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Agro-Industrial Contributions to Soil Microplastic Pollution: Evidence from a Rice Milling Facility in Birnin Kebbi, Nigeria

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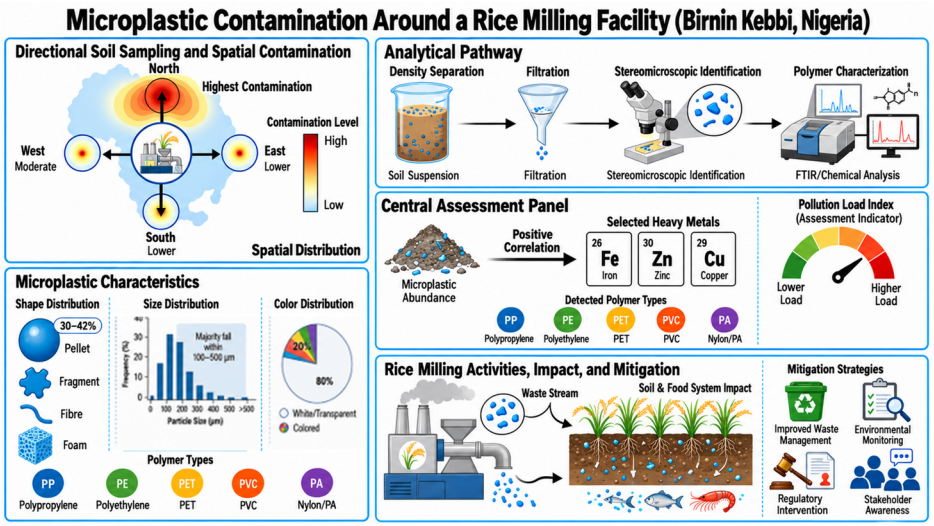
microplastics; pellets; polyethylene; polymers; rice mill

Highlights

- Microplastic concentrations in soils around Labana Rice Mills ranged from 626 to 1112 particles kg^{-1}
- Pellets dominated particle morphology, with most microplastics in the 100–500 µm size range
- Polypropylene, polyethylene, PET, PVC, and nylon were the major polymers identified
- Positive correlations were observed between microplastics and heavy metals (Fe, Zn, Cu)
- Microplastic abundance showed clear spatial variation, with the northern axis having the highest concentration

Abstract: Microplastic contamination in terrestrial environments is an emerging concern, yet its association with agro-industrial activities and heavy metal contamination remains poorly understood. This study characterized microplastics in soils surrounding Labana Rice Mills, Birnin Kebbi, Nigeria, and assessed their co-occurrence with selected heavy metals. Soil samples were collected along four cardinal directions of the facility and analyzed using density separation, stereomicroscopy, and attenuated total reflection–Fourier transform infrared (ATR-FTIR) spectroscopy. Microplastic concentrations ranged from 626 ± 11 to 1112 ± 41 particles kg^{-1}, with the northern axis having the highest. These concentrations were comparable to values reported for agro-environments in Bangladesh (660–1309 particles kg^{-1}) and India (400–1370 particles kg^{-1}). Pellets and fragments were the dominant shapes, while particle size 100–500 µm and transparent/white coloration predominated. Identified polymer types included polypropylene, polyethylene, polyethylene terephthalate, polyvinyl chloride, and polyamide. Iron, copper, and zinc were detected in all samples and showed positive correlations with microplastic abundance (R^2 = 0.72, 0.52, and 0.46, respectively; $p < 0.01$). Contamination factor indicated very high contamination across all axes, while pollution load index (PLI = 8.95) confirmed significant microplastic pollution. Polymer risk assessment classified polypropylene as low risk, polyethylene, polyethylene terephthalate, and polyvinyl chloride as moderate risk, and polyamide as high risk. The predominance of pellets suggests potential contributions from rice milling activities. The co-occurrence of microplastics and heavy metals highlights potential ecological risks and underscores the need for improved waste management practices, routine environmental monitoring, and targeted regulatory interventions in agro-industrial systems.

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1. Introduction

The pervasive use of plastic materials in modern society has led to a growing environmental challenge, most notably microplastic pollution. Microplastics, plastic particles less than 5 mm in diameter, are now ubiquitous in water, air, and soil [1]. Their sources are diverse, ranging from the degradation of larger plastic debris (secondary microplastics) to the direct release of microbeads from personal care products and industrial processes (primary microplastics) [2,3]. Microplastics vary widely in sizes, shapes, colors, and polymer types. Common shapes include fibers, fragments, films, pellets, and foams [4], while frequently reported polymers include polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) [5]. Their small sizes, combined with diverse polymer types and physical characteristics, facilitate their dispersal and widespread distribution in the environment [6].

The extensive distribution of microplastics has raised global concern due to their potential toxicity to aquatic and terrestrial organisms, environmental systems, and human health. Beyond the physical risks associated with their size, shape, and polymer, microplastics often contain toxic additives such as bisphenols, phthalates, forever chemicals, and heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg), which are used as pigments and stabilizers [7]. They also act as vectors for microorganisms and environmental contaminants, particularly heavy metals [8]. Human exposure to microplastics has been associated with increased risks of cardiovascular diseases, cancer, diabetes, hypertension, and infertility [9,10]. In ecological systems, microplastics can cause physical harm like intestinal blockages and reduced feeding, chemical harm through pollutant transfer, and ecosystem-level disruptions by altering behavior, reproduction, and food-web dynamics [11]. These environmental and health implications have intensified global interest in microplastic occurrence, distribution, and toxicity studies across various environmental matrices. However, relatively few studies have investigated the microplastic pollution potentials of industrial facilities. Addressing this knowledge gap is essential for understanding and managing emerging sources of microplastic contamination.

Evaluating rice milling facilities worldwide in particular has become a priority as the industry continues to expand to meet rising global demand. The demand for rice, a major food staple for more than half the world's population, is steadily increasing due to population growth, particularly in Asia and Africa [12]. Global rice production reached 523.9 million tonnes in 2023/24 season and is predicted to rise to 567 million tonnes by 2030 [12]. This sustained growth has driven significant expansion and technological advancements within the rice milling sector. However, it has also led to increased environmental pollution. Pollution from rice milling facilities includes substantial air, water, and soil contamination arising from solid wastes (husks, bran, ash), liquid effluents (wastewater), and airborne particulate matter (dust, smoke). Rice milling activities in Anambra and Kogi States, Nigeria have been linked to elevated heavy metal concentrations including cadmium (Cd), lead (Pb), and zinc (Zn) in the surrounding soil [13]. The industry is also a significant source of microplastic emissions through the degradation of plastic materials used during processing, packaging, and transport [14]. Microplastics have been detected in rice consumed by humans [15]. These pollutants pose serious environmental and public health risks, prompting numerous studies on toxicity and exposure around rice mills globally. However, none of these studies including those by Yahaya et al. [16], Yahaya et al. [17], and Challa et al. [18] have assessed microplastic pollution around rice mills. This highlights the need to evaluate the microplastic pollution potential of rice milling facilities worldwide.

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Labana Rice Mills in Kebbi State, northwestern Nigeria, is one of the largest rice milling facilities in the country. The facility employs thousands of workers and contributes significantly to both the local and national economy. However, its operations also release pollutants and wastewater, which are visibly present in the air and surrounding environment. Regular monitoring of this facility is therefore essential to safeguard workers and nearby residents by assessing pollutant levels, including microplastics. Soils, being a universal sink for environmental contaminants, are ideal for evaluating pollutant levels and exposure risks, as microplastics in the soil can be ingested or inhaled. An effective method for quantifying and characterizing microplastics in soil is the combination of density separation and Fourier transform infrared (FTIR) spectroscopy. Density separation is a widely used method for extracting microplastics from soil due to its cost-effectiveness and reliability across a broad range of common polymers [19]. FTIR spectroscopy is a powerful tool for microplastics identification, offering detailed chemical characterization, and enabling high-throughput, automated analysis [20]. This study aims to determine microplastic concentrations in soil samples collected from the four directional axes surrounding the rice milling facility as well as within its premises. Additionally, the detected microplastics will be characterized by shapes, sizes, and polymer type. As the first of its kind in the Nigerian rice milling industry, the findings will provide baseline data for future microplastic monitoring at this and similar facilities.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted around Labana Rice Mills, located in Birnin Kebbi, Kebbi State, Nigeria. Birnin Kebbi lies at latitude 12.4317585° N and longitude 4.1956212° E within the Sudano–Sahelian ecological zone (Figure 1). The major indigenous ethnic groups in the city are Hausa, Fulani, and Zuru, alongside a substantial proportion of non-indigenes from various ethnic groups across the country. The climate is semi-arid tropical, with distinct wet (May–October) and dry (November–April) seasons. Mean annual temperatures range from 27 °C to 34 °C, and annual rainfall averages 600–800 mm [17]. Vegetation consists mainly of scattered umbrella-shaped trees and shrubs. The dominant soil type is sandy loam with moderate organic matter, typical of the northwestern plains of Nigeria.

Kebbi State is largely agrarian, with residents extensively engaged in grain farming, especially rice, corn, and millet. The widespread cultivation of rice in Birnin Kebbi contributed to the establishment of Labana Rice Mills. The facility plays a major role in food production and employment at both regional and national levels. However, its operations generate solid wastes and wastewater that may introduce toxic pollutants, including microplastics, into the surrounding environment. The facility is bordered by residential, commercial, and agricultural areas, placing workers and nearby residents at potential risk of exposure to contaminants through soil, water, and air.

A background/reference site was also selected within Birnin Kebbi to provide a local baseline for comparison with soils surrounding the rice milling facility. The site was located outside the 1–2 km sampling radius of Labana Rice Mills, in an area with no major industrial facilities, workshops, dumpsites, wastewater outfalls, or other point sources of plastic debris. Land use was limited to sparsely vegetated, non-cultivated sandy-loam terrain typical of the northwestern plains of Nigeria. Before sampling, the site was inspected to confirm the absence of direct industrial discharges, intensive waste-disposal activity, and heavy traffic corridors. Soil at the background site was collected at the same depth (0–15 cm) and with the same stainless-steel auger protocol described in Section 2.2. The location of the background site relative to Labana Rice Mills and the four sampling axes is shown in Figure 1.

2.2. Sample Collection

Soil samples were collected between May and June 2025 from five locations: the northern, southern, eastern, and western axes within a 1–2 km radius of Labana Rice Mills, and one background/reference site outside the immediate influence of the facility. Sampling was conducted weekly for three consecutive weeks. During each sampling event, five samples were collected at every location, giving 15 samples per location and 75 samples in total. Soil samples were collected from a depth of 0–15 cm using a stainless-steel hand auger, in accordance with established microplastic soil sampling protocols [21]. Before sampling, the auger was rinsed with distilled water and wiped with lint-free aluminum foil to avoid cross-contamination between sites. Each soil replicate was homogenized thoroughly and transferred into pre-cleaned aluminum foil containers. Plastic materials were strictly avoided during sampling, handling, and storage to minimize external microplastic contamination. All samples were labeled with the sampling date, location, and GPS coordinates, then transported to the laboratory in a sealed non-plastic cooler for further analysis.

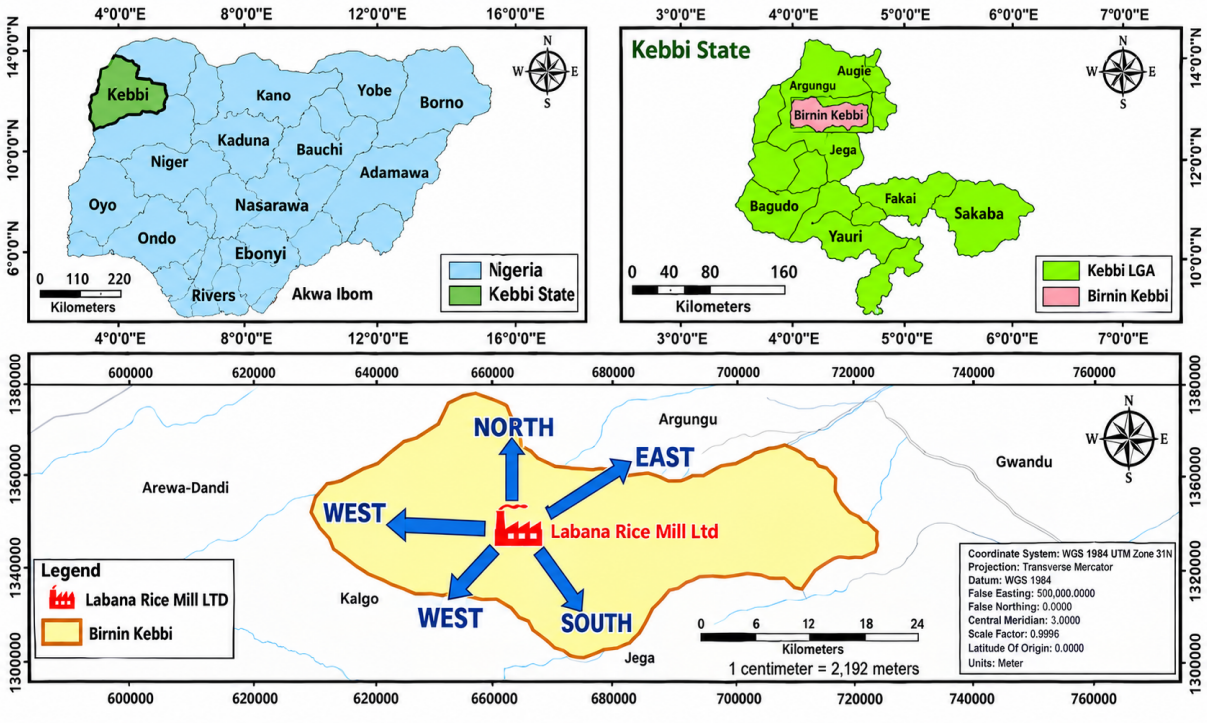


Figure 1. Map of the study area.

2.3. Microplastic Extraction and Identification

Microplastics were extracted from the soil samples using a modified density separation and filtration method adapted from Yahaya et al. [22]. Exactly, 10 g of oven-dried soil (dried at 60 °C for 24 h) was homogenized and transferred into a 250 mL glass separation flask. Initially, 100 mL of saturated sodium chloride (NaCl) solution (density ≈ 1.20 g cm^{-3}) was added to separate low-density polymers. Following recovery of the supernatant, the remaining sediment was subjected to a second density separation using zinc chloride ($ZnCl_2$) solution (density 1.6–1.7 g cm^{-3}) to improve the recovery of high-density polymers, including polyethylene terephthalate (PET) and polyvinyl chloride (PVC). During each extraction step, the suspension was vigorously agitated on an orbital shaker at 200 rpm for 10 min to ensure thorough dispersion of soil particles and microplastics, after which it was allowed to settle for 24 h at room temperature (≈25 °C). The supernatant was carefully decanted and vacuum-filtered through a Whatman GF/C glass microfiber filter (1.2 µm particle retention; 47 mm diameter; Whatman, Maidstone, Kent, United Kingdom) using a glass filtration apparatus. To maximize recovery efficiency, the density separation procedure was repeated two additional times for each sample, and the filtrates from all extractions were combined on the same filter. The filters were subsequently dried in a laboratory oven at 40 °C for 12 h and stored in covered glass Petri dishes until analysis. Recovered microplastics were quantified as particles per gram (particles g^{-1}) using Equation (1).

Microplastics retained on the filters were examined using a Nikon SMZ745 stereomicroscope (Nikon Corporation, Tokyo, Japan) at ×40 magnification. Suspected microplastics were visually identified and classified based on shape (fibers, fragments, foams, and pellets), size, and color. Microplastic abundance was determined by stereomicroscopic screening based on particle morphology, size, and color. Particles displaying obvious mineral or biological characteristics were excluded during visual screening. Particle sizes were measured using an integrated digital measurement software attached to an 18.0 MP digital microscope camera (AmScope, Irvine, California, USA), and representative photomicrographs were captured for documentation and polymer verification.

To minimize contamination, all laboratory procedures were conducted using glass or metal equipment only, and plastic materials were avoided throughout the analysis. Glassware was thoroughly rinsed with distilled water and pre-filtered NaCl solution before use. Work surfaces were cleaned with 70% ethanol, and all samples and containers were covered with aluminum foil during processing. Laboratory and procedural blanks containing only NaCl solution were processed alongside the samples under identical conditions to monitor potential airborne or handling-related contamination.

$$C = \frac{N}{W} \quad (1)$$

where:

C = concentration of microplastics (particles g^{-1}),
N = number of microplastic particles observed,
W = Mass of soil sample analyzed (g).

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2.4. Polymer Identification

Recovered microplastic particles from each sampling location were pooled to obtain sufficient mass for spectral analysis and analyzed using a Nicolet Nexus 470 Attenuated Total Reflection–Fourier Transform Infrared (ATR-FTIR) spectrometer (Thermo Fisher Scientific Madison Wisconsin, United States) equipped with OMNIC spectral analysis software, version 8 developed by Thermo Fisher Scientific. Prior to analysis, filters were carefully inspected under a stereomicroscope, and representative particles were manually transferred onto the ATR crystal using stainless-steel tweezers. Infrared spectra were acquired over the wavenumber range of 650–4000 cm^{-1} at a spectral resolution of 4 cm^{-1}, with 32 scans accumulated per spectrum to improve the signal-to-noise ratio. The ATR crystal (diamond/ZnSe) was cleaned before each measurement, and a background spectrum of the clean crystal was recorded prior to each sample run and after every three sample measurements to minimize instrumental drift and ensure spectral accuracy. After each analysis, the ATR crystal was thoroughly cleaned with 70% ethanol and lint-free tissues to prevent cross-contamination between samples. TR-FTIR analysis was performed on representative particles selected from the visually identified particle pool to verify polymer identity; therefore, spectroscopic confirmation was not conducted for every particle counted by stereomicroscopy. Polymer assignments were accepted only when spectra achieved a library match of ≥80% and showed diagnostic absorption bands consistent with the assigned polymer. Polymer identification was performed by comparing the obtained spectra with reference spectra in the Thermo Fisher Scientific OMNIC Spectra Polymer Library (Specta versions 1.0). Identification was further verified by examining characteristic absorption bands and functional group assignments and by comparison with reference spectra reported in Yahaya et al. [22]. The detected polymers included polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyamide/nylon (PA), and polyethylene terephthalate (PET). Only spectra with a library match score of ≥80% were considered valid polymer identifications. The accepted spectra exhibited match scores ranging from 80% to 90%, indicating good agreement with the reference spectra and supporting reliable polymer identification.

2.5. Heavy Metal Analysis

The heavy metals in the soil samples were determined as described by Yahaya et al. [23]. Soil samples were air-dried at room temperature under dust-free conditions and gently disaggregated using a porcelain mortar and pestle. Visible debris such as stones, roots, and organic residues were removed manually. The dried samples were then sieved through a 2 mm mesh to obtain the fine fraction for analysis.

The samples were then digested by measuring 1.0 g of each sample into a clean digestion flask. A mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a ratio of 3:1 (v/v) was added to the sample. The mixture was allowed to predigest at room temperature for 12–16 h to reduce vigorous reactions. Subsequently, the samples were heated on a hot plate at a controlled temperature (≈120–150 °C) until a clear or near-clear solution was obtained and dense fumes subsided, indicating complete digestion. After cooling, the digest was filtered using acid-washed filter paper into a volumetric flask and diluted to 50 mL with deionized water. The digested samples were stored in acid-washed polyethylene bottles prior to analysis.

The concentrations of iron (Fe), copper (Cu), lead (Pb), and zinc (Zn) in the digested soil samples were determined using a PG-990 atomic absorption spectrophotometer (AAS) (Beijing Purkinje General Instrument Co., Ltd., Beijing, China). Calibration curves were prepared using a series of standard solutions for each metal, and instrument parameters were optimized according to the manufacturer's guidelines. Appropriate wavelengths were selected for each element, and measurements were performed under standardized operating conditions.

Strict quality control procedures were implemented throughout sample preparation, digestion, and analysis to ensure data accuracy and reliability. All reagents used were of analytical grade (ANALAR), and all glassware and digestion vessels were soaked in 10% nitric acid for 24 h, thoroughly rinsed with distilled water, and dried prior to use to minimize contamination. Procedural blanks were included in each digestion batch to monitor potential contamination from reagents and laboratory procedures. Duplicate samples were analyzed to assess analytical precision, while triplicate measurements were performed for each sample, with reproducibility consistently exceeding 95%. Calibration standards were run at the beginning and after every set of samples to check instrument stability. To validate accuracy, certified reference materials (CRMs) or standard reference solutions were analyzed alongside the samples, and recovery rates were maintained within acceptable limits (typically 85–115%). The limits of detection (LOD) and limits of quantification (LOQ) for each metal were determined based on standard methods. Instrument drift was monitored and corrected through periodic recalibration during analysis (Table 1). Concentrations below the LOD are reported as below detection limit (BDL).

Table 1. Analytical performance of heavy-metal determination in soil.

Metal	Wavelength (nm)	LOD (mg kg⁻¹)	LOQ (mg kg⁻¹)	Spike Recovery (%)	CRM Recovery (%)	R^2
Fe	248.3	1.26	4.20	98.4	97.8	0.9994
Cu	324.8	0.24	0.80	96.7	95.9	0.9989
Zn	213.9	0.075	0.25	99.1	98.6	0.9996
Pb	217.0	0.015	0.050	97.3	96.8	0.9991

Analytical criteria: LOD was calculated as 3σ, while LOQ was calculated as 10σ, equivalent to 10/3× LOD. The resulting LOQs satisfy the required thresholds for Fe (≤4.74 mg kg⁻¹), Cu (≤0.90 mg kg⁻¹), and Zn (≤0.30 mg kg⁻¹). Pb was considered below the detection limit when concentrations were <0.015 mg kg⁻¹. Abbreviations: LOD = Limit of detection, LOQ = limit of quantification, CRM = certified reference material.

2.6. Microplastic Health Risk Assessment

The potential risks of microplastics in the soil samples were evaluated using the contamination factor (CF), pollution load index (PLI), and polymer risks.

2.6.1. Contamination Factor (CF)

The contamination factor of microplastics in the soil were assessed using Equation (2) [24].

$$CF = C_{sample}/C_{background} \quad (2)$$

where C_{sample} is the concentration of microplastic at each location, and $C_{background}$ is the background concentration. The CF values were interpreted as follows: CF < 1 = low contamination, 1 ≤ CF < 3 = moderate contamination, 3 ≤ CF < 6 = considerable contamination, and CF ≥ 6 = very high contamination.

2.6.2. Pollution Load Index (PLI)

The pollution load index (PLI) was used to evaluate the overall level of microplastic pollution. It was calculated as the geometric mean of the contamination factors across all sampling locations, as shown in Equation (3).

$$PLI = (CF_1 \times CF_2 \times CF_3 \times CF_4)^{1/4} \quad (3)$$

A PLI value > 1 indicates pollution, while PLI ≤ 1 indicates no pollution or baseline conditions. Abbreviations: PLI = Pollution load index.

2.6.3. Polymer Risk Index (PRI)

The polymer risk index (PRI) was used to assess the potential risk associated with the composition of microplastic polymers, as shown in Equation (4) [1].

$$PRI = \sum PMP \times PS \quad (4)$$

where PMP is the percentage (%) of each microplastic polymer in the sample, and PS is the hazard score assigned to each polymer based on literature values. The polymer hazard scores used were: polyethylene (PE) = 11, polypropylene (PP) = 1, polyethylene terephthalate (PET) = 4, polyvinyl chloride (PVC) = 35, and polyamide (PA) = 47 [1,25]. The Polymer risk index (PRI) was categorized as follows: less than 10 was designated as risk level I, 10–100 as risk level II, 100–1000 as risk level III, and greater than 1000 as risk level IV [1,26].

2.7. Data Analysis

The data were analyzed using descriptive and inferential statistical methods with Minitab (version 16, developed by Minitab, LLC based in State College, Pennsylvania, USA) and Microsoft Excel 2019 (version 2019, Part of Microsoft Office 2019, developed by Microsoft Corporation in Redmond, Washington, USA). Results were expressed as mean ± standard deviation (SD) based on triplicate determinations. One-way analysis of variance (ANOVA) was employed to evaluate significant differences in microplastic abundance and heavy metal concentrations among the sampling locations. Where significant differences were observed, post hoc multiple comparison tests were performed to separate the means. Pearson correlation analysis was further conducted to determine the relationships between microplastic concentrations and heavy metal levels in the soil samples. Statistical significance was established at $p < 0.05$.

3. Results

3.1. Concentrations of Microplastics in Soil Samples Obtained around Labana Rice Mills

Microplastic concentrations in soil samples collected around the Labana Rice Mills exhibited clear spatial variation across the four sampling axes (Table 2). One-way analysis of variance (ANOVA) showed significant differences in microplastic concentrations among the sampling locations ($p < 0.05$). Post hoc mean separation indicated that the northern axis (1112 ± 41 items kg⁻¹) had significantly higher concentrations than the southern (879 ± 14 items kg⁻¹), western (753 ± 15 items kg⁻¹), eastern (626 ± 11 items kg⁻¹), and background locations (92 ± 4 items kg⁻¹). Each sampling axis differed significantly from one another, as indicated by different superscript letters (a–e). Compared with background contamination levels reported for Birnin Kebbi metropolis (92 ± 4 items kg⁻¹) [22], the values recorded in the current study were significantly higher, indicating pronounced anthropogenic enrichment within the study area. The relatively low standard deviation values across all sampling locations suggest limited intra-site variability and reflect good precision and consistency of the

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measurements. Overall, the distribution pattern reveals a distinct gradient of contamination, with microplastic abundance decreasing from the northern axis toward the eastern axis.

Table 2. Microplastics concentration in soil samples obtained from Labana Rice Mills.

Sampling Location	Concentration (Items kg^{-1})
North axis	1112 ± 41 [a]
South axis	879 ± 14 [b]
West axis	753 ± 15 [c]
East axis	626 ± 11 [d]
Birnin Kebbi Background level	92 ± 04 [e]

Note: Samples were presented as mean ± standard deviation (n = 15 for each axis). Means with different superscript letters (a–e) within the same column differ significantly at $p < 0.05$.

3.2. Comparison of Microplastic Concentrations in Labana Rice Mills with Those Reported in Other Countries

Table 3 compares the microplastic concentrations observed in soils around Labana Rice Mill, Birnin Kebbi, Nigeria, with concentrations reported from milling and rice-growing environments in other countries. The concentration recorded in the current study (626–1112 items kg^{-1}) falls within the range reported globally for agricultural and rice-associated environments. Similar concentrations were reported in agricultural soils from Kerala, India (400–1370 particles kg^{-1}) and in Bangladesh (660–1309 particles kg^{-1}). Higher concentrations were however documented in rice-growing soils from Xiangtan, China (776.33–1774.33 items kg^{-1}) and Gilan, Iran (400–1952.86 particles kg^{-1}), suggesting more severe contamination levels in these regions.

Compared with Japan and Thailand, notable differences were observed due to differences in measurement units and environmental matrices. Japanese paddy soils contaminated by fertilizer-derived microplastics showed lower concentrations in terms of particle abundance but were reported in mg kg^{-1}, making direct comparison difficult. Similarly, Thailand studies reported concentrations in surface water and sediments rather than agricultural soils, indicating methodological and environmental variations. Overall, the findings indicate that microplastic contamination around Labana Rice Mill is comparable to contamination levels reported in major rice-producing regions worldwide. The variations observed among countries may be attributed to differences in agricultural practices, waste management systems, irrigation sources, industrial activities, and analytical methods used for microplastic extraction and quantification.

Table 3. Comparison of microplastic concentrations in Labana Rice Mills with those reported in other countries.

Location/Country	Environment	Microplastic Conc.	Reference
Birnin Kebbi, Nigeria	Soil around Labana rice mill	626–1112 items kg^{-1}	Current study
Gilan, Iran	Soil around rice mill/rice field areas	400–1952.86 particles kg^{-1}	[27]
Bangladesh	Agricultural soils	660–1309 particles kg^{-1}	[1]
Kerala, India	Rice paddy field	400–1370 particles kg^{-1}	[28]
Xiangtan, China	Rice-growing agricultural soils	776.33–1774.33 items kg^{-1}	[29]
Japan	Paddy soils contaminated by fertilizer-derived microplastics	6–369 mg kg^{-1} (mean: 144 mg kg^{-1})	[30]
Thailand	Surface water/sediments	85.8 items L^{-1} (surface water), 0.43 items g^{-1} (sediments/soil)	[31]

3.3. Concentrations of Heavy Metals in Soil Samples Collected around Labana Rice Mills

The concentrations of heavy metals in the soil samples are presented in Table 4. One-way analysis of variance (ANOVA) revealed significant differences ($p < 0.05$) in Fe, Cu, and Zn concentrations among sampling locations. Post hoc comparison showed that the north axis consistently exhibited significantly higher concentrations than the other sampling axes. Iron (Fe) was the most abundant metal detected across all sampling locations, with concentrations ranging from 4.74 ± 0.20 mg kg^{-1} at the east axis to 13.90 ± 0.28 mg kg^{-1} at the north axis. Copper (Cu) and Zn were also detected at varying levels, following a similar spatial distribution pattern as the microplastics. The north axis exhibited the highest concentrations for both Cu (2.00 ± 0.12 mg kg^{-1}) and Zn (6.90 ± 0.30 mg kg^{-1}). Lead (Pb) was below the detection limit (BDL) in all sampled locations, indicating minimal or no contamination from this heavy metal within the study area. The consistent spatial pattern observed between microplastic concentrations and heavy metal levels suggests a possible association between microplastic accumulation and heavy metal retention in soils, potentially due to adsorption of metals onto microplastic surfaces.

3.4. Correlation between Microplastics and Heavy Metals

The correlation between microplastics and heavy metals in the soil samples is presented in Table 5. A significant positive relationship was observed between microplastic abundance and Fe ($R^2 = 0.72$, $p < 0.01$), Cu ($R^2 = 0.52$, $p < 0.01$), and Zn ($R^2 = 0.46$, $p < 0.01$). These relationships indicate spatial co-occurrence between microplastic abundance and Fe, Cu, and Zn concentrations; however, the correlation analysis alone does not establish direct sorption of metals onto microplastic surfaces or a causal relationship.

Table 4. Concentrations of heavy metals in soil samples obtained around Labana Rice Mill.

Sampling Location	Fe (mg kg⁻¹)	Cu (mg kg⁻¹)	Zn (mg kg⁻¹)	Pb (mg kg⁻¹)
North	13.90 ± 0.28 [a]	2.00 ± 0.12 [a]	6.90 ± 0.30 [a]	BDL
South	12.60 ± 0.31 [b]	1.60 ± 0.09 [b]	2.40 ± 0.10 [b]	BDL
West	10.60 ± 0.25 [c]	1.50 ± 0.07 [b]	2.10 ± 0.09 [b]	BDL
East	4.74 ± 0.20 [d]	0.90 ± 0.05 [c]	0.30 ± 0.02 [c]	BDL

Note: Values are mean ± standard deviation (n = 15 per axis). Means with different superscript letters (a–d) within the same column differ significantly at $p < 0.05$. BDL, below the method detection limit of 0.015 mg kg⁻¹ for Pb.

Table 5. Correlation between microplastics and heavy metals in the soil samples.

Heavy Metal	r	R^2	*p*
Fe	0.85	0.72	<0.01
Cu	0.72	0.52	<0.01
Zn	0.68	0.46	<0.01

Note: Pearson correlation analysis showing the relationship between microplastic abundance and heavy-metal concentrations. r denotes Pearson's correlation coefficient, and R^2 denotes its squared value. Statistical significance was considered at $p < 0.05$.

3.5. Characteristics of Microplastics Identified in the Soil Samples Obtained from Labana Rice Mills

The distribution of microplastic shapes in soil samples from the study locations is revealed in Figure 2. Four distinct microplastic shapes were identified: pellets, fragments, fibers, and foams. Among these, pellets were the most dominant in all locations, with the highest proportion recorded in the north axis (42%), followed by the south axis (31%), the west axis (18%), and the lowest in the east axis (10%). Fragments were recorded at 40% in the north axis, followed by the west axis (24%), the south axis (27%), and the lowest in the east axis (10%). Fibers were moderately distributed, with higher proportions observed in the north axis (38%), followed by the east axis (17%), the west axis (20%), and the south axis (25%). Foams were also observed, with 35% recorded in the north axis, followed by the south axis (29%), the west axis (22%), and the lowest in the east axis (14%). Figure 3 presents the photomicrographs of the identified microplastic shapes.

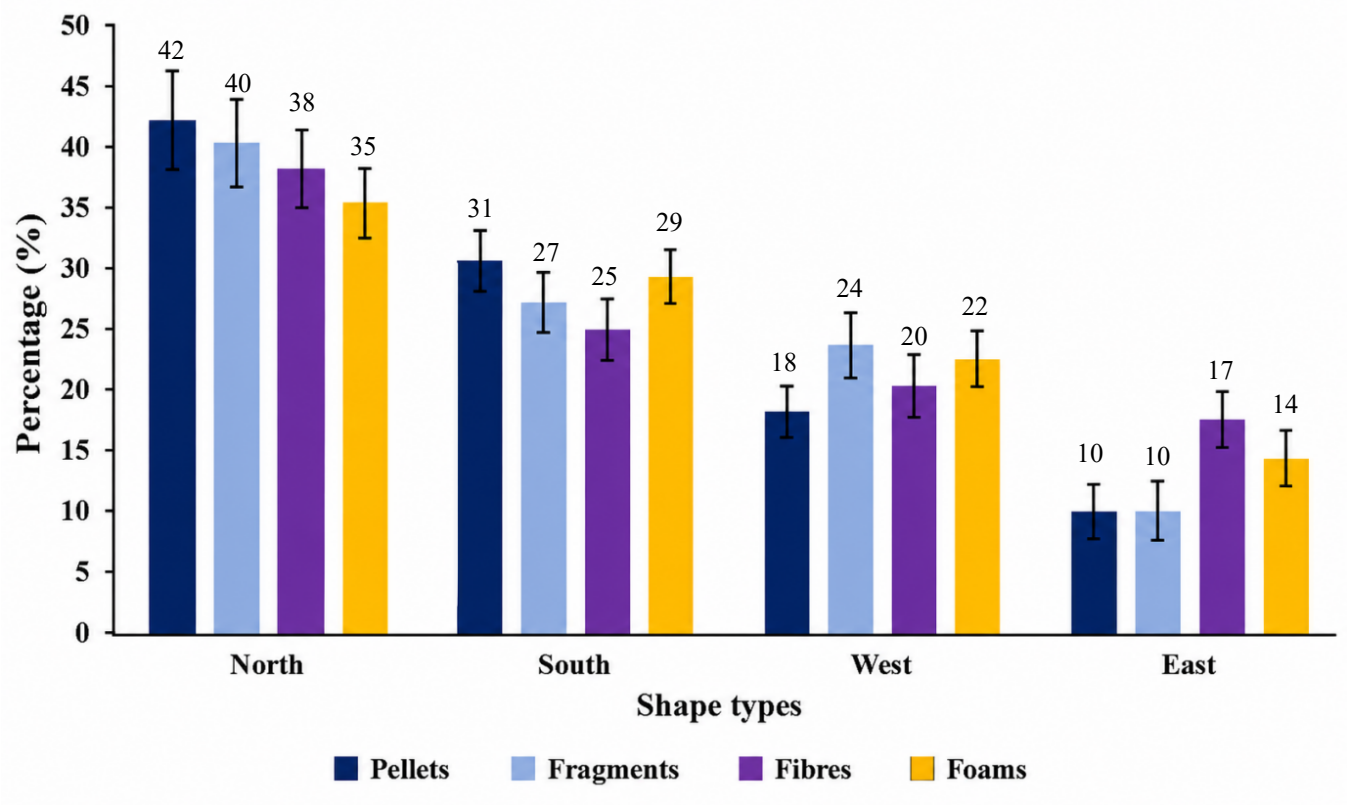


Figure 2. Distribution of microplastic shapes in soil samples collected from Labana Rice Mills. Note: Percentages may not sum to 100% due to rounding.

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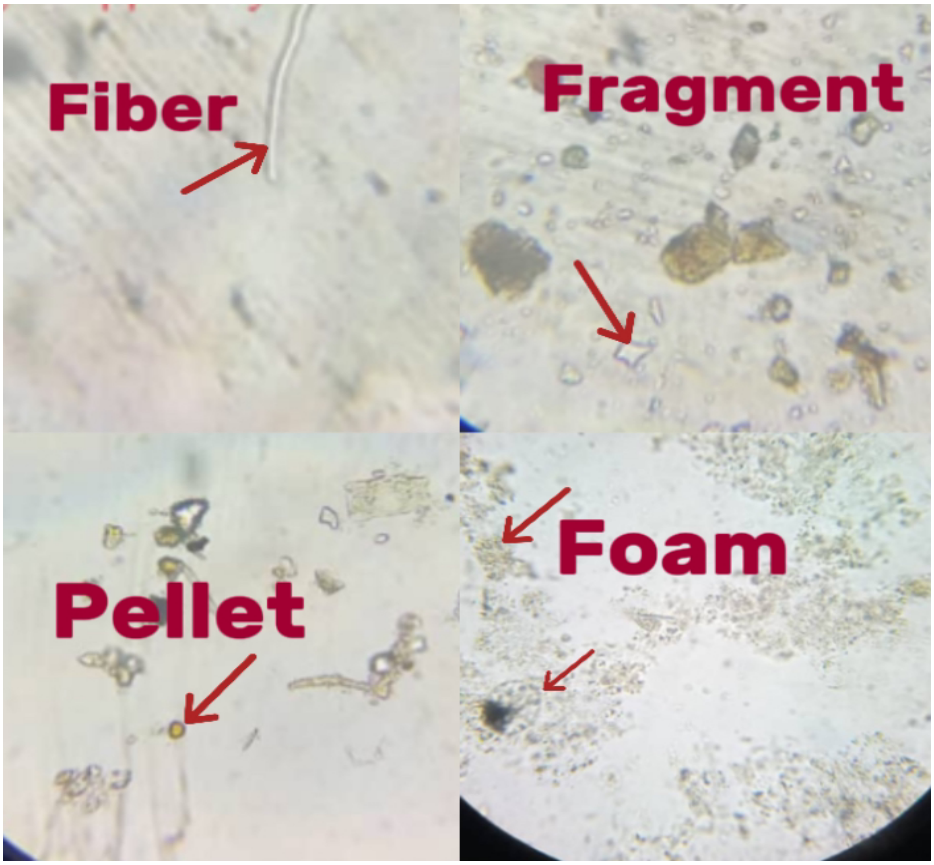


Figure 3. Photomicrographs of microplastic shapes identified in the soil samples collected from Labana Rice Mills.

Figure 4 presents the percentage distribution of microplastics sizes in the soil samples. In all the locations, the sizes of the majority of microplastics were 100–500 µm, followed by 0–100, 500–1000, and 1000–1500 µm, respectively.

The percentage distribution of microplastics colors in the soil samples is shown in Figure 5. Transparent/white was the dominant color, followed by black, blue, red, green, and other.

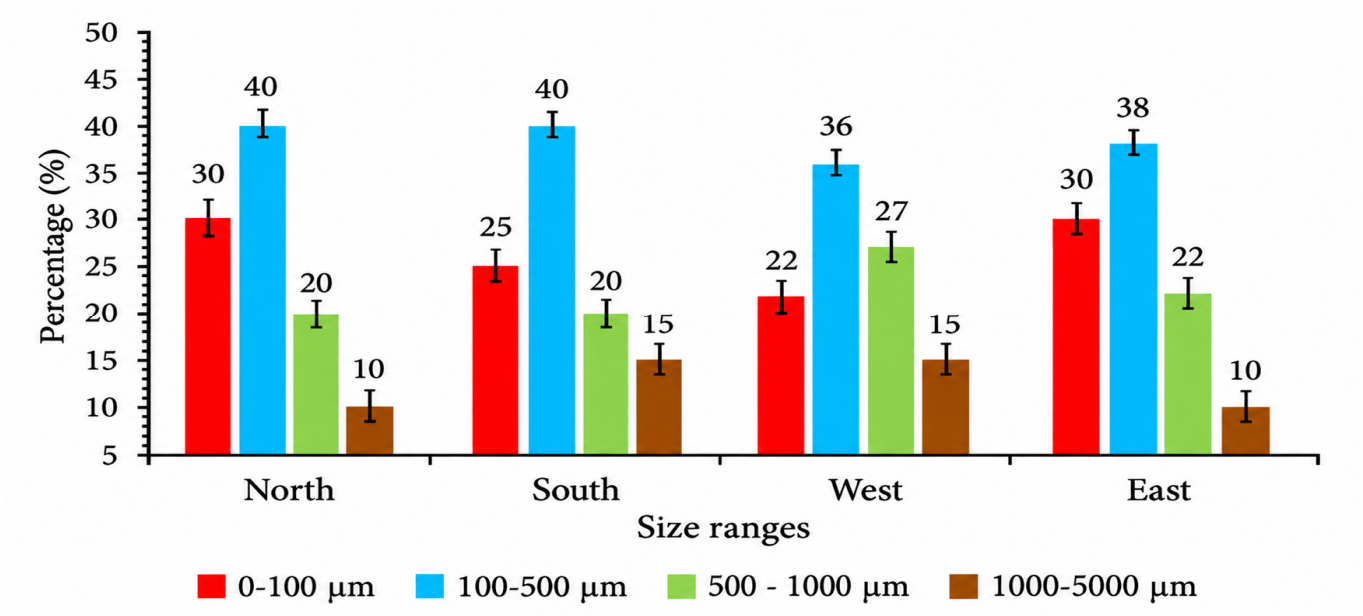


Figure 4. Distribution (%) of microplastic size in the soil samples.

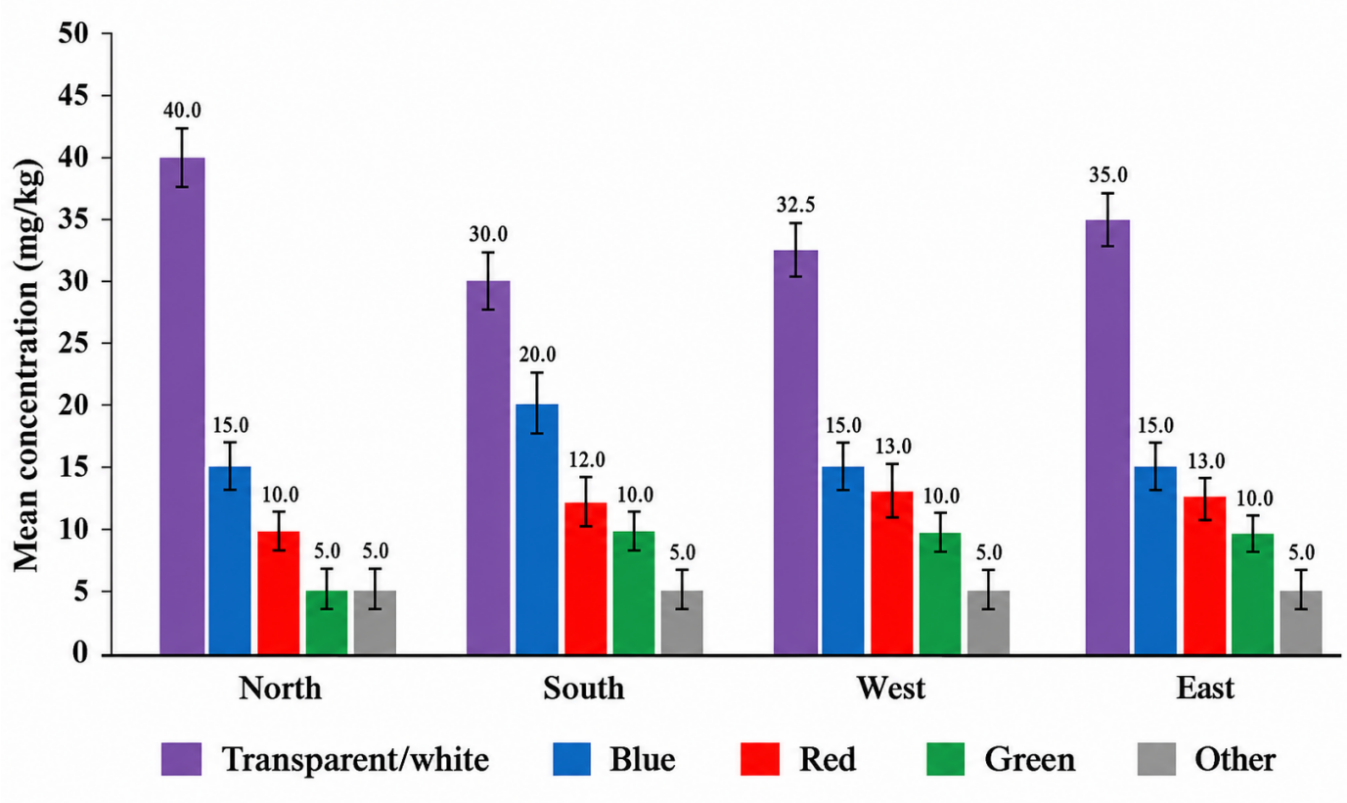


Figure 5. Distribution (%) of microplastic colors in the soil samples.

3.6. Microplastic Polymer Types Identified and Distribution in Soil Samples Collected from Labana Rice Mills

Table 6 and Figure 6 presents the absorbance peaks, associated functional groups, and polymer types identified in soil samples collected around Labana Rice Mills.

Polyethylene (PE) was identified by strong absorption peaks at 2921 and 2858 cm^{-1}, corresponding to asymmetric and symmetric C–H stretching vibrations of methylene (–CH_2–) groups. Additional bands at 1470 cm^{-1} (CH_2 bending) and 720 cm^{-1} (CH_2 rocking) further support its identification. Polyethylene was detected in soil samples from the north, south, west, and east locations.

Polypropylene (PP) was confirmed by characteristic absorption peaks around 2950 and 2835 cm^{-1}, attributed to asymmetric and symmetric C–H stretching vibrations of methyl (–CH_3) and methylene (–CH_2–) groups. The absorption peak near 1455 cm^{-1} corresponds to CH_3 asymmetric bending, while the band around 1375 cm^{-1} is due to symmetric bending of methyl groups. Weak skeletal vibrations in the range of 1167–998 cm^{-1} further support the identification of polypropylene. These spectral features confirm the presence of PP fragments in soil samples from all four locations (north, south, west, and east).

Polyvinyl chloride (PVC) was identified by absorption peaks around 2910–2960 cm^{-1}, corresponding to aliphatic C–H stretching vibrations. A prominent band near 1425 cm^{-1} is attributed to CH_2 bending vibrations. A key diagnostic feature of PVC is the strong absorption band in the 600–700 cm^{-1} region, corresponding to C–Cl stretching vibrations. This polymer was detected in soil samples from the north, south, and east locations.

Polyamide (PA), also known as nylon (NY), was confirmed by a broad absorption peak around 3300 cm^{-1}, corresponding to N–H stretching vibrations of amide groups. Peaks observed at 1630–1650 cm^{-1} are attributed to amide I (C=O stretching), while those at 1535–1550 cm^{-1} correspond to amide II (N–H bending coupled with C–N stretching). Additional bands at 1240–1300 cm^{-1} are assigned to C–N stretching vibrations. These characteristic absorptions confirm the presence of polyamide microplastic fragments in soil samples from the north, west, and east locations.

Polyethylene terephthalate (PET) was identified by a strong absorption peak in the range of 1715–1730 cm^{-1}, corresponding to ester carbonyl (C=O) stretching vibrations. Bands near 1240 cm^{-1} and 1090–1120 cm^{-1} are attributed to C–O stretching of the ester linkage. Aromatic ring vibrations observed between 1400 and 1500 cm^{-1} further confirm the presence of a benzene ring structure. The combination of ester carbonyl and aromatic ring absorptions is characteristic of PET, confirming its presence in soil samples from the south and west locations.

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Table 6. Microplastic polymer types detected in soil samples from the Labana Rice Mills.

Polymer Type [22]	Absorbance Peak (cm^{-1})	Functional Group	Locations Detected
PP	2950–2835, 1455, 1375, 1167–998	C-H stretching, CH_3 bending and C-C stretching	North, south, west, east
PE	2921, 2858, 1470, 720	Asymmetric and symmetric C-H stretching, CH_2 bending and rocking	North, south, west, East
PVC	2910–2960, 1425, 600–700	C-H stretching, CH_2 bending, C-Cl stretching	North, south, east
NY	3300, 1630–1650, 1535–1550, 1240–1300	N-H stretching, Amide I (C=O), Amide II (N-H bending/C-N stretching)	North, west, east
PET	1715–1730, 1240, 1090–1120, 1400–1500	Ester C=O stretching, C-O stretching, C-O-C stretching	South, west

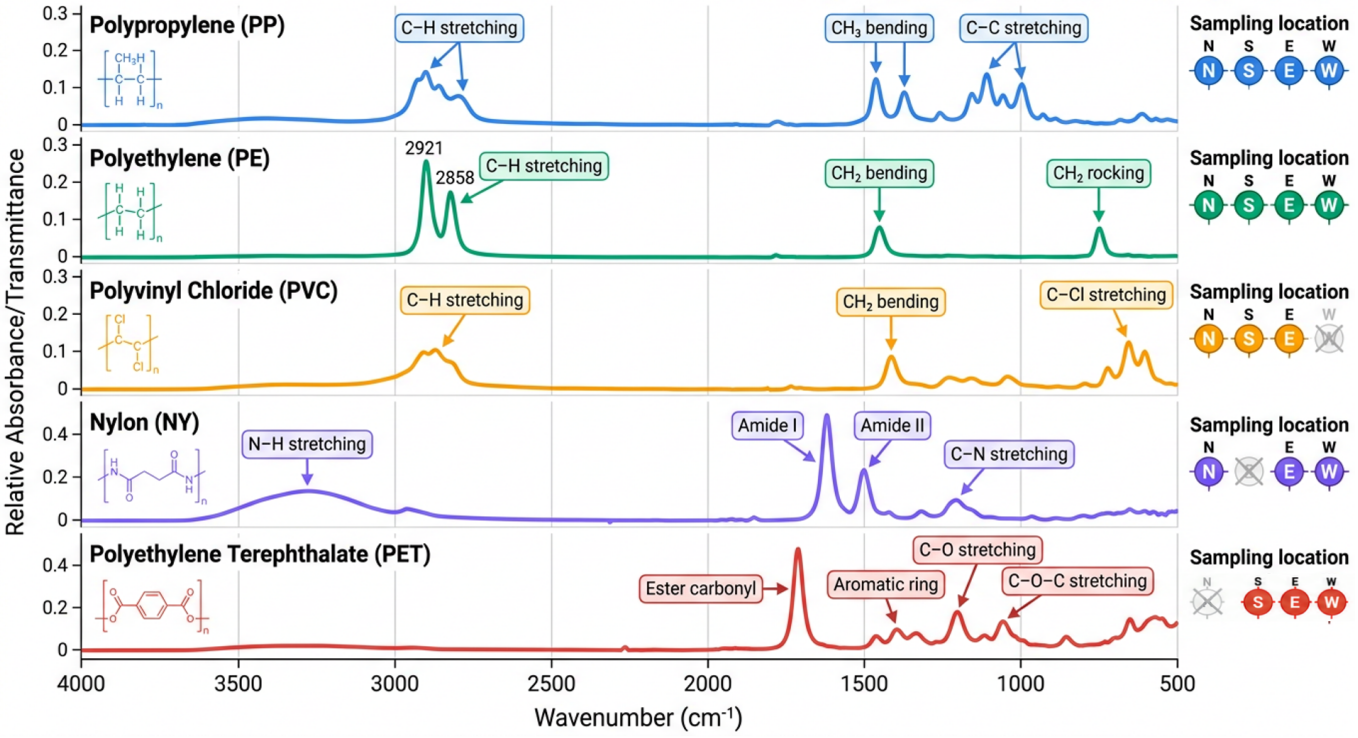


Figure 6. Representative ATR-FTIR spectra of microplastics from each sampling axis.

Figure 7 illustrates the percentage distributions of polymer types in the samples. Polyethylene emerges as the dominant polymer, accounting for 40% in the northern locations, 34% in eastern locations, 33% in western locations, and 32% in southern locations. This trend was followed by NY, with percentages of 32% in the eastern locations, 23% in southern locations, 23% in the western locations, and 20% in the northern locations. Polyvinyl chloride constitutes 23% in the southern locations, 20% in the northern locations, 15% in western locations, and 14% in the eastern locations. Polypropylene accounts for 17% in the western locations, 12% in the eastern locations, 10% in the northern locations, and 9% in the southern locations. Polyethylene terephthalate accounts for 14% in the southern locations, 12% in the western locations, 10% in the northern locations, and 8% in the eastern locations.

3.7. Potential Risks of Microplastics in the Soil Samples

Table 7 presents the contamination factor (CF) and pollution load index (PLI) of microplastics in soil samples across the study locations. All locations exhibit very high contamination category (CF ≥ 6). The northern axis exhibited the highest level of contamination (CF = 12.09), followed by the southern axis (CF = 9.55), the western axis (CF = 8.18) and the eastern axis (CF = 6.80).

The overall PLI value for microplastics was 8.95, which is greater than 1, indicating that the study area is heavily polluted with microplastics.

Table 7. Microplastic pollution levels of soil across locations.

Location	CF Value	Pollution Level
North	12.09	Very high
South	9.55	Very high
West	8.18	Very high
East	6.80 (PLI = 8.95)	Very high

Note: A PLI value > 1 indicates pollution, while PLI ≤ 1 indicates no pollution or baseline conditions. Abbreviations: CF = Contamination factor.

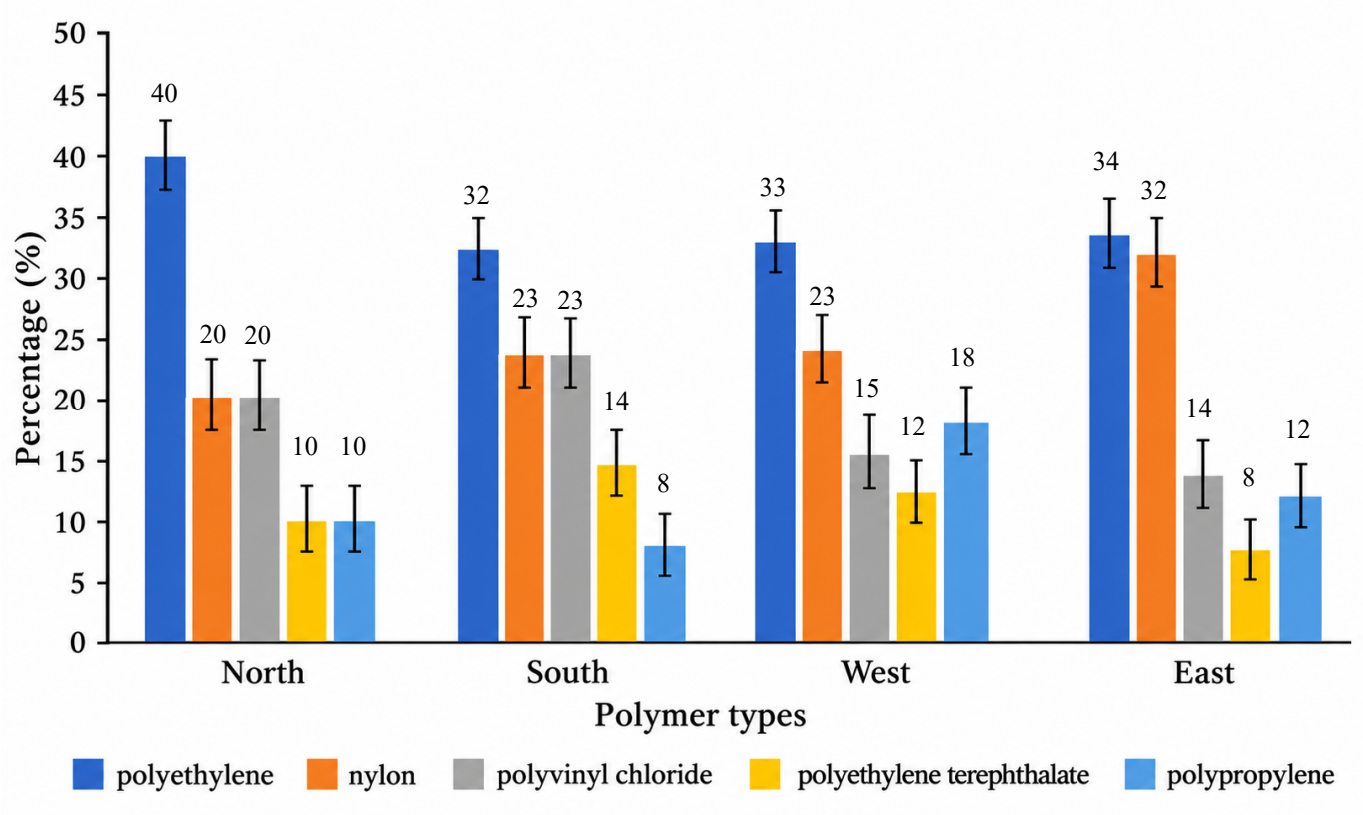


Figure 7. Distribution (%) of polymer types in the soil samples.

Table 8 presents the risk index of the microplastic polymers in the soil samples. Across all locations, PP exhibited a risk level II, PE, PVC, and PET exhibited a risk level III, and nylon (NY) demonstrated a risk level IV.

Table 8. Polymer risk index of microplastic in the soil samples.

Location	PP	PE	PET	PVC	NY
North	21.0	148.2	183.4	408.3	2014.4
South	17.1	123.7	706.5	850.1	1616.7
East	15.4	146.5	627.4	714.6	1939.1
West	25.5	154.0	372.1	906.3	1886.6
Risk level	II	III	III	III	IV

Note: II = low risk, III = moderate, IV = high; PRI values are dimensionless indices, so they are unitless. Abbreviations: (Polymer risk index)

4. Discussion

This study assessed the concentrations, characteristics, and associated risks of microplastics in soil samples collected around the Labana Rice Mills, Birnin Kebbi, Nigeria. Measurable levels of microplastics were detected, which were significantly higher than the background microplastic levels in environmental matrices in Birnin Kebbi, Nigeria. Such enrichment strongly suggests a localized, anthropogenic source of contamination. The elevated microplastic burden can reasonably be attributed to activities associated with the rice milling facility, including the extensive use of plastic materials in processing, packaging, storage, and transportation, as well as inadequate waste handling and disposal practices. These observations are consistent with growing global evidence identifying industrial and agro-processing facilities as important point sources of microplastic pollution. Previous studies [32–34] have similarly reported elevated microplastic concentrations in soils and surrounding environments impacted by industrial activities, attributing such contamination to continuous material handling, plastic usage, and inefficient waste management systems.

The overall microplastic concentrations observed in this study (626–1112 particles kg^{-1}) are similar to concentrations (660 to 1309 particles kg^{-1}) detected in agricultural soils in Bangladesh [1] and 400 to 1370 items kg^{-1} observed in agricultural soils in Kerala, India [28]. These show that terrestrial environments within agro-industrial zones can accumulate substantial levels of plastic pollutants. These concentrations are high enough to raise environmental concern, particularly given the persistence of microplastics. Once deposited in soil, microplastics can persist for decades, gradually fragmenting into smaller particles, including nanoplastics, which are more mobile and potentially more harmful [35]. This long-term persistence underscores the need for proactive mitigation efforts. The implications of these findings extend beyond general environmental contamination. Microplastics can alter soil structure, reduce water retention, and disrupt microbial processes essential for nutrient cycling [36]. When ingested or inhaled, microplastics can accumulate

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in various organs, induce inflammation and oxidative stress, and contribute to long-term health issues such as respiratory disorders, gastrointestinal disturbances, and organ damage [37]. In addition, microplastics in soil can enter groundwater through leaching and surface runoff, posing further risks to humans and ecological health [38].

Microplastic abundance was highest at the northern axis, likely because this area is closest to the core milling, packaging, and loading operations. Increased foot traffic, extensive use of plastic containers and packaging materials, and frequent movement of goods likely contribute to the elevated presence of microplastics in this zone. In addition, the study period (May–June) in Birnin Kebbi coincides with the onset of the rainy season, characterized by strong pre-monsoon winds, increased atmospheric turbulence, and episodic rainfall events. Prevailing southwesterly winds during this period may facilitate the transport and subsequent deposition of airborne microplastics toward the northern axis, while rainfall can enhance wet deposition and accumulation in nearby soils. These meteorological conditions likely contributed to the higher microplastic load observed in this area. The spatial distribution observed in this study aligns with patterns reported elsewhere, where microplastic concentrations decrease with increasing distance from the emission source [39,40]. This trend is further supported by the moderate levels recorded at the western site and the lower levels observed at the eastern site, which are farther from zones of intensive industrial activity.

The detection of pellets, fragments, fibers, and foams in the samples indicates a complex contamination profile originating from multiple sources. The dominance of pellets across nearly all sampling locations is particularly noteworthy. Pellet-shaped particles are generally classified as primary microplastics when they represent intentionally manufactured resin pellets or pre-production plastic feedstock, whereas fragments, fibers, and foams are commonly considered secondary microplastics when they arise from the fragmentation or degradation of larger plastic products [41]. In the context of a rice mill, these pellets may originate from resin-based packaging materials, sealing beads, industrial adhesives, or worn plastic components within milling machinery [42]. Their spherical or cylindrical shape and low density make them easily transported by wind and surface runoff, which may account for their high abundance [43,44]. Ecologically, the predominance of pellets can affect soil porosity and aeration [45]. Health concerns associated with exposure to plastic pellets include inflammation, oxidative stress, immune disruption, reproductive toxicity, metabolic disorders, and an increased risk of cancer and cardiovascular complications [46]. Fragments and fibers, although less abundant in this study, represent secondary microplastic particles formed through the degradation of larger plastic materials [47]. The rice milling environment typically involves extensive use of PP sacks, woven packaging bags, conveyor belts, nylon ropes, and synthetic fabrics used in workers' uniforms. Continuous friction, abrasion, exposure to sunlight, and mechanical stress contribute to the breakdown of these materials into fragments and fibers [48]. These microplastic types have been linked to reduced soil aggregation and disrupted root growth, raising concerns about potential impacts on agricultural productivity in nearby areas [49]. When inhaled or ingested, fragments and fibers can induce inflammation, oxidative stress, and cellular damage in the respiratory and gastrointestinal systems, potentially leading to asthma, chronic coughing, and other lung-related diseases [38]. Foam microplastics detected in the samples represent another form of secondary microplastics. In rice milling operations, they originate from the degradation and fragmentation of plastic packaging and other materials used during handling, storage, transportation, and processing [15]. Mechanical stress, frequent handling, and temperature fluctuations contribute to the breakdown of these materials into small foam particles. Foam microplastics can act as endocrine disruptors and have been associated with health risks, including certain cancers and developmental abnormalities [50]. Beyond direct health effects, foam microplastics alter soil physical and chemical properties and can be taken up by plants, raising further concerns about their transfer through the food chain and long-term implications for human health and ecosystem integrity.

The wide range of microplastic sizes detected (0–100, 100–500, 500–1000, and 1000–1500 μm) indicates multiple sources and transformation pathways within the study area. The dominance of the 100–500 μm fraction suggests ongoing fragmentation of larger plastic debris into secondary microplastics through mechanical abrasion, UV weathering, and thermal degradation associated with milling and open-environment exposure. In contrast, the presence of smaller particles (0–100 μm) points to more advanced degradation stages and/or direct input from primary microplastics, which are of particular concern due to their higher surface area, enhanced mobility, and greater potential for adsorption of toxic contaminants such as heavy metals and organic pollutants. Larger particles (500–1500 μm) likely represent recently introduced or less degraded plastic materials originating from packaging, storage sacks, and agricultural inputs used within and around the milling facility. The coexistence of these size fractions highlights continuous input alongside in situ fragmentation processes. Furthermore, smaller particles are more susceptible to wind-driven dispersion and water-mediated transport, especially during the onset of the rainy season, thereby influencing their spatial distribution and accumulation in soils. These observed size distributions are consistent with previous findings around industrial and agricultural environments. Similar size ranges were reported around a cement factory in

Sokoto, Nigeria [34], and in two major rivers in Birnin Kebbi [22], suggesting comparable sources and environmental processes. Likewise, Yustres et al. [14] reported varied microplastic sizes in rice-based farming systems, with particles <100 μm dominating in the Chicoral district of Espinal-Tolima, Colombia, while Ye et al. [29] documented a broad spectrum of microplastic sizes in agricultural soils in China.

The detection of microplastics in a range of colors, predominantly transparent/white, with smaller proportions of black, blue, red, and green, indicates diverse sources of contamination in the surrounding soils. Transparent/white microplastics are commonly associated with the degradation of low-density PE and PP materials widely used in agricultural handling, packaging, and processing activities [27]. Consistent with the present findings, Amirhosseini et al. [27] also reported a predominance of white-colored microplastics in environmental samples collected around a rice milling facility in Iran. The occurrence of black-colored particles may be linked to rice husk ash, a by-product generated from the combustion of rice husks as fuel during the parboiling process [51]. This material is often stored, transported, or disposed of under conditions that facilitate its dispersion into the surrounding environment. Meanwhile, the presence of blue, red, and green microplastics likely reflects mixed inputs from agricultural plastic residues, industrial packaging waste, and wastewater-related contamination pathways [52].

The diverse polymer types detected in the samples further reveal the multiple sources of microplastics within the rice milling facility. Polyethylene (PE), one of the most common polymers identified, is widely used throughout the rice production chain, from farming operations to processing and packaging, and can contribute significantly to microplastic contamination [53]. Polyethylene terephthalate (PET), a strong and durable thermoplastic, was also detected. PET contamination in rice mills typically originates from packaging materials, storage containers, and handling processes, rather than from the rice itself or the natural milling procedure [53]. Exposure to PE can cause skin and respiratory irritation, particularly when the material is heated and releases harmful gases; in some cases, chemicals that leach from PE may act as endocrine disruptors [54]. Similarly, PET poses environmental and human health risks. It can leach endocrine-disrupting compounds, contribute to organ toxicity, and release harmful gases when improperly burnt [55]. Additionally, PET waste degrades slowly, negatively affecting soil quality, water systems, and animal health.

The pollution load index (PLI) of microplastics exceeding the critical threshold value of 1 clearly indicates that the study area is experiencing significant contamination. A PLI > 1 is widely interpreted as evidence of deteriorating environmental quality, suggesting that microplastic accumulation has reached levels capable of exerting measurable ecological stress. This level of contamination raises concern not only for soil integrity but also for trophic transfer, as microplastics can be ingested by soil biota and subsequently enter the food chain, thereby posing indirect human health risks. Further strengthening this concern is the polymer risk index, which identified NY as presenting a very high risk. This elevated risk may be attributed to the physicochemical properties of NY, including its durability, resistance to degradation, and strong affinity for sorbing toxic contaminants. Such characteristics enhance its capacity to act as a vector for hazardous substances, including organic pollutants and heavy metals, thereby amplifying its ecological toxicity. Although other detected polymers exhibited low to moderate risk levels, their long environmental residence time and tendency for fragmentation into smaller particles increase their bioavailability and potential for bioaccumulation. Over time, these factors may result in a transition from moderate to high ecological risk, particularly under continuous input conditions. The positive associations observed between microplastic abundance and Fe, Cu, and Zn should be interpreted cautiously because correlation does not demonstrate direct adsorption or a causal relationship. In soils, interactions between microplastics and heavy metals are primarily governed by sorption and desorption processes and are influenced by polymer type, particle size, environmental aging, metal speciation, and soil physicochemical properties [56]. Weathering may increase surface roughness and specific surface area and alter oxygen-containing functional groups, thereby modifying the affinity of microplastic surfaces for metals. Soil pH, organic matter, competing ions, mineral coatings, and microbial biofilms may further enhance or suppress metal retention and release. Consequently, the spatial co-occurrence observed in the present study may reflect direct microplastic–metal interactions, common pollution sources, or a combination of both. Direct measurement of metals associated with isolated microplastic particles and controlled adsorption–desorption experiments would be required to establish the underlying mechanism and its implications for metal bioavailability. The findings of this study are consistent with previous reports. Sangilidurai et al. [28] documented similarly elevated ecological and polymer risk indices in agricultural soils in India, attributing the risks to continuous anthropogenic inputs and poor waste management practices. Likewise, Amirhosseini et al. [27] reported high ecological risks associated with microplastics originating from a rice milling facility in Iran, emphasizing the role of industrial activities as significant contributors to microplastic pollution. Collectively, these studies reinforce the growing evidence that microplastic contamination in terrestrial ecosystems

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is an emerging global concern, requiring urgent attention and the implementation of effective mitigation strategies.

Environmental aging may also influence the spectroscopic identification of microplastics. Weathering can induce oxidation, surface cracking, biofilm formation, and the attachment of soil organic and mineral matter, resulting in changes to surface functional groups and FTIR spectral characteristics. These alterations may weaken, shift, broaden, or overlap diagnostic absorption bands and thereby reduce the reliability of conventional library matching for heavily aged or contaminated particles [57]. Although polymer identification in the present study was supported by characteristic absorption bands together with a library-match threshold of ≥80%, environmentally aged particles may still produce altered spectra. This represents a source of analytical uncertainty, particularly because ATR-FTIR confirmation was performed on representative particles rather than on every microscopy-counted particle.

A limitation of the present study is that particle-spiking recovery efficiency was not experimentally determined. Although sequential NaCl and $ZnCl_2$ density separation was repeated to maximize particle recovery, incomplete extraction cannot be excluded; therefore, the reported microplastic abundances should be interpreted as recovered rather than recovery-corrected concentrations and may underestimate the actual levels in soil. Future studies should incorporate polymer- and size-specific recovery experiments to quantify extraction efficiency.

5. Conclusions

The findings of this study suggest that soils surrounding the Labana Rice Mills in Birnin Kebbi are impacted by microplastic contamination, with concentrations exceeding local background levels and indicating a strong anthropogenic origin. The findings demonstrate that agro-industrial activities, particularly those involving plastic use in processing, packaging, storage, and transportation, are important contributors to microplastic release into terrestrial environments. The observed concentrations, comparable to those reported in other agricultural systems globally, underscore the growing significance of soil as a sink for microplastics. The diversity in particle types, sizes, colors, and polymer compositions reflects multiple input pathways and ongoing fragmentation processes within the study area. The dominance of pellet-shaped particles, which may represent primary microplastics, alongside secondary forms such as fragments, fibers, and foams, suggests multiple potential input and fragmentation pathways within the study area. Spatial patterns further confirm that proximity to operational zones and prevailing environmental conditions, including wind and rainfall, play critical roles in the distribution and accumulation of microplastics in soils. Importantly, the persistence of microplastics and their potential to degrade into smaller, more bioavailable particles pose long-term ecological and human health concerns. Their ability to alter soil properties, disrupt microbial processes, and act as vectors for toxic substances such as heavy metals and organic pollutants amplifies their environmental risk. Moreover, the potential for transfer into groundwater and the food chain raises additional concerns regarding chronic exposure and associated health effects. Overall, the study highlights the urgent need for targeted mitigation strategies, including improved waste management practices, reduction in single-use plastics, adoption of alternative biodegradable materials, and stricter environmental regulations for agro-industrial facilities.

Author Contributions

Conceptualization: T.O.Y.; Data curation: A.M.S.; Formal analysis: J.D.B. and A.M.S.; Investigation: J.D.B. and A.I.; Methodology: T.O.Y., M.K.A., and J.D.B.; Project administration: A.M.S.; Resources: A.M.S.; Software: A.I. and M.K.A.; Supervision: T.O.Y.; Validation: Z.M.Y.; Visualization: J.D.B. and M.K.A.; Writing—original draft: T.O.Y.; Writing—review & editing: T.O.Y., Z.M.Y., H.A., and A.I. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

All data collected during this study are included in the published article.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, authors used CHATGPT in order to improve grammatical expression and fluency. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

1. Islam, A.; Hossain, B.; Hossain, M.E.; et al. Microplastics in agricultural soils: Evidence from an industrial suburb of Bangladesh. *J. Hazard. Mater. Adv*. **2025**, *20*, 100928. https://doi.org/10.1016/j.hazadv.2025.100928.
2. Auta, H.S.; Emenike, C.U.; Fauziah, S.H. Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. *Environ. Int.* **2017**, *102*, 165–176. https://doi.org/10.1016/j.envint.2017.02.013.
3. Sharma, S.; Chatterjee, S. Microplastic pollution, a threat to marine ecosystem and human health: A short review. *Environ. Sci. Pollut. Res.* **2017**, *24*, 21530–21547. https://doi.org/10.1007/s11356-017-9910-8.
4. Marrone, A.; La Russa, M.F.; Randazzo, L.; et al. Microplastics in the Center of Mediterranean: Comparison of the Two Calabrian Coasts and Distribution from Coastal Areas to the Open Sea. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10712. https://doi.org/10.3390/ijerph182010712.
5. Yahaya, T.O.; Salisu, T.F.; Musa, K.; et al. Microplastic Exposure Impairs Weight Gain, Reproduction, Blood Glucose Levels, and Organ Health in Rats (Rattus norvegicus). *J. Exp. Lab. Med.* **2025**, *2*, 44–55. https://doi.org/10.5455/jelm.20241203024659.
6. Ho, K.T.; Bjorkland, R.; Burgess, R.M. Comparing the definitions of microplastics based on size range: Scientific and policy implications. *Mar. Pollut. Bull.* **2024**, *207*, 116907. https://doi.org/10.1016/j.marpolbul.2024.116907.
7. Belmaker, I.; Anca, E.D.; Rubin, L.P.; et al. Adverse health effects of exposure to plastic, microplastics and their additives: Environmental, legal and policy implications for Israel. *Isr. J. Health Policy Res.* **2024**, *13*, 44. https://doi.org/10.1186/s13584-024-00628-6.
8. Ebong, B. Review on microplastic-polymer composite interactions: Assessing contaminant adsorption, structural integrity, and environmental impacts. *Commun. Phys. Sci.* **2025**, *12*, 770–777. https://doi.org/10.4314/cps.v12i3.8.
9. Govind, A.; Nishitha, K. Plastic and its Side Effects on Humans—A Review Article. *Asian Pac. J. Environ. Cancer* **2023**, *6*, 81–85. https://doi.org/10.31557/apjec.2023.6.1.81-85.
10. Zurub, R.E.; Cariaco, Y.; Wade, M.G.; et al. Microplastics exposure: Implications for human fertility, pregnancy and child health. *Front. Endocrinol.* **2024**, *14*, 1330396. https://doi.org/10.3389/fendo.2023.1330396.
11. Jeong, E.; Lee, J.Y.; Redwan, M. Animal exposure to microplastics and health effects: A review. *Emerg. Contam.* **2024**, *10*, 100369. https://doi.org/10.1016/j.emcon.2024.100369.
12. Mohidem, N.A.; Hashim, N.; Shamsudin, R.; et al. Rice for Food Security: Revisiting Its Production, Diversity, Rice Milling Process and Nutrient Content. *Agriculture* **2022**, *12*, 741. https://doi.org/10.3390/agriculture12060741.
13. Erhuen, E.; Okonkwo, H.N.; Nwaezeapu, A.O.; et al. The Impact of Rice Milling Activities on the Quality of Soil. *Int. J. Innov. Sci. Res. Technol.* **2024**, *9*, 2619–2626. https://doi.org/10.38124/ijisrt/ijisrt24jun1730.
14. Muñoz Yustres, J.L.; Zapata-Restrepo, L.M.; Garcia-Chaves, M.C.; et al. Microplastics in rice-based farming systems and their connection to plastic waste management in the Chicoral district of Espinal-Tolima. *Chemosphere* **2025**, *378*, 144423. https://doi.org/10.1016/j.chemosphere.2025.144423.
15. Amelba, B.T.; Daud, A.; Amqam, H.; et al. Microplastics found in rice consumed by humans. *J. Posit. Sch. Psychol.* **2022**, *6*, 7809–7818.
16. Yahaya, T.; Anyebe, D.A.; Adebayo, A.O.; et al. Characterization and toxicological evaluation of Labana Rice Mill wastewater in Kebbi State Nigeria. *Uniport J. Eng. Sci. Res.* **2019**, *4*, 34–42.
17. Yahaya, T.O.; Aliero, A.A.; Oladele, E.O.; et al. Concentration and Cytogenotoxicity of Heavy Metals and Microorganisms in Labana Rice Mills Wastewater Birnin Kebbi, Northwestern Nigeria. *Niger. Res. J. Eng. Environ. Sci.* **2021**, *6*, 216–225. https://doi.org/10.5281/zenodo.5048285.
18. Challa, M.; Dash, R.R.; Behera, M. A review on treatment of rice mill wastewater with emphasis on biological technologies. *Int. Biodeterior. Biodegrad.* **2024**, *195*, 105895. https://doi.org/10.1016/j.ibiod.2024.105895.
19. Seo, Y.; Chevali, V.; Lai, Y.; et al. Microplastics in soils: A comparative review on extraction, identification and quantification methods. *J. Environ. Manag.* **2025**, *377*, 124556. https://doi.org/10.1016/j.jenvman.2025.124556.
20. Tkachenko, Y.; Niedzielski, P. FTIR as a Method for Qualitative Assessment of Solid Samples in Geochemical Research: A Review. *Molecules* **2022**, *27*, 8846. https://doi.org/10.3390/molecules27248846.
21. Mohammed, S.A.; Agada, J.; Abdulazeez, A.M.; et al. Comparative study of inorganic pollutants in soils obtained from selected farmlands in Millennium City and Unguwan Kudu, Kaduna State, Nigeria. *IRASS J. Multidiscip. Stud.* **2024**, *1*, 65–71.
22. Yahaya, T.; Adewale, M.K.; Fagbayi, T.; et al. Concentration, characterization, and risk assessment of microplastics in two main rivers in Birnin Kebbi, Nigeria. *Environ. Health Eng. Manag.* **2024**, *11*, 315–325. https://doi.org/10.34172/ehem.2024.31.
23. Yahaya, T.; Umar, A.; Abubakar, M.; et al. Heavy Metals in the Soil Around a Cement Company in Sokoto, Northwestern Nigeria Pose Health Risks. *Ind. Domest. Waste Manag.* **2023**, *3*, 17–26. https://doi.org/10.53623/idwm.v3i1.183.
24. Wang, Y.; Zhu, Y.; Guo, G.; et al. A comprehensive risk assessment of microplastics in soil, water, and atmosphere: Implications for human health and environmental safety. *Ecotoxicol. Environ. Saf.* **2024**, *285*, 117154. https://doi.org/10.1016/j.ecoenv.2024.117154.
25. Lithner, D.; Larsson, Å.; Dave, G. Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. *Sci. Total Environ.* **2011**, *409*, 3309–3324. https://doi.org/10.1016/j.scitotenv.2011.04.038.
26. Xu, P.; Peng, G.; Su, L.; et al. Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China. *Mar. Pollut. Bull.* **2018**, *133*, 647–654. https://doi.org/10.1016/j.marpolbul.2018.06.020.

27. Amirhosseini, K.; Haghani, Z.; Alikhani, H.A. Microplastics pollution in rice fields: A case study of Pir Bazar rural district of Gilan, Iran. *Environ. Monit. Assess.* **2023**, *195*, 1473. https://doi.org/10.1007/s10661-023-12111-x.
28. Amaneesh, C.; Kim, H.S.; Ramanan, R. Plastics aplenty in paddy lands: Incidence of microplastics in Indian rice fields and ecotoxicity on paddy field phytoplankton. *Environ. Monit. Assess*. **2025**, *197*, 308. https://doi.org/10.1007/s10661-025-13737-9.
29. Ye, C.; Lin, J.; Li, Z.; et al. Characteristics of Microplastic Pollution in Agricultural Soils in Xiangtan, China. *Sustainability* **2024**, *16*, 7254. https://doi.org/10.3390/su16177254.
30. Katsumi, N.; Kusube, T.; Nagao, S.; et al. Accumulation of microcapsules derived from coated fertilizer in paddy fields. *Chemosphere* **2021**, *267*, 129185. https://doi.org/10.1016/j.chemosphere.2020.129185.
31. Khamboonruang, P.; Prommi, T.O. Using aquatic insects as indicators of microplastic pollution in rice field ecosystems. *Ecol. Montenegrina* **2024**, *80*, 106–127. https://doi.org/10.37828/em.2024.80.10.
32. Yarahmadi, A.; Heidari, S.; Sepahvand, P.; et al. Microplastics and environmental effects: Investigating the effects of microplastics on aquatic habitats and their impact on human health. *Front. Public Health* **2024**, *12*, 1411389. https://doi.org/10.3389/fpubh.2024.1411389.
33. Karakurt, O.; Altuntaş, O.; Şimşek, İ.; et al. Microplastics from industrial sources: A known but overlooked problem. *J. Water Process Eng.* **2025**, *72*, 107487. https://doi.org/10.1016/j.jwpe.2025.107487.
34. Yahaya, T.O.; Adamu, J.W.; Sifau, M.; et al. Microplastic pollution from cement production: Health risks in tomato fruits (*Solanum lycopersicum*) cultivated around the Sokoto cement plant. *J. Hazard. Mater. Plast.* **2026**, *3*, 100046. https://doi.org/10.1016/j.hazmp.2026.100046.
35. Kochanek, A.; Grąz, K.; Potok, H.; et al. Micro- and Nanoplastics in the Environment: Current State of Research, Sources of Origin, Health Risks, and Regulations—A Comprehensive Review. *Toxics* **2025**, *13*, 564. https://doi.org/10.3390/toxics13070564.
36. de Souza Machado, A.A.; Lau, C.W.; Kloas, W.; et al. Microplastics Can Change Soil Properties and Affect Plant Performance. *Environ. Sci. Technol.* **2019**, *53*, 6044–6052. https://doi.org/10.1021/acs.est.9b01339.
37. Huang, Y.; Shang, P.; Li, Y.; et al. Lung hazards of microplastics and their toxicological mechanisms. *Environ. Pollut.* **2025**, *385*, 127149. https://doi.org/10.1016/j.envpol.2025.127149.
38. Lee, Y.; Cho, J.; Sohn, J.; et al. Health Effects of Microplastic Exposures: Current Issues and Perspectives in South Korea. *Yonsei Med. J.* **2023**, *64*, 301–308. https://doi.org/10.3349/ymj.2023.0048.
39. Corradini, F.; Meza, P.; Eguiluz, R.; et al. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. *Sci. Total Environ.* **2019**, *671*, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368.
40. Yu, H.; Zhang, Z.; Zhang, Y.; et al. Metal type and aggregate microenvironment govern the response sequence of speciation transformation of different heavy metals to microplastics in soil. *Sci. Total Environ.* **2021**, *752*, 141956. https://doi.org/10.1016/j.scitotenv.2020.141956.
41. Jolaosho, T.L.; Rasaq, M.F.; Omotoye, E.V.; et al. Microplastics in freshwater and marine ecosystems: Occurrence, characterization, sources, distribution dynamics, fate, transport processes, potential mitigation strategies, and policy interventions. *Ecotoxicol. Environ. Saf.* **2025**, *294*, 118036. https://doi.org/10.1016/j.ecoenv.2025.118036.
42. Laftah, W.A.; Wan Abdul Rahman, W.A. Rice waste–based polymer composites for packaging applications: A review. *Polym. Polym. Compos.* **2021**, *29*, S1621–S1629. https://doi.org/10.1177/09673911211046775.
43. Boucher, C.; Morin, M.; Bendell, L.I. The influence of cosmetic microbeads on the sorptive behavior of cadmium and lead within intertidal sediments: A laboratory study. *Reg. Stud. Mar. Sci.* **2016**, *3*, 1–7. https://doi.org/10.1016/j.rsma.2015.11.009.
44. Boucher, J.; Friot, D. *Primary Microplastics in the Oceans: A Global Evaluation of Sources*; International Union for Conservation of Nature (IUCN): Gland, Switzerland, 2017. https://doi.org/10.2305/iucn.ch.2017.01.en.
45. Sarfraz, U.; Qian, Y.; Yu, Q.; et al. Microplastic effects on soil nitrogen storage, nitrogen emissions, and ammonia volatilization in relation to soil health and crop productivity: Mechanism and future consideration. *Front. Plant Sci.* **2025**, *16*, 1621542. https://doi.org/10.3389/fpls.2025.1621542.
46. Abbas, G.; Ahmed, U.; Ahmad, M.A. Impact of Microplastics on Human Health: Risks, Diseases, and Affected Body Systems. *Microplastics* **2025**, *4*, 23. https://doi.org/10.3390/microplastics4020023.
47. Bajt, O. From plastics to microplastics and organisms. *FEBS Open Bio* **2021**, *11*, 954–966. https://doi.org/10.1002/2211-5463.13120.
48. De Falco, F.; Di Pace, E.; Cocca, M.; et al. The contribution of washing processes of synthetic clothes to microplastic pollution. *Sci. Rep.* **2019**, *9*, 6633. https://doi.org/10.1038/s41598-019-43023-x.
49. Lozano, Y.M.; Lehnert, T.; Linck, L.T.; et al. Microplastic Shape, Polymer Type, and Concentration Affect Soil Properties and Plant Biomass. *Front. Plant Sci.* **2021**, *12*, 616645. https://doi.org/10.3389/fpls.2021.616645. Erratum in: *Front. Plant Sci.* **2021**, *12*, 714541. https://doi.org/10.3389/fpls.2021.714541.
50. Trestrail, C.; Walpitagama, M.; Hedges, C.; et al. Foaming at the mouth: Ingestion of floral foam microplastics by aquatic animals. *Sci. Total Environ.* **2020**, *705*, 135826. https://doi.org/10.1016/j.scitotenv.2019.135826.
51. Kumar Das, S.; Adediran, A.; Rodrigue Kaze, C.; et al. Production, characteristics, and utilization of rice husk ash in alkali activated materials: An overview of fresh and hardened state properties. *Constr. Build. Mater.* **2022**, *345*, 128341. https://doi.org/10.1016/j.conbuildmat.2022.128341.

52. Ferreira-Marques, I.; Silva, A.M.; Prata, J.C. Microplastics in rice: A systematic review. *RevSALUS* **2025**, *7*, 32. https://doi.org/10.51126/revsalus.v7isup.1027.
53. Bhavsar, P.S.; Solanki, M.B.; Shimada, Y.; et al. Microplastic contamination in Indian rice: A comprehensive characterization and health risk assessment. *J. Hazard. Mater.* **2024**, *480*, 136208. https://doi.org/10.1016/j.jhazmat.2024.136208.
54. Yao, Z.; Seong, H.J.; Jang, Y.S. Environmental toxicity and decomposition of polyethylene. *Ecotoxicol. Environ. Saf.* **2022**, *242*, 113933. https://doi.org/10.1016/j.ecoenv.2022.113933.
55. Dhaka, V.; Singh, S.; Anil, A.G.; et al. Occurrence, toxicity and remediation of polyethylene terephthalate plastics. A review. *Environ. Chem. Lett.* **2022**, *20*, 1777–1800. https://doi.org/10.1007/s10311-021-01384-8.
56. Liu, B.; Zhao, S.; Qiu, T.; et al. Interaction of microplastics with heavy metals in soil: Mechanisms, influencing factors and biological effects. *Sci. Total Environ.* **2024**, *918*, 170281. https://doi.org/10.1016/j.scitotenv.2024.170281.
57. Shi, Y.; Shi, L.; Huang, H.; et al. Analysis of aged microplastics: A review. *Environ. Chem. Lett.* **2024**, *22*, 1861–1888. https://doi.org/10.1007/s10311-024-01731-5.