



Microplastic Contamination in Sewage Sludge–Amended Soils and Plant Uptake

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Abstract— The application of sewage sludge as agricultural fertilizer introduces microplastics into arable soils, raising concerns about long-term soil health and food safety. This study investigated the abundance, distribution, and polymer composition of microplastics in soils receiving sewage sludge amendments over varying durations (0, 3, 6, and 10 years) at three agricultural sites in the Indo-Gangetic Plain, India. Additionally, the uptake and translocation of microplastics in wheat (*Triticum aestivum*) and lettuce (*Lactuca sativa*) cultivated in sludge-amended soils were examined. Soil samples were collected at two depth intervals (0–20 cm and 20–40 cm), and microplastics were extracted using density separation with ZnCl_2 solution (1.6 g/cm^3) followed by identification via micro-FTIR spectroscopy. Results indicated that microplastic concentrations increased significantly with sludge amendment duration, ranging from 320 ± 45 particles/kg in unamended control soils to $2,870 \pm 410$ particles/kg in soils with ten years of amendment history. Polyethylene, polypropylene, and polyester fibres constituted over 78% of all recovered particles. Root tissues of both crop species contained microplastics in the size range of 10–150 μm , with lettuce accumulating significantly higher concentrations than wheat. These findings underscore the role of sewage sludge application as a persistent pathway of microplastic entry into agricultural ecosystems and the human food chain.

Keywords— microplastics; sewage sludge; biosolids; soil contamination; plant uptake; food safety; FTIR spectroscopy

INTRODUCTION

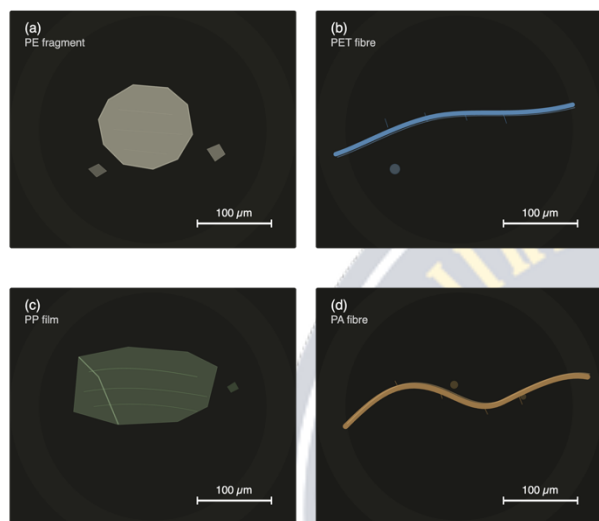
Microplastics, defined as synthetic polymer particles smaller than 5 mm, have emerged as ubiquitous environmental contaminants detected across marine, freshwater, atmospheric, and terrestrial compartments. While early research focused predominantly on aquatic ecosystems, growing evidence suggests that agricultural soils may serve as one of the largest reservoirs of microplastic pollution globally (Nizzetto et al., 2016). A primary route through which microplastics enter agricultural land is the application of sewage sludge, also referred to as biosolids, as an organic soil amendment.

Wastewater treatment plants effectively capture microplastics from influent water, concentrating them in the sludge fraction. Studies have demonstrated that treated sludge can contain microplastic concentrations ranging from 1,500 to over 170,000 particles per kilogram of dry weight, depending on the treatment process and the population served (Mahon et al., 2017). When this sludge is applied to farmland, the embedded microplastics are deposited into the soil matrix, where they may persist for decades owing to the recalcitrance of synthetic polymers under ambient environmental conditions (Rillig, 2012).

The ecological consequences of microplastic accumulation in soils are multifaceted. Microplastics can alter soil structure, water-holding capacity, and microbial community composition, thereby affecting nutrient cycling and plant growth (de Souza



Machado et al., 2018). Furthermore, microplastics act as vectors for the sorption and transport of organic pollutants and heavy metals, potentially amplifying the exposure of soil organisms and crops to co-contaminants (Hodson et al., 2017). Of particular concern is the possibility that microplastics can be taken up by crop plants through root absorption, translocated to edible tissues, and thus enter the human food chain (Li et al., 2020).



Particles recovered from 10-year sludge-amended soil (Site D), imaged via micro-FTIR (ATR mode)

Fig. 1. Micro-FTIR micrographs of representative microplastic particles

Despite the growing body of literature on microplastics in soils, quantitative field data linking long-term sludge amendment history to soil microplastic burdens and crop uptake remain limited, particularly in the context of South Asian agricultural systems where sludge reuse is an expanding practice. The present study addresses this gap by quantifying microplastic contamination in sewage sludge-amended soils across a chronosequence of amendment durations and by evaluating the uptake and distribution of microplastics in two commonly consumed crop species.

LITERATURE REVIEW

The recognition of microplastics as terrestrial pollutants has accelerated considerably since Rillig (2012) first called attention to the potential scale of soil contamination from synthetic fibres and fragments. Subsequent field surveys have confirmed that agricultural soils receiving biosolid amendments harbour substantially elevated microplastic concentrations relative to unamended controls. Corradini et al. (2019) reported that Chilean farmland treated with biosolids for over 20 years

contained microplastic levels an order of magnitude higher than untreated fields, with concentrations increasing as a function of cumulative sludge loading. Similarly, van den Berg et al. (2020) found that microplastic abundances in sludge-amended soils in southeastern Spain ranged from 930 to 4,030 particles/kg dry weight, with fibres and fragments as the dominant morphological categories.

The polymer types most frequently identified in sludge-amended soils include polyethylene, polypropylene, polyester (polyethylene terephthalate), polyamide, and polystyrene (Mahon et al., 2017). These polymers originate from diverse sources within the wastewater stream, including laundering of synthetic textiles, degradation of packaging materials, and personal care products containing microbeads (Browne et al., 2011). Nizzetto et al. (2016) developed a mass-balance model estimating that between 63,000 and 430,000 tonnes of microplastics may be added annually to European farmlands through sludge application alone, a figure that rivals the estimated annual input of microplastics to the global ocean surface.

The fate of microplastics in the soil column is governed by particle size, shape, density, and soil properties. Smaller particles tend to migrate deeper through macropore flow and bioturbation, while fibres become entangled in the soil organic matrix (O'Connor et al., 2019). Soil organisms, particularly earthworms, have been shown to facilitate the vertical transport of microplastics through their burrowing and casting activities (Rillig et al., 2017). This bioturbation-mediated redistribution can move microplastics beyond the plough layer and into subsoil horizons, complicating remediation efforts.

The interaction between microplastics and soil physicochemical properties has been extensively investigated. De Souza Machado et al. (2018) demonstrated through greenhouse experiments that the addition of microplastic fibres significantly altered soil bulk density, water-holding capacity, and aggregate stability, with effects varying by polymer type and concentration. These changes can indirectly influence plant performance by modifying root zone conditions, water availability, and nutrient transport.

Concerning plant uptake, Li et al. (2019) provided early evidence that microplastics smaller than 1 µm could enter the root vascular system of wheat plants and translocate to shoots and leaves under hydroponic conditions. Subsequent studies using fluorescently labelled polystyrene beads confirmed that particles in the sub-micrometre to low-micrometre range can penetrate root apical meristems and move through the xylem

pathway (Luo et al., 2022). Larger particles, while less likely to enter the vascular system, can accumulate on root surfaces and within root cortical cells, particularly at sites of lateral root emergence where the endodermal barrier is incomplete (Li et al., 2020).

Root morphology and crop species influence the extent of uptake. Crops with dense, fibrous root systems and high transpiration rates tend to accumulate more particles than those with coarser tap-root architectures (Conti et al., 2020). Lettuce and other leafy vegetables have been identified as particularly susceptible to microplastic accumulation due to their high water uptake rates and the relatively porous structure of their root cortex (Oliveri Conti et al., 2020). The implications for dietary exposure are considerable, given that these crops are consumed raw and undergo minimal processing before ingestion.

Analytical methods for microplastic extraction from soil and plant matrices have evolved rapidly but remain subject to methodological inconsistencies. Density separation using concentrated salt solutions (NaCl, ZnCl₂, NaI) is the most widely applied technique, with ZnCl₂ at a density of 1.6–1.8 g/cm³ favoured for its ability to float denser polymers such as PVC and PET (Claessens et al., 2013). Spectroscopic identification, particularly FTIR and Raman microscopy, is considered the standard for polymer confirmation, though throughput limitations have prompted the development of automated imaging workflows (Löder et al., 2017).

MATERIALS AND METHODS

Study Area and Sampling Design

The study was conducted at three agricultural sites in the upper Indo-Gangetic Plain (Uttar Pradesh, India) where municipal sewage sludge from secondary treatment facilities has been applied as a soil amendment. Sites were selected to represent a chronosequence of sludge amendment durations: Site A (no sludge history, control), Site B (3 years of annual sludge application at approximately 10 tonnes dry weight/ha/year), Site C (6 years), and Site D (10 years). Soils across all sites were classified as alluvial sandy loam (Typic Ustochrepts) with comparable baseline texture and organic carbon content prior to sludge application.

At each site, five replicate plots (10 m × 10 m) were delineated. Composite soil samples were collected from each plot at two depth intervals (0–20 cm and 20–40 cm) during the post-harvest period (April 2024) using a stainless-steel auger. Each composite sample comprised five sub-samples pooled and

homogenised in the field. Samples were stored in aluminium-lined bags, transported to the laboratory in insulated containers, and air-dried at 40°C prior to analysis.

Microplastic Extraction and Identification

Microplastics were extracted from 100 g (dry weight) sub-samples using a sequential procedure. Organic matter was first digested by treating samples with 30% H₂O₂ at 60°C for 72 h, followed by density separation in ZnCl₂ solution ($\rho = 1.6$ g/cm³). The supernatant containing the floating fraction was vacuum-filtered through stainless-steel mesh filters (10 μ m pore size). Filters were examined under a stereomicroscope, and suspected microplastic particles were mapped and subsequently analysed using a Thermo Scientific Nicolet iN10 MX micro-FTIR spectrometer in attenuated total reflectance (ATR) mode. Spectra were matched against a commercial polymer reference library (Hummel Polymer and Additives Library) with a match threshold of $\geq 70\%$.

Strict contamination control measures were observed throughout sample handling. Cotton laboratory coats were worn, all glassware was rinsed three times with filtered deionised water, and procedural blanks (n = 5 per batch) were processed alongside field samples. The mean blank contamination was 3.2 ± 1.1 particles per sample, and all reported values were blank-corrected.

Plant Uptake Experiment

A pot experiment was conducted in a greenhouse to assess crop uptake. Sludge-amended field soil from Site D (10-year history) and control soil from Site A were filled into polypropylene-free ceramic pots (5 kg soil per pot). Seeds of wheat (*Triticum aestivum* cv. HD-2967) and lettuce (*Lactuca sativa* cv. Grand Rapids) were sown in five replicate pots per soil type per crop species. Plants were irrigated with filtered deionised water and grown to maturity (wheat: 120 days; lettuce: 60 days). At harvest, roots, stems/shoots, and edible portions (wheat grains; lettuce leaves) were carefully washed with deionised water to remove adhering soil, digested in 10% KOH at 60°C for 48 h, and processed through the same density separation and micro-FTIR workflow described above.

Statistical Analysis

All data were analysed using R (version 4.3.1). Differences in microplastic concentrations among sites and depths were evaluated by two-way ANOVA followed by Tukey's HSD post-hoc test. Plant tissue data were compared using independent-

samples t-tests (sludge-amended vs. control) and one-way ANOVA across tissue types. Statistical significance was set at $p < 0.05$.

RESULTS

Microplastic Abundance in Soils

Microplastic concentrations in the 0–20 cm soil layer increased progressively with sludge amendment duration (Table 1). Unamended control soil (Site A) contained 320 ± 45 particles/kg, while soils with 3, 6, and 10 years of amendment history contained 980 ± 130 , $1,740 \pm 260$, and $2,870 \pm 410$ particles/kg, respectively ($p < 0.001$). At the 20–40 cm depth, concentrations were lower but followed the same trend, ranging from 110 ± 30 particles/kg (control) to 860 ± 150 particles/kg (10-year site). Across all amended sites, topsoil (0–20 cm) concentrations were significantly higher than subsoil (20–40 cm) levels ($p < 0.01$).

Table 1. Microplastic abundance (particles/kg dry soil, mean $\pm$ SD, $n = 5$) across sites and soil depths.

Site	Amendment Duration	0–20 cm	20–40 cm
A (Control)	0 years	320 ± 45	110 ± 30
B	3 years	980 ± 130	340 ± 65
C	6 years	$1,740 \pm 260$	590 ± 110
D	10 years	$2,870 \pm 410$	860 ± 150

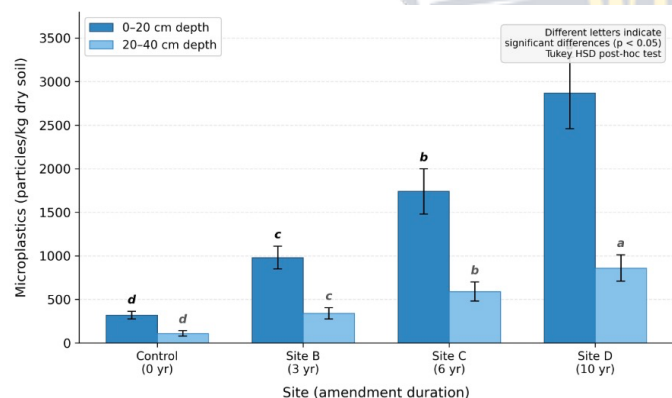


Fig. 2. Microplastic abundance in sludge-amended soils across sites and depths

Polymer Composition and Morphology

Polyethylene (PE) was the most abundant polymer across all sites, accounting for 34.2% of all identified particles, followed by polypropylene (PP, 24.6%), polyester/PET (19.8%), polyamide (10.3%), polystyrene (6.1%), and others (5.0%). Fibres were the dominant morphological category (52.4%), followed by fragments (31.7%) and films (15.9%). The polymer profile remained broadly consistent across amendment durations, though the relative proportion of polyester fibres increased marginally in more recently amended soils.

Table 2. Polymer composition (% of total identified particles) across amendment durations.

Polymer	Control	3-year	6-year	10-year
PE	30.1	33.5	35.0	36.8
PP	26.4	25.1	24.0	23.6
PET/Polyester	16.3	18.7	20.2	21.5
Polyamide	12.5	11.0	10.1	8.9
PS	8.2	6.5	5.9	5.2
Others	6.5	5.2	4.8	4.0

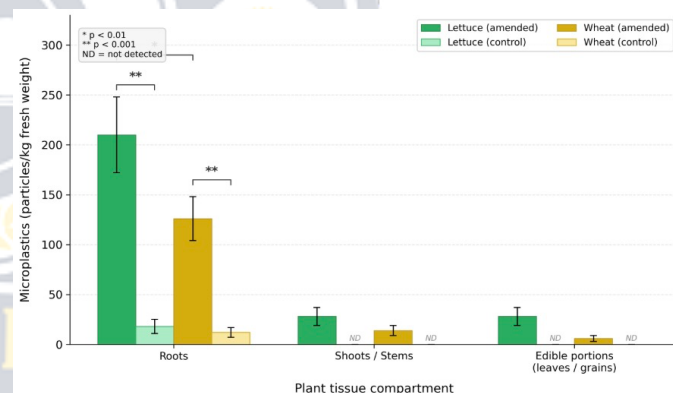


Fig. 3. Microplastic distribution across plant tissue compartments

Plant Uptake

Microplastics were detected in root tissues of both crop species grown in sludge-amended soil. Lettuce roots contained 210 ± 38 particles/kg fresh weight, significantly higher than wheat roots at 126 ± 22 particles/kg ($p < 0.01$). In above-ground tissues, lettuce leaves contained 28 ± 9 particles/kg, while wheat stems held 14 ± 5 particles/kg. Wheat grains contained trace levels at 6 ± 3 particles/kg. Plants grown in control soil showed minimal root contamination (lettuce: 18 ± 7 ; wheat: 12 ± 5 particles/kg) and no detectable above-ground microplastics. The particles recovered from plant tissues were predominantly

in the 10–150 μm size range, with PE and PET as the principal polymers.

Table 3. Microplastic concentrations in plant tissues (particles/kg fresh weight, mean $\pm$ SD, n = 5).

Tissue	Lettuce (Amended)	Lettuce (Control)	Wheat (Amended)	Wheat (Control)
Roots	210 $\pm$ 38	18 $\pm$ 7	126 $\pm$ 22	12 $\pm$ 5
Shoots/Stems	28 $\pm$ 9	ND	14 $\pm$ 5	ND
Edible (leaves/grains)	28 $\pm$ 9	ND	6 $\pm$ 3	ND

ND = not detected.

DISCUSSION

The results of this study confirm that long-term sewage sludge application leads to a progressive and substantial accumulation of microplastics in agricultural topsoil. The nearly nine-fold increase in microplastic concentration from unamended to 10-year amended soil aligns with the cumulative loading estimates reported by Corradini et al. (2019) for Chilean agricultural fields, though absolute concentrations in the present study are somewhat lower, likely reflecting differences in sludge application rates and source wastewater characteristics. The strong concentration gradient between topsoil and subsoil horizons suggests that most microplastics remain within the plough layer under the tillage practices typical of Indo-Gangetic agriculture, although the non-negligible subsoil concentrations indicate that downward transport occurs, consistent with the bioturbation and preferential flow mechanisms described by Rillig et al. (2017).

The predominance of fibrous morphologies and the polymer profile dominated by PE, PP, and PET are consistent with the textile and packaging origins typical of municipal wastewater streams (Browne et al., 2011). The slight enrichment of polyester fibres in more recently amended soils may reflect the increasing prevalence of synthetic textiles in the consumer market over time.

The detection of microplastics in root tissues of both wheat and lettuce validates concerns raised by Li et al. (2020) regarding crop uptake from contaminated soils. The significantly higher uptake by lettuce is attributable to its fibrous root architecture

and high transpiration-driven water flux, which enhances particle entrainment at the root surface and facilitates entry through lateral root junctions where the Casparian strip is not fully developed (Conti et al., 2020). The translocation to edible leaves, though occurring at lower concentrations than in roots, represents a direct pathway of human dietary exposure. Wheat grains, protected by multiple tissue barriers, accumulated only trace quantities, suggesting that cereal crops may present a comparatively lower risk than leafy vegetables, corroborating the findings of Oliveri Conti et al. (2020).

There are several limitations to the present study. The density separation method, while effective for polymers with densities below 1.6 g/cm³, may underestimate contributions from denser polymers such as PVC. Furthermore, particles smaller than 10 μm were excluded by the filtration step, and the actual burden of nanoplastics, which may be more readily taken up by plants, remains unquantified. Future studies should integrate pyrolysis-GC/MS or Raman imaging for mass-based quantification and should extend the analysis to additional crop types, soil textures, and climatic conditions.

CONCLUSION

This study provides field-based evidence that sewage sludge application to agricultural soils results in cumulative microplastic contamination that increases with amendment history. Polyethylene, polypropylene, and polyester fibres are the dominant contaminants, accumulating primarily in the topsoil horizon. The uptake of microplastics by wheat and lettuce roots, with translocation to edible tissues, confirms the potential for dietary exposure through consumption of crops grown on sludge-amended land. Given the expanding practice of sludge reuse in South Asian agriculture, there is an urgent need for regulatory frameworks that set permissible microplastic limits in biosolids destined for land application and for the development of sludge treatment technologies capable of reducing microplastic loads prior to field deployment.

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