Occurrence, sources, and impact mechanisms of soil microplastics and adsorbed heavy metals in the Ebinur Lake Basin, northwest China

Zhang Zhaoyong (baiyangdian313@163.com)
Xinjiang University
Guo Jieyi
Xinjiang University
Wang Pengwei
Xinjiang University

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Abstract

There is a lack of research on soil microplastics in arid oases considering the rapid economic development of northwest China and Central Asia. Here, we studied the occurrence forms, pollution status, and sources of microplastics in soils, as well as the relationship between microplastics and adsorbed heavy metals in the Ebinur Lake Basin, a typical oasis in an arid area. Results showed that (1) the average microplastic content in all soil samples was 36.15 ± 3.27 mg/kg. The contents of microplastics at different sampling points ranged between 3.89 ± 1.64 and 89.25 ± 2.98 mg/kg. Overall, the proportions of various microplastic shapes diminished in the 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 diminished in the 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 analyses showed that PET, PP, PC, PE, and PS occurred in the studied soils. (3) Random forest predictions showed that industrial and agricultural production activities and the discharge of domestic plastic waste were related to soil microplastic pollution. Agricultural plastic film was the most important factor in soil pollution in the study area. (4) Seven heavy metals extracted from microplastics in soil samples showed significant positive correlations with soil pH, EC, and total salt, N, P, and K contents ($p < 0.01$), indicating that these soil factors could significantly affect the contents of heavy metals carried by microplastics.

1. Introduction

In 2018, the total global plastic production reached 360 million tons, and the wide use of plastic products is accompanied by the generation of large amounts of plastic waste. From 1950 to 2015, the world's plastic waste amounted to about 6.3 billion tons (Chae & An, 2018; Bradney et al., 2019; Ju et al., 2021). Although most plastics are durable and recyclable materials, only 6–26% of plastic waste is recycled. Most of the rest ends up in landfills or is directly discarded into the environment (de Souza Machado et al., 2018; Windsor et al., 2019). Under ultraviolet radiation, weathering, and biological activities, large pieces of plastic garbage are gradually decomposed to form plastic fragments, particles, or fibers with particle sizes lower than 5 mm, i.e., microplastics (Qi et al., 2018; Jebe, 2020).

As an emerging pollutant, microplastics have attracted the attention of scholars and the general public in recent years (Browne et al., 2011; Cole et al., 2013). Due to their light weight, small particle size, large quantity, and difficult degradation, microplastics are found in rivers, lakes, oceans, and even in drinking water and salt (Yan et al., 2019; Malankowska et al., 2021). Microplastics can exhibit diverse forms and complex chemical compositions. At present, common chemical types of microplastics include polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyamide (PA), and polyester (PES) (Free et al., 2014; Oni et al., 2020; Qi et al., 2020; Zhang et al., 2020). Microplastics have a certain hydrophobicity, which can cause the enrichment of microorganisms and pollutants on their surface. They can also accumulate in microorganisms through feeding, change the biological metabolism of organisms, and produce biological effects such as immune responses, neurotoxicity, genotoxicity, and inflammatory reactions (Eerkes-Medrano et al., 2015; Xiong et al., 2019; Hernández-Sánchez et al., 2021). They can be transferred from low to high trophic levels in food webs, thus affecting biodiversity, ecosystem services, and human health (Yang et al., 2015; Shen et al., 2020; Wong et al., 2020).

To date, the microplastic pollution of aquatic ecosystems, especially marine environments, has been widely studied. Global research on microplastic has mainly focused on the oceans (Costa and Barretta, 2015; Kooi et al., 2016; Taylor et al., 2016), polar glaciers (Obbard et al., 2014), and coastlines of continents (Browne, 2015). Microplastics have been found even in aquatic organisms far away from human settlements, such as deep-sea corals (Woodall et al., 2014). Compared with ocean studies, there are many reports on freshwater microplastics globally (Zhang et al., 2018; Xiong et al., 2018; Lahive et al., 2019; Zhang et al., 2020). Among those, most studies on microplastics in rivers and lakes are from Europe, followed by North America and Asia. For example, Fischer et al. (2016) analyzed the contents of microplastics in 36 lakeshore sediment samples from Italy and found contents ranging from 268 to 3360 particles/kg. Vaughan et al. (2017) evaluated the concentration of microplastics in the sediments of small lakes and urban lakes in the UK for the first time. Maximum concentration reached 25–30 particles per 100 grams of dry sediments, and fibers and films were the most common microplastic types. Sruthy & Ramasamy (2017) studied microplastics in Vembanad Lake in India. The abundance of microplastics in sediments ranged from 96 to 496 particles/m^2, with an average abundance of 252.80 ± 25.76 particles/m^2. Low-density polyethylene was the main polymer component of microplastics.

Soil is one of the most valuable resources on earth and provides a series of important ecosystem functions and services to humans and other organisms. It provides the medium for plant growth, participates in biogeochemical cycles and carbon sequestration, and maintains soil biodiversity (Hü-Tsch et al., 2002; Waldrop et al., 2010; Mohanty et al., 2013). Due to increasing human activities, the soil suffers from erosion, heavy metal pollution, compaction, and salinization (Arias-Estévez et al., 2008; Rosowiecka & Nawrocki, 2010). As an emerging pollutant, microplastics also threaten soil health and may lead to land degradation. The pollution of soil with microplastics has attracted much attention in recent years (Andrady, 2011; Obbarb et al., 2014; Law & Thompson, 2014). It is estimated that the total amount of microplastics entering the soil environment every year is about 4–23 times that of the marine environment. In Europe and North America, more than 700,000 t of microplastics accumulate in the soil every year, which greatly exceeds the total weight of microplastics in the global ocean and surface water (93,000–236,000 t) (Andrady, 2017; Zhang et al., 2020). Soil has become a huge microplastic sink and considering its core role in terrestrial ecosystems, it is imperative to study the impact of microplastics on terrestrial systems, especially the soil environment. At present, the main contents of researches include (i) the sources and migration of soil plastics and the basic characteristics of long-term storage in soil, (ii) the impacts of soil microorganisms on plastics, and (III) the impacts of plastic pollution on the soil microbial community and enzyme activity, soil animals, crop production, and global terrestrial ecosystem function (He et al., 2018; Scheurer & Bigalke, 2018; Ju et al., 2021).

Here, we studied the Ebinur Lake basin, an oasis in Xinjiang with rapid industrial and agricultural development, and investigated occurrence characteristics, the pollution status, occurrence relationships, and sources of microplastics in the soil and heavy metal pollutants. Our results may provide a scientific basis and reference for preventing and controlling microplastic pollutants in oasis soils in the Ebinur Lake Basin and other arid areas in Central Asia.

2. Materials And Methods

The geographical location of the Ebinur Lake Basin is between 43°38" and 45°52" N and 79°53" and 85°02" E. The Ebinur Lake Basin includes Bole City, Wenquan County, and Jinghe County in the Bortala Mongolian Autonomous Prefecture, the south of Wusu and Tori County in the Tacheng area, Kuitun city in the Ili Kazak Autonomous Prefecture, and the Dushanzi District of Karamay City (Abuduwaili et al., 2015). This basin covers an area of 50,621 km^2, including 24,317 km^2 of mountain area, 25,762 km^2 of plain area, and 542 km^2 of lake area. It has a typical temperate dry and early continental climate. There are 47 rivers in the basin, and its total surface runoff is $37.46 \cdot 10^8$ m^3/a. The total precipitation of the basin is $134.0 \cdot 10^8$ m^3/a, and mountainous areas account for 75% of the total precipitation ($100.4 \cdot 10^8$ m^3/a). The total precipitation in plain areas is $33.6 \cdot 10^8$ m^3/a, accounting for 25% of the total precipitation. The basin lies in the distribution zone of dry early desert soil, brown desert soil, and gray desert soil. There are about 53 families, 191 genera, and 385 species of plants. The main vegetation types include the *Haloxylon ammodendron* formation, *Populus euphratica* formation, *Populus tomentosa* group, *Populus alopecuroides* group, *elm* group, *Achnatherum splendens* group, and reed group. With the rapid development of industry and agriculture, urban construction, and transportation in recent years, heavy metals and other pollutants have increased in the soils and sediments of the basin and microplastics have appeared (Zhaoyong et al., 2018).

2.1 Sampling and laboratory analyses

The grid method was used to collect soil samples across the Ebinur Lake Basin. A total of 120 soil sampling points were established, including 60 farmland, 30 forest land, and 30 desert sampling points (Figure. 1). The sampling grid was 1 km, and a five-point sampling method was used for sampling. The collection steps were as follows: first, a stainless-steel sampling shovel was used to collect surface soil (0–5 cm). A total of 3 parallel samples were taken at each sampling point. After collecting soil samples, large stones and tree branches were removed. Samples were then stored in clean aluminum boxes, sealed with sealing film, placed into self-sealing bags, transported to the laboratory, and stored at 4 °C in the dark until analysis.

The density flotation method with saturated zinc chloride ($ZnCl_2$) solution was used to separate and extract soil microplastics (Wang et al., 2016; Kang et al., 2020). The steps were as follows: 300 g of each soil sample was transferred to a white porcelain tray and dried at 60 °C in a vacuum drying oven. The dried soil was evenly mixed and passed through 5- and 2-mm stainless steel screens to remove large stones and branches retained on the two screens. The sieved soil sample was then evenly mixed, and 200 g was divided into three equal parts. Before the experiment, $ZnCl_2$ solution (ρ = 1.6 g/cm^3) was filtered through a mixed cellulose ester membrane with a diameter of 47 mm and a pore diameter of 0.45 μm. Then, 50 g of the sieved soil sample (n = 3) was weighed into a 500 ml glass beaker, and 150 ml $ZnCl_2$ solution was added. This slurry was continuously stirred on an electrothermal constant temperature magnetic stirrer for 30 min, followed by a 12-hour sedimentation step. After solid-liquid stratification, the supernatant was filtered through a vacuum suction filter. The filter was a nitrocellulose membrane (Whatman AE 98) with a diameter of 47 mm and a pore diameter of 0.45 μm.

The inner wall of the filter was rinsed repeatedly with deionized water, and the flushing solution was also filtered. The filter membrane containing microplastics was transferred into a 60 mm glass Petri dish with stainless steel tweezers for storage and digestion to remove the residual organic matter of the sample for subsequent observation, selection, and treatment. Microplastics were picked with toothless stainless-steel tweezers and anatomical needles under a stereomicroscope (Olympus SZ61). Then, we placed the selected potential microplastic particles on a Whatman WME membrane and marked it. Samples were classified according to their color and morphological characteristics and recorded in a spreadsheet. A single layer picture of the sample was taken, and the size of potential microplastic particles was measured as the maximum diameter. A Fourier micro infrared spectrometer (Perkin Elmer spotlight 400) was used to identify the polymer composition and characterize the functional groups of particles with a particle size of 0–5000 μm. Then the spectrum was compared with the standard spectrum library. Samples corresponding to the spectrum with a matching degree of 60% or more were considered microplastic, and their composition was determined.

Soil analyses followed "The method of soil agrochemical analysis" by Lu et al. (2002). Soil physical and chemical variables were determined as follows: Moisture content was determined with the drying method. pH with the glass electrode method, and electric conductance (EC) with an electrode (HJ 802–2016). The total salt content was determined with a gravimetric method, potassium content with ammonium acetate ($NH_4CH_3CO_2$) extraction flame spectrophotometry, and phosphorus content with sodium bicarbonate extraction molybdenum antimony anti-colorimetry. The potassium content was determined with the nitrogen alkali hydrolysis diffusion method (Lu et al., 2002). The heavy metals Cu, Ni, Cd, Pb, Cr, Mn, and CO in microplastics were analyzed as follows: First, we weighed 1 g of microplastic particles into a centrifugal tube, then added 1 ml 2% HNO_3, and used an ultrasonic instrument for auxiliary digestion. After digestion, the contents of the seven heavy metals were determined by inductively coupled plasma mass spectrometry (ICP-MS). During analyses, the blank tests were performed as with soils metals of Standard Material of China (GSS). To verify the accuracy of these measurements, 15% of the soil samples were measured in duplicate. The accuracy or precision of the measurements was determined to be 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 of analytical grade and were used without further purification. All solutions were prepared with Milli-Q water.

Figure 1. Research area and soil samples in the Ebinur lake basin.

2.2 Random forest regression analysis

Random forest is a classifier integration algorithm based on decision trees proposed by Breiman (2001). Several samples are randomly selected from the original sample set by bootstrap resampling to generate different new sample sets. Then, the decision tree is constructed based on the new sample sets to form the decision forest. For regression analysis, the model takes the average value of N cart decision trees trained according to the weighted mean as the final prediction result (Li et al., 2013; Sihag et al., 2015). Compared with other algorithms, the advantages of the random forest model are: (1) No preprocessing of data, no requirements regarding data type and distribution, and strong robustness to noise and outliers, (2) the decision tree can be generated in parallel without pruning, and (3) the prediction result has high precision and prevents the phenomenon of data overfitting (Antipov & Pokryshevskaya, 2012). The stochastic forest model is flexible and easy to understand. Its many excellent properties make it an analysis tool widely used in many fields in recent years.

Here, we used the random forest tool package in the R software to build random forest regression models. The mean square standard error %IncMSE was used to evaluate the influence of each prediction variable on the abundance of microplastics in farmland soils. The model's parameters mtry, nTree, and nodesize were set before analysis. Mtry represents the number of sample predictors at each split node (Zhang et al., 2021). Generally, one-third of the number of predictor variables is used for regression analysis. NTree represents the number of growth trees and nodesize the minimum number of decision tree nodes. Default values were adopted in the model. Therefore, the final parameters were set as: mtry = 4, nTree = 500, and nodesize = 5. The final result of the model evaluation is represented by the %IncMSE. The larger the %IncMSE, the higher the correlation between the predicted and the dependent variable.

This study considered various factors directly related to the occurrence of microplastics in soil, such as the level of economic development, industrial and living sources, population, agricultural use of plastics, and soil physical and chemical properties. Twelve predictive variables were selected: gross domestic product (GDP), industrial GDP, population, agricultural use of plastic film, domestic sewage discharge, industrial sewage discharge, chemical oxygen demand of industrial wastewater, cotton sowing area, and the proportions of sand, silt, and clay. Soil particle sizes were measured with a soil particle size analyzer. Other data were obtained from Bole City, Jinghe County, the Bortala Mongolian Autonomous Prefecture, and the Xinjiang Statistical Yearbook (SBXAR, 2020).

2.3 Data processing

The abundance of microplastics was expressed as $n \cdot kg^{-1}$ and the content as $mg \cdot kg^{-1}$. The data were plotted using the software Origin 9.0. IBM SPSS 22.0 was used to test the significance of differences in the abundance of microplastics in the sampling area (One-way ANOVA), and a significance level of $\alpha = 0.05$ was adopted.

3. Results

3.1 Distribution characteristics of microplastics in soils of the Ebinur lake basin

Using relevant analytical methods (Browne et al., 2011; Eriksen et al., 2013), we divided the detected microplastics into the five shape types film, fragment, fiber, foam, and particle (Figure. 2). Overall, the proportion of microplastics shapes diminished in the order: film (54.25%) > fiber (18.56%) > particle (15.07%) > fragment (8.66%) > foam (3.46%). Further, five colors of soil microplastics were found: white, black, green, transparent, and yellow. Among all microplastic particles, white accounted for the largest proportion (52.93%), followed by green (24.15%), black (12.17%), transparent (7.16%), and yellow (3.59%; Fig. 3). The film was white (41.32%), and most fibers were also white (58.86%). Most particles (36.21%) and fragments (37.45%) were green. Yellow (27.9%) accounted for the largest proportion of foam. Microplastics in farmland (54.61%) and forest soil (39.41%) were mainly white. Desert had mainly black microplastics (25.31%).

According to the literature (Free et al., 2014), particle sizes of microplastics were divided into five classes: 0–100, 100–500, 500–1000, 1000–2000, and 2000–5000 μm. As shown in Fig. 4, the proportion of microplastic size classes in the 120 soil samples decreased in the 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 largest proportions of particle sizes of film, fiber, particles, fragments, and foam were 1000–2000 μm (39.41%), 1000–2000 μm (45.32%), 1000–2000 μm (33.21%), 1000–2000 μm (58.32%), and 1000–2000 μm (35.21%), respectively. The particle size classes with the largest proportions in farmland, woodland, and desert soil were 2000–5000 (29.58%), 1000–2000 (50.16%), and 1000–2000 μm (36.32%), respectively.

In this study, microplastic pollutants were analyzed in 120 soil samples, and an average content of 36.15 ± 3.27 mg/kg was found. The contents of microplastics across sampling points ranged between 3.89 ± 1.64 and 89.25 ± 2.98 mg/kg (Table 1). The point with the highest content of microplastics was located in farmland soil near the Bortala estuary, followed by Bole City. The average content of microplastics in farmland soil was 45.13 ± 2.3 mg/kg, followed by forest soil (34.17 ± 3.21 mg/kg), and finally, desert soil (29.15 ± 1.89 mg/kg). The film content was 18.62 ± 2.34 mg/kg, the fiber content 15.16 ± 1.29 g/kg, the particle content 34.45 ± 2.45 mg/kg, the fragment content 20.16 ± 2.54 mg/kg, and the foaming content 30.15 ± 3.21 g/kg. One-way ANOVA showed significant differences in the distribution of microplastics among species, and there were also significant differences among the three land-use types (Table 1).

Table 1
Statistical characteristics of soil microplastics in the Ebinur Lake Basin.

Microplastic and land use types	Sample number	Abundance (n/m^2)	Average (mg/kg)	Range (mg/kg)	Median (mg/kg)	Proportion (%)
Fiber	120	21.51 ± 2.14[a]	15.16 ± 1.29[a]	0.86–68.56	14.13 ± 1.89	18.56
Film	120	15.15 ± 2.01[b]	18.62 ± 2.34[b]	0.49–32.17	15.62 ± 3.23	54.25
Fragment	120	26.54 ± 1.24[c]	20.16 ± 2.54[c]	1.25–40.56	22.54 ± 3.54	8.66
Foam	120	35.74 ± 1.65[d]	30.15 ± 3.21[d]	3.25–50.14	26.23 ± 4.23	3.46
Granular	120	30.55 ± 2.35[e]	34.45 ± 2.45[e]	6.61–20.19	35.41 ± 2.61	15.07
Farmland	120	46.54 ± 1.58[f]	45.13 ± 2.3[f]	2.91–68.56	28.27 ± 4.23	59.67
Woodland	120	36.25 ± 1.89[g]	34.17 ± 3.21[g]	3.65–50.14	36.16 ± 2.32	20.15
Desert	120	35.15 ± 2.14[h]	29.15 ± 1.89[h]	2.64–40.27	33.32 ± 2.52	20.18

Different lowercase letters indicate significant differences in the abundance of microplastic types in different soil types.

The shape characteristics of microplastics were different among sampling points. For example, the sampling points B-1 and B-11 only had fiber and film, while microplastics of five shapes and types were found at B-25 and 26, and B-57–59 had mainly fiber, fragments, and particles. These results are similar to those from the Weihe area, in which fiber and film microplastics accounted for the largest proportion (Ding et al., 2019). Thin film and fibrous microplastics were detected at all points in this study, accounting for 15.23–72.41%. Similarly, Zhou et al. (2016) detected fiber and fragment microplastics in soil and atmospheric dust at all sampling points in coastal areas.

Figure 2. Morphology of soil microplastics.

Figure 3. Soil microplastic colors.

Figure 4. Particle size classification of soil microplastics.

Table 1. Statistical characteristics of soil microplastics.

Different lowercase letters indicate significant differences in the abundance of microplastic types in different soil types.

3.2 Composition of soil microplastics

The microplastic contents of sampling points near towns in the Ebinur Lake Basin were significantly higher than those in other areas, and the microplastic contents of downwind sampling points in the south were higher than those in upwind settlements in the north. The contents of microplastics in dustfall near the Bortala and Jinghe rivers and their estuaries, such as Bole City and Jinghe City, were significantly higher than those in other river sections. The contents of microplastics in forest and desert soil were the lowest. This showed that microplastics in soil samples near cities and towns mainly came from the urban discharge of plastic pollutants. Microplastics in the atmospheric dust near farmland mainly came from the weathering, debris, and near the ground settlement of chemical fertilizer and pesticide packaging materials and agricultural plastic film coverage. This is consistent with Zhang et al. (2020), who analyzed the main sources of soils microplastics in farmland are industrial areas. In our study, the sampling occurred in summer, and the farmland was frequently covered with plastic film because millions of Mu (1/15 hectare)of cotton in Xinjiang needed to be covered with plastic film.

The components of five types of soil microplastics were determined by infrared spectrum analysis in our study. The first type of soil microplastics was Polyethylene terephthalate (PET; Fig. 5a,b), which has a typical C = O functional group at wave 1700, C-O at wave 1500, and P-disubstituted benzene at wave 800–860 (Fig. 5a). The second type was polypropylene (PP) which has a typical C = C functional group at wave 1630, $-CH_3$ at wave 1570, and $R-CH = CH_2$ at 900–1000 (Fig. 5b). The third type was polycarbonate(PC), which has typical monosubstituted benzene functional group at waves 690–710 and 750–770, p-disubstituted benzene at wave 800–860, =C-H, O-H at wave > 3000, and C = O at wave 1700 (Fig. 5c). The fourth type was polyethylene (PE), with a typical C = C functional group at wave 1550 and C-O at wave 1000 (Fig. 5d). The fifth type was Polystyrene (PS), which has a typical C = C functional group at wave 1670, and monosubstituted benzene at waves 690–710 and 750–770 (Fig. 5e).

Figure 5. FTIR spectra of soils microplastic

3.3 Source identification of soils microplastics

There are many factors affecting the occurrence of microplastics in soil. This study used the random forest regression model to analyze the entire Ebinur Lake Basin. The main factors were industrial GDP, industrial wastewater discharge, agricultural film use, population, regional GDP, domestic sewage discharge, chemical oxygen demand of industrial wastewater, corn sowing area, cotton sowing area, proportion of silt and sand, proportion of sand, and proportion of clay. Then an importance ranking analysis of the possible influencing factors was carried out. The results show that the contents of soil microplastics in the Ebinur Lake Basin were closely related to the use of agricultural plastic film, total industrial output, and population (Fig. 6). The main land-use type in the basin was farmland (Abuduwaili et al., 2015). The most sample collection points in this study was also on farmland. Therefore, agricultural activities were the most important factor affecting the soil in this area, followed by industrial activities and domestic emissions. The importance ranking results of random forest variables indicated, to a certain extent, the source of soil microplastics. Activities such as industrial and agricultural production and the discharge of domestic waste plastics were related to soil microplastic pollution. The use of agricultural plastic film was the most important factor in soil pollution in this area.

Figure 6. Importance ranking of random forest variables.

Industrial-v industrial GDP, Industrial-s industrial wastewater discharge, Film-A agricultural film use, Population-population, GDP- regional GDP, Domestic-s domestic sewage discharge, COD-c chemical oxygen demand of industrial wastewater; Corn-p corn sown area, Cotton-p cotton sown area, Silt-proportion of silt, Sand-sand, Clay-clay.

In this study, the main components of film microplastics in the soil of the Ebinur Lake Basin were PE and PP. We speculated that broken waterproof film layers of daily life plastic products, such as food packaging bags, and woven bags for industrial and agricultural production, were the main source of film microplastics. In our research, the main components of fragment microplastics were PP and PE. We speculated that it mainly came from broken fragments of large-scale plastic industrial packaging materials or woven plastic bags, as the edges had regular shapes (Zhang et al., 2020). In the Ebinur Lake Basin, the decomposition of woven plastic bags of chemical fertilizer and cement probably was the main source. The main component of foam and granule was PS, with mostly lamellar and columnar shapes, and the main colors were white and colorless. The sources of these microplastics include microbubbles in foam plastics and personal care products (Zhou et al., 2016). The main component of fiber was PET, mostly black and yellow, probably coming from the sewage discharge after washing of fabrics in clothing and textile industries near cities and towns. In addition, fishing gear, atmospheric deposition, and surface runoff are also potential sources of plastic fibers. During the sampling period, fragments of foam, packaging bags, chemical bags, plastic bottles, and food packaging paper were found in towns and farmland and forest soil. This indicated that microplastic pollutants in the Ebinur Lake Basin mainly come from industrial and agricultural production and domestic sources.

4. Discussion

4.1 Comparative evaluation of soils microplastic pollution in the Ebinur lake basin

Compared with relevant Chinese and international studies (Table 2), the content of microplastics in the studied soils was relatively low, and the soil environment was in good condition. Soil microplastics abundances in our study were much lower than those of industrial land in some areas of Australia (Yang et al., 2021), cultivated land in Iran (Rezaei et al., 2019), cultivated land in Chile (Corradini et al., 2019), and green land in the United States (Helcoski et al., 2020) and Mexico (Huerta et al., 2017). Soil microplastic contents in the Ebinur basin were also lower than those of cultivated land and tidal flats in some Chinese provinces, such as cultivated land in the provinces Yunnan (Zhang & Liu, 2018), Zhejiang (Zhou et al., 2020), Heilongjiang (Zhang et al., 2020a), Guangxi (Zhang et al., 2020b), Shaanxi (Ding et al., 2020), Hubei (Chen et al., 2020), Shandong (Zhou et al., 2016), and Hebei (Lv et al., 2019), as well as Shanghai city (Liu et al., 2018). However, contents were higher than those in Mexican green space and cultivated soil in Shanghai city (Huerta et al., 2017; Liu et al., 2018).

Table 2
Abundance statistics of soil microplastics in China and worldwide.

Region, land use types	Component	Shape	Particle size	Abundance (n/kg)	References
Australia, industrial land	PE/PVC/PS	/	< 1	300-67500	Yang et al. (2021)
Iran, cultivated land	PE	Fragment	40–740 μm	67–400	Rezaei et al. (2019)
Chile, cultivated land	/	Fiber	< 4 mm	600-10400	Corradini et al. (2019)
Germany, cultivated land	PE, PS	Debris, film	< 5 mm	0.34 ± 0.36	Piehl et al. (2018)
USA, green space	PE, PS	Fiber	< 5 mm	334–3068	Helcoski et al. (2020)
Switzerland, beach	PE, PP	/	< 2 mm	0-55.5	Scheurer & Bigalke (2018)
Mexico, green space	PE	Particle	10–50 μm	870 ± 190	Huerta et al. (2017)
Yunnan, cultivated land	/	Fiber	1-0.05 mm	7100–42960	Zhang & Liu (2018)
Zhejiang, cultivated land	PE, PP	Debris, fiber	< 5 mm	0-2760	Zhou et al. (2020)
Heilongjiang, cultivated land	PE	Film	< 5 mm	0-800	Zhang et al. (2020a)
Guangxi, cultivated land	PP, PE, PET	Debris, fiber	< 5 mm	5-549.9	Zhang et al. (2020b)
Shaanxi, cultivated land	PS, PE, PP	Fiber, particle	< 5 mm	1430–3410	Ding et al. (2020)
Hubei, cultivated land	PA, PP	Fiber, particle	< 0.2 mm	320-12560	Chen et al. (2020)
Shandong, beach	PE, PP, PS	Foam, debris	< 5 mm	1.3-14712.5	Zhou et al. (2016)
Hebei, beach	/	Particle, fragment	1.56 ± 0.63 mm	0-634	Lv et al. (2019)
Shanghai, cultivated land	PP, PE	Fiber	< 1 mm	10.3 ± 0.2	Liu et al. (2018)
Ebinur lake basin	PP, PE, PVC	Foam, debris, fiber, film	< 5 mm	36.15	This research

Our study showed that the main microplastic components in the Ebinur Lake Basin were PE, PVC, and PS, which is consistent with other Chinese and international studies. We found many types of microplastics in the environment, such as fiber, film, foam, and particles. Fiber-based microplastics were found to be dominant in soil samples. However, this study found that the total proportion of film microplastics in the soil of the Ebinur Lake Basin was higher than that of fiber microplastics because the debris had a lower specific surface volume and migrated more easily into the soil (Yang et al., 2021). Granular, foam, and debris microplastics accounted for the smallest proportion of all soil microplastics in this study (3.46–15.07%). This corresponded well with Corradini et al. (2019), who reported microplastic accumulation in agricultural soil DGE disposal and that debris accounted for a large proportion. The possible reason for this is that granular microplastics are mainly derived from the decomposition of hard plastics, which takes a long time. The color distribution characteristics of microplastics are obviously different from the wide sources of microplastics and the interference of human activities. The colored microplastics in domestic sewage (e.g., from laundry) discharged from residential areas, and sewage treatment plants stimulate the biological vision inhabiting in the soil, and then damage their health (Zhang et al., 2020).

This paper provides a preliminary analysis of the spatial distribution of different microplastics in the soil of the Ebinur Lake Basin. There were many farms near Bole City and Jinghe County, and the proportion of thin-film microplastics was the largest in these regions. Therefore, we speculated that the main reason for the high abundance of microplastics in these two points is the crushing and decomposition of agricultural plastic film and domestic plastic waste. In addition, the Bortala River estuary had a low current velocity, and the sediments deposited near the sampled river bend may have carried microplastic particles, resulting in a relatively large abundance of microplastic (B-57 sample supply Table 1). Although there were plastic processing plants and sewage treatment plants near Bole City and Jinghe County, the population density was high, and film and fiber microplastics at these sampling points accounted for 50% of total microplastics. Therefore, we speculated that the main origin of these microplastics was clothes particles from washing and discarded plastic garbage bags. There were differences in the content of soil microplastics near Bole City and Jinghe County, and the content was often higher than in other sampling points. The reason for this may have been that the population near the town was dense, and there was more garbage than in other areas, resulting in increased microplastic pollution. It is also possible that sewage treatment plants and plastic processing plants represented direct sources, increasing the abundance of microplastics, which should be assessed in the future.

Table 2. Abundance statistics of microplastics in China and worldwide

4.2 Mechanisms of soils microplastic and adsorbed metal impacts, and further research directions

The contents of heavy metals adsorbed to collected soil microplastics collected were analyzed. We further analyzed correlations between the abundance, contents, color, carried heavy metals of different microplastics types, and soil physical and chemical variables to assess the mobility of metals and influencing factors. The abundance and contents of microplastics had no significant correlation with soil pH, EC, and total salt contents (Table 3). However, there was a significant negative correlation with soil moisture and water volume ($p < 0.01$), and the correlation coefficients were 0.85 for the correlation abundance-soil moisture, 0.45 for abundance-precipitation, 0.42 for content-soil moisture, and 0.35 for content-precipitation, indicating that high soil moisture or scouring caused by factors such as rain caused the migration of microplastics, and the increase of soil moisture resulted in the migration and export of microplastics and reduced their abundance (Zhang et al., 2020). The color of microplastics had no significant correlation with pH, EC, total salt content, nitrogen, phosphorus, potassium, and precipitation, indicating that these soil variables do not affect the color of microplastics. The abundance and content of soil microplastics were significantly correlated with the contents of N, P, and K. The correlation coefficients were 0.56 for abundance-N, 0.69 for abundance-P, 0.65 for abundance-K, 0.52 for content-N, 0.51 for content-P, and 0.54 for content-K ($p < 0.01$), indicating that microplastics changed significantly with agricultural fertilization activities. This corresponds well with the study of Liu et al. (2018) on the effects of farmland soil microplastics and agricultural fertilization in the suburbs of Shanghai.

Table 3
Correlation matrix between microplastic abundance, heavy metal content, and soil physical and chemical variables.

Soil variables	Abundance	Content	Color	Cu	Ni	Cd	Pb	Cr	Mn	Co
pH	0.49	0.37	0.64	0.55**	0.56**	0.64**	0.68**	0.61**	0.75**	0.80**
EC	0.41	0.50	0.31	0.56**	0.52**	0.60**	0.58**	0.53**	0.56**	0.61**
Total salt	0.42	0.36	0.28	0.51**	0.61**	0.62**	0.57**	0.53**	0.52**	0.49*
Soil Moisture	-0.85**	-0.42**	0.41	-0.31*	-0.29*	-0.33*	-0.26*	-0.19*	-0.42*	-0.33*
N	0.56**	0.52**	0.54*	0.58**	0.52**	0.49*	0.56**	0.57**	0.52**	0.54**
P	0.69**	0.51**	0.45	0.53**	0.56**	0.45*	0.58**	0.61**	0.49*	0.64**
K	0.65**	0.54**	0.49	0.51**	0.53**	0.54**	0.62**	0.56**	0.48*	0.51**
Precipitation	-0.45*	-0.35*	-0.27	-0.16*	-0.11*	-0.21*	-0.18*	-0.17*	-0.35*	-0.44*
*significant at p < 0.05 (bilateral); **significant at p < 0.01 (bilateral)										

The seven heavy metals extracted from microplastics in our study showed a significant positive correlation with soil pH, EC, and total salt, N, P, and K contents ($p < 0.01$), indicating that these soil variables significantly affected the content of heavy metals carried by microplastics. The seven heavy metals were significantly negatively correlated with soil moisture and precipitation, and the correlation coefficients were 0.31 for Cu-soil moisture, 0.29 for Ni-soil moisture, 0.33 for Cd-soil moisture, 0.26 for Pb-soil moisture, 0.19 for Cr-soil moisture, and 0.42 for Mn-soil moisture, and 0.33 for Co-soil moisture ($p < 0.01$). Accordingly, heavy metals carried by microplastics can be changed and reduced by increasing soil moisture contents in future soil management, which is consistent with Zhou et al. (2021), who also showed that microplastic contamination is ubiquitous in rural soils and strongly related to elevation, precision, and population density.

Table 3. Correlation matrix between microplastic abundance, heavy metal contents, and soil physical and chemical variables.

*significant at p < 0.05 (bilateral), **significant at p < 0.01 (bilateral)

Compared with the microplastic pollution of aquatic systems, our understanding of soil microplastic pollution is still very limited. One of the reasons may be the lack of standard methods for studying soil microplastics. Therefore, it is necessary to establish standard methods for collecting, separating, and analyzing various types of microplastics in soil samples in the future (Rillig et al., 2017). Accurate, simple, and efficient analysis technology will be the basis for an in-depth understanding of soil microplastic pollution (Koelmans et al., 2020; Yang et al., 2021). At present, the land use type most studied regarding soil microplastic pollution is cultivated land, and existing data are insufficient to analyze the pollution of soil microplastics in China or worldwide (Zhang et al., 2020). Therefore, future research should focus on the analysis of the pollution degree of microplastics in the soil of various land-use types and explore sources and relevant characteristics of the microplastics, which will also help managers take targeted measures to control soil microplastic pollution (Zhang et al., 2017; Shahul et al., 2018).

In previous studies, microplastics were often regarded as a simple polymer. In fact, microplastics may contain many chemical additives (such as plasticizers and flame retardants) (Eriksen et al., 2013; Galloway et al., 2017). In addition, due to the large specific surface area of microplastics, it is necessary to further study the effects of plastic additives and adsorbed pollutants on soil ecosystems in the future in order to assess the impact mechanisms of microplastic pollution. To date, most studies have been simulations under laboratory conditions, and the concentrations of microplastics have been very high in some studies, leading to a certain incompatibility between experimental microplastic concentrations and concentrations in the natural environment (Figure. 7). Therefore, it is necessary to explore whether and how microplastic pollution affects soil animals, microorganisms, and plants *in situ* in the future which is also essential to truly grasp the environmental effects of microplastics (Weithmann et al., 2018; Zhang et al., 2020).

Figure 7. Occurrence, sources, and ecological effects of soil microplastics

5. Conclusions

(1) The proportions of microplastics of various shapes diminished in the order: film (54.25%) > fiber (18.56%) > particles (15.07%) > fragments (8.66%) > foam (3.46%). The colors with the highest proportions in film, fiber, particle, fragment, and foam microplastics were white (41.32%), white (58.86%), green (36.21%), green (37.45%), and yellow (27.9%), respectively.

(2) The particle size classes with the highest proportions in farmland, woodland, and desert soil were 2000–5000 μm (29.58%), 1000–2000 μm (50.16%), and 1000–2000 μm (36.32%), respectively. The particle size classes with the highest proportions in film, fiber, particle, fragment, and foam microplastics were 1000–2000 μm (39.41%), 1000–2000 μm (45.32%), 1000–2000 μm (33.21%), 1000–2000 μm (58.32%), and 1000–2000 μm (35.21%), respectively. FTIR analysis showed that PET, PP, PC, PE, and PS were the main microplastic types in soils of the Ebinur basin.

(3) Random forest predictions showed that the microplastic contents were closely related to the use of agricultural plastic film, total industrial output, and population. Activities such as industrial and agricultural production and the discharge of domestic waste plastics were related to soil microplastic pollution, and the use of agricultural plastic film was the most important factor of soil pollution in this area.

(4) Compared with relevant Chinese and international studies, the contents of microplastics in the soil of the Ebinur Lake Basin were relatively low, and the soils were in good condition. Heavy metals extracted from microplastics showed significant positive correlations with pH, EC, and total salt, N, P, and K contents in soil ($p < 0.01$), indicating that these soil variables significantly affected the contents of heavy metals carried by microplastics.

Declarations

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Author’s contribution: Zhang Zhaoyong designed and wrote the paper, Guo Jieyi and Wang Pengwei participated in the field sampling and experimental work.

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Ethical approval: The study was not related any Clone that need ethical approval.

Human or animal rights: This study does not involve any animal experiments.

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Figures

Figure 1

Research area and soil sampling points in the Ebinur lake basin.

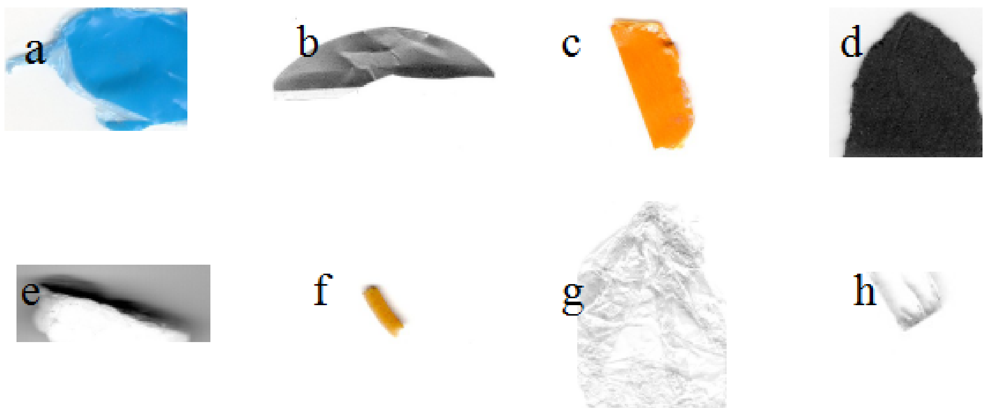

Figure 2

Morphology of soil microplastics a- film, b- fragment, c- film, d- particle, e- foam, f- particle, g- fiber, h- fragment

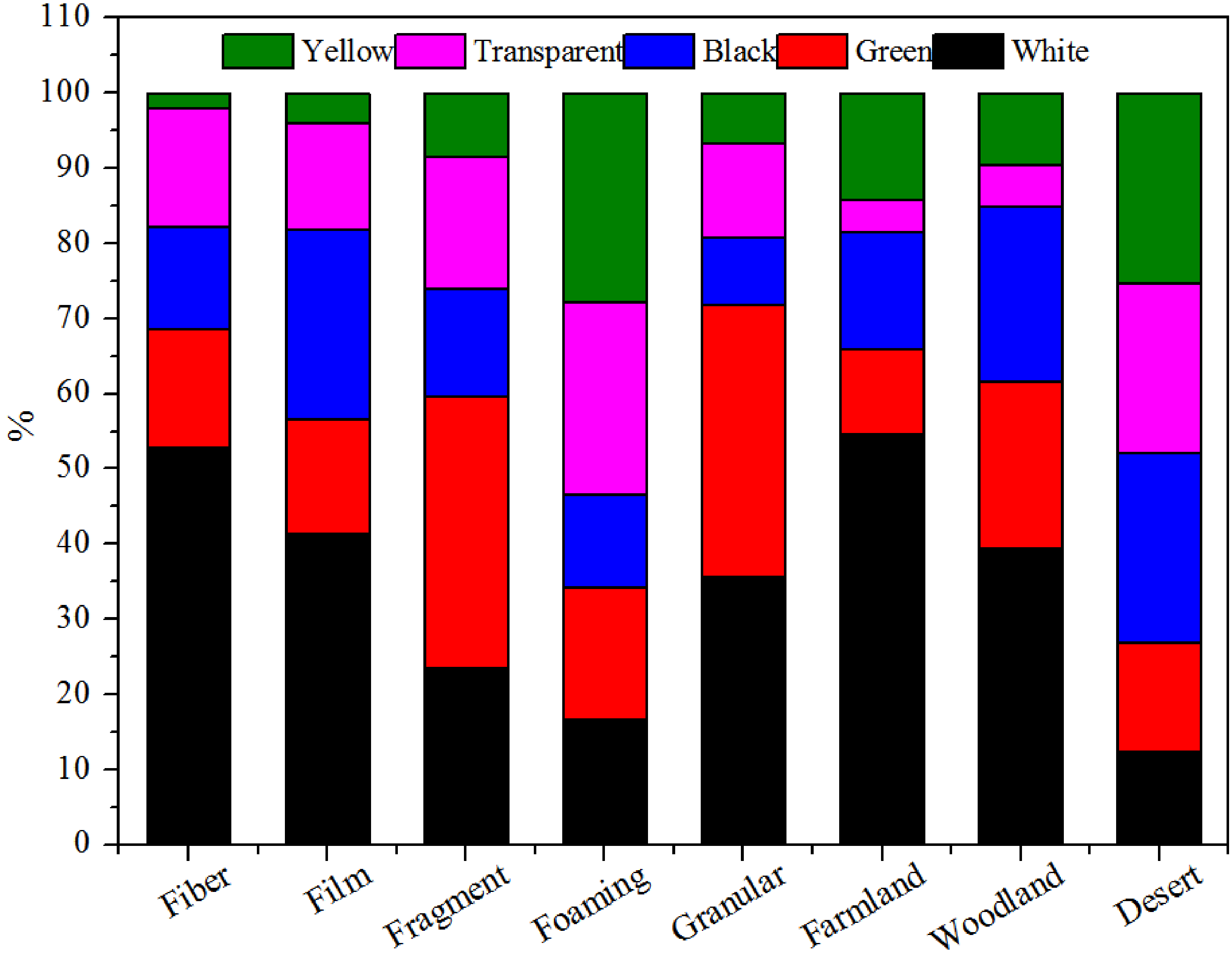

Figure 3

Soil microplastic colors

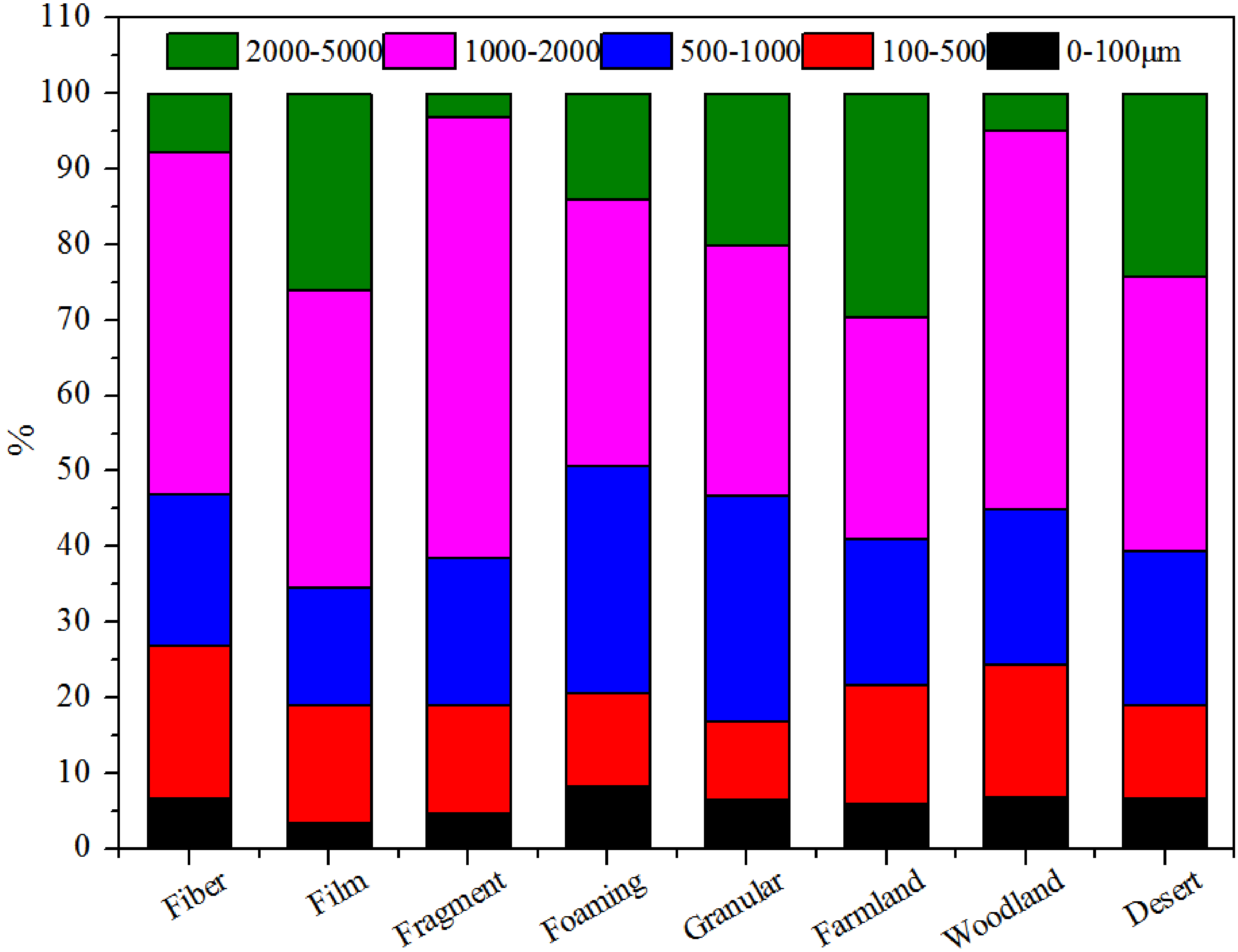

Figure 4

Particle size classification of soil microplastics

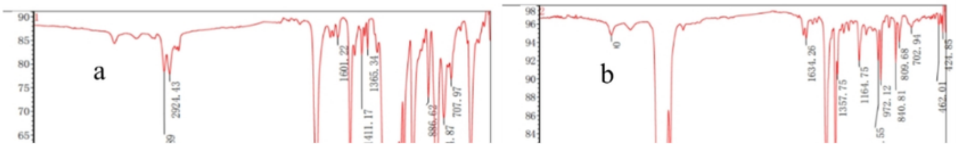

Figure 5

FTIR spectra of soils microplastic

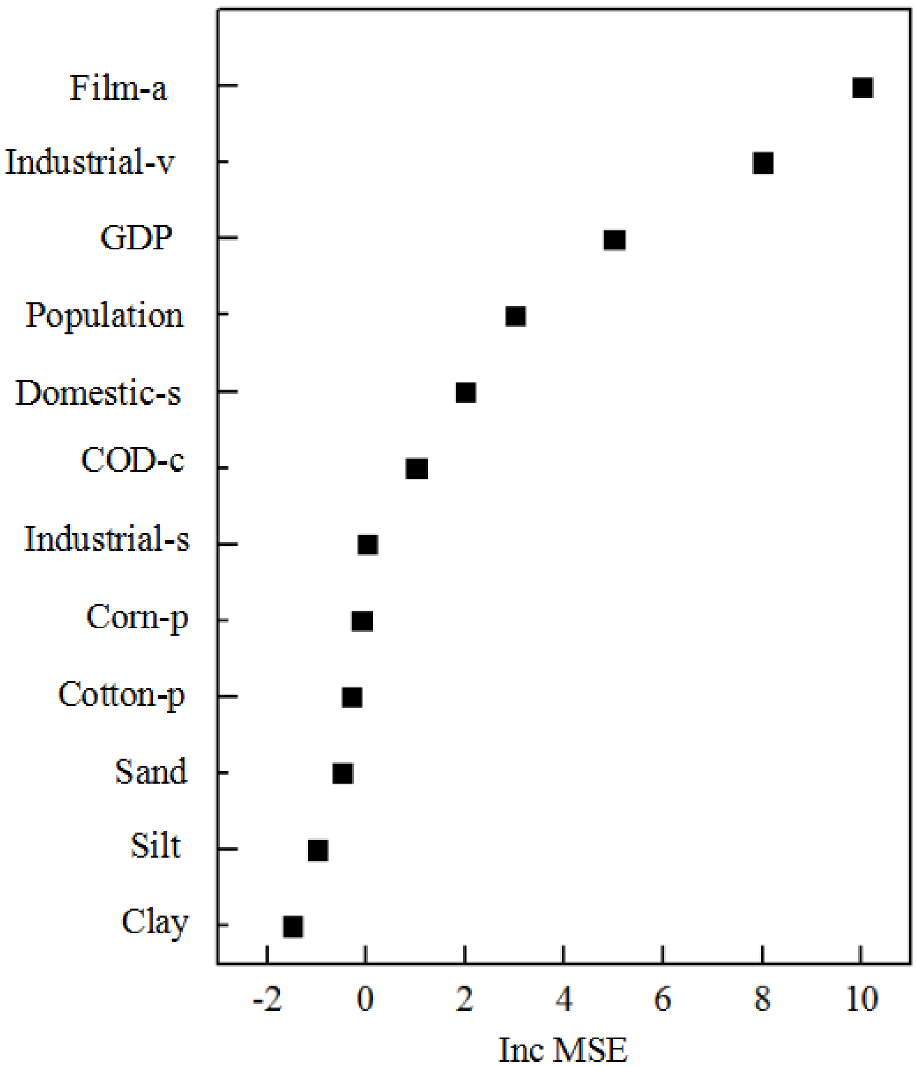

Figure 6

Importance ranking of random forest variables.

Industrial-v: industrial GDP, Industrial-s: industrial wastewater discharge, Film-a: agricultural film use, Population: population, GDP: regional GDP, Domestic-s: domestic sewage discharge, COD-c: chemical oxygen demand of industrial wastewater, Corn-p: corn sown area, Cotton-p: cotton sown area, Silt: proportion of silt, Sand: sand, Clay: clay.

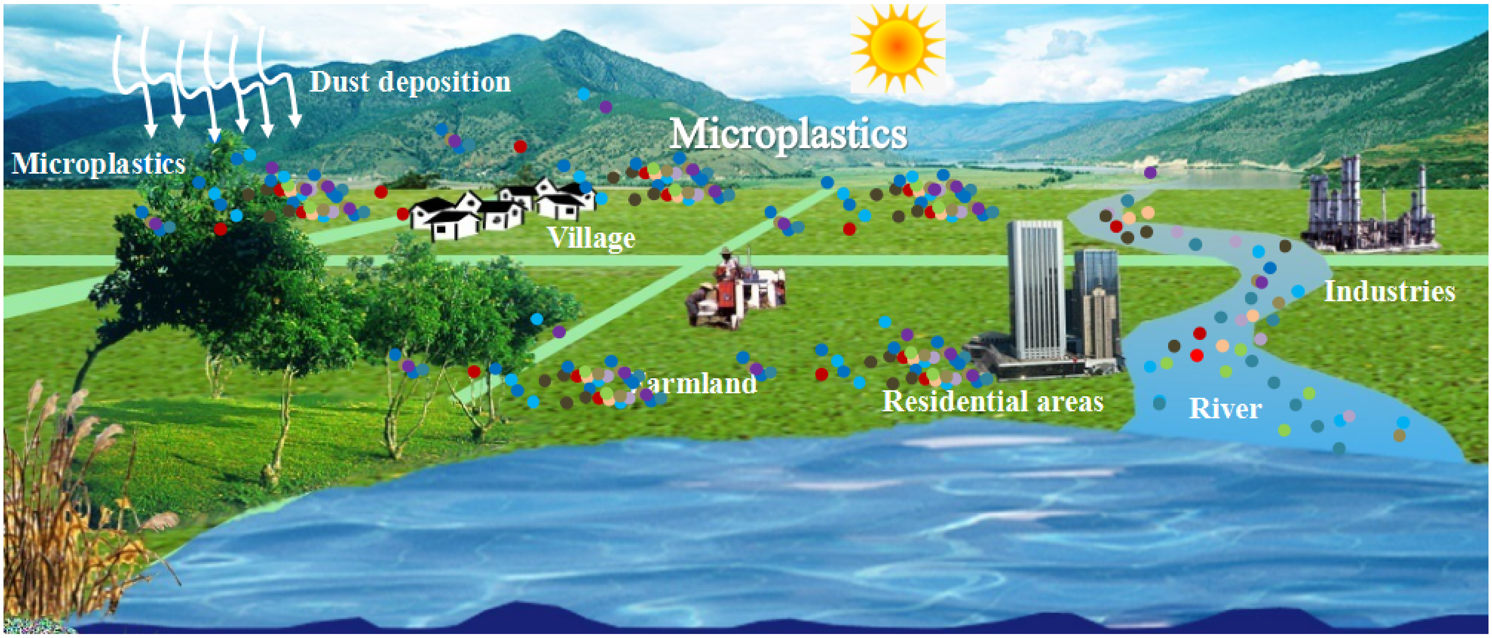

Figure 7

Occurrence, sources, and ecological effects of soil microplastics