



Distribution and composition of plastic debris along the river shore in the Selenga River basin in Mongolia

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Abstract

Plastic pollution in aquatic environments is one of the most fatal environmental issues in the world. Although the distribution of plastic debris in the sea and at coasts has been addressed, the transportation of plastics through a river system is unclear but important. The distribution of plastic debris in the Selenga River system is responsible for the environmental pollution of Lake Baikal. Twelve sampling sites along the river shore of the Selenga River system have been surveyed considering the industrial activity and population density. The number of plastics significantly correlates with the population density. The higher the number of plastics is, the smaller is the average size. The size fractions of foam and film plastics show a significant relationship, suggesting that the plastic debris fragmented on-site on the river shores. The most abundant plastic debris is polystyrene foam (PSF), which is usually used for construction and packaging. Plastic debris occurs due to insufficient plastic waste management. Its distribution is affected by seasonal changes of the water level and flow rate of tributaries. Furthermore, the fragmentation of plastic debris is related to temperature changes associated with freeze and thaw cycles, solar radiation, and mechanical abrasion. Smaller microplastics with microscopic sizes were detected in PSF debris. Based on micro-Fourier transform infrared spectroscopy, these microplastics are polystyrene and polyethylene. This study proves that invisible and visible microplastics are transported together.

Keywords Microplastics · Micro-FTIR · Plastic fragmentation · Polystyrene foam · Adsorption

Introduction

One of the environmental concerns of the last century is plastic debris, which is accumulated and scattered in the environment due to the increase in the population and consumption of plastic materials. Annually, more than 300 million tons of plastic materials are produced and consumed in the world (PlasticsEurope 2016; Zalasiewicz et al. 2016; Andrady 2017). Therefore, plastics released by humans on land are

major sources of marine plastic debris, accounting for 80% of the release (Sheavly 2005; Andrady 2011) from the land to the marine environment through riverine transport (Sadri and Thompson 2014; Horton et al. 2017). The transportation of masses of plastic debris has been reported for major rivers such as the Los Angeles River (Moore et al. 2011), Yangtze Estuary (Zhao et al. 2014), Tamar Estuary (Sadri and Thompson 2014), Danube (Lechner et al. 2014), and Rhine (Mani et al. 2015). Apart from the occurrence of plastic debris, there is little information about plastic debris in freshwater environments in high and low population areas and its distribution pathway. Understanding the behavior of plastic waste in a river environment is essential and the main focus of plastic debris studies because it is preliminary information for further studies on its effect on the environment.

Plastic debris originates from various sources but can be categorized into two types: primary debris, which is directly released to the environment without any degradation from the source, and secondary waste plastics, which are fragmented from the original size to smaller sizes by any type of force (Barnes et al. 2009; Gregory 2009; Cole et al. 2011; Wagner et al. 2014). Synthetic plastics that originate from both types

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of plastic debris lead to multiple environmental concerns (Wilkinson et al. 2017). The size reduction of plastic debris is one of the environmental concerns because it affects the biosystems by increasing the bioaccumulation through ingestion processes by various types of organisms (Cole et al. 2013; Lima et al. 2014; Mattsson et al. 2015; Tanaka and Takada 2016; Lei et al. 2018). Smaller debris has a high potential to adsorb persistent organic pollutants (POPs) (Frias et al. 2010; Browne et al. 2013; Zhang et al. 2015), accompanied by the release of chemical additives into the environment. Furthermore, plastic waste can carry other pollutants (Engler 2012). Based on this process, organic pollutants can be concentrated, which are then distributed into the oceanic environment. The ingestion of microplastics by organisms is also a serious environmental concern (Cole et al. 2014; Eerkes-Medrano et al. 2015; Vandermeersch et al. 2015; Li et al. 2016). The fragmentation of large plastics by physical processes (solar radiation) and/or mechanical forces is responsible for the release of microplastics into the environment (Barnes et al. 2009; Gewert et al. 2015; Kooi et al. 2017).

In a freshwater system, most detected and potentially transportable plastic materials are micro-sized fibers (Dris et al. 2015a, b; Miller et al. 2017; Lei et al. 2018). The higher concentration of microfibers in a river is the result of mixing of sewage water, water released from wastewater treatment plants (WWTPs), and atmospheric fallout. However, fragments and foamed plastics were also observed in several freshwater rivers and lakes (Moore et al. 2011; Mani et al. 2015). Because of the lack of data about plastic debris, there is little information about processes associated with fragmentation, redistribution, and changes of the properties of plastic debris in freshwater environments.

The main reason for the wide distribution of plastic waste in the environment is inappropriate waste management due to the lack of understanding of the behavior of plastic waste. Statistical data indicate that the production of plastic waste is higher than the recovery of plastic waste (Barnes et al. 2009). The fate of plastic debris released on ground surfaces has not yet been determined. The identification of the transportation pathway of plastic debris in large areas is necessary to understand its further distribution and reactivity. Fate of plastic debris in many developing countries is now addressed because rapid economic growth increases the production and consumption of plastics, but recovery systems are not established.

Mongolia, which is one of the developing countries, is a landlocked country in Central Asia. Since the 1990s, drastic socioeconomic changes led to environmental changes in Mongolia such as increased urbanization, air pollution in Ulaanbaatar City, water pollution caused by mining activities (Fan et al. 2016; McIntyre et al. 2016), and increased plastic material consumption (30%, produced in Mongolia; 70%, imported from other countries) (National Statistical Office of Mongolia 2015; Customs General Administration of Mongolia 2017).

Based on the abundance of plastic debris in areas with high population densities, rivers potentially transport plastics to open water systems. The tributaries of the Selenga River system flowing to the largest freshwater lake “Baikal” represent the largest waterway in Mongolia. Economic growth of the twenty-first century led to an increased quality of life and consumption of industrial products, including plastics, in populated cities, such as Ulaanbaatar, Darhan, and Erdenet, in the Selenga River basin in northern Mongolia. Recent heavy metal contamination studies showed that basic and anthropogenic activities, such as mining, land use change, and urbanization and socioeconomic activities strongly influence the health of the environment in Mongolia and of Lake Baikal (Batbayar et al. 2017; Batsaikhan et al. 2017; Malsy et al. 2017; Myangan et al. 2017). With respect to the abundance and distribution of plastics in Mongolia, only one study focused on the remote mountain lake Khuvsgul (Free et al. 2014). The results showed an abnormally high concentration of plastic debris (average microplastic 20,264 particles km⁻²) in the lake, which is far from populated areas.

In this study, we firstly focused on the occurrence, behavior, and fragmentation of plastic debris on river shores of the Selenga River system to ascertain the distribution of visible plastics along the river. Secondly, we determined the characteristics and occurrence of microplastics that are attached to surfaces of polystyrene foam (PSF) and identified types of fragmented plastics because microplastics, which are one of the fragmented pieces of plastic debris, have a great potential to be distributed in the whole ecosystem based on different pathways. We also evaluated the frequency of plastic debris in the river basin, potential for microplastics transportation to downstream aquatic environments, and structural properties of microplastics attached to plastic debris.

Materials and methods

Waste management in Mongolia

The study area is in the Selenga River Basin, which consists of the following five tributary basins: Tuul River (length 704 km; catchment 50,074 km²), Kharaa River (length 291 km; catchment 17,697 km²), Yeruu River (length 323 km; catchment 22,280 km²), Sharyn River (relatively small river, included in the Kharaa River Basin), and Orkhon River (length 1124 km; catchment 53,455 km²) (Fig. 1). Major cities, such as Ulaanbaatar, Darkhan, Erdenet, and Sukhbaatar, have high population densities and industrial activities including several types of mining and quarrying, processing and other manufacturing industries, and constructions and trade markets. These cities are located along these major tributaries and affecting the waste management. In Mongolia, various types of wastes released from industries, agriculture, and daily

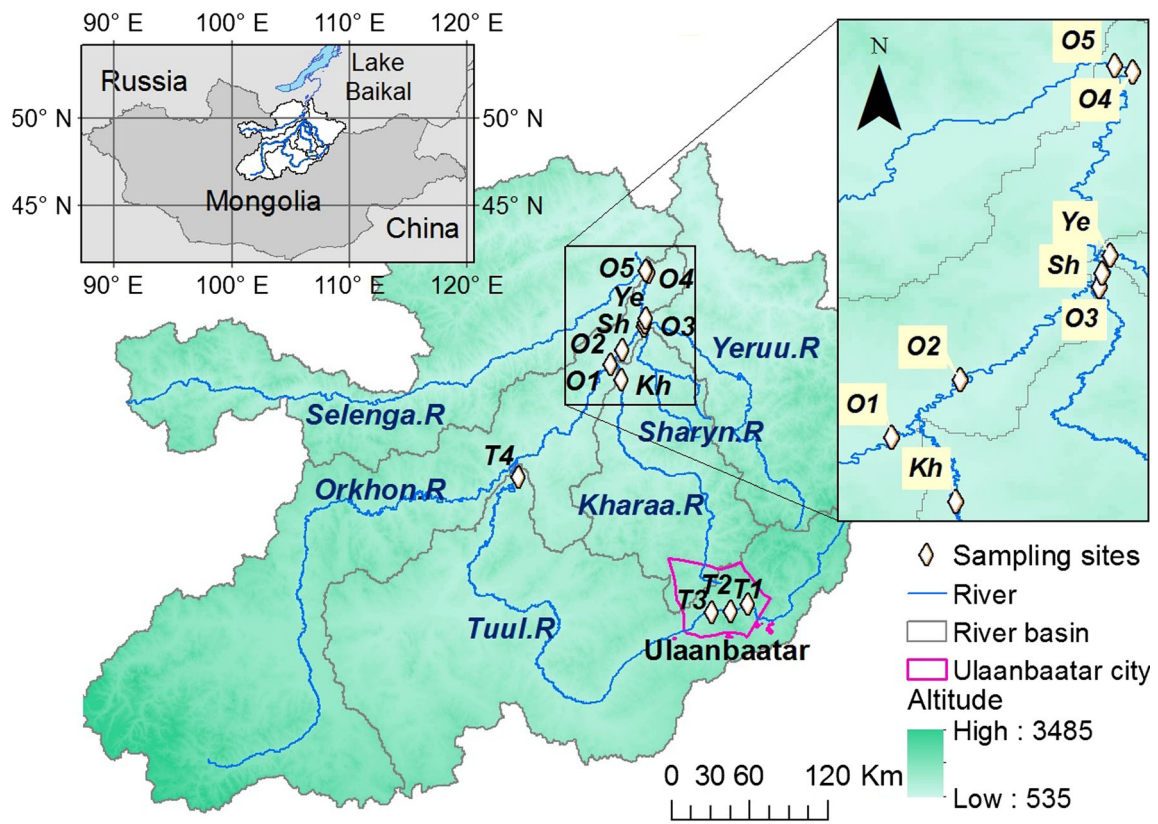


Fig. 1 Selenga River basin in Mongolian territory and survey sites in the basin with sampling points

life are mainly managed by landfill method without any specific treatment and measures to prevent scattering wastes to the air. In 2015, 2.3 million tons of waste were disposed into 371 landfill sites in Mongolia (Environmental Information Center 2015). The major part of generated waste (89.5–92.2%, in 2015) was transported to the landfill sites, and the rest of waste was lost into surrounding environment during transportation and/or illegal deposition (JICA 2012; Delgermaa and Matsumoto 2016). Residential area settlement and low levels of sewage water systems have been recognized as a major pollution source of river water (Itoh et al. 2011). In some residential areas, especially in remote area, household waste and sewage water have been dumped to the nearest illegal dumping sites such as on hills, on yards and alongside roads and waterways (Delgermaa and Matsumoto 2016). The rivers are subjected to various sources of pollution due to land use such as mining activities, agriculture, pasture land degradation, and WWTP in their watersheds (Nadmitov et al. 2015; Batbayar et al. 2017; Myangan et al. 2017).

Waste dispersion from landfill and illegal dumping sites are major sources of plastic debris in river catchments. Officially, there are three big landfills in Ulaanbaatar City and several landfills in towns or villages. Most of them are in the upland area of Ulaanbaatar (Byamba and Ishikawa 2017). The three main landfill sites in Ulaanbaatar weekly take approximately 18,000 t of waste, which include polyethylene terephthalate

(PET) bottles and other plastic wastes with the rate of 2% of the whole of wastes (Mongolian National Recycling Association 2018). Many other illegal small disposal sites are located around residential areas in Ulaanbaatar. Waste from personal disposal was found on the ground along roads, ditches, and riversides. Scattering of waste from small dumping sites by wind is also common. To clean up scattered waste, social volunteers and city official workers started to collect disposed waste along the Tuul riverside in Ulaanbaatar (Tuul River Basin Authority 2017). For example, the Tuul riverside in the Ulaanbaatar City area was cleaned up 13 times and 159.4 t of waste were collected in the 67 km² area of the river catchment by volunteers in Spring 2017. Cleanup activities usually focus on macro-sized plastic debris and most collected waste includes PET bottles and plastic polyethylene (PE) sheets. Broader and intensive inspection and strict control of the illegal disposal of waste are now considered along the tributaries. Low-density and smaller-sized plastics, which are easily blown away by wind (Free et al. 2014), are trapped by plants on the river shores and are redistributed by river flow during the snowmelt and rainy seasons when the water level and flow rate are high.

Field survey and sample collection

The study area is located in the Selenga River watershed between 47° 55' 24.92" N and 50° 14' 29.93" N and 104° 48' 33"

E and 107° 09' 56.09" E, ranging from central to northern Mongolia (Fig. 1). Twelve sampling sites were selected to investigate the distribution of plastic debris on the river shores, from the capital Ulaanbaatar City to Sukhbaatar City close to the border. The field survey and sampling have been conducted in the early August when was lower water level in the year. Plastic distribution on the shore is essential data to evaluate plastic pollution in the river and its accumulation through a year because floating plastics carried on high flow season have been left on the shore with decreasing water level on drought season on August. Active season for field recreation is also a good timing for the survey. Plastic distribution density as a volume basis has been determined in a large river with enough water depth trolling a net with fine mesh by a boat (Sadri and Thompson 2014). Since the water depth of the research tributaries was too shallow to collect plastics by trolling and the sparse flow in the river width makes it impossible to collect floating plastics with installed net across the tributary. The distribution on the shores can be a good indicator to compare differences along the river. Sampling sites were covered by various kinds of feather grass vegetation and broader particle sizes of stones. The sampling sites T1 to T3 are located at the upper stream in the river basin and included in Ulaanbaatar City. The shores were occupied by large stones, and feather grass vegetation was sparsely distributed on fine earth ground. The site T4 is at the conjunction of the two tributaries Tuul and Orkhon in the village Orkhontuul. The shore is muddy with low frequency of stones and is covered with less vegetation. Five sampling points (O1 to O5) were set along the Orkhon River. The sites O1, O2, and O3 are located at conjunctions with Kharaa, Sharyn, and Yeruu rivers, respectively. The shores of O1, O2, and O3 are stony and covered with less vegetation. Both O4 and O5 sampling sites are in Sukhbaatar City, which is near the border between Mongolia and Russia. The shores of two sites are sandy with low frequency of stones. Feather grass vegetation was sparsely covered on the sampling quadrates. The three sites Ye, Sh, and Kh are located at the lower tributaries of the Yeruu, Sharyn, and Kharaa rivers, respectively. The shore of Ye is occupied by boulders with grass vegetation. The Sh and Kh sites were sandy shores covered with sparse grass vegetation. Since the research methods such as NOAA (Masura et al. 2015) and GESAMP (2015) for plastic distribution density at sandy sea shores were not applicable in this study. The only way to evaluate plastic distribution on river shores was to collect all visible plastics in a unit area.

On the river shores along the tributaries, triplicate quadrates with 100 m² areas were selected to count plastics. Visible plastic debris was completely collected by several persons who were trained to find microplastics within the quadrate by hand. The collected plastic pieces were counted and classified based on their size and morphotypes in the field. The size of the collected plastics was classified into mega- (> 100 mm), macro- (>

20 mm), meso- (5–20 mm), and microfractions (< 5 mm; Suaria and Aliani 2014; Lee et al. 2015). Furthermore, the plastics were classified into four morphotypes, such as fiber, film, foam, and fragment (Davis and Murphy 2015; Horton et al. 2017), based on their appearance and characteristics. The polymer types of the categorized plastics, that is, PE, polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), PET, and polyurethane (PU), were identified. Triplicate measurements enabled us to calculate the average number of plastic pieces and standard deviations for each sampling site. Population density data for corresponding cities, towns, and villages were collected from the National Statistical Information Center in Mongolia (National Statistical Office of Mongolia 2015).

Extraction of microplastics from PSF pieces

Microplastics adsorbed onto visible PSFs were identified using a micro-Fourier transform infrared (micro-FTIR) spectrometer (Shimadzu Co. Ltd., Kyoto Japan) after elimination of organic matter by Wet Peroxide Oxidation (WPO) (Baker et al. 2015). A subsample of the PSF debris in a tall beaker (500 mL) was digested with concentrated hydrogen peroxide (30%, H₂O₂) on a hot plate covered with a watch glass to avoid airborne contamination. The beaker was placed in an ultrasonic bath for several minutes to separate microplastic particles from PSF fragments. After the digestion, the solution was filtered through a Whatman glass microfiber filter (GF/F, pore size: 0.7 μm) to collect both visible PS foams and microplastics separated from the PSF plastics. Visible PSF samples were removed from the filter using tweezers. Microplastics collected on the filter were identified with a digital microscope (VH-7000, Keyence, Japan) and photographs were taken. The microplastics were further identified by micro-FTIR spectroscopy (Shimadzu Kyoto, Japan). Infrared spectra were obtained from the targeted square with a side of 100 μm and by repeated scanning (100 scans) from 4000 to 500 cm⁻¹. The target area is the smallest to obtain FTIR spectra with enough resolution for identification of plastic materials. Since some microplastics were too thin below the detection limit of 100 μm² to collect IR spectra, those small fragments and fibers were excluded from the identification of attached microplastics because of their small sizes.

Statistical analysis

Principal component analysis (PCA) and hierarchical cluster analysis (HCA) were conducted using IBM SPSS 22 (IBM Co Ltd.). The Ward's method was applied to extract principal components from collected data for PCA to characterize the distribution of plastics in the research area. The HCA was used to categorize the research sites based on the distribution and composition of plastic debris. Correlation analysis was carried out using Microsoft Excel to identify statistically significant

relationships between the sizes and morphotypes of the plastics.

Results and discussion

Total abundance and its characterization

Plastics were found in every sampling plot at all 12 studied sites. Typical plastic pieces collected on the shore of the Tuul River are shown in Fig. 2. The average number of plastics of all sites is 133.6 pieces/100 m² area; it ranges from 2 to 506 pieces/100 m² area. Table 1 shows the average number of different size fractions (mega, macro, meso, and micro) of plastics found on river shores. The average number of total microplastics (120.14 ± 121.49 pieces/100 m²) is higher than that of other size fractions of plastics (> 5 mm). Fragmentation is probably the major reason for the high number of visible microplastics. The most abundant morphotype of mega- and macro-sized and meso- and micro-sized plastics is PE film and PSF, respectively (Table 1). Pieces of PSF are characteristic for both micro- and meso-sized fractions in the study area. Both PSF and polyurethane foam (PUF) were found on the river shores. These materials are used as heat insulators in any type of construction. Both PSF and PE film materials are the most widely produced and consumed polymers in the world (PlasticsEurope 2015). Lee et al. (2015) found an average number of 919.1 particles/m² consisting of micro- (880.4), meso- (37.7), and macro-particles (1.0) per m² at high strand-lines of beaches in South Korea. The composition indicated the dominance of styrofoam and fiber in micro- and meso-sized and macro-sized fractions, respectively. Previous studies reported PE and PS as dominant types of plastic materials. The common composition of plastics can be attributed to high

production and consumption related to the population density (Fig. 3), and anthropogenic and land use activities in the studied river catchments. Blettler et al. (2017) reported 729.97 items/m² consisting of micro- (704), meso- (25.1), and macro-items (0.87) per m². Hard plastics, foamed plastics, and films have been found in the micro-, meso-, and macro-size fractions on the shore of the Setúbal Lake in South America (Blettler et al. 2017).

Size distribution and composition of plastic

The size distribution of the plastics is shown in Fig. 4a for each research site. An extremely high number of plastics was observed at sites T1, T2, and T3 close to Ulaanbaatar City. The locations close to both Darhkan City and Sukhbaatar City (Kh and O5) have a relatively high number of plastics. Small numbers of plastics were observed at the other sites along the tributaries of the Orkhon River (T4, O1, O2, O3, O4, and Sh) in locations far away from urban areas. The higher the number of plastics is, the smaller is the size. On the other hand, mega- and macro-size fractions are common at sites with a low number of plastic debris. The proportion of visible microplastics decreases from urbanized areas to areas with low population. The source and distribution of plastics could not be clearly identified in regions with lower population; however, plastics were still distributed from one to a few pieces within a 100 m² area, which were probably carried by river currents and wind from urbanized areas.

Four types of plastic materials (films, 14.7%; fibers, 1.7%; foams, 75.6%; and fragments, 8.0%) were identified in the study area (Fig. 4b). The predominant type of plastic pieces at each site depends on the regional environmental background including the population density and industrial and construction activities. Resin pellets represent common plastic

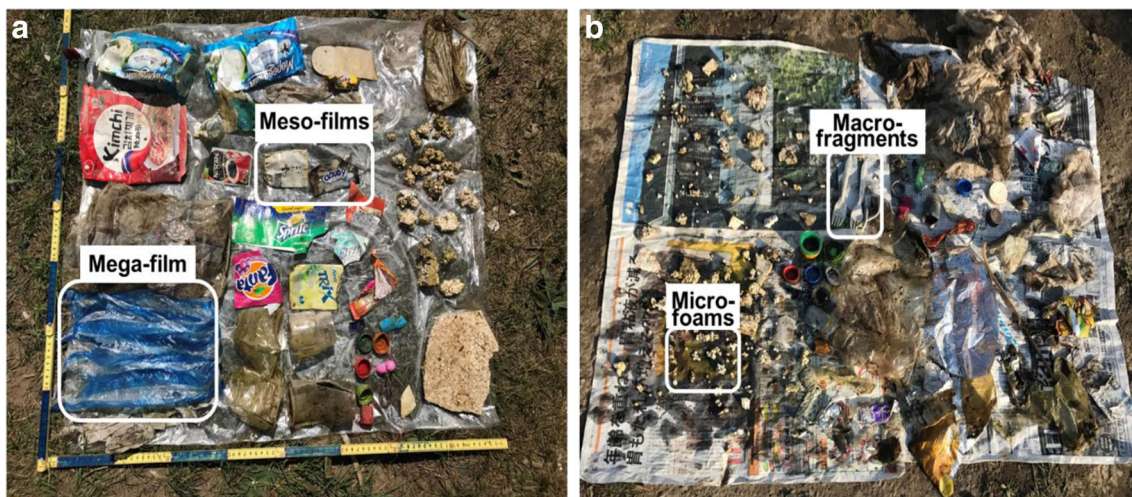


Fig. 2 Plastic debris collected at the T2 site on the shore of the Tuul River. **a** Mega- and meso-films are indicated by white squares. **b** Microfoams and macro-fragments are marked by white squares

Table 1 Abundance of plastic pieces according to different size fractions, dominant morphotypes, and polymer types observed in the research fields

Size	Average number of pieces/100 m ² ± SD	Dominant type of plastic material (%)	Major polymer type
Mega	3.93 ± 13.73	Film (51.2%)	PE
Macro	10.88 ± 37.03	Film (43.4%)	PE
Meso	14.90 ± 30.04	Foam (77.5%)	PS
Micro	120.14 ± 121.49	Foam (99.0%)	PS

SD standard deviation

debris in coastal and oceanic environments (Mato and Isobe 2001; Antunes et al. 2013) but were not found on the studied river shores due to the lack of plastic processing factories. The predominant plastic material in the microsize category is PSF, which was broken into pieces during the transport along the tributary.

Relationship between plastic distribution and urban areas

Figure 3 shows a significant relationship between the plastic abundance and population density ($R^2 = 0.949$). The study field T1 is upstream of the Tuul River; T2 and T3 are on the shore of the Tuul River, close to the urban district of Ulaanbaatar City. The total number of plastics is always higher on the river shore close to the city center. A relatively high plastics content was determined on the shore of the Kharaa River (Kh) near Darkhan City. A small number of plastics was observed along the Orkhon River. There are few

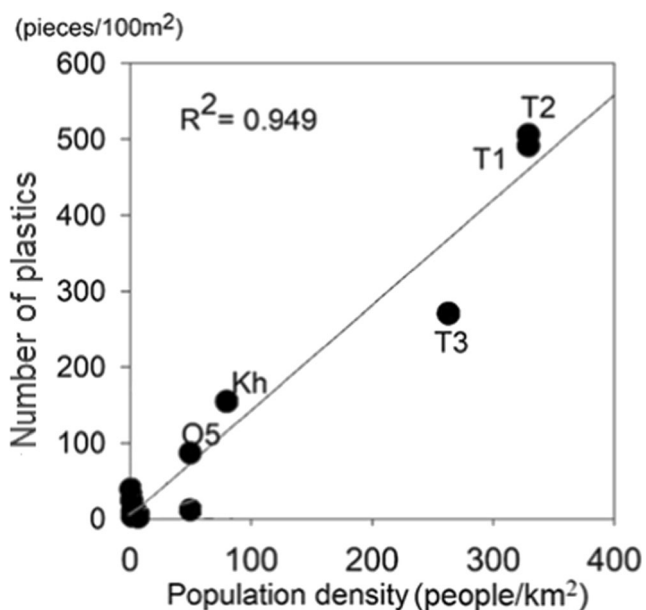


Fig. 3 Relationship between the number of plastics in a research area and population density at the town or village including the sampling site

larger residential areas along the Orkhon River, resulting in a small number of released plastics along the river shore. Populated areas are big sources of plastics along the river shores. An increase in the plastic waste with increasing population has been pointed out in Browne et al. (2011) and Andradý (2017). Nevertheless, Wang et al. (2017) noted that the abundance of microplastics in freshwaters in China is directly related to the distance from the urban center ($r = -0.895$, $p < 0.001$). The relationship between the population and plastic waste was also mentioned in other studies on lakes (Eriksen et al. 2013; Free et al. 2014). Although there is no significant relationship between the distance from the urban district to plastic waste deposits, our study also indicates a larger number of plastic wastes on the river shore close to urban districts than observed in any remote research field.

Multivariate statistical analysis

The PCA was conducted to characterize the plastic distribution using social statistics and data related to plastics. Two principal components were extracted from the PCA (Table 2) with 94.4% of the eigenvalue ($Ev = 7.6$). The first component (63.2%, $Ev = 5.1$) is plastic debris in urban districts, which strongly depends on macro- (0.897), meso- (0.984), and micro-sized (0.990) plastics; foam type (0.993); and population density (0.973; Table 2). The PSFs from the construction or manufacturing processes and home garbage used as packaging materials are the major sources of this urban distribution of plastics. The three size fractions in the first PC are predictable for a fragmentation process during transportation along the river. The second component (31.2%, $Ev = 2.5$) is characterized by mega-sized plastics (0.943), films (0.725), and fibers (0.958; Table 2). The plastic debris associated with the second component is distributed in remote areas because of the low contribution of population density. Mega-films and fiber plastic materials, such as plastic bags, sand bags, and plastic ropes, are the main components. During our field survey, we realized that many illegal dumping sites are in gullies on hills in the Ulaanbaatar District. The number of mega- and macro-sized films (e.g., sheets and plastic bags) is higher than that of meso- and micro-sized films in scarce population regions (Fig. 4), indicating that mega-film litter in and around urbanized areas is transported aerodynamically from the upstream through the river valley by water flow and wind (Barnes et al. 2009).

Based on the two components, the plastic debris along tributaries is concentrated in urbanized areas due to improper waste management and illegal littering and the plastic distribution can be discriminated based on the properties of the plastics. Film-type plastics with large sizes are naturally transported from urbanized areas to remote places by wind and river flow despite of the small number of plastics.

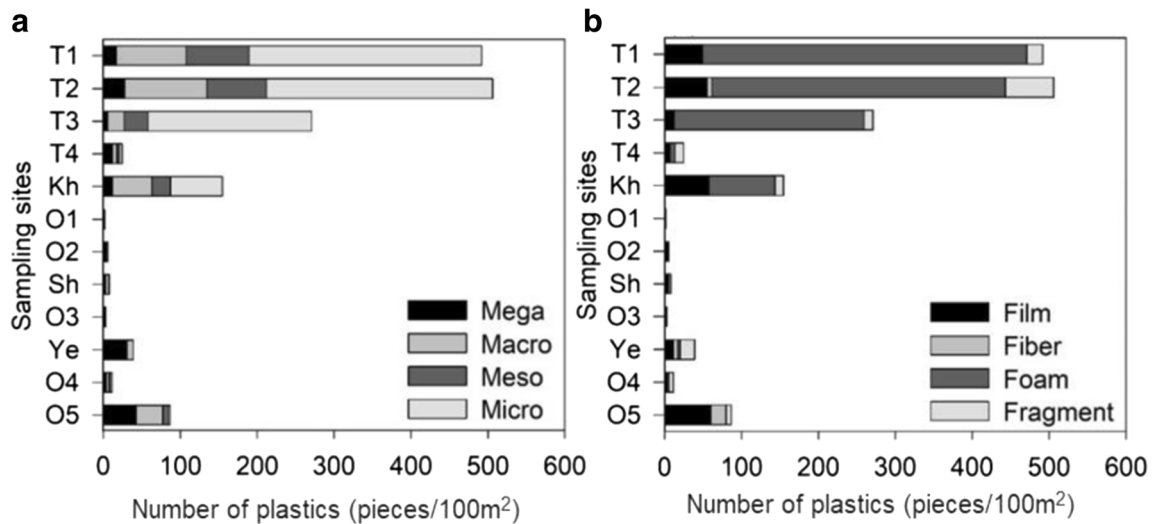


Fig. 4 Plastics counted at the study sites. **a** Composition of the size fractions at each site. **b** Composition of plastic morphotypes at each site

Foam-type plastics roll with the wind on the ground and flow with water flow along the tributary.

Based on the combined HCA and PCA, the sampling sites were classified into two clusters (Fig. 5), which can be distinguished by their plastic composition. Sites T1–T3 near Ulaanbaatar City were assigned to the first cluster. Other sampling sites were assigned to the second cluster. In addition, the Kh (Darkhan City) and O5 (Sukhbaatar City) sites can be discriminated from other sites in the second cluster based on the population density. Statistical multivariate analyses prove that major plastic waste mainly consists of microplastics concentrated in highly populated areas, while light mega-sized plastics are transported from the urban district to remote places. In addition, micro-PSF and plastic bags or sand bags represent typical plastic waste on river shores of Northern Mongolia with high population densities.

Table 2 Extracted component of PCA

	Component	
	1	2
Mega	0.152	0.943*
Macro	0.897*	0.375
Meso	0.984*	0.136
Micro	0.990*	0.021
Film	0.574	0.725
Fiber	-0.114	0.958*
Foam	0.993*	0.030
Pop.den.	0.973*	0.072

Pop.den. Population density

* Significant values

Relationship between plastic size fractions

The number of smaller-sized plastics is significantly correlated with that of larger-sized ones (Fig. 6 and Table 3). The significant positive correlation suggests that plastics on a river shore degrade into the smaller size fraction by aging through solar radiation, freeze–thaw cycles, and physical abrasion by wind and compaction processes (Andrady 2011, 2017). Because the size fractions consist of different polymer materials, it is difficult to prove that all larger-sized plastics are fragmented into the smaller size fractions on-site due to bio-fouling (Chubarenko et al. 2016). Significant correlations between size fractions of plastics were also reported for

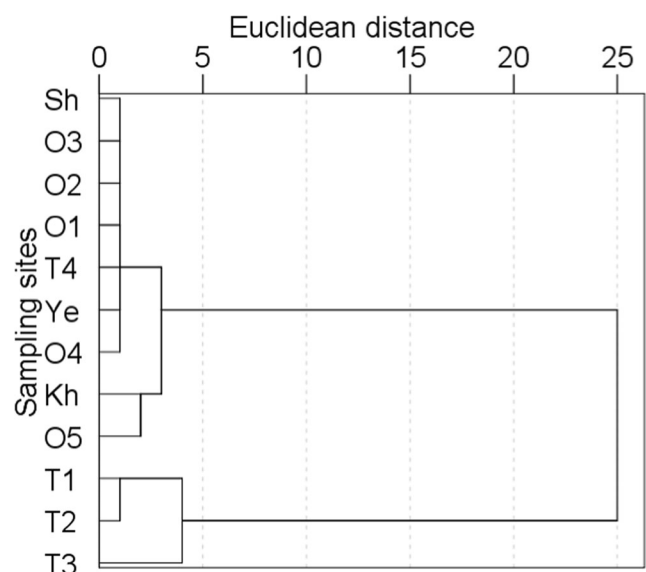


Fig. 5 The hierarchic cluster of sampling sites based on the principal component analysis

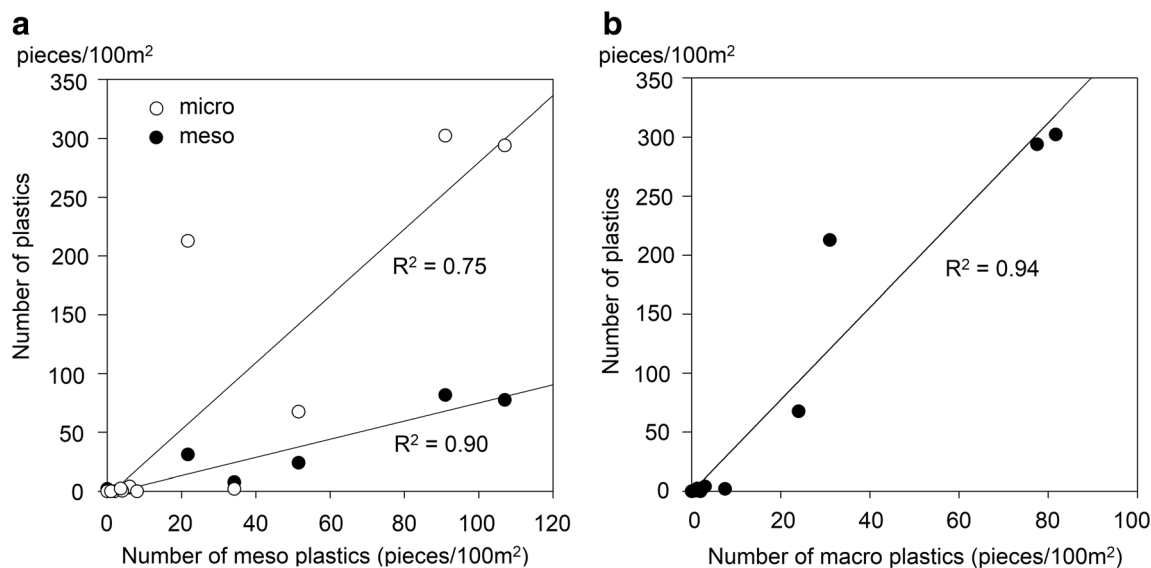


Fig. 6 Relationships between the numbers of plastics in the size fractions. **a** Macro- and meso-sized plastics, and macro- and micro-sized plastics. **b** Meso- and micro-sized plastics

Mediterranean Sea surface water (Faure et al. 2015b) and South Korean beach sediments (Lee et al. 2015). Despite of the differences in the magnitudes of the criteria of the size fractions, on-site fragmentation of plastic waste can occur everywhere in the world.

In addition, there are significant linear correlations between larger and smaller size fractions of film and foam plastics, indicating that on-site degradation of plastics leads to a consistent size composition of the two types of plastics (Table 3). Most PS and PE plastics degrade on-site and are accumulated at the same site. This reveals that plastics are potentially degraded and gradually distributed through river flow processes. Andrady (2011) and Mattsson et al. (2015)

mentioned that plastic degradation processes include biodegradation, thermooxidative degradation, photodegradation, thermal degradation, hydrolysis, and mechanical/physical degradation.

Significant relationships ($p < 0.001$) were observed between the size fractions of film materials (Table 3(a)). Meso-sized films show the highest correlation coefficient with the population density ($p < 0.05$), indicating that meso-sized films were fragmented from larger-sized materials and accumulated on-site in high population areas. The reason for the low content of mega- and macro-films is that those large-sized films on the river shores near the boundary were cleaned by volunteers or city sweepers. Microfilms released from the fragmentation of meso- and macro-films have a smaller correlation coefficient with the population density because they were broken down to invisible smaller-sized plastics or their long transport from urban areas smears the relationship.

Stronger correlations with significant correlation coefficients were observed between the size fractions of foamed plastic materials ($p < 0.01$; Table 3(b)). Furthermore, the population density is significantly correlated with macro- ($p < 0.01$), meso- ($p < 0.01$), and micro-PSFs ($p < 0.001$). On-site degradation of PSF can occur on the river shores, indicating that used PSF can break down to PSF units. In contrast, no significant relationships were observed for the size fractions of other types of plastics (fragments and fibers) because of their structure and shape. However, construction and littering of plastics and their management are the main factors for plastic pieces accumulated along the studied tributaries, and this plastic debris might be transported by river flow from upstream to downstream during extreme rainfall events (Axelsson and van Sebille 2017). However, in this study, we did not observe a significant relationship between the visible plastics from

Table 3 Correlation matrix of film and foamed plastic material

	Mega	Macro	Meso	Micro	Pop.den
(a) Film					
Mega	1				
Macro	0.81**	1			
Meso	0.82**	0.89***	1		
Micro	0.57	0.41	0.77**	1	
Pop.den	0.45	0.51	0.71*	0.60*	1
(b) Foam					
Mega	1				
Macro	0.30	1			
Meso	0.29	0.98***	1		
Micro	0.27	0.92**	0.97***	1	
Pop.den.	0.22	0.90**	0.95**	0.99***	1

Pop.den. population density

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

upstream and downstream study fields, indicating that fragmentation of larger plastics can occur on-site under natural conditions due to various physical and mechanical forces.

Regional specific plastic “PSF” and attached microplastic onto PSF

In this study, we determined a relatively high number of foamed plastics, specifically microsized PS (Fig. 7, Supplementary material Fig. A1), in the Selenga River system. High-density distributions were observed on the river shore near Ulaanbaatar City (T1–T3) and that of the Kharaa River near Darkhan City (Kh). The effects of environmental factors, such as mechanical fragmentation, on foamed materials explain the large number of visible and invisible microsized foams on the river shores (Supplementary material Fig. A2). Meso- and

macro-size fractions were also abundant in the city area. The use of mega-sized foamed plastics for heat insulators and packaging for facilities are major sources leading to the fragmentation into smaller size fractions. Harsh climate conditions during the long, extremely cold winter season are the main reason for the consumption of foamed plastic material as heat insulator. However, the field survey near Sukhbaatar City (O4 and O5) indicated 2.3 and 0.5 pieces per unit area (100 m²) of micro- (O4) and macro-sized (O5) PSFs, respectively, probably due to the smaller population density in Sukhbaatar compared with that in Ulaanbaatar and Darkhan. Similarly, only a few pieces of mega- and macro-sized PSFs were observed in the study area at the O3 and Ye sites. Foams were not observed at the study sites O1, O2, and Sh. The lower number of foamed plastics at remote sites suggests that construction in urbanized areas and packaging are the main reasons for PSF occurrence in areas with

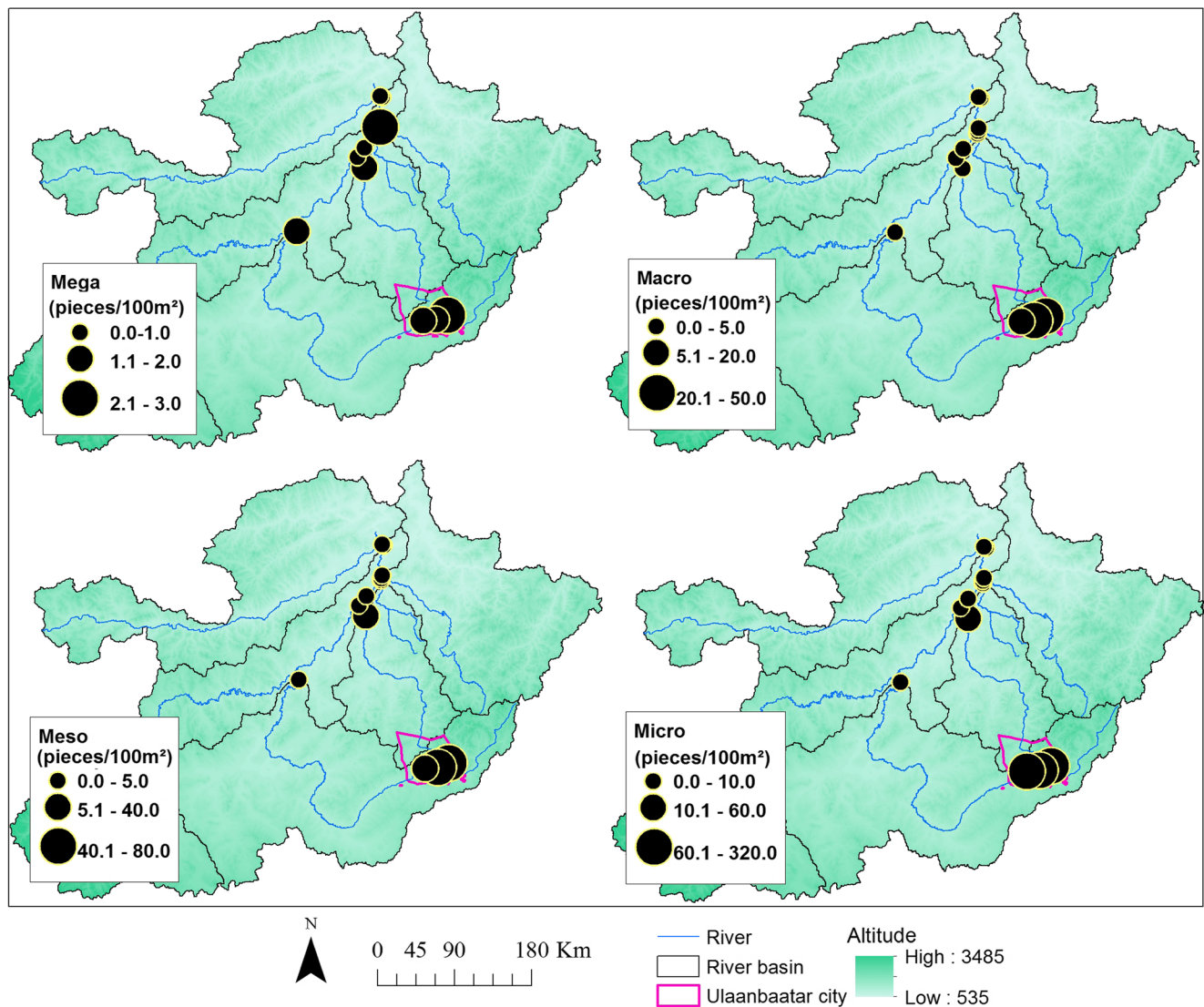


Fig. 7 Distribution of polystyrene foam (PSF) according to its size fraction at the sampling sites. The sizes of closed circles are the number of plastic fragments in a surveyed area (100 m²)

high population densities, while only several pieces of foamed plastic materials were counted at remote field sites. The scattering of plastic waste in remote places with low population densities possibly decreases the number of plastic wastes during the transportation from populated zones to river shores.

Several studies highlighted that foamed microplastics originate from packaging, fishing gear, and materials for horticulture in river systems and ocean systems (Barnes et al. 2009; Moore et al. 2011; Lee et al. 2013; Reisser et al. 2013; Faure et al. 2015a; Besseling et al. 2017; Fok et al. 2017). In addition, the PSFs in the study area are specific indicators for carriers of synthetic chemicals and small-sized microplastics in the environment. Figure 8 indicates microplastics attached to floating PSFs. The attached microplastics were identified using a digital microscope. Based on their appearance under the microscope, they include foams, fibers, films, and fragments. Attached microplastics are relatively dominated by foams and films based on their color difference.

The number of potentially harmful plastic debris has been identified. It could be confirmed that these materials transport

chemicals, such as POPs (Mato and Isobe 2001), including chemicals prohibited to be produced (e.g., PCBs, DDEs) and plastic additives (e.g., plasticizers, heat stabilizers, and pigments) (Mato and Isobe 2001; Talsness et al. 2009), microorganisms and chemicals (Barnes 2002) to other locations. Based on the current study, foamed plastic materials have a high potential to adsorb fragmented microsized plastics during their transport. The PUF can also carry plastics, heavy metals, and other pollutants of the beach sediment of southwestern England (Turner and Lau 2016).

Figure 9 shows the IR spectra of attached microplastics found on a PSF surface. The microplastics were identified as PE and PS polymers based on the spectra certified by Nicodom Ltd. in 2007 (Nicodom 2017). The PS and PE are also the most abundant polymer types in visible plastics in the fields. Progressed fragmentation of PS and PE plastics enhances the adsorption capacity compared with that of other plastic materials (Williams and Simmons 1996; Cooper and Corcoran 2010; Zbyszewski and Corcoran 2011); therefore, dominant microplastics of PS and PE were accumulated onto PSF debris, followed by further transport.

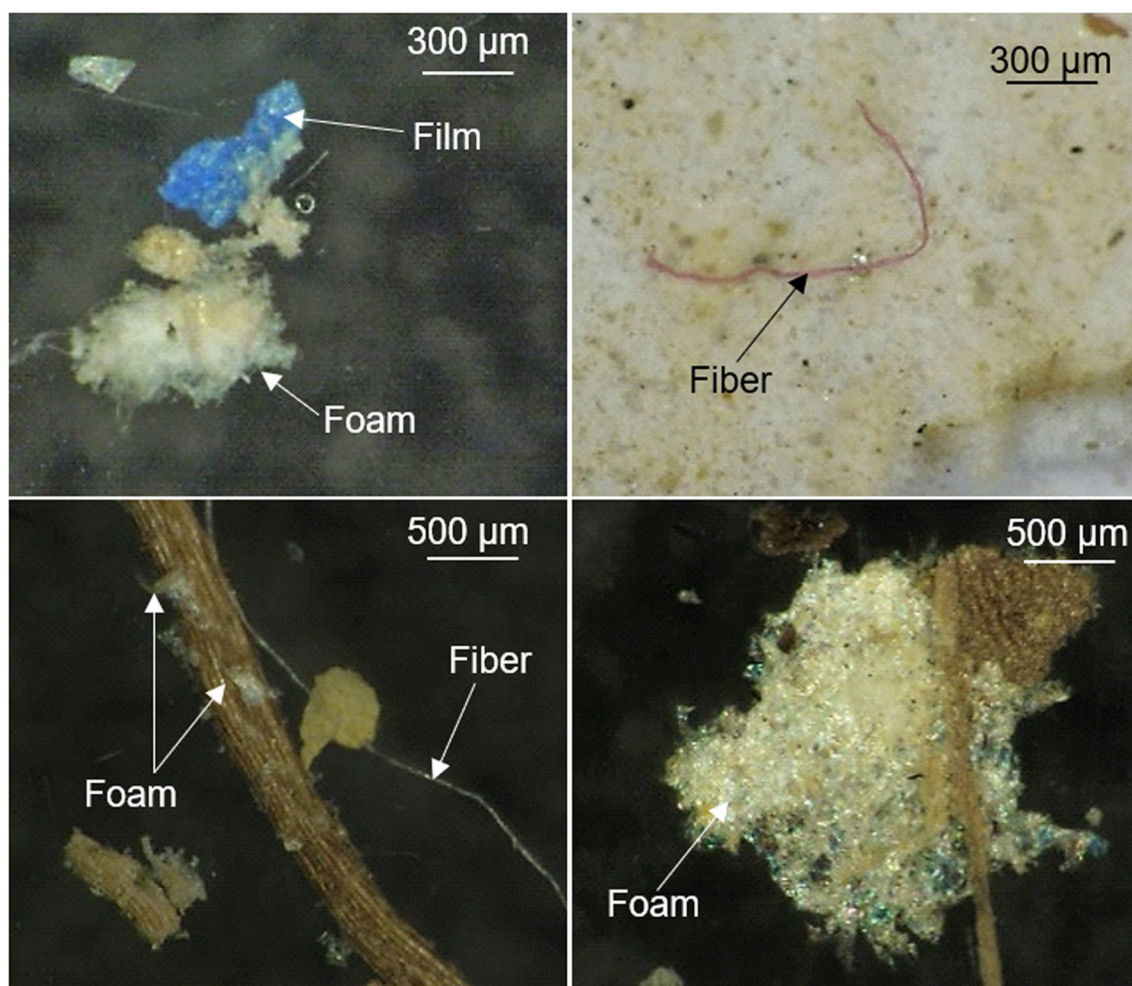
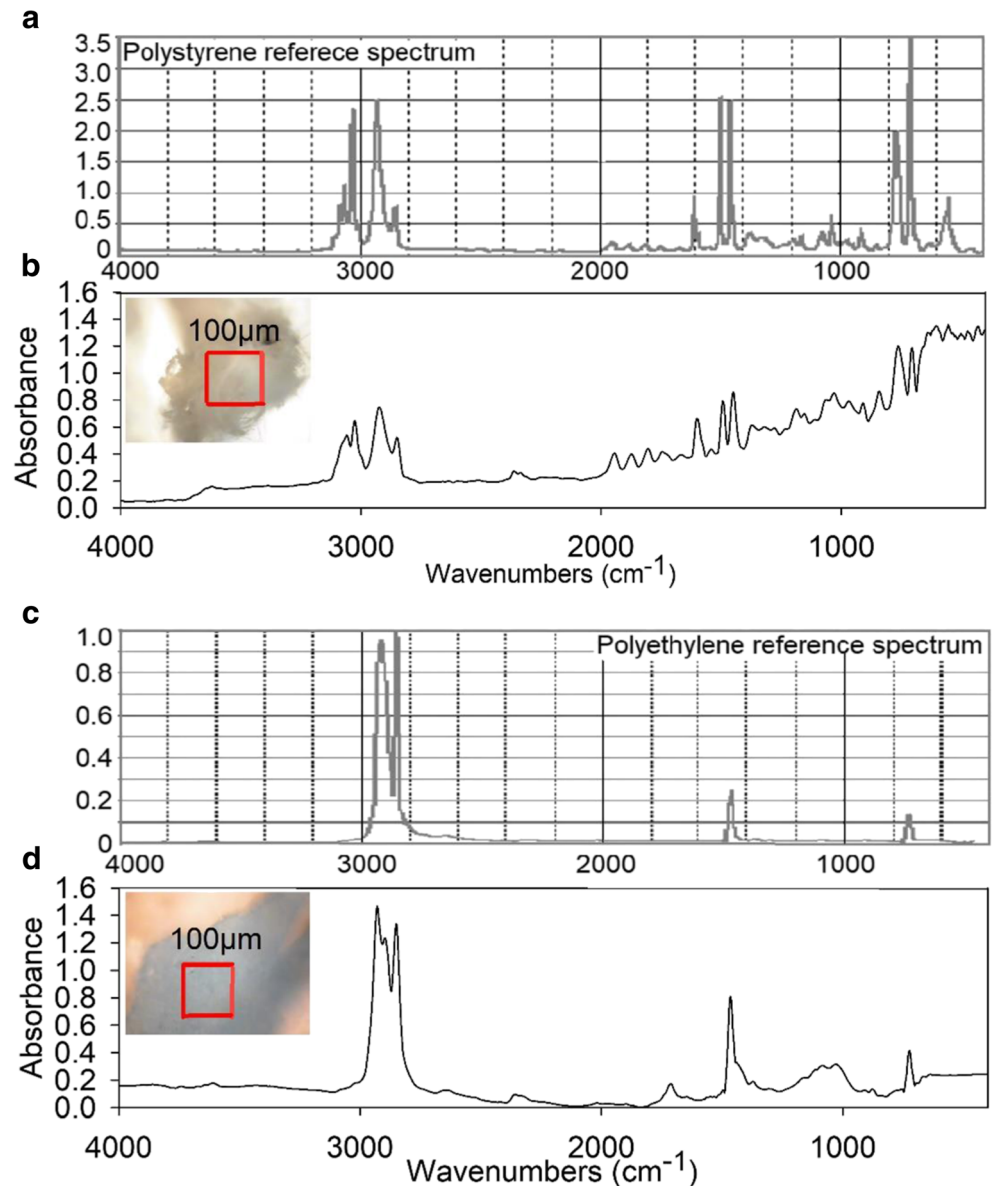


Fig. 8 Microscopic view of microplastics attached onto visible polystyrene foam (PSF)

Fig. 9 Infrared spectra of microscopic microplastics attached onto visible PSF. The spectra shown in **a** and **c** are reference spectra of polystyrene and polyethylene, respectively, provided by Nicodrom Ltd.; the spectra shown in **b** and **d** were recorded on a microplastic observed under the microscope (shown in the photograph) by micro-FTIR microscopy of the area shown by red squares ($100 \times 100 \mu\text{m}$) in the photographs. Both spectra shown in **b** and **d** match the respective reference spectra **a** and **c**



Overall, our study confirms that a high degree of degradation of PSF with high concentrations of attached microplastics in the freshwater environment would be dangerous with respect to the food web in aquatic environments. It is necessary to study PSF pieces and understand their pathways in the freshwater environment.

Conclusion

The average number of plastics debris found on the river shores is not comparable to that of previous studies, but the composition of the size fractions and materials are rather similar to that of other studies. A river system is one of the major pathways for the distribution of plastic debris from populated areas to open water environments. The high proportion of PSF

in the study area is characteristic compared with other studies, which indicates the high contribution of PE films, PP fragments, and fibers. Heat insulator and construction materials contribute to this PSF debris in the environment. The plastic debris can be differentiated based on the type of material and the sizes during its transport.

The distribution of plastic debris is distinctively high around the capital with a high population density. The capital and other towns are the source of plastics, which are spread to remote places along tributaries by water currents and water level changes. Although the pathways of plastic debris to aquatic environments, such as the ocean and lakes, have never been fully documented, the plastics originate in cities with high population densities.

Significant linear correlations between the size fractions of PSF and PE films indicate that all research sites represent

plastics with similar size fractions. The size reduction of these plastics occurs on-site by freeze–thaw processes, solar radiation, and physical fragmentation. The dominance of plastic debris by microplastics in aquatic environments reflects the size reduction during their transport.

Plastic debris can also carry other fragmented microplastics through surface adsorption, indicating that plastic debris with larger surface areas can be an active carrier and sorbent of microplastics and hydrophobic chemicals. The increase of the surface area through size reduction enhances the potential for the transport of chemicals and plastics. It is necessary to address the aging processes of plastic debris, which enhances the surface area and thus the potential as pollutant carrier.

Future management can reduce the amount and distribution of plastics, but plastic debris released in the past cannot be recovered and will resist chemical changes for a long time.

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