Journal of Environmental Management 348 (2023) 119353

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Microplastic transport during desertification in drylands: Abundance and characterization of soil microplastics in the Amu Darya-Aral Sea basin, Central Asia

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ARTICLE INFO

Handling Editor: Raf Dewil

Keywords:
Desertification
Microplastics
Soil physicochemical properties
Microplastic migration
Amu Darya-Aral Sea basin

ABSTRACT

Desertification and microplastic pollution are major environmental issues that impact the function of the ecosystem and human well-being of drylands. Land desertification may influence soil microplastics' abundance, transport, and distribution, but their distribution in the dryland deserts of Central Asia's Amu Darya-Aral Sea basin is unknown. Here, we investigated the abundance and distribution of microplastics in dryland desert soils from the Amu Darya River to the Aral Sea basin in Central Asia at a spatial scale of 1000 km and soil depths ranging from 0 to 50 cm. Microplastics were found in soils from all sample locations, with abundances ranging from 182 to 17841 items kg^{-1} and a median of 3369. Twenty-four polymers were identified, with polyurethane (PU, 37.3%), silicone resin (SR, 17.0%), and chlorinated polyethylene (CPE, 9.8%) accounting for 64.1% of all polymer types. The abundance of microplastics was significantly higher in deep (20–50 cm) soils than in surface (0–5, 5–20 cm) soils. The main morphological characteristics of the observed microplastics were small size (20–50 μm) and irregular particles with no round edges (mean eccentricity 0.65). The abundance was significantly and positively related to soil EC and TP. According to the findings, desertification processes increase the abundance of microplastic particles in soils and promote migration to deeper soil layers. Human activities, mainly grazing, may be the region's primary cause of desertification and microplastic pollution. Our findings provide new information on the diffusion of microplastics in drylands during desertification; these findings are critical for understanding and promoting dryland plastic pollution prevention and control.

1. Introduction

Microplastics were first described in reports of marine plastic pollution as plastic particles or fragments less than 5 mm in diameter (Thompson et al., 2004). Plastics have been produced on a large scale since the 1950s and grow at 8.4% per year (Geyer et al., 2017). Because of their low cost, lightweightness, and durability, plastics are growing much faster than most other artificial materials (Rosenboom et al., 2022; Stubbins et al., 2021). Global annual plastic production is expected to exceed 300 million tons by 2020, with nearly 10 billion tons of plastic produced cumulatively (Hale et al., 2020). However, until now, the average percentage of plastics recycled globally was only 10%, with the remaining 90% entering the natural environment through incineration, landfills, or direct disposal (OECD, 2022). Plastics in the background do not degrade significantly due to their synthetic nature and resistance to corrosion and impact; instead, they continue to break into smaller and smaller pieces or particles and remain in the natural environment for long periods, causing severe environmental pollution (Brahney et al., 2021; Koelmans et al., 2022; MacLeod et al., 2021).

Plastic pollution is one of the most common and persistent anthropogenic changes on Earth's surface, causing global ecosystems to change (Barnes et al., 2009; Koelmans et al., 2019; Santos et al., 2021). As plastics are manufactured, primarily used, and discarded in terrestrial habitats and undergo an environmental journey that affects their fate, they eventually accumulate in the natural environment (Baho et al., 2021; Stubbins et al., 2021; Sun et al., 2022). Thus, microplastics may

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https://doi.org/10.1016/j.jenvman.2023.119353
Received 15 July 2023; Received in revised form 9 October 2023; Accepted 14 October 2023

first interact with biota, causing environmental toxicity and ultimately affecting soil function by altering the soil's geochemical and biophysical environment (Koelmans et al., 2022; Zhu et al., 2022). For example, microplastics in the environment can affect soil processes and plant production (Rillig, 2012; Zhao et al., 2022a), alter the composition of microbial communities (Qin et al., 2023; Zhu et al., 2022), be taken up by biological communities leading to health damage or death (Bouaicha et al., 2022; Sridharan et al., 2022), move up the food chain (Abdolahpur Monikh et al., 2022; Okeke et al., 2022), and act as carriers of contaminants (Hu et al., 2022; Sewwandi et al., 2023). Microplastics have also been shown to be ingested by terrestrial animals, including insects, reptiles, birds, and mammals, and often occur in areas with high human activity and dense plastic waste (Baho et al., 2021; Souza Machado et al., 2018). At the same time, there is evidence that microplastic particles have been detected in human tissue and will adversely affect human health (Kadac-Czapska et al., 2022; Vethaak and Legler, 2021; Yates et al., 2021). Therefore, it is critical to understand the distribution and effects of microplastics in various ecosystems, particularly in less studied ecosystems such as arid desert regions (MacLeod et al., 2021; Rochman, 2018; Rochman and Hoellein, 2020).

Drylands cover 41–45% of the Earth's land area, sustain 38% of the population, and are mainly concentrated in developing countries (Huang et al., 2016; Maestre et al., 2021). Meanwhile, drylands hold 35% of terrestrial biodiversity, provide 44% of global arable land and 50% of livestock, and are critical to maintaining international sustainable development (Laban et al., 2018; Maestre et al., 2021; Wang et al., 2022a). However, drylands also face a severe threat of desertification, which has affected a quarter of the world's land surface (Heshmati and Squires, 2013; Olsson et al., 2019), resulting in approximately 2.5 million people affected by desertification each year, affecting economic development and human well-being (Mirzabaev et al., 2019; UNCCD, 2022). This figure is expected to rise significantly due to future climate change and increased human activity (Huang et al., 2016; Prăvălie, 2016). Because plastics are becoming more abundant in soils, biota, and the atmosphere, it is necessary to clarify and quantify the abundance, distribution, and transport of microplastics in dryland environments to prepare an assessment of the global plastic cycle (Allen et al., 2019; Rochman and Hoellein, 2020; Stubbins et al., 2021). However, survey data on dryland desert ecosystems are scarce. It is critical to accurately assess the risk of plastic pollution in drylands by quantifying the abundance and distribution of microplastics during dryland desertification.

In this study, we attempted to answer the following questions using field survey sampling and laboratory analysis at larger spatial scales in the Amu Darya-Aral Sea basin at approximately 1000 km: (1) the abundance, characteristics, and polymer types of microplastics at 0–50 cm depth of soil during desertification in drylands, (2) whether the desertification process affects the abundance and distribution of microplastics to deeper soil layers, and (3) the relationship between microplastic abundance and vegetation and soil properties. This study aims to assess the distribution characteristics of soil microplastics during land desertification in Central Asia's Amu Darya-Aral Sea basin, as well as the influence of desertification on their abundance and migration to lower soil, to provide a foundation for accurate assessment of microplastic soil distribution and plastic pollution prevention and control during desertification in dryland ecosystems.

2. Materials and methods

2.1. Study area

The study area is located in the Amu Darya-Aral Sea basin on the territory of the Republic of Uzbekistan (Fig. 1). The average annual precipitation in the region is 170 mm, with winter and early spring accounting for roughly 80% of total rainfall. Summer and early fall, on the other hand, are dry and hot, with an average temperature of 30 °C and temperatures as low as −30 °C in winter (Wang et al., 2020).

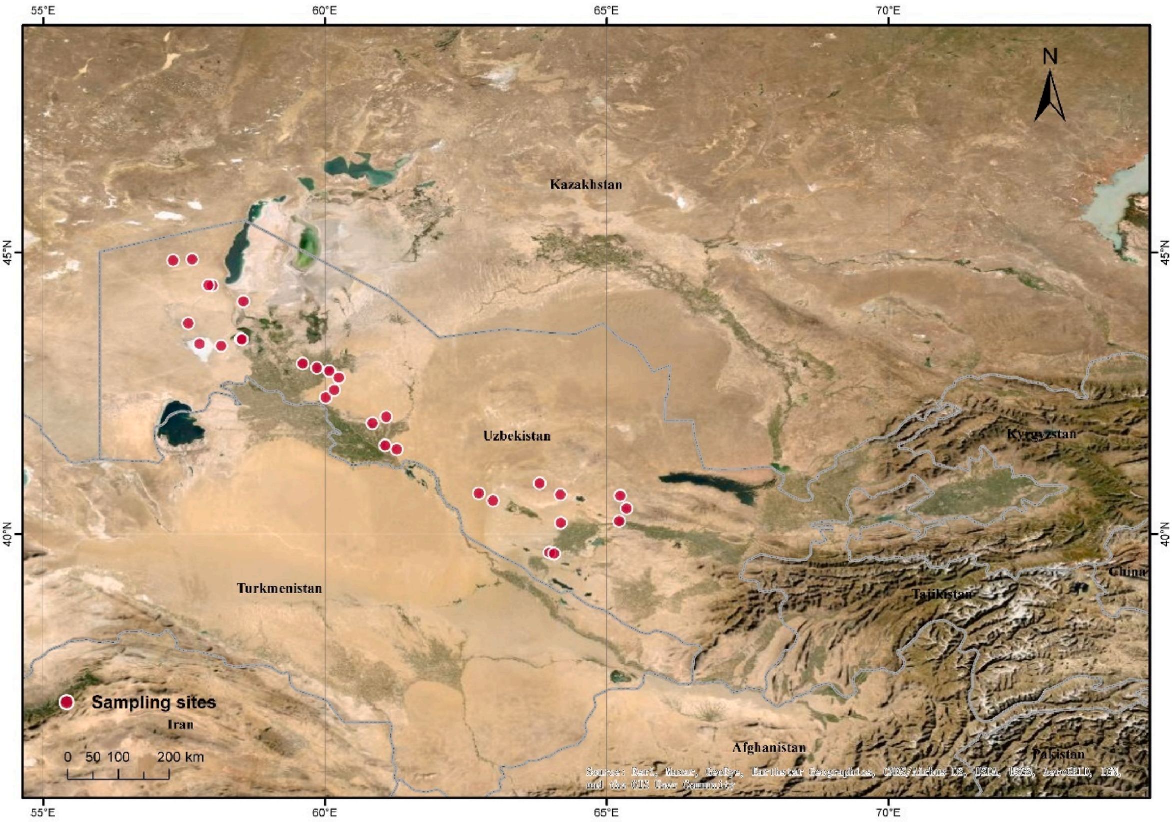

Fig. 1. Field survey sampling sites in the Amu Darya-Aral Sea basin.

Drylands in Uzbekistan account for 97.28% of the country's land area (Prăvălie, 2016). About 57% of the country's land is rangeland, of which about 78% is desert and semi-desert plains (Toderich et al., 2013). Since the 1990s, land desertification has increased in the Amu Darya basin to the Aral Sea region, where desertified land accounts for approximately 23.71% of the country's land area (He et al., 2021).

2.2. Field survey and sample collection

In August–September 2019, a vegetation survey and soil collection were conducted on a spatial scale of about 1000 km from the Amu Darya River to the Aral Sea basin in Uzbekistan (Fig. 1). At the selected survey site, a 10 m × 10 m survey sample plot was established. All shrub species and essential characteristics within the sample plot were investigated. Then, three small 1 m × 1 m sample plots were randomly set up within the selected sample plots to study the species and cover all herbaceous plants in the sample plots. Finally, three soil profiles with a depth of 50 cm were randomly excavated with a stainless steel shovel within the 10 m × 10 m sample plots. Soil water content (SWC), soil temperature (ST), and soil conductivity (EC) were measured in layers (0–5, 5–10, 10–20, 20–30, 30–50 cm) with three replicates using a portable soil measurement system (data collector: CR300, Campbell, USA; sensor: Hydra Probe II, Stevens, USA), and soil samples were collected in layers (0–5, 5–20, 20–50 cm) using a stainless steel spatula at the end of the measurements. Each soil sample was randomly divided into two subsamples: one soil subsample was kept in a vehicle-mounted cryostat and brought back to the laboratory to be stored at low temperature for backup; the other subsample was wrapped in tin foil, homogenized immediately after transfer to the laboratory, and stored for backup. Nonplastic tools and containers were used during sampling, transportation, and preservation to avoid sample contamination as much as possible.

2.3. Sample preparation, microplastic identification, and quality control

A $ZnCl_2$ solution of 1.7–1.8 kg/L was prepared in the laboratory. The weighted soil sample (15 g) was placed in a 100 mL beaker, weighed, and 60 mL of $ZnCl_2$ solution was added, stirred thoroughly for 2 min, and left for 12 h. The supernatant was then separated by decantation, and the remaining suspension was transferred by siphoning to another beaker. Then, 60 ml of 30% H_2O_2 was added to remove the organics, stirred well, and left at room temperature for 24 h to allow the hydrogen peroxide to react fully. Then, the hydrogen peroxide-treated solution was vacuum filtered, and the obtained aluminum membrane was immersed in ethanol solution for sonication so that the substances on the membrane were dispersed in the ethanol solution. The membrane was removed from the ethanol solution and washed several times with ethanol. The ethanol solution was concentrated and added to the high inverse glass dropwise. Finally, after the ethanol was evaporated entirely, the test was performed using an Agilent 8700 LDIR laser infrared imaging spectrometer (Agilent 8700 LDIR, Santa Clara, CA, USA), selecting the particle analysis mode with a match >0.65 and a particle size range of 20–500 μm. Reagent blanks, instrument background blanks, and sampling blanks were tested before on-board analysis. (Blank testing details are in the Supplementary Material) The test soil samples were dried samples, and the abundance values of microplastics were expressed as the dry weight. The abundance of microplastics was described as dry soil weight.

Nonplastic material tools and containers are used for sampling, transportation, and storage to avoid sample contamination. Samples were kept sealed and stored before analysis. Cotton clothes were worn during laboratory handling and analysis, and all instruments and benches used in the experiments were cleaned with ultrapure water. Blank tests were also set up to eliminate the influence of chemical reagents, air, and ultrapure water on the experimental results. The solutions left to stand during sample preparation were covered with clean aluminum foil to reduce exposure to air.

2.4. Soil physicochemical properties determination

Soil samples collected at each sampling site were analyzed in the laboratory for soil water content (SWC), pH, electrical conductivity (EC), texture composition, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), and total potassium (TK) using standard methods (Carter and Gregorich, 2007; Nelson and Sommer, 1982). Specifically, soil texture was determined by the pipette method. Soil pH (pH) was measured by a pH meter (Remagnet PHSJ-4F, China). Soil organic matter (SOM) was analyzed and measured by the H_2SO_4–$K_2Cr_2O_7$ oxidation method. Soil total nitrogen (TN), soil total phosphorus (TP) and soil total potassium (TK) were measured by Kjeldahl nitrogen determination (SKD-5000, PEIOU, China), colorimetric method (UV–visible spectrophotometer, TU-1810PC, China), and flame photometer (Flame Photometer, FP6410, China), respectively.

2.5. Statistical analysis

Statistical data analysis was performed using SPSS 26.0 (IBMCorp., Armonk, NY, USA) software. Graphs were produced using OriginPro 2023 (OriginLab Corporation, Northampton, MA, USA) software. Descriptive statistics were first performed for all indicators involved in this study. After passing the normal distribution test, one-way analysis of variance (ANOVA) was used to compare microplastic differences in abundance under different vegetation types, desertification levels, and soil depths. Pearson's correlation analysis was used to analyze the correlation between the number of microplastics and indicators such as soil and vegetation. Data were expressed as mean (standard deviation) or mean ± standard error, and the statistical significance threshold was set at $P < 0.05$.

3. Results

3.1. Vegetation and soil characteristics

Based on vegetation and soil characteristics, all survey sites were classified into six types: natural desert (ND), saline desert (SLD), light desertification desert (LD), moderate desertification desert (MD), heavy desertification desert (HD), and sandy desert (SD) (codes are used below). The richness of shrub species in the study area was significantly higher in SD, HD, and MD (mean 3.7 ± 0.3) than in ND, SLD, and LD (mean 2.4 ± 0.5) (Fig. 2a). LD had the highest herbaceous species richness, followed by MD (non-significant difference), which was significantly higher than ND, SLD, HD, and SD (Fig. 2b). Shrub cover was significantly higher in SLD than in ND, HD, and SD, with non-significant differences between it and LD and MD (Fig. 2c). Aboveground biomass of herbaceous plants was highest in SLD ($18.6 \pm 0.7\ g/m^{-2}$), followed by ND ($14.8 \pm 0.5\ g/m^{-2}$), with non-significant differences in LD, MD, and HD (mean $4.4 \pm 0.5\ g\ m^{-2}$) and lowest in SD ($3.0 \pm 0.5\ g\ m^{-2}$), with significant differences between types ($P < 0.001$) (Fig. 2d).

From natural desert to sandy desert, the proportion of sandy soil particles at a depth of 0–50 cm increased significantly (ND < SLD < LD < MD < HD < SD, $P < 0.001$). The proportion of clay particles ($P < 0.001$) and silt particles ($P < 0.001$) decreased significantly (Fig. 3) with the increase in desertification. The saline desert survey sites near the Aral Sea had the highest SWC and the lowest sandy desert, with significant differences between sites ($P < 0.001$) (Fig. 3).

The soils differed significantly ($P < 0.001$) in SOM content at depths 0–50 cm, with SLD being the highest, followed by ND, with insignificant differences between samples of different degrees of desertification and SD the lowest (Fig. 4a). The soils in the study area were alkaline with a pH between 8.00 and 8.37 with significant differences ($P = 0.004$) (Fig. 4b), the saline desert soils had the lowest temperature. The sandy desert had the highest significant differences ($P < 0.001$) (Fig. 4c). Total soil nitrogen (Fig. 4d), total phosphorus (Fig. 4e), and total potassium (Fig. 4f) differed significantly ($P < 0.001$). Total nitrogen and potassium

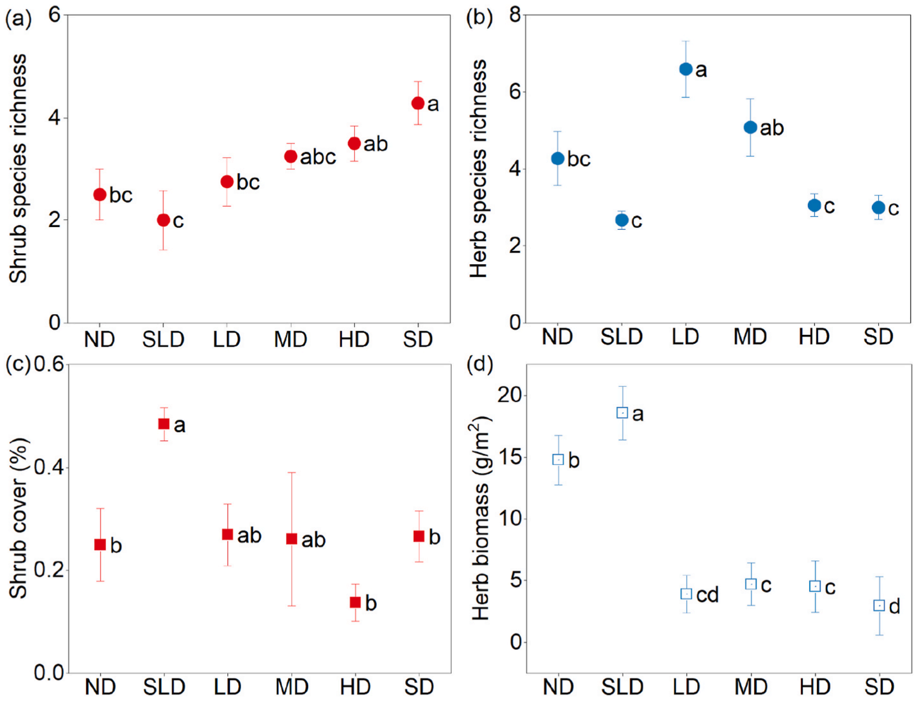

Fig. 2. Characteristics of shrub species richness (a), herbaceous species richness (b), shrub cover (c), and herbaceous aboveground biomass (d) in different vegetation types and desertification degree sample sites. Different lowercase letters indicate significant differences at the level of $P < 0.5$.

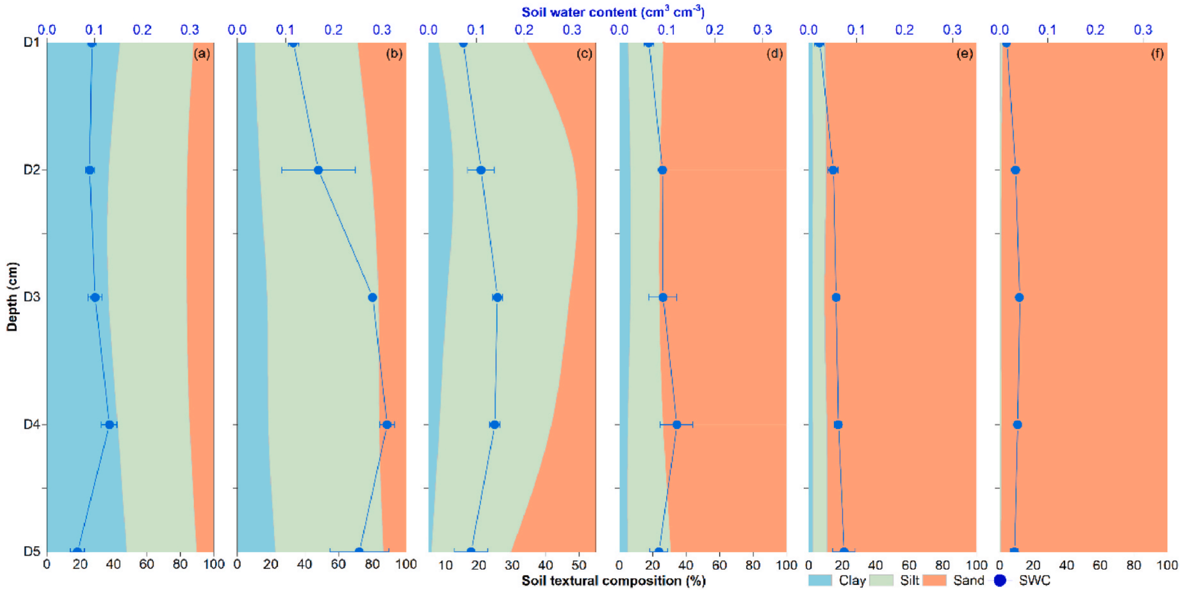

Fig. 3. Soil texture composition and soil moisture content in 0–50 cm soil layers in ND (a), SLD (b), LD (c), MD (d), HD (e), and SD (f). D1-D5 refer to 0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, and 30–50 cm soil depths, respectively. (The same abbreviations are used in the following).

decrease with increasing desertification (Fig. 4df), while total phosphorus increases and decreases with desertification (Fig. 4e).

3.2. The abundance of microplastics

Microplastics were detected in soils at 0–50 cm depths in all surveyed sites. The abundance of microplastics detected ranged from 182 to 17,841 items kg^{-1} (dry weight), with a median of 3369 items kg^{-1}. The abundance of soil microplastics differed between vegetation types ($P < 0.001$), with the highest SLD (8096 ± 2291 items kg^{-1}) and the lowest SD (339 ± 42 items kg^{-1}). The abundance was not significantly different at different levels of desertification, with a mean of (4611 ± 705 items kg^{-1}) (Fig. 5a). The quantity at 20–50 cm depth (6419 ± 1362 items kg^{-1}) was significantly higher than at 0–5 cm (2064 ± 288 items kg^{-1}) and 5–20 cm (3567 ± 533 items kg^{-1}) at all sample sites ($P = 0.03$) (Fig. 5b). Microplastic abundance significantly decreased with increasing soil depth at SD and ND sample sites in the study area (Fig. 5c). At the same time, LD, MD, HD, and SLD, in contrast, showed a significant increase in microplastic abundance with increasing soil depth (Fig. 5c). The abundance varied significantly under different types of vegetation desertification in the same soil layer (Fig. 5c).

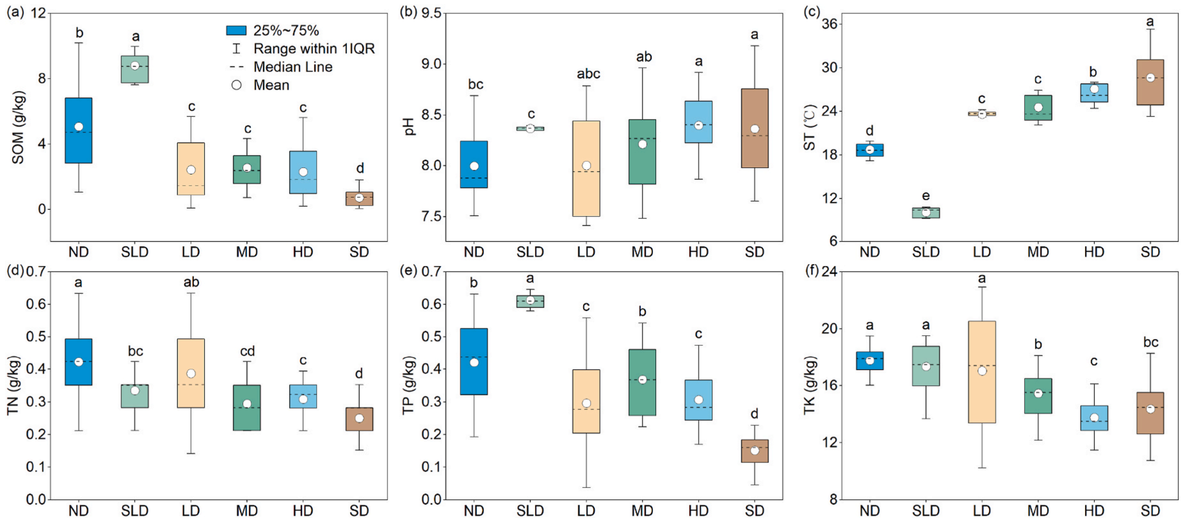

Fig. 4. Characteristics of SOM (a), pH (b), ST (c), TN (d), TP (e), and TK (f) characteristics of the sample plots with different types of vegetation and degrees of desertification. Box plot elements show the median (mean, white dots), the 25% and 75% interquartile range (box boundaries), and the 1 × interquartile range of data points (whiskers). Different lowercase letters indicate significant differences at the $P < 0.5$ level.

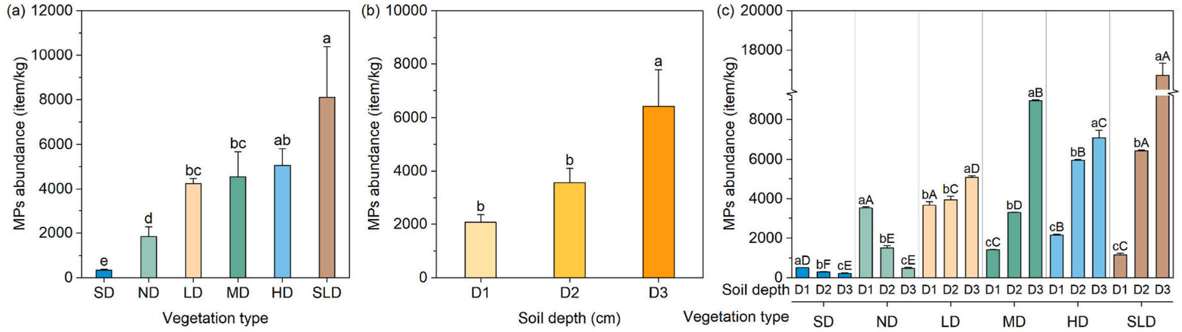

Fig. 5. Soil microplastic abundance under different vegetation and desertification types (a), different soil depths (b), and various vegetation desertification types and soil depths (c). Different lowercase letters indicate significant differences under vegetation desertification type and soil depth (a, b). Different lowercase letters indicate significant differences between different soil depths for the same vegetation type, and other uppercase letters indicate significant differences between different vegetation desertification types for the same soil layer (c). D1-D3 refers to soil depths of 0–5, 5–20, and 20–50 cm, respectively.

3.3. Types of microplastic polymers

A total of 24 microplastic polymers were detected, and the top three with the highest abundance were PU (37.3%), SR (17.0%), and CPE (9.8%), accounting for a total of 64.1% (Fig. 6, top left, all plots). The two maximum polymer abundances of microplastic in different soil layers were both PU and SR, with a combined percentage of D1 (17 types, 67.2%), D2 (15 types, 53.7%), and D3 (17 types, 48.1%), respectively (Fig. 6, top right, D1-D3). The maximum two polymer abundances of soil microplastics in the sample sites SD (3 types, 94.9%), ND (14 types, 70.0%), and LD (10 types, 85.9%) were also PU and SR (Fig. 6, bottom). Twelve types were detected in MD, and the top three abundance types were CPE (25.5%), BR (12.4%) and SR(9.7%), with a total of 47.6%; 11 types were detected in HD, and the top five types with the highest abundance were PLA (26.4%), SR (24.4%), PU (20.3%), CPE (14.3%), and PMMA (8.1%), which together accounted for 93.5%; twelve types were detected in the SLD, and the top three types with the highest abundance were PU (39.8%), POM (9.3%), and PET (8.8%), which together accounted for 57.9% (Fig. 6, bottom).

The types and relative abundance of soil microplastic polymers in the study area are shown in Fig. 7a, with eight types with abundance >3%, accounting for 86%, and the remaining 16 types accounting for only 14%. The composition and relative abundance of microplastic polymer types for different kinds of vegetation desertification and soil depths are shown in Fig. 7b, with significant differences in the composition and abundance from natural deserts (14 types), deserts with different degrees of desertification (10–12 types) and, saline deserts (12 types) sandy deserts (3 types). The polymer types of microplastics varied slightly from one soil layer to another (15–17 types), with a total of 11 polymer types in the three soil layers (Fig. 7c).

3.4. Morphological features of microplastics

The particle size of microplastics in this study was detected in the 20–500 μm range. The median width, height, and aspect ratio of microplastic particles in the study area were 51 μm, 45 μm, and 1. The sizes were concentrated in the range of 20–60 μm, with significant differences in width ($P = 0.05$), height ($P < 0.001$), and aspect ratio ($P = 0.011$) between the different layers of soil. The size of the microplastic particles in the D3 layer of soil was significantly more extensive than that of the D1 and D2 (Fig. 8a). The median microplastic particle area, diameter, and perimeter were 813 μm^2, 32 μm, and 240 μm. The differences in microplastic particle area ($P = 0.001$), diameter ($P = 0.001$), and circumference ($P = 0.025$) were significant among different soil layers (Fig. 8b).

The correlation between microplastic size, area, and shape indicators was strong (Fig. 9a). Microplastic abundance was only significantly and positively correlated with soil EC and TP. It was not significantly

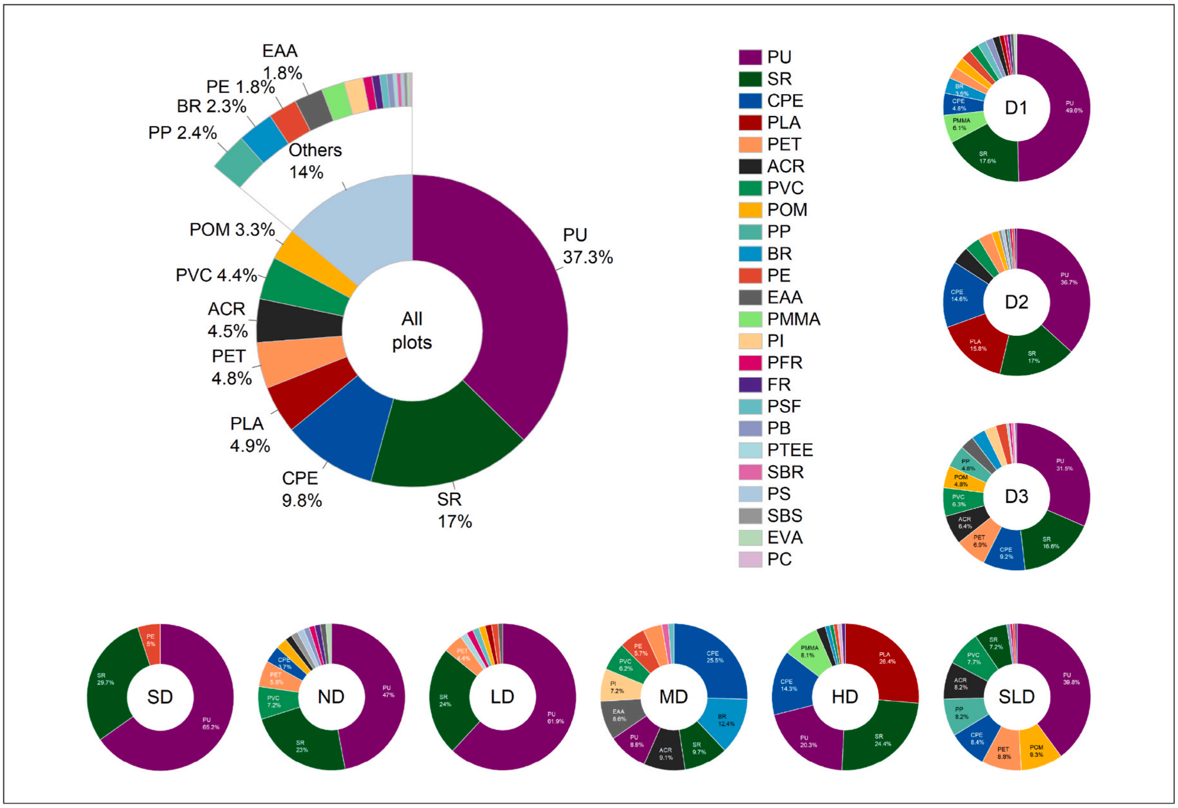

Fig. 6. Composition of soil microplastic polymer types at each site (top left), at different depths of soil (top right), and at different vegetation types of desertification types (bottom) in the study area. PU: Polyurethane; SR: Silicone resin; CPE: Chlorinated polyethylene; PLA: Polylactic acid; PET: Polyethylene terephthalate; ACR: Acrylates; PVC: Polyvinylchloride; POM: Polyoxymethylene; PP: Polypropylene; BR: Butadiene rubber; PE: Polyethylene; EAA: Ethylene acrylic acid; PMMA: Polymethylmethacrylate; PI: Polyimide; PFR: Perfluoroether rubber; FR: Fluororubber; PSF: Polysulfone; PB: Polybutadiene; PTEE: Poly tetra fluoroethylene PTFE; SBR: Polymerized styrene-butadiene rubber; PS: Polystyrene; SBS: Styrene-butadiene-styrene; EVA: Ethylene vinyl acetate copolymer; PC: Polycarbonate.

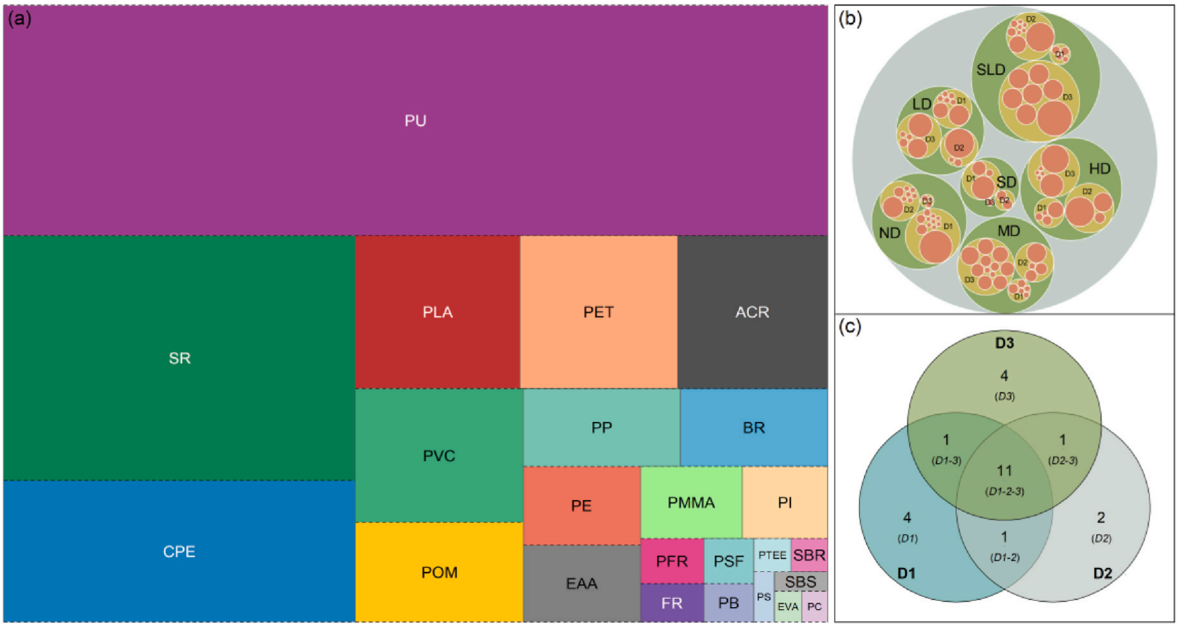

Fig. 7. Composition and relative abundance of soil microplastic polymer types at all survey sample sites (a), different vegetation, desertification types (b, circle nested plots showing the variety (number of red circles) and abundance (indicated by red circle size) of microplastic polymer types in samples of different vegetation types and desertification levels (green circles) and at different soil depths (earthy yellow curls)), and other soil depths (c).

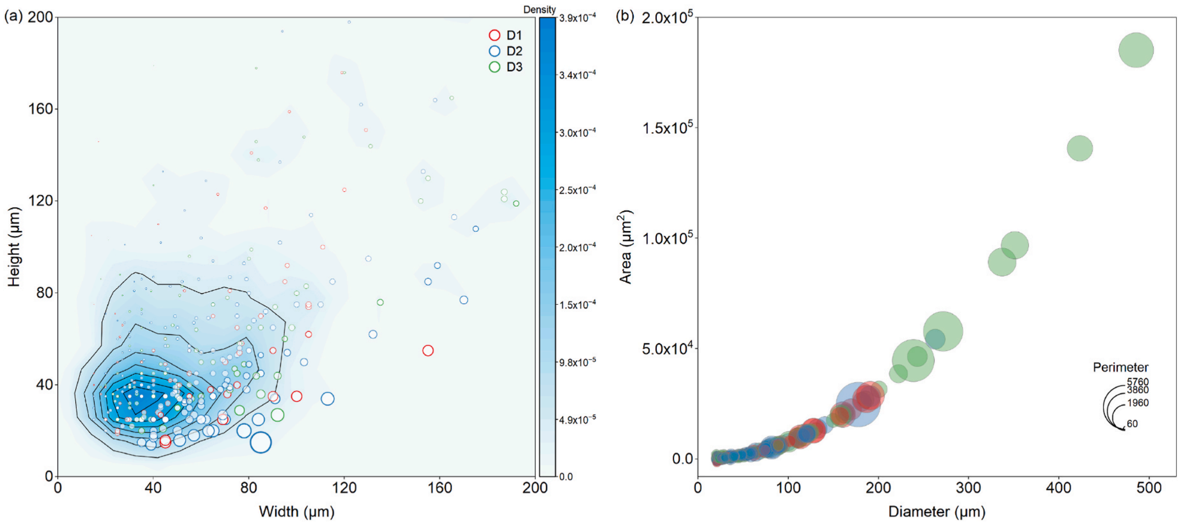

Fig. 8. Size (a) and area (b) characteristics of microplastic particles at different soil depths.

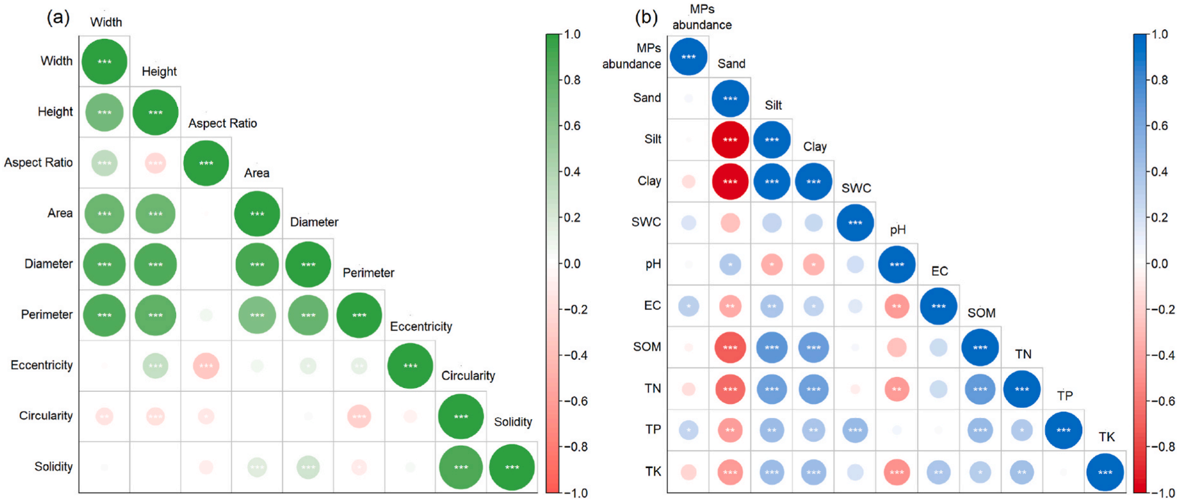

Fig. 9. Pearson correlation between microplastic morphological indicators (a), microplastic abundance, and soil factors (b). $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. SOM: soil organic matter; pH: soil pH; EC: soil electrical conductivity; TN: total nitrogen; TP: total phosphorus; TK: total potassium.

associated with other soil indicators (Fig. 9b).

4. Discussion

4.1. Effects of desertification on vegetation and soil properties

Desertification is land degradation that occurs in drylands and affects the function of dryland ecosystems in providing services (UNCCD, 2022; Whitford and Duval, 2020). In this study, desertification significantly reduced soil nutrient levels and altered soil texture composition, hydrothermal conditions, and vegetation characteristics (Figs. 2–4). The results of the study are consistent with those observed during desertification in different regions of the world, i.e., the soils become coarser and drier, and soil organic matter or nutrient content of the soil decreases rapidly with increasing desertification levels (An et al., 2019; Arneth et al., 2021; Hu et al., 2020; Wang et al., 2022a). Dryland desertification is typically caused by climate change and human activities. In recent decades, climate change has caused desertification in more areas of Central Asia (Yu et al., 2019), and this rapid expansion will significantly impact ecosystems and the populations and animals that rely on them (Guglielmi, 2022). As global temperatures have increased, the mid-latitude desert climate in Central Asia has expanded more than 100 km northward since the 1980s (Hu and Han, 2022). In addition, evident grazing traces, such as livestock foraging, trampling, or dung left behind, were observed in almost all sample sites during field surveys. We speculate that grazing may be the most critical anthropogenic factor contributing to land desertification in the region, in addition to climatic factors such as warming, changing rainfall patterns, and extreme weather.

4.2. Effect of desertification on the abundance and distribution of microplastics

Microplastic particles were detected in all soil samples in this study, with abundances ranging from 182 to 17841 items kg^{-1} and significant differences between sites (Fig. 5a). The results were within the range of microplastic abundances detected in different terrestrial environments worldwide (Boyle and Örmeci, 2020; Chang et al., 2022; Chia et al., 2022; You et al., 2022; Zhao et al., 2022a). In global studies of microplastics in terrestrial environments, differences in sampling environments, sampling depths (the vast majority of sampling depths are between 0 and 10 cm), land-use types, disturbance histories, and detection methods have led to wide variations in the results of the studies and difficulties in comparing and assessing the abundance of microplastics in different terrestrial environments (Fok et al., 2020; Ivleva, 2021; Praveena et al., 2022; Silva et al., 2018). However, almost all results show that in areas with heavy plastic use, such as mulched agricultural fields (Jin et al., 2022; Li et al., 2022; Yang et al., 2022; Zhang et al., 2022a), or sites where plastic pools, such as sludge or sediment (Nguyen et al., 2022), or where high human activity and densely populated areas, such as periurban areas (Liu et al., 2022), soils have a higher abundance of microplastics. Our results showed that microplastic abundance was lowest in SD, followed by ND, and highest in SLD, while the difference in microplastic abundance between the sample sites with different degrees of desertification (LD, MD, HD) was insignificant. On the contrary, the SLD sample sites were located near the Aral Sea, and the survey sample sites were in the sedimentation zone after the Aral Sea shrank. Microplastics are usually pooled on the shore, thus having the highest microplastic abundance in soil sediments (Fig. 5a).

In studies on environmental microplastics in agricultural fields (Li et al., 2022; Zhao et al., 2022b), wetlands (Lu et al., 2022), sediments (Kabir et al., 2022), and offshore mudflats, soil samples were typically collected from the surface layer (Li et al., 2023). In this study, soil samples were collected in three layers at 0–50 cm depth, and microplastics were detected in samples at all depths. Overall, deeper layers had higher microplastic abundance, significantly higher than shallow layers (Fig. 5b). However, the variation was inconsistent at different sites, with a higher abundance in surface soils in sandy deserts and natural deserts and the opposite in desertified deserts and saline deserts, where the abundance was higher in deeper soils (Fig. 5c). In general, it is believed that, in addition to climatic factors thought, desertification is usually caused by irrational human activities, such as agricultural production, overgrazing, land development, and recreational activities (UNCCD, 2022). Human activities may bring more plastic products, such as bags, fertilizers, mulch, plastic tools, waste, etc., together with disturbances caused by human activities in a hot and dry environment, resulting in large plastic fragments being mechanically broken or becoming smaller in size or particles by weathering and erosion (Zhang et al., 2022b; Zhao et al., 2022b). At the same time, as the degree of desertification increased, the sand particles in the soil increased significantly, the content of silt and clay particles decreased, and the soil became looser and drier with higher soil temperature (Figs. 3 and 4c). All of these factors favor the fragmentation, fracturing, weathering, and migration of plastic debris. Either carried further away in windy weather or affected during rainfall, it migrates with rainwater to deeper soil layers, where it eventually collects (Fig. S1). Compared to desertified soils, surface soils under natural vegetation are more intact and dense, have a higher content of clay and silt particles, are less disturbed, and plastic debris or particles usually accumulate in the surface layer (Fig. 3). On the contrary, sandy deserts rarely get in deeper layers because of less human disturbance. At the same time, typical windy weather carries microplastic particles along with sand and dust to distant areas (Wang et al., 2021a). The dry and wet deposition also predominantly affects the transport and abundance of microplastics in the air (Abbasi and Turner, 2021; Sridharan et al., 2021).

4.3. *Types of microplastic polymers*

According to statistics, plastic products are used mainly in packaging (45%), construction (19%), and transportation (7%) (Geyer et al., 2017). The main types and the percentage of their use were in descending order: polyethylene (PE, 36%) > polypropylene (PP, 21%) > polyvinyl chloride (PVC, 12%) > polyethylene terephthalate (PET, 10%) > polyurethane (PU, <10%) > polystyrene (PS, 8%) (Geyer et al., 2017). A total of 24 plastic polymers were detected in this study, with the top three highest abundances being PU (37.3%), SR (17.0%), and CPE (9.8%), and the abundance of their species was essentially the same across soil depths, with 11 polymers in the three soil layers (Fig. 7a, Fig. S5), with slight differences in the variety of sites (Figs. 6 and 7b,c, Fig. S5). Cluster analysis showed that ND differed from MD, where SD and HD were similar, and LD was similar to SLD (Fig. S3a). Different types of plastic polymers were also categorically clustered (Fig. S3b).

Because plastic is a synthetic product, its accumulation in the natural environment is closely related to the type and amount of plastic used in local production. For example, PE, PP, and PS are common types of plastic in agricultural soils (Jin et al., 2022); PP, PE, and PS are usually dominant in the ocean and sediments (McGlade et al., 2021), while atmospheric microplastic is more diverse, with PET, PE, PS, and PP (Brahney et al., 2021). Unfortunately, we did not collect data on the production and use of plastic products in the region; therefore, future research will need to identify local plastic product types and use them to identify microplastic sources better.

4.4. *Effect of desertification on the morphological characteristics of microplastics*

More than 80% of the microplastic particles detected in this study were smaller than 0.5 mm, with a full-size distribution of 20–60 μm, and significant differences between samples and soil layers (Fig. 8, Figs. S1 and S2a). Microplastic abundance increased with decreasing particle size, in agreement with previous reports (Bi et al., 2023; Wang et al., 2021b). It has been shown that smaller microplastic particles can easily migrate between ecosystems under wind, rain, etc., with detrimental effects on soil organisms (Chang et al., 2022). For example, soil animals are more likely to absorb and ingest smaller microplastic particles, adversely affecting their health (Lim, 2021). At the same time, smaller particle sizes mean that microplastics are more likely to be carried by the wind into the atmosphere and transported to more distant locations, resulting in microplastic transport pollution (Allen et al., 2019; Bergmann et al., 2019; Brahney et al., 2020; Rochman, 2018). A recent modeling study showed that as the Aral Sea rapidly shrinks, the winds lift large amounts of dust from the Aralkum Desert and disperse it into Central Asia, raising public health concerns (Banks et al., 2022). This dust is more dangerous than ordinary particulate matter because it contains salts and residues from agricultural pesticides and fertilizers discharged into the Aral Sea. There is no doubt that these mixtures also contain large amounts of microplastic particles (Long et al., 2022).

The microplastic particles detected in the study were predominantly noncircular (Fig. 8, Fig. S2b, Fig. S5). The shape of microplastic particles may affect their transport distribution in the environment (Glaser, 2015). Additionally, it may affect direct uptake by organisms or cause physiological toxicity, which in turn may affect the health of organisms (Lin et al., 2022; Sridharan et al., 2022; Wang et al., 2022b). Some controlled experiments on microplastic addition usually considered only the abundance of microplastics added and ignored the size and shape of microplastic particles, which need to be given adequate consideration in future studies.

Microplastics that enter the soil through different pathways (e.g., mulch cover, wet and dry deposition, irrigation, human activities, etc.) can be transported horizontally and vertically in the subsurface as a result of land management, water cycling, and bioturbation. During this process, microplastics may affect soil physicochemical properties (Wang et al., 2022b). For example, sandy soils' capacity decreases with the increase of microplastics (de Souza Machado et al., 2019). Plastic films affect the infiltration and redistribution of soil water (Junhao et al., 2022), as well as the heavy metals in the soil (Feng et al., 2022), soil properties (Chia et al., 2022; de Souza Machado et al., 2019; Wang et al., 2022c). However, our study did not find a good correlation between microplastics and vegetation and soil properties. Only microplastic amount was found to be positively correlated with soil pH. Particle area correlated with EC, while roundness and solidity negatively correlated with TP (Fig. 9, Fig. S4). This could be because the desertification sample sites in the study area experienced more soil disturbance, resulting in smaller microplastic particles. Plastic particles migrated and aggregated to the deep soil layers and did not correlate significantly. It is also important to note that the detection range of microplastic particles in this experiment was 20–500 μm in size, which does not exclude that smaller microplastic particles were not adequately observed migrating to deeper soil layers due to the detection limit. It has also been confirmed that lower mass concentrations (7%) of microplastics have a minimal effect on soil properties (Liu et al., 2017). Given that the actual microplastic content in the soil is significantly lower than this percentage, the impact of microplastics on soil properties needs to be further investigated in depth through rigorously controlled experiments.

5. Conclusions

The abundance and distribution of microplastics in soils from 0 to 50 cm deep during desertification in the drylands of the Amu Darya-Aral Sea basin in Central Asia were investigated. The microplastic abundance in the study area ranged from 182 to 17841 items kg^{-1}, with significant differences in microplastic abundance in natural vegetation areas, desertified desert and saline desert soils, and significantly different microplastic distribution in different soil layers. The desertification process greatly affected the abundance and led to the migration of microplastic particles to deeper soil layers. Small size (20–60 μm) and non-round shape were the main microplastic particle characteristics observed. A total of 24 polymer types were detected, with PU, SR, and CPE being the dominant polymer types, accounting for 64.1%. Desertification significantly affected the physicochemical properties, hydrothermal conditions of the soil, and vegetation characteristics, increased the abundance of microplastics in the soil, and promoted the migration of microplastic particles to deeper soil layers. Grazing is probably the most essential anthropogenic factor in the region's land desertification and microplastic input. In general, these findings highlight the abundance and distribution of microplastics in desertified soils in Central Asia, and the results provide meaningful guidance for an accurate assessment of the microplastic distribution of microplastics during desertification in drylands and prevention and control.

CRediT authorship contribution statement

Peng Zhang: Conceptualization, Methodology, Software, Data curation, Validation, Writing – original draft, Visualization, Investigation, Writing – review & editing, Supervision. **Jin Wang:** Methodology, Data curation, Validation. **Lei Huang:** Data curation, Validation, Visualization, Investigation. **Mingzhu He:** Data curation, Validation, Visualization, Investigation. **Haotian Yang:** Data curation, Validation, Visualization, Investigation. **Guang Song:** Methodology, Investigation. **Jiecai Zhao:** Methodology, Investigation. **Xinrong Li:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (Grant numbers: 32061123006), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant numbers: XDA2003010301).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119353.

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