Occurrence, sources, and relationships of soil microplastics with adsorbed heavy metals in the Ebinur Lake Basin, Northwest China postprint

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Abstract

Research on soil microplastics in arid oases remains limited despite rapid economic development in northwestern China. This study investigated the occurrence and sources of microplastics in soil, as well as their relationships with adsorbed heavy metals in the Ebinur Lake Basin, a typical arid oasis in China. Results showed that: (1) the average microplastic content in all soil samples was 36.15 ($±3.27)*mg/kg, withsite − specificcontentsrangingfrom*3.89(±1.64)*to*89.25(±$2.98) mg/kg. Overall, the proportions of various microplastic shapes decreased in the following order: film (54.25%) > fiber (18.56%) > particle (15.07%) > fragment (8.66%) > foam (3.46%). (2) Among all microplastic particles, white particles accounted for the largest proportion (52.93%), followed by green (24.15%), black (12.17%), transparent (7.16%), and yellow particles (3.59%). The proportions of microplastic particle size ranges across all soil samples decreased in the following order: 1000–2000 µm (40.88%) > 500–1000 µm (26.75%) > 2000–5000 µm (12.30%) > 100–500 µm (12.92%) > 0–100 µm (7.15%). FTIR (Fourier transform infrared) analyses identified polyethylene terephthalate (PET), polypropylene (PP), polycarbonate (PC), polyethylene (PE), and polystyrene (PS) in the studied soils. (3) Random forest predictions revealed that industrial and agricultural production activities and the discharge of domestic plastic waste were related to soil microplastic pollution, with agricultural plastic film being the most important factor contributing to soil pollution in the study area. (4) Seven heavy metals extracted from microplastics in soil samples showed significant positive correlations with soil pH, EC, total salt, N, P, and K contents (P<0.01), indicating that these soil factors significantly affect the heavy metal loads carried by soil microplastics. This research demonstrated that soil microplastic contents in the Ebinur Lake Basin are lower than those reported for other areas worldwide, and they

Full Text

Preamble

Occurrence, Sources, and Relationships of Soil Microplastics with Adsorbed Heavy Metals in the Ebinur Lake Basin, Northwest China

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Abstract: Research on soil microplastics in arid oases remains limited despite rapid economic development in northwestern China. This study investigated the occurrence and sources of microplastics in soil, as well as their relationships with adsorbed heavy metals in the Ebinur Lake Basin, a typical arid oasis in China. Results showed that: (1) the average microplastic content in all soil samples was 36.15 ($±3.27)mg/kg,withsite − specificcontentsrangingfrom3.89(±1.64)to89.25(±$2.98) mg/kg. Overall, the proportions of various microplastic shapes decreased in the following order: film (54.25%) > fiber (18.56%) > particle (15.07%) > fragment (8.66%) > foam (3.46%). (2) Among all microplastic particles, white particles accounted for the largest proportion (52.93%), followed by green (24.15%), black (12.17%), transparent (7.16%), and yellow particles (3.59%). The proportions of microplastic particle size ranges across all soil samples decreased in the following order: 1000–2000 µm (40.88%) > 500–1000 µm (26.75%) > 2000–5000 µm (12.30%) > 100–500 µm (12.92%) > 0–100 µm (7.15%). FTIR (Fourier transform infrared) analyses identified polyethylene terephthalate (PET), polypropylene (PP), polycarbonate (PC), polyethylene (PE), and polystyrene (PS) in the studied soils. (3) Random forest predictions revealed that industrial and agricultural production activities and the discharge of domestic plastic waste were related to soil microplastic pollution, with agricultural plastic film being the most important factor contributing to soil pollution in the study area. (4) Seven heavy metals extracted from microplastics in soil samples showed significant positive correlations with soil pH, EC, total salt, N, P, and K contents (P<0.01), indicating that these soil factors significantly affect the heavy metal loads carried by soil microplastics. This research demonstrated that soil microplastic contents in the Ebinur Lake Basin are lower than those reported for other areas worldwide, and they primarily originate from industrial and agricultural activities within the basin.

Keywords: occurrence characteristics; source analysis; soil microplastics; heavy metals; Ebinur Lake Basin

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1 Introduction

In 2018, global plastic production reached 360×10^{6} t, and the widespread use of plastic products generated enormous quantities of plastic waste. From 1950 to 2015, cumulative global plastic waste reached approximately 6.3×10^{9} t [?, ?, ?]. Although most plastics are durable and recyclable materials, only 6%–26% of plastic waste is recycled, with the majority ending up in landfills or being directly discarded into the environment [?, ?]. Under ultraviolet radiation, weathering, and biological activity, large plastic debris gradually decomposes into fragments, particles, or fibers smaller than 5 mm, known as microplastics [?]. As an emerging pollutant, microplastics have attracted increasing attention from scholars and the public in recent years [?, ?]. Due to their light weight, small particle size, large quantities, and resistance to degradation, microplastics are now found in rivers, lakes, oceans, and even in drinking water and salt [?, ?].

Microplastics exhibit diverse forms and complex chemical compositions. Common polymer types include polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyamide (PA), and polyester (PES) [?, ?, ?, ?]. Microplastics possess hydrophobic properties that facilitate the enrichment of microorganisms and pollutants on their surfaces. They can accumulate in organisms through ingestion, altering biological metabolism and inducing effects such as immune responses, neurotoxicity, genotoxicity, and inflammatory reactions [?, ?, ?]. Microplastics can also be transferred from low to high trophic levels through food webs, thereby affecting biodiversity, ecosystem services, and human health [?, ?, ?].

To date, microplastic pollution in aquatic ecosystems, particularly marine environments, has been extensively studied. Global research has primarily focused on oceans [?, ?, ?], polar glaciers [?], and continental coastlines [?]. Microplastics have even been detected in aquatic organisms far from human settlements, such as deep-sea corals [?]. Compared with marine studies, numerous reports on freshwater microplastics exist globally [?, ?, ?], with most research on rivers and lakes originating from Europe, followed by North America and Asia. For example, [?] analyzed microplastic contents in 36 lakeshore sediment samples from Italy, finding concentrations ranging from 268 to 3360 particles/kg. [?] evaluated microplastic concentrations in sediments of small and urban lakes in the UK for the first time, reporting maximum concentrations of 25–30 particles/100 g dry sediment, with fibers and films being the most common types. [?] studied microplastics in Vembanad Lake, India, finding sediment abundances ranging from 96 to 496 particles/m^{2}, with an average of 253 (±26) $particles/m^{2}$, and identified low-density polyethylene as the main polymer component.

Soil represents one of Earth's most valuable resources, providing critical ecosystem functions and services to humans and other organisms. It serves as the medium for plant growth, participates in biogeochemical cycles and carbon sequestration, and maintains soil biodiversity [?, ?, ?]. However, increasing human activities have led to soil erosion, heavy metal pollution, compaction, and salinization [?, ?]. As an emerging pollutant, microplastics also threaten soil health and may contribute to land degradation. Soil microplastic pollution has garnered significant attention in recent years [?, ?, ?]. It is estimated that the annual input of microplastics to soil environments is 4–23 times greater than that to marine environments. In Europe and North America, over 7$×10^{5}$ t of microplastics accumulate in soils annually, substantially exceeding the total weight of microplastics in global oceans and surface waters (93$×10^{{3}−236×10}{3}$ t) [?, ?]. Soil has thus become a major sink for microplastics. Given its central role in terrestrial ecosystems, studying the impacts of microplastics on terrestrial systems, particularly soil environments, is imperative. Current research primarily addresses: (1) sources and migration of soil plastics and their long-term storage characteristics; (2) effects of soil microorganisms on microplastics; and (3) impacts of plastic pollution on soil microbial communities, enzyme activities, soil fauna, crop production, and global terrestrial ecosystem function [?, ?, ?].

This study focused on the Ebinur Lake Basin, an oasis in Xinjiang, Northwest China experiencing rapid industrial and agricultural development. We investigated the occurrence characteristics, status, and sources of soil microplastics and their relationships with heavy metal pollutants. Our results provide a scientific basis and reference for preventing and controlling microplastic pollution in oasis soils of the Ebinur Lake Basin and other arid regions of Central Asia.

2 Materials and Methods

The Ebinur Lake Basin is located in northwestern Xinjiang Uygur Autonomous Region, China (43°38′N–45°52′N and 79°53′E–85°02′E), bordered by the Bortala Valley to the west, the Jinghe River alluvial fan to the south, and the Gobi Desert to the east (Fig. 1 [Figure 1: see original paper]; [?, ?]). The basin covers an area of 50,621 km^2, including 24,317 km^2 of mountainous area, 25,762 km^2 of plain area, and 542 km^2 of lake area. The region has a typical temperate arid continental climate. The basin contains 47 rivers with total surface runoff of 37.5$×10^{8}$ m^3/a. Total annual precipitation is 134.0$×10^{8}$ m^3/a, with mountainous areas receiving 75% of total precipitation (100.4$×10^{8}$ m^3/a) and plain areas receiving 33.6$×10^{8}$ m^3/a (25% of total). The vegetation comprises approximately 53 families, 191 genera, and 385 species, with dominant types including *Haloxylon ammodendron* (C. A. Mey.) Bunge, *Populus euphratica* Oliv., *Populus tomentosa* Carr., *Populus alopecuroides* L., *Ulmus pumila* L., *Achnatherum splendens* (Trin.) Nevski, and *Phragmites australis* (Cav.). Rapid industrial and agricultural development, urban construction, and transportation have increased heavy metals and other pollutants in basin soils, with microplastics now appearing [?].

2.1 Sampling and Laboratory Analyses

Sampling was conducted in June 2021, a period with minimal interference from wind-sand activities, agricultural operations, and precipitation. Soil samples were collected across the Ebinur Lake Basin using a grid method, establishing 120 sampling sites: 60 in farmland, 30 in woodland, and 30 in desert (Fig. 1 [Figure 1: see original paper]). The sampling grid was 1 km, and a five-point sampling method was employed. Surface soil (0–5 cm) was collected using a stainless-steel shovel, with three parallel samples taken at each point. After collection, large stones and branches were removed, and samples were stored in clean aluminum boxes, sealed with film, placed in self-sealing bags, transported to the laboratory, and stored at 4°C in darkness until analysis.

Microplastics were separated and extracted from soil using the density flotation method with saturated zinc chloride ($ZnCl_2$) solution [**?**, **?**]. The procedure was as follows: 300 g of each soil sample was transferred to a white porcelain tray and dried at 60°C in a vacuum oven. The dried soil was thoroughly mixed and passed through 5-mm and 2-mm stainless steel screens to remove large debris. The sieved soil was then mixed, and 200 g was divided into three equal portions. $ZnCl_2$ solution (=1.6 g/cm^3) was pre-filtered through a mixed cellulose ester membrane (47 mm diameter, 0.45 µm pore size). Then, 50 g of sieved soil (n=3) was placed in a 500-mL glass beaker with 150 mL $ZnCl_2$ solution, stirred continuously on an electrothermal constant-temperature magnetic stirrer for 30 min, followed by 12 h of sedimentation. After solid-liquid separation, the supernatant was vacuum-filtered through a nitrocellulose membrane (Whatman AE 98, 47 mm diameter, 0.45 µm pore size). The filter walls were rinsed repeatedly with deionized water, and the rinse solution was also filtered. The filter membrane containing microplastics was transferred to a 60-mm glass Petri dish using stainless steel tweezers for storage and digestion to remove residual organic matter.

Microplastics were manually picked using toothless stainless steel tweezers and anatomical needles under a stereomicroscope (Olympus SZ61, Olympus Corporation, Tokyo, Japan). Selected potential microplastic particles were placed on a Whatman membrane, marked, and classified by color and morphology, with data recorded in a spreadsheet. A single-layer photograph of each sample was taken, and particle size was measured as the maximum diameter. Polymer composition was identified using a Fourier transform micro-infrared spectrometer (Perkin Elmer Spotlight 400, Perkin Elmer GmbH, Waltham, USA) to characterize functional groups of particles sized 0–5000 µm. Spectra were compared with a standard spectral library, and samples with matching degrees $ $60% were identified as microplastics.

Soil analyses followed the methods described in “Soil Agrochemical Analysis” by [**?**]. Soil physicochemical properties were determined as follows: moisture content by the drying method, pH by the glass electrode method, and electrical conductivity (EC) by electrode (HQ1130, HACH Co., Ltd., Colorado, USA). Total salt content was determined gravimetrically, potassium content by ammonium acetate ($NH_4CH_3CO_2$) extraction flame spectrophotometry, phosphorus content by sodium bicarbonate extraction molybdenum-antimony anti-colorimetry, and nitrogen content by alkali hydrolysis diffusion method [?]. Heavy metals (Cu, Ni, Cd, Pb, Cr, Mn, and Co) in microplastics were analyzed by placing 1 g of microplastic particles in a centrifuge tube, adding 1 mL of 2% HNO_3, and using ultrasonic-assisted digestion. After digestion, heavy metal concentrations were determined by inductively coupled plasma mass spectrometry (ICP-MS, Jena analytical instruments Co., Ltd., Germany). Blank tests were performed alongside soil metal calibrations using Chinese Standard Materials. To verify accuracy, 15% of samples were measured in duplicate, yielding measurement precision of 93.56%–97.98%. Prior to analysis, glassware was soaked in 5% HNO_3 for 24 h, rinsed with ultrapure water, and dried. All reagents were analytical grade and used without further purification, with all solutions prepared using Milli-Q water.

2.2 Single-Factor Pollution Index

The single-factor pollution index is widely used to evaluate the concentration characteristics of pollutants such as heavy metals and organic contaminants in soil [?, ?]. The formula is:

$$P_i = \frac{C_i}{S_i}$$

where P_i is the environmental quality index for pollutant i in soil, C_i is the measured concentration of pollutants (n/kg), and S_i is the evaluation standard for pollutants (n/kg). In this study, we used the average microplastic concentration in the Ebinur Lake Basin as the evaluation standard. P_i values of 0.0–0.7 indicate no pollution, 0.7–1.0 indicate slight pollution, and >1.0 indicate pollution [?].

2.3 Random Forest Regression Analysis

Random forest is a classifier ensemble algorithm based on decision trees, proposed by [?]. It employs bootstrap resampling to randomly select multiple samples from the original dataset to generate new sample sets, then constructs decision trees to form a random forest. For regression analysis, the model uses the average value of N CART decision trees trained via weighted mean as the final prediction result [?, ?]. Compared with other algorithms, random forest offers several advantages: (1) no data preprocessing requirements, no restrictions on data type or distribution, and strong robustness to noise and outliers; (2) parallel decision tree generation without pruning; and (3) high prediction accuracy with prevention of data overfitting [?]. The stochastic forest model is flexible and interpretable, and has been widely applied across many fields in recent years due to these excellent properties.

We used the random forest package in R software to build regression models. The mean square standard error %IncMSE was used to evaluate the influence of each predictive variable on microplastic abundance in farmland. Model parameters (mtry, nTree, and nodesize) were set before analysis. Mtry represents the number of sample predictors at each split node [**?**], typically using one-third of predictor variables for regression analysis. NTree represents the number of trees grown, and nodesize represents the minimum number of decision tree nodes. Default values were adopted, resulting in final parameters of: mtry=4, nTree=500, and nodesize=5. The final model evaluation is represented by %IncMSE, where larger values indicate higher correlation between predicted and dependent variables.

This study considered various factors directly related to microplastic occurrence in soil, including economic development level, industrial and domestic sources, population, agricultural plastic use, and soil physicochemical properties. Twelve predictive variables were selected: gross domestic product (GDP), industrial GDP, population, agricultural plastic film use, domestic sewage discharge, industrial sewage discharge, chemical oxygen demand of industrial wastewater, cotton sowing area, and proportions of sand, silt, and clay. Soil particle sizes were measured using a soil particle size analyzer, while other data were obtained from the Bole Municipal Bureau of Statistics, Jinghe County Bureau of Statistics, Bortala Mongolian Autonomous Prefecture Bureau of Statistics, and Xinjiang Statistical Yearbook [**?**].

2.4 Data Analysis

Soil microplastic abundance was expressed as n/kg and content as mg/kg. Data visualization was performed using Origin v.9.0 (OriginLab Corporation, Northampton, MA, USA). SPSS v.22.0 (SPSS Inc., Chicago, IL, USA) was used to test for significant differences in microplastic abundance across sampling areas using one-way analysis of variance (ANOVA), with significance level set at $P<0.05$.

3 Results

3.1 Distribution and Pollution Degree of Microplastics in Soil

Using appropriate analytical methods, we classified microplastics into five morphological types: film, fragment, fiber, foam, and particle (Fig. 2 [Figure 2: see original paper]). Overall, the proportions of microplastic shapes decreased in the following order: film (54.25%) > fiber (18.56%) > particle (15.07%) > fragment (8.66%) > foam (3.46%). Five colors of soil microplastics were identified: white, black, green, transparent, and yellow. White particles dominated (52.93%), followed by green (24.15%), black (12.17%), transparent (7.16%), and yellow (3.59%; Fig. 3 [Figure 3: see original paper]). Films were predominantly white (41.32%), most fibers were white (58.86%), while most particles (36.21%) and fragments (37.45%) were green. Yellow microplastics accounted for the largest proportion of foam (27.90%). Microplastics in farmland (54.61%) and woodland (39.41%) were mainly white, whereas desert sites had predominantly black microplastics (25.31%).

Microplastic particle sizes were divided into five classes: 0–100, 100–500, 500–1000, 1000–2000, and 2000–5000 µm. As shown in Figure 4 [Figure 4: see original paper], the proportions of size classes across 120 soil samples decreased in the following order: 1000–2000 µm (40.88%) > 500–1000 µm (26.75%) > 2000–5000 µm (12.30%) > 100–500 µm (12.92%) > 0–100 µm (7.15%). The dominant size fractions for each shape were 1000–2000 µm for film (39.41%), fiber (45.32%), particles (33.21%), fragments (58.32%), and foam (35.21%). The dominant size classes in farmland, woodland, and desert were 2000–5000 µm (29.58%), 1000–2000 µm (50.16%), and 1000–2000 µm (36.32%), respectively.

Analysis of 120 soil samples revealed an average microplastic content of 36.15 ($±3.27)mg/kg, withsite−specificcontentsrangingfrom3.89(±1.64)to89.25(±2.98)mg/kg(Table1).Thehighes specificcontentswere : film18.62(±2.34)mg/kg, fiber15.16(±1.29)mg/kg, particle34.45(±2.45)mg/kg, fragm mg/kg. One-way ANOVA showed significant differences in microplastic distribution among shapes and among the three land use types (Table 1).

The single-factor pollution index indicated that 76.50% of farmland samples, 55.47% of woodland samples, and 34.25% of desert samples were polluted (P_i>1.0). Thus, pollution degree among land use types decreased in the order: farmland > woodland > desert. Morphological characteristics of microplastics varied among sampling sites. For example, sites B-1 and B-11 contained only fiber and film, while sites B-25 and B-26 had all five shapes, and sites B-57–59 contained mainly fiber, fragments, and particles. Thin film and fibrous microplastics were detected at all sites, accounting for 15.23%–72.41% of total microplastics.

3.2 Composition of Soil Microplastics

Microplastic contents at sampling sites near towns in the Ebinur Lake Basin were significantly higher than in other areas, with downwind southern sites showing higher contents than upwind northern settlements. Microplastic contents in dustfall near estuaries such as Bole City and Jinghe County were significantly higher than at other sites, while woodland and desert sites had the lowest contents. These results suggest that soil microplastics near cities and towns primarily originated from urban discharge of plastic pollutants, while atmospheric dust microplastics near farmland mainly came from weathering, debris, and near-ground deposition of chemical fertilizer and pesticide packaging materials and agricultural plastic film residues.

Infrared spectroscopy analysis identified five polymer types among soil microplastics. The first type was polyethylene terephthalate (PET; Fig. 5a [Figure 5: see original paper] and b), characterized by a typical C=O functional group at 1700 cm^{-1}, C–O at 1500 cm^{-1}, and p-disubstituted benzene at 800–860 cm^{-1} (Fig. 5a [Figure 5: see original paper]). The second type was

PP, with a typical C=C functional group at 1630 cm^{-1}, $-CH_3$ at 1570 cm^{-1}, and $R\text{-}CH{=}CH_2$ at 900–1000 cm^{-1} (Fig. 5b [Figure 5: see original paper]). The third type was PC, characterized by monosubstituted benzene functional groups at 690–710 and 750–770 cm^{-1}, p-disubstituted benzene at 800–860 cm^{-1}, =C–H and O-H at >3000 cm^{-1}, and C=O at 1700 cm^{-1} (Fig. 5c [Figure 5: see original paper]). The fourth type was PE, with a typical C=C functional group at 1550 cm^{-1} and C-O at 1000 cm^{-1} (Fig. 5d [Figure 5: see original paper]). The fifth type was PS, characterized by a typical C=C functional group at 1670 cm^{-1} and monosubstituted benzene at 690–710 and 750–770 cm^{-1} (Fig. 5e [Figure 5: see original paper]).

3.3 Source Identification of Soil Microplastics

Multiple factors affect microplastic occurrence in soil. This study applied random forest regression modeling to analyze the entire Ebinur Lake Basin and rank the importance of potential influencing factors. Results showed that soil microplastic contents were closely related to agricultural plastic film use, total industrial output, and population (Fig. 6 [Figure 6: see original paper]). Farmland is the dominant land use type in the basin, and most sampling sites were located in farmland. Therefore, agricultural activities were the most important factor affecting soil microplastics in this area, followed by industrial activities and domestic emissions. The importance ranking of random forest variables thus indicated, to some extent, the sources of soil microplastics. Activities such as industrial and agricultural production and domestic plastic waste discharge were related to soil microplastic pollution, with agricultural plastic film use being the most significant contributor.

The main components of film microplastics in the Ebinur Lake Basin soils were PE and PP. We speculate that broken waterproof film layers from daily life plastic products (e.g., food packaging bags) and woven bags for industrial and agricultural production represent the primary sources of film microplastics. Fragment microplastics consisted mainly of PP and PE, likely originating from broken fragments of large-scale industrial packaging materials or woven plastic bags, as evidenced by their regular edges. In the Ebinur Lake Basin, decomposition of woven bags used for chemical fertilizer and cement likely constitutes the main source. Foam and granular microplastics consisted primarily of PS, with lamellar and columnar shapes and white/colorless appearance. Fiber microplastics were mainly PET, predominantly black and yellow, likely originating from sewage discharge after fabric washing in clothing and textile industries near urban areas. Additionally, fishing gear, atmospheric deposition, and surface runoff represent potential sources of plastic fibers. During sampling, fragments of foam, packaging bags, chemical bags, plastic bottles, and food packaging paper were observed in towns, farmland, and woodland, indicating that microplastic pollutants in the Ebinur Lake Basin mainly originate from industrial and agricultural production and domestic sources.

4 Discussion

4.1 Soil Microplastic Pollution in the Ebinur Lake Basin

Compared with previous studies (Table 2), the microplastic content in our study soils was relatively low, indicating good soil environmental condition. Microplastic abundances were much lower than those reported for industrial land in Australia [?], cultivated land in Iran [?], cultivated land in Chile [?], and green space in the United States [?] and Mexico [?]. Soil microplastic contents in the Ebinur Lake Basin were also lower than those in cultivated land and tidal flats in Chinese provinces including Yunnan [?], Zhejiang [?], Heilongjiang [?], Shaanxi [?], Hubei [?], Shandong [?], Hebei [?], and Guangxi Zhuang Autonomous Region [?]. However, microplastic contents were higher than those in Mexican green space and cultivated land in Shanghai [?, ?].

Our study showed that the main microplastic components in the Ebinur Lake Basin were PE, PVC, and PS, consistent with other studies [?, ?]. We found diverse microplastic types including fiber, film, foam, and particles. While fiber-based microplastics often dominate soil samples, this study found that film microplastics accounted for a higher proportion than fibers in the Ebinur Lake Basin, possibly because debris with lower specific surface area migrates more easily into soil [?]. Granular, foam, and debris microplastics accounted for the smallest proportions (3.46%–15.07%), which aligns with [?], who reported that debris accounted for a large proportion of microplastics in agricultural soil. This may be because granular microplastics mainly derive from hard plastic decomposition, which requires extended time periods. Color distribution characteristics of microplastics vary widely due to diverse sources and human activity interference. Colored microplastics in domestic sewage (e.g., from laundry) discharged from residential areas and sewage treatment plants can be ingested by soil organisms, damaging their health [?].

This study provides a preliminary analysis of the spatial distribution of different microplastic types in Ebinur Lake Basin soils. Numerous farms near Bole City and Jinghe County showed the highest proportions of film microplastics. We therefore speculate that the high microplastic abundance at these sites primarily results from fragmentation and decomposition of agricultural plastic film and domestic plastic waste. Additionally, the Bortala River estuary has low current velocity, and sediments deposited near sampled river bends may carry microplastic particles, resulting in relatively high abundances. Although plastic processing plants and sewage treatment plants are located near Bole City and Jinghe County, high population density and the predominance of film and fiber microplastics (accounting for 50% of total microplastics) at these sites suggest that clothing particles from washing and discarded plastic garbage bags are the main sources. Differences in soil microplastic contents near Bole City and Jinghe County, which were often higher than at other sites, may be attributed to dense populations and waste accumulation near towns, as well as contributions from sewage treatment and plastic processing plants.

4.2 Relationships Between Soil Microplastics and Adsorbed Metals

We analyzed heavy metal contents adsorbed by collected soil microplastics and examined correlations among microplastic abundance, content, color, carried heavy metals, and soil physicochemical properties to assess metal mobility and influencing factors. Microplastic abundance and content showed no significant correlation with soil pH, EC, or total salt content (Table 3). However, significant negative correlations were found with soil moisture and precipitation ($P<0.01$), with correlation coefficients of 0.85 between microplastic abundance and soil moisture, 0.45 between abundance and precipitation, 0.42 between content and soil moisture, and 0.35 between content and precipitation. This indicates that high soil moisture or rainfall scouring causes microplastic migration, with increased soil moisture leading to microplastic export and reduced abundance [**?**]. Microplastic color showed no significant correlation with pH, EC, total salt content, nitrogen, phosphorus, potassium, or precipitation, suggesting these soil variables do not affect microplastic color.

Soil microplastic abundance and content were significantly correlated with N, P, and K contents, with correlation coefficients of 0.56 between abundance and N, 0.69 between abundance and P, 0.65 between abundance and K, 0.52 between content and N, 0.51 between content and P, and 0.54 between content and K ($P<0.01$). This indicates that microplastic contents vary significantly with agricultural fertilization activities. The seven heavy metals extracted from microplastics showed significant positive correlations with soil pH, EC, total salt, and N, P, and K contents ($P<0.01$), indicating these soil variables significantly affect heavy metal loads carried by microplastics. This suggests that heavy metals on microplastic surfaces mainly originate from soil fertilization and are influenced by pH, EC, and soil N, P, K, and total salt contents. Previous studies have shown that heavy metal contents and speciation in soil are significantly related to these factors [**?**]. The seven heavy metals were significantly negatively correlated with soil moisture and precipitation, with correlation coefficients of 0.31 for Cu, 0.29 for Ni, 0.33 for Cd, 0.26 for Pb, 0.19 for Cr, 0.42 for Mn, and 0.33 for Co ($P<0.01$).

The lack of standardized methods for studying soil microplastics makes soil safety assessment difficult. Therefore, establishing standard methods for collecting, separating, and analyzing various microplastic types in soil samples is necessary [**?**]. Accurate, simple, and efficient analytical technologies will be essential for in-depth understanding of soil microplastic pollution [**?**, **?**]. Currently, cultivated land is the most studied land use type regarding soil microplastic pollution, and existing data are insufficient for comprehensive analysis of soil microplastic pollution in China or worldwide [**?**]. Previous studies often treated microplastics as simple polymers, but microplastics may contain numerous chemical additives (e.g., plasticizers, flame retardants) [**?**]. Most research has been conducted under laboratory conditions with high microplastic concentrations, creating discrepancies with natural environmental concentrations. Therefore, future research should explore whether and how microplastic pollution affects soil fauna, microorganisms, and plants under in situ conditions, which is essential for deeply understanding the environmental effects of microplastics [?, ?].

5 Conclusions

Random forest prediction confirmed that microplastic contents were closely related to agricultural plastic film use, total industrial output, and population. Industrial and agricultural production activities and domestic plastic waste discharge were related to soil microplastic pollution, with agricultural plastic film use being the most important factor for soil pollution in this area. Compared with previous studies, microplastic content in the Ebinur Lake Basin was relatively low, and soil conditions were generally good. Future research should focus on analyzing pollution degrees of microplastics in different land use types and exploring microplastic sources to help managers develop effective measures for controlling soil microplastic pollution.

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Note: Figure translations are in progress. See original paper for figures.