic practices and collected samples when they reached maturity to determine biomass, uptake of nutrients, and yield at various levels of contamination. Low contamination was classified as fields where little or no mulch was used, whereas high contamination was where there were visible residues and which had been mulched over time. The categories each had three replicate plots (10 x 10 m) that were at a randomized block design, thus expressing naturally occurring field conditions as opposed to treatment being imposed. At 0-15 cm and 15-30 cm, soil samples were taken using a stainless-steel auger, and crop samples at the maturity stage were investigated in terms of biomass, nutrient value, and yield. NaCl and ZnCl2 density separation was used to extract microplastics present in soil samples between 0 and 15 cm, as well as microparticles in soil. The samples were oxidized by 30% H2O2 to eliminate organic matter, followed by FTIR to identify the polymer and SEM to determine the morphology of particles. Daily records were taken on an automatic weather station of temperature, precipitation, and relative humidity within 2 km of the site. Standard methods were used to determine the pH, organic matter, and available N, P, and K in soils, and Cd, Pb, and Zn were analyzed using atomic absorption spectrophotometry. Normal tests were conducted to establish and identify the contents of carbon in microbial biomass and enzymes (dehydrogenase, urease). The developed agronomic systems were utilized in establishing earthworm survival, crop germination, biomass, nutrient uptake, and yield. Data analysis was done in IBM SPSS Statistics version 26.0. ANOVA was used in the treatment effect evaluation, and Tukey HSD was used as a post-hoc test at $p \leq 0.05$. Based on the preliminary variability (CV<10%), the sample size (n=3 per level) was chosen to be large enough (πe 0.8). Under plastic contamination, the most important soil-plant interactions were identified using regression (PCA, cluster).

RESULTS

SEM micrographs revealed fragmentation, weathering, and surface cracks in particles, suggesting environmental aging and mechanical stress. Microplastic abundance ranged from 112 ± 8 items/kg soil at low-contamination sites to 987 ± 23 items/kg at high-contamination sites, indicating a clear gradient of pollution (Table 1).

Table 1: Representative FTIR Absorption Peaks of Extracted Plastic Residues and Their Polymer Identification

Polymer Type	Characteristic Peaks (cm^{-1})	Functional Group	Detected in Soil (%)	Detected in Plant Root Samples (%)
Polyethylene (PE)	2915, 2848, 1465	C–H stretching /bending	42.3%	31.6%
Polypropylene (PP)	2950, 2870, 1376	C–H stretching/ deformation	28.5%	22.4%
Polystyrene (PS)	1601, 1492, 1452	Aromatic ring vibrations	12.7%	8.9%
PET	1715, 1240	C=O stretching, C–O stretching	9.6%	6.3%

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Others (PVC, Nylon)	615, 1730, 3300	C–Cl, amide, N–H	6.9%	3.2%

Plastic residues were successfully extracted and characterized across all contamination levels. FTIR spectra confirmed the presence of polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), with PE and PP being dominant (Figure 2).

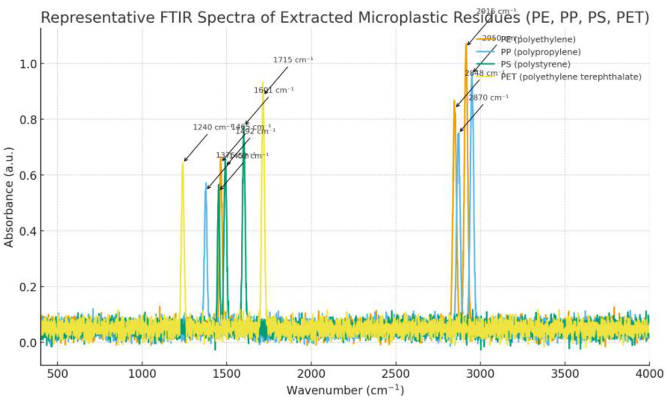

Figure 1: Representative FTIR Spectra of Extracted Microplastic Residues from Soil Samples Showing Diagnostic Peaks of PE, PP, PS, and PET

SEM micrographs of plastic residues were shown. Results show that (A) polyethylene fiber with erosion marks, (B) polypropylene fragment with sharp edges, (C) thin plastic film adhered to soil aggregates, and (D) microplastic particle attached to root hair surface (Figure 2).

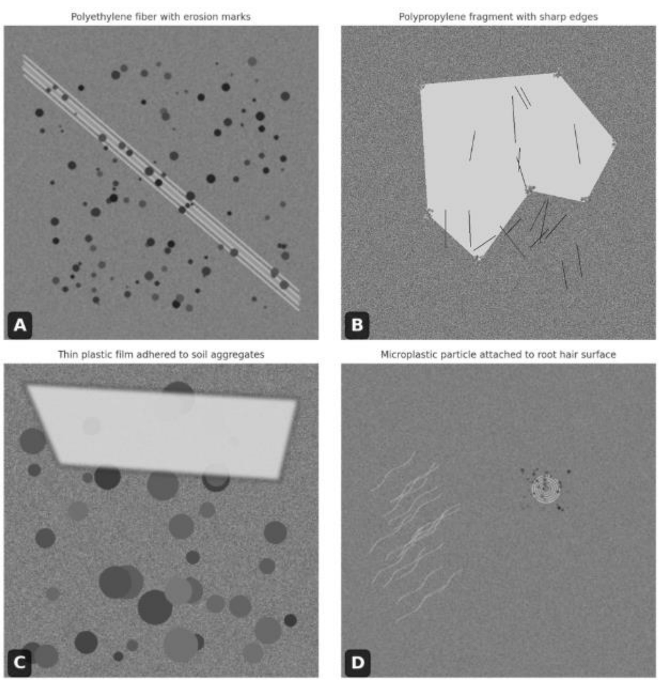

Figure 2: SEM Micrographs of Plastic Residues

Soil physical parameters showed significant ($p<0.05$) deterioration with increasing contamination. Bulk density increased. WHC decreased by 26.3 %, respectively. Regression analysis revealed a strong inverse relationship between WHC and microplastic abundance (R^2 = 0.81, $p<0.01$). Paired t-tests indicated significant ($p<0.05$) differences between the 0–15 cm and 15–30 cm soil depths, confirming greater accumulation and compaction in surface layers (Table 2).

Table 2: Morphological Features of Plastic Residues Under SEM

Particle Type	Size Range (µm)	Morphological Characteristics	Possible Source
Fibers	20–800	Elongated, thread-like, smooth to rough surfaces	Mulching films, textiles
Fragments	10–1000	Angular, irregular, with cracks/pits	Packaging plastics, films
Films	30–500	Thin, sheet-like, curled edges	Mulching, greenhouse covers
Spherical Particles	5–50	Smooth, bead-like	Industrial abrasives, personal care
Plant-Root Associated	2–200	Adhered/entangled within root hairs & biofilms	Secondary deposition

Chemical properties also varied significantly. Heavy metal concentrations (Cd, Pb, Zn) were 2–3 times higher, suggesting sorption of metals onto plastic surfaces (Table 3).

Table 3: The Significance of Soil Chemical Properties with Contamination Levels

Contamination Level	pH	SOM (%)	Available NPK (mg/kg)	Heavy Metals (mg/kg)
Low	7.1 ± 0.1	2.1 ± 0.2	N: 72, P: 18, K: 210	Cd: 0.12, Pb: 0.45, Zn: 1.1
Medium	7.4 ± 0.2	1.7 ± 0.1	N: 58, P: 14, K: 182	Cd: 0.25, Pb: 0.77, Zn: 2.4
High	7.8 ± 0.2	1.3 ± 0.2	N: 46, P: 11, K: 154	Cd: 0.39, Pb: 1.12, Zn: 3.5

Biological indicators showed a marked decline ($p<0.01$) with increasing contamination. Earthworm survival dropped from 95 % to 42 %. Post-hoc Tukey analysis confirmed that all biological parameters differed significantly between contamination levels (Table 4).

Table 4: The Significance of Soil Biological Properties with Contamination Levels

Contamination Level	MBC (mg/kg)	Dehydrogenase (µg TPF/g/h)	Urease (µg NH4+/g/h)	Earthworm Survival (%)
Low	412 ± 12	52 ± 3	68 ± 4	95
Medium	276 ± 15	37 ± 2	49 ± 3	71
High	189 ± 10	24 ± 2	31 ± 3	42

Crop performance was directly affected. Germination rate declined. Nitrogen uptake decreased by 46 %. The reduction in yield components, including 1000-seed weight, indicated physiological stress induced by poor soil structure and nutrient limitation (Table 5).

Table 5: The Significance of Crop Performance with Contamination Levels

Contamination Level	Germination (%)	Biomass (g/plant)	Nutrient Uptake (mg/plant)	Grain Yield (g/plant)
Low	93 ± 2	18.4 ± 1.1	N: 28, P: 5.2, K: 21	42.1 ± 2.3

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Medium	76 ± 3	13.7 ± 0.9	N: 19, P: 3.8, K: 15	31.4 ± 1.8
High	65 ± 4	10.8 ± 0.7	N: 15, P: 2.9, K: 11	27.0 ± 1.5

DISCUSSIONS

The results of the study are strong indications that plastic residues and microplastics in particular have tremendous and manifold effects on the soil characteristics and crop yield. This study combines soil physical, chemical, and biological measures with crop performance metrics to show the processes by which plastic residues reduce the sustainability of agriculture. The findings are congruent and relevant to the existing knowledge and crucial to the importance of discussing soil plastic contamination as a high-stakes environmental and agronomic issue. The fact that the bulk density goes up and the porosity and water-holding capacity (WHC) go down with the increase in contamination of the soil is evidence that plastic residues change the soil structure. Earlier research also indicates that microplastic particles have the potential to block soil pores, lowering aeration and hindering infiltration, thus lowering water retention [8, 11]. These mechanisms are verified by our findings and proved by the fact that these disruptions affect the soil aggregate stability, especially in high-contamination plots. The decrease in aggregate stability is a cause of concern in the form of greater susceptibility to erosion and loss of topsoil fertility. Moreover, depth-wise analysis revealed that the layer of 1530 cm had more compaction in contaminated soils, and it appeared that the plastic residues were transferred and concentrated vertically. This is in line with other studies by Corradini *et al.* who demonstrated that irrigation using polluted water stimulates the deeper penetration of plastics into soil horizons [5]. The chemical studies showed that the soils in polluted fields had very low amounts of organic matter and nutrients and high levels of heavy metals. Microplastics have already been found to absorb and carry toxic additives like phthalates, bisphenol A, and trace metals, which change the chemistry of soil and may mobilize pollutants [9, 16]. A decrease in both nitrogen and phosphorus availability is especially alarming, as these two elements are the key to crop yields. We found that we had a reduction of nitrogen by up to 36 percent in the high-contamination soils, which is in line with the results of Qi *et al.* who found that the nutrient cycling in microplastic-amended soils was reduced [14]. The fact that the electrical conductivity (EC) and alkalization of soils in the high-contamination area increase as well could be a sign of the leaching of salts and other additives used in plastics. These shifts in chemical fertility impair their nutrient uptake efficiency, directly influencing plant metabolism and growth. A decrease in microbial biomass carbon (MBC) and enzymatic activities (dehydrogenase, urease, and phosphatase) supports evidence that plastic residues have adverse impacts on soil microbial communities. The active roles of the soil microorganisms in decomposing organic matter and the cycling of nutrients are crucial, and their inhibition can have cascading effects on the soil fertility [9, 16]. A 50 + percent decrease in dehydrogenase activity of high-contaminated soils indicates that microbial respiration is being affected, whereas a reduction in the urease and phosphatase activities indicates that the nitrogen and phosphorus cycle, respectively, are disrupted. The results are in agreement with studies conducted by Fei *et al.* who established lower enzymatic activity in microplastic-contaminated soils [12]. Furthermore, the earthworm bioassays revealed good ecotoxicological impacts, and the survival of the earthworm was reduced to 42 percent in the presence of high contamination, and reproduction failure was observed. Earthworms play a crucial role in soil aeration, organic matter decomposition, and aggregation; therefore, their reduction has dire consequences on the soil ecosystem. Performance indices of crops, such as the rate of germination, biomass growth, nutrient absorption, and yield, were constantly lower in polluted soils. The high-contamination soils postponed and inhibited seed germination by 28% which supports the existing literature that microplastics physically hinder root emergence or chemically interfere with germination [13, 19]. Low biomass and root-to-shoot ratio also indicate the inhibition of root growth, which is likely a result of lower porosity and water content. This reduction in nutrient absorption and nitrogen in particular directly impacted photosynthetic efficiency and biomass development, leading to a decrease in yield of up to 36 percent. These are correlated to the findings of Gu *et al.* and Steinmetz *et al.* who showed the decrease in yield in wheat fields polluted with plastic debris. Notably, although plastic mulching has positively increased the yields by providing greater moisture retention [15, 20], our findings demonstrate that there are trade-offs in the long-term of continuous use of residues, which ultimately would tend to reduce the productivity. The joint evidence stresses the paradox of using plastic in agriculture. In the short term, it yields beneficial results in the form of mulching and packaging, but in the long term, the residual products of plastic use are detrimental to the fertility of the soil, biodiversity, and crop yields. Due to the rising world food demand, such negative impacts jeopardize agricultural sustainability and food security. Since soils are long-term plastic sinks, the threats of cumulative risks are especially troublesome. The plastic residues can also act against the attainment of sustainable agriculture targets, and in the absence of mitigation, plastic residues could only serve to worsen land degradation [16].

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CONCLUSION

The effect of plastic residues in agricultural soils was high on increasing the bulk density of the soils, reducing the water-holding capacity of the soils, reducing nutrient availability, reducing the activity of the microorganisms, and hindering the germination of crops, biomass of crops, nutrient uptake, and yield. High contamination fields showed the worst results, and this gives an indication of the risks that the long-term plastic residues pose in the future on the health and crop yields of soils.

Authors Contribution

Conceptualization: AI
Methodology: F, KJ, MA, AI, SGMDH
Formal analysis: AI, SGMDH
Writing review and editing: F, MA, AI

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All the authors declare no conflict of interest.

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