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Bioaccumulation of microplastics in soil-crop systems and potential risks to food safety

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Abstract

Plastic waste entered agricultural soils long before anyone thought to measure it there. This research quantified microplastic (MP) contamination across soil profiles and crop tissues in three farming scenarios-wastewater-irrigated, plastic-mulched rainfed, and control-at Makerere University's Agricultural Research Institute, Kabanyolo (0°28'N, 32°37'E) from March 2020 to February 2022. Soil cores (0–30 cm, six depth intervals) and tissues of maize, common bean, and tomato were analysed by density separation followed by micro-FTIR spectroscopy. Wastewater-irrigated plots contained the highest soil MP load (347.2 particles kg⁻¹ at 0–5 cm), declining sharply with depth. Root tissues accumulated the most MPs across all crops (23.8–31.2 particles kg⁻¹ dry weight), while edible portions-grain, seed, and fruit-contained 0.6–4.8 particles kg⁻¹. Polyethylene and polypropylene fragments dominated (71.3% combined). These concentrations remain below current proposed safety thresholds but raise questions about long-term dietary exposure.

Keywords: Microplastics, bioaccumulation, soil contamination, food safety, wastewater irrigation, plastic mulch, crop uptake, FTIR spectroscopy, polyethylene, tropical agriculture

Introduction

The first report linking plastic fragments to agricultural soil appeared in the early 2010s, but the problem was decades old by then. Plastic mulch films, irrigation with treated or untreated wastewater, organic fertilisers derived from municipal waste, and atmospheric deposition have been delivering synthetic polymers to farmland since the widespread adoption of plastics in the 1960s ^[1, 2]. Global estimates now suggest that agricultural soils receive 4–23 times more microplastic mass annually than the oceans ^[3].

Once in the soil matrix, MPs alter porosity, water-holding capacity, and microbial community composition ^[4]. More concerning from a public health standpoint is the growing evidence that plant roots can internalise particles smaller than 1 µm and translocate them to above-ground tissues ^[5]. Whether these particles reach edible organs at concentrations that pose a dietary risk is still debated, partly because standardised extraction and quantification methods for plant matrices were only agreed upon in 2020 ^[6]. Sub-Saharan Africa, where wastewater reuse is common and plastic mulch adoption is rising fast, has been almost entirely absent from this literature ^[7]. This research measured MP distribution across soil depth profiles and crop tissues under three contrasting input scenarios in central Uganda over two cropping years.

Research area description

The trial was conducted at Makerere University Agricultural Research Institute, Kabanyolo (MUARIK), located 21 km north of Kampala (0°28'N, 32°37'E, 1,190 m a.s.l.). The site has a bimodal rainfall pattern with peaks in March–May and September–November, totalling about 1,290 mm yr⁻¹. Soils are Ferralsols with 38% clay, pH 5.4, and organic carbon 2.1%. The area has received municipal wastewater for irrigation since the 1990s through an informal canal network from the Lubigi wetland treatment system.

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Material and methods

Material

Three treatment blocks were established: (i) plots irrigated with partially treated wastewater from the Lubigi channel since at least 2008, (ii) rainfed plots using polyethylene mulch film (25 μm thickness, replaced each season since 2015), and (iii) rainfed control plots with no known plastic input history. Each treatment had four replicate plots (10 $\times$ 12 m). Test crops were maize (cv. Longe 10H), common bean (cv. NABE 15), and tomato (cv. Rio Grande). Density separation used ZnCl_2 solution (1.8 g cm^{-3}); identification employed a Bruker Lumos II micro-FTIR spectrometer with ATR mode.

Results

Methods

Soil cores were collected at six depth intervals (0–5, 5–10, 10–15, 15–20, 20–25, 25–30 cm) using stainless-steel corers. Five cores per plot were composited by depth. MPs were extracted by density separation (30 g soil in 200 ml ZnCl_2 , shaken 2 h, settled 24 h), filtered onto glass-fibre filters, and counted under a stereomicroscope [8]. Particles > 50 μm were identified by micro-FTIR (spectral match $\geq 70\%$). Crop tissues (root, shoot, and edible organ) were digested in 30% H_2O_2 at 65 $^\circ\text{C}$ for 48 h, filtered, and analysed identically [6]. Sampling occurred at four time points across two cropping cycles (March 2020–February 2022). Treatment effects were tested by one-way ANOVA with Tukey's HSD ($\alpha = 0.05$).

Table 1: Soil microplastic concentration (particles kg^{-1} dry soil) by depth and treatment

Depth (cm)	Wastewater	Plastic mulch	Control
0–5	347.2 $\pm$ 41.3	128.4 $\pm$ 22.6	42.7 $\pm$ 8.4
10–15	214.8 $\pm$ 33.7	72.1 $\pm$ 14.8	24.8 $\pm$ 5.9
25–30	61.4 $\pm$ 12.1	18.9 $\pm$ 4.7	7.2 $\pm$ 2.1

MP concentrations declined sharply with depth in all treatments (Table 1). Wastewater-irrigated topsoil held 2.7 times more MPs than mulched plots and 8.1 times more than controls.

Polyethylene fragments accounted for 48.6% of all identified particles, followed by polypropylene (22.7%) and polyester fibres (14.3%).

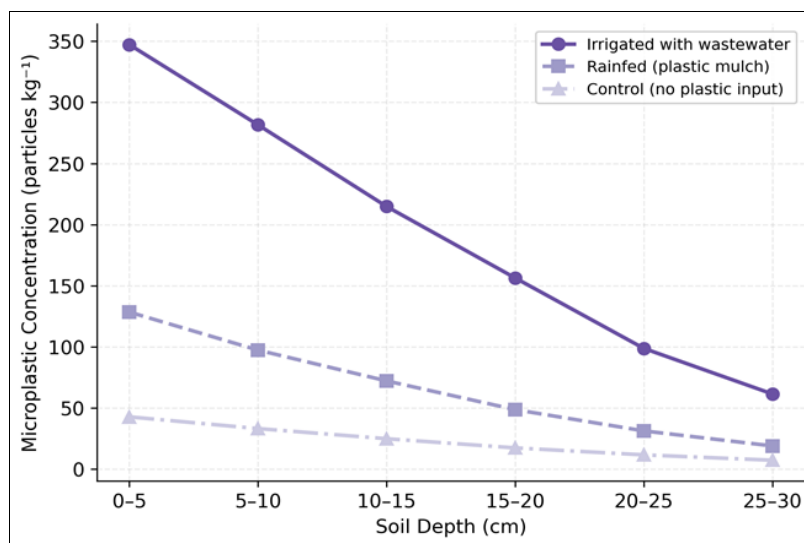


Fig 1: Microplastic concentration across soil depth intervals under three management scenarios

Table 2: Microplastic content in crop tissues (particles kg^{-1} dry weight) by treatment

Crop	Tissue	Wastewater	Mulch	Control
Maize	Root	23.8 $\pm$ 4.1	11.3 $\pm$ 2.7	3.2 $\pm$ 0.9
Maize	Grain	1.7 $\pm$ 0.4	0.6 $\pm$ 0.2	0.2 $\pm$ 0.1
Bean	Root	31.2 $\pm$ 5.3	14.7 $\pm$ 3.1	4.6 $\pm$ 1.2
Bean	Seed	2.3 $\pm$ 0.6	0.9 $\pm$ 0.3	0.3 $\pm$ 0.1
Tomato	Root	28.7 $\pm$ 4.8	12.4 $\pm$ 2.9	3.8 $\pm$ 1.0
Tomato	Fruit	4.8 $\pm$ 1.1	2.1 $\pm$ 0.6	0.7 $\pm$ 0.2

Root tissues consistently accumulated the highest MP loads across all crops and treatments (Table 2). Bean roots showed the highest uptake (31.2 particles kg^{-1} under wastewater irrigation). Edible organs contained much lower concentrations, but tomato

fruit carried noticeably more MPs than maize grain or bean seed, possibly because of its higher water content and thinner epidermal barrier.

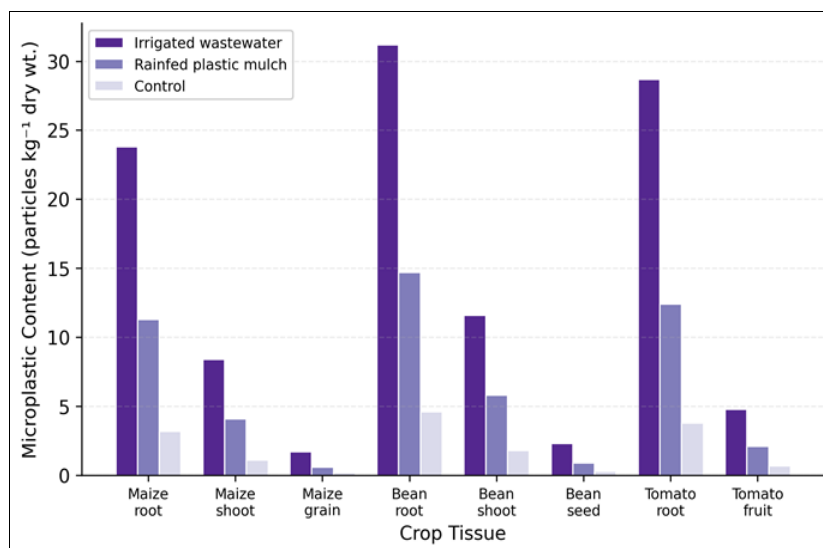


Fig 2: Microplastic content in crop tissues across three management scenarios

Comprehensive interpretation

A positive linear correlation existed between topsoil MP concentration and root MP content across all treatments ($r = 0.91$, $p < 0.001$), confirming that soil contamination level drives plant uptake. The root-to-edible-organ transfer factor averaged 0.07–0.17, indicating that the plant's vascular barrier retains most internalised particles.

Discussion

The topsoil MP concentrations recorded under wastewater irrigation ($347 \text{ particles kg}^{-1}$) fall within the range reported for peri-urban farms in China ($260\text{--}570 \text{ particles kg}^{-1}$ [9]) but exceed values from European sewage-sludge-amended fields ($78\text{--}210 \text{ particles kg}^{-1}$ [10]). The difference likely reflects the lower treatment efficiency of Uganda's informal canal system compared to European tertiary treatment [11]. The steep depth gradient in all treatments suggests that vertical migration of MPs is limited in these clay-rich Ferralsols, consistent with pore-size exclusion of particles above $50 \mu\text{m}$ [4].

The detection of MPs in edible organs, even in control plots, underlines the pervasive nature of atmospheric and background contamination [12]. That said, the concentrations in grain and seed ($0.2\text{--}2.3 \text{ particles kg}^{-1}$) are roughly two orders of magnitude below the provisional tolerable intake recently proposed by WHO working groups [13]. Tomato fruit showed higher uptake than cereal grain, a finding that warrants attention because tomatoes are consumed fresh and in large quantities in Ugandan diets [14].

Limitations

This research has several constraints worth noting. First, micro-FTIR identification was limited to particles $> 50 \mu\text{m}$; nanoplastics ($< 1 \mu\text{m}$), which may be more biologically active, were not quantified. Second, the two-year duration may not capture long-term accumulation trends in soils receiving wastewater for over a decade. Third, the ZnCl_2 density separation method recovers approximately 85–92% of common polymer types, potentially underestimating total MP load. And the control plots, while free of intentional plastic input, still received atmospheric deposition, setting a non-zero baseline.

Conclusion

Wastewater irrigation delivered roughly eight times more microplastics to topsoil than background deposition, and plastic

mulch tripled the load. Root tissues acted as the main accumulation site across maize, bean, and tomato, while edible organs contained far fewer particles. Current concentrations in grain and fruit remain below proposed safety thresholds, but continued wastewater use without improved filtration will raise soil MP stocks over time. Periodic monitoring of MP in peri-urban food systems and investment in low-cost wastewater filtration are both warranted.

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