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ENVIRONMENTAL ANALYSIS

Microplastics in Surface Waters and Sediments in the Sebou Estuary and Atlantic Coast, Morocco

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ABSTRACT
Microplastics (MPs) are emerging contaminants and present risks to human and environmental health. Microplastic levels were examined in sediment and surface water samples at stations along the Sebou Estuary and Atlantic Coast of Morocco. The microplastic abundance, distribution, and characteristics were characterized. The microplastics were separated into fragments, fibers, films, and granules. The results at all stations showed that the microplastic abundance in water samples ranged from 10 to 168 particles/m^3, whereas in the sediment samples, the levels were from 10 to 300 particles/kg. Stations adjacent to Kenitra City showed significantly high levels of microplastics ($p < 0.001$) compared with the Atlantic Coast, likely due to population density and human activity. The majority of the detected microplastics was from 0.1 to 0.5 mm, followed by 0.5 to 1 mm. The predominant shape in water and sediments were fragments. The results for the type, size, and color of the microplastics suggest the Sebou Estuary is a hotspot on the Atlantic Coast. The results of this study may contribute to increased awareness and better implementation of solid waste management plans, especially at Kenitra City, to protect the biologically diverse ecosystem of the Moroccan Estuary and Atlantic Coast.

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Atlantic Coast; microplastics; microplastic contamination hotspot; Morocco; Sebou Estuary

Introduction

The literature and worldwide media report the scientific community's concern with pollution caused by plastics and microplastics (MPs) (Gimiliani et al. 2020). Plastic products are widely used, but while they bring convenience to people's lives, plastic waste also brings great pressure to the environment. Plastic persists in the environment for 400–1000 years and approximately 4.8–12.7 million tons of plastics reach the oceans annually (Jambeck et al. 2015). After a long period of physical, chemical, and biological degradation, the plastic breaks into plastic fragments in the natural environment, giving rise to microplastics.

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MPs are particles between 1 µm and 5 mm in size (Frias and Nash, 2019) and are considered emerging contaminants (Avio, Gorbi, and Regoli 2017) due to their ubiquity in the environmental compartments including the atmosphere (Brahney et al. 2020), surface water, water column, sediments and soil (Wang et al. 2016), and the risks they present to aquatic organisms (Moore 2008). MPs may be ingested by aquatic organisms, causing physical obstruction (Derraik 2002; Moore 2008) and chemical contamination due to leaching of inherent and adsorbed hazardous contaminants on their surfaces that may be transferred along the trophic chain (Browne et al. 2011), reaching humans. In addition to food and fish intake (Barboza et al. 2020; Zhang et al. 2020), human beings are also subject to MPs by inhalation, cell damage or inflammation, and immune reactions (Vethaak and Legler 2021).

The properties of microplastics have been extensively studied (Browne, Galloway, and Thompson 2010; Ivar do Sul, Spengler, and Costa 2009; Krelling and Turra 2019). These particles are in constant motion until stranded in aquatic environments and several are their sources for aquatic ecosystems with 80% primarily from terrestrial sources (Jambeck et al. 2015). They may travel thousands of kilometers from their origin by sea currents and be stranded in remote (Ivar do Sul, Spengler, and Costa 2009) and densely populated areas (Pham et al. 2014), accumulating up to 10^6 times above the level of contamination during transport. For this reason, they are called environmental carriers (Mato et al. 2001).

Meteorological factors also contribute to the dispersion of MPs in the aquatic environment and consequently in their deposition in coastal regions. The dynamics between estuaries and beaches is governed by the presence of tides, fluvial discharges, winds, and interactions with bathymetry and morphology, which can influence not only the transport of MPs but also their deposition and remobilization (Browne, Galloway, and Thompson 2010; Krelling and Turra 2019; Tramoy et al. 2019).

The complexity of transporting debris in coastal regions (Ryan and Perold 2021) leads to interest in the understanding of the sources of MPs and their dispersion between two coastal regions under anthropic pressures, especially the Sebou Estuary which is in a constant cycle of almost infinite deposit and remobilization, becoming a "microplastics factory" from the fragmentation of larger plastic waste before reaching the ocean (Tramoy et al. 2019).

The presence and distribution of microplastics in environmental samples has been reported in the northeast Atlantic Coast (Fytianos et al. 2021; Maaghloud et al. 2020). However, there are no studies on environmental diagnosis carried out in the Sebou Estuary. Therefore, an unprecedented investigation was performed regarding the presence and distribution of microplastics in the coastal areas of the Atlantic and in the Sebou Estuary in Morocco. Our objective was to carry out an integrated analysis of the dispersion of microplastics using the abundance, types, sizes, and colors in samples of surface water and sediment to identify possible sources in the region. This region was selected because of its ecological and economic importance and the consequent probable contribution to marine plastic waste in the oceans. The study also aims at providing baseline information on the status of the microplastic contamination and rising awareness on the need for the management and treatment of pollution in the study area.

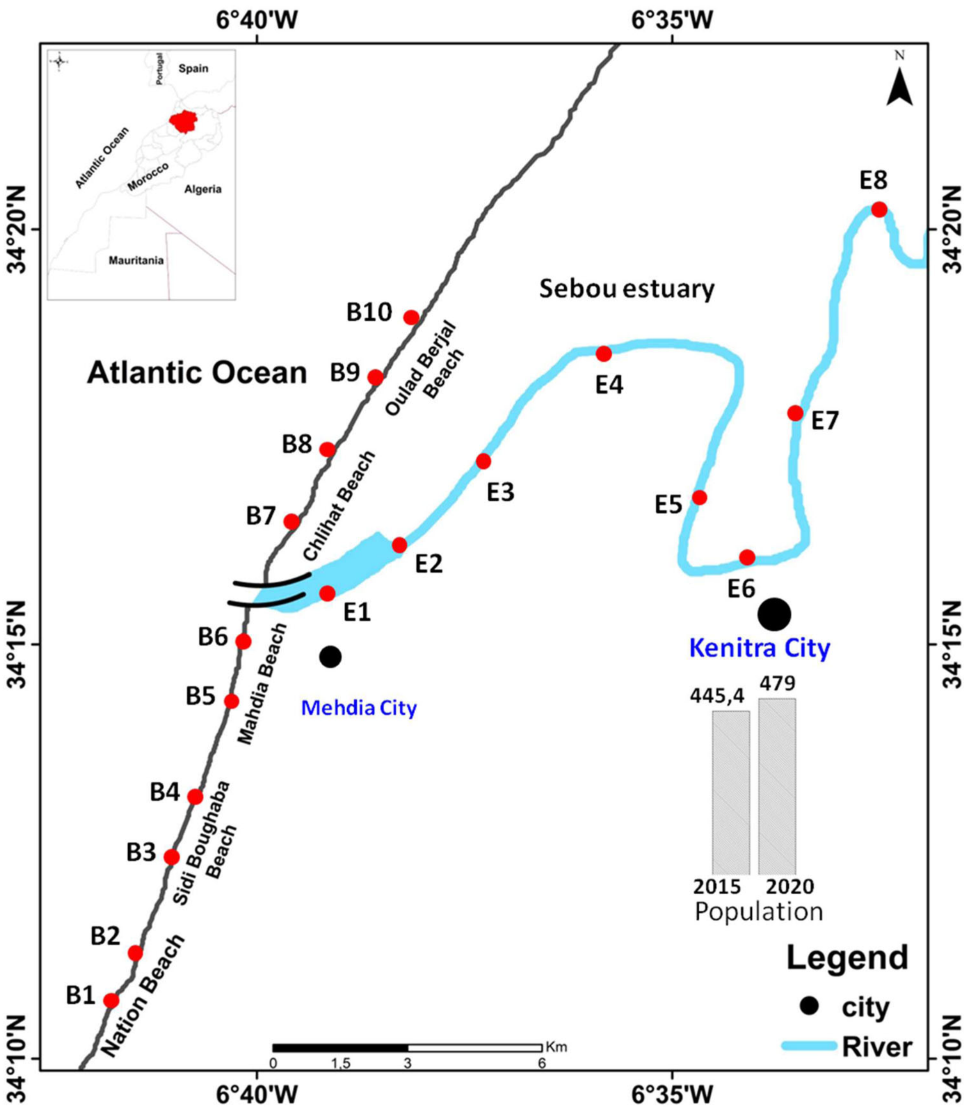

Figure 1. Study area with sampling sites. E1–E8 are estuarine sites and B1–B10 beach sites.

Materials and methods

Study areas

Sebou estuary

The Sebou River is the largest Moroccan river, draining approximately 40,000 km^2. It stretches 614 km from its source in the Middle Atlas Mountains to the Atlantic Ocean, representing 6% of Morocco's total land area (Figure 1). Kenitra Harbor, about 17 km from the ocean, has commercial traffic, while Mehdia Harbor, which is only 2 km from the mouth, is busy with fishing activities. During low flow periods in this estuary, the hydrodynamic regime is controlled by the Lalla Aïcha Dam 62 km upstream from the mouth (Haddout, Igouzal, and Maslouhi 2016). The tide near the estuary mouth is

Table 1. Study stations and their geographical coordinates.

Station code	Coordinates (North, West)
E1	34.266380, −6.665383
E2	34.271487, −6.649933
E3	34.301839, −6.620751
E4	34.310630, −6.600151
E5	34.281132, −6.588135
E6	34.269217, −6.576462
E7	34.313466, −6.559296
E8	34.337283, −6.552430
B1	34.147128, −6.742287
B2	34.157924, −6.734391
B3	34.180649, −6.718254
B4	34.193713, −6.711045
B5	34.230338, −6.693192
B6	34.244246, −6.687355
B7	34.293613, −6.659203
B8	34.317719, −6.641350
B9	34.346354, −6.620407
B10	34.363360, −6.605301

mainly semi-diurnal with a 12.27-h tidal cycle and with tidal range varying from 0.9 to 3.10 m, depending on the conditions (Haddout et al. 2019).

Atlantic coast

This study area is located along the Atlantic coast of Kenitra City, Morocco and extends 20 km from latitude N 34°17′12″ and N 34°7′15″. The beaches are bordered by high eolian dunes from 5 to 15 m, with consolidated backing from 3 to 5 km (Aberkan 1989). The coastline includes eroding beaches are separated by the Sebou River (SE) trained by two dikes that extends approximatively 845 m seaward from the low tide level shoreline. The coast is influenced by high energy waves traveling roughly from the northwest. The current, which moves parallel to the shoreline, is among the main driving forces of sediment distribution and mobilization along the coast (Azidane et al. 2020).

Sample collection and preparation

Water and sediment samples were collected on 16 December 2020, and a total of 18 sampling sites were distributed as evenly as possible in the Sebou Estuary (E1–E8) and Atlantic Coast (B1–B10) (Figure 1). Stations E1–E8 were along the estuary axis, and surrounded by dense populations (E1 and E2, Mehdia City; E5 and E6, Kenitra City). Points B1–B10 were from five sectors: Oulad Berjal Beach, Chlihat Beach, Mehdia Beach, Sidi Bouaghaba Beach, and Nations Beach (Figure 1).

Sampling locations (Figure 1 and Table 1) were located using a global positioning system (GPS). Before sampling, all materials and containers were cleaned with filtered pure water. Two replicates of 20 L of surface water were collected from each site with a steel sampler. 500-g of sediment were collected in duplicate from the margins at the same site. The sediment collected from each site was stored in an aluminum bag for transportation to the laboratory.

The quality of the methods was ensured due to the use of free plastic materials during the sampling and analysis to avoid contamination. Good laboratory practices were applied, as well as the use of cotton coats to minimize contamination by synthetic fibers and decontamination with pure filtered water on the surfaces of the materials to reduce or eliminate false positive results.

The samples were investigated according to modified NOAA laboratory methods for microplastics in water and sediments (Masura et al. 2015). The water samples were run through metal sieves, rinsed carefully with distilled water to avoid leaving plastic particles on the sieves, and separated into fractions (Hidalgo-Ruz et al. 2012). Particles with a size > 5 mm were not classified as MPs and were discarded (Masura et al. 2015). Waters were incubated at room temperature with 10 mL 30% H_2O_2 overnight to degrade the organic matter (Wang et al. 2017). The digested solution was diluted and filtered using 0.45-μm gridded filter paper. The filters were stored in covered glass dishes and air dried for further analysis. Sediments were dried at 50 °C for 48 h. Microplastics were extracted from each sediment by density separation according to the method developed by Thompson et al. (2004) and Masura et al. (2015). The sediment grain size analysis was investigated with standard sieves. A portion of each sample was dried and separated using metal sieves. The Wentworth scale was used to define the size fraction of the sediments. The calculation was performed by the Gradistat 9.1 software (Blott and Pye 2001).

Identification of microplastics

Microplastics were visually identified and quantified according to their physical characteristics using a literature method (Hidalgo-Ruz et al. 2012). The number, shape (fiber, film, fragment, and granule), color (transparent, white, black, and colored), and size of the plastics were recorded. The size of the plastic particles was divided into four categories: 1–5 mm, 0.5–1 mm, 0.1–0.5 mm, and <0.1 mm.

Results and discussion

The results on the abundance in the sediment and surface water samples from the Sebou Estuary and the Atlantic Coast are shown in Figure 2(a,b), respectively, showing the total number of microplastics at each site. The abundance of microplastics were from 10 to 300 particles/kg in the sediments and from 10 to 168 particles/m^3 in the water samples. The number of microplastics in the sediments from the Sebou Estuary in samples E1–E8 exceeded those in water samples from the same location by a factor of two. Sediment is a microplastic sink, and hence, a useful environmental compartment in the evaluation and monitoring of microplastics in aquatic environments. Approximately 70% of plastic waste is deposited on the ocean floor, in riverbeds, and on the bottom of estuaries (Gimiliani et al. 2020; Kershaw 2016). Because it presents fine silt to clay sediment (Haddout et al. 2021), characteristic of a low-energy environment, the Sebou Estuary is a favorable environment for the accumulation of microplastics on intertidal regions. Unlike samples from the estuary, sediments from the Atlantic Coast (B1–B10) showed smaller quantities than in the water samples. This difference

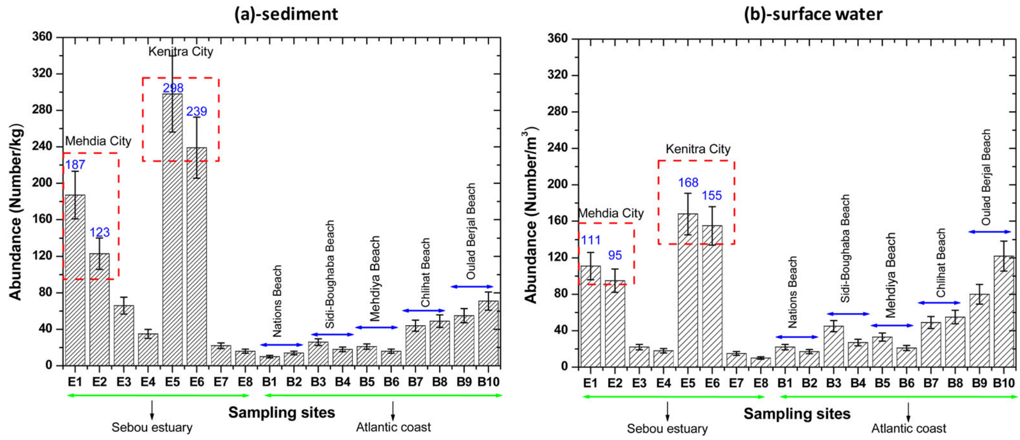

Figure 2. Number of microplastics in sediments and surface water.

may be explained by conditions in the locations. On the beaches, the energy is considered medium to low (Azidane et al. 2020) because waves and coastal currents reduce the deposition of microplastics in the sediment or even displace plastic particles in the sediment to the water column.

The abundance of microplastics was higher at sites E1, E2, E5, and E6 near Kenitra City, probably due to the presence of direct disposal of sewage and solid wastes. The microplastics may have been transported to E3, E4, E7, and E8 by the tides ebbing and flooding along the estuary. The influence of sewage on plastic contamination has been reported (Browne, Galloway, and Thompson 2010; Leads and Weinstein 2019). The presence of microplastics from the fragmentation of plastic waste for domestic use is expected, explaining the presence of films and fibers (Figure 3(a,b)), probably from food packaging and clothes washing (Browne, Galloway, and Thompson 2010; Leads and Weinstein 2019). The presence of fragments and fibers at sites E1 and E2 may be attributed to Mehdia Harbor due to fishing the accompanying disposal of line and gear.

In surface water, the fiber content was relatively low compared to in the sediments. Pohl et al. (2020) reported fibers sink or deposit faster in sediments due to their elongated shape and greater surface area. They are trapped between the sediment grains more easily, justifying a greater abundance of these microplastics in the sediment in several studies (Claessens et al. 2011).

The presence of granules at site E5, and in relatively greater quantities than at other locations, suggests the disposal of pellets near Kenitra Harbor. Pellets are primary microplastics, whose sources are industrial and ports. They are raw materials used in the manufacture of plastic products. Their loss during transport and handling and consequent disposal to the environment in the vicinity of industries and ports has been increasingly reported (Ogata et al. 2009; Li, Su, et al. 2020). The presence of these granules in the sediments at the E1 and E6 sites may due to tidal transportation that reached the beaches at Sidi Baughaba (B3 and B4), Chlihat (B7 and B8), and Oulad Berjal (B9 and B10) due to currents. More microplastics were observed at site B10 due to currents that flow predominantly northwards. The presence of granules on these beaches suggests the Sebou Estuary may be a microplastic contamination hotspot. Several studies have reported an increase in the presence of pellets on the beaches near

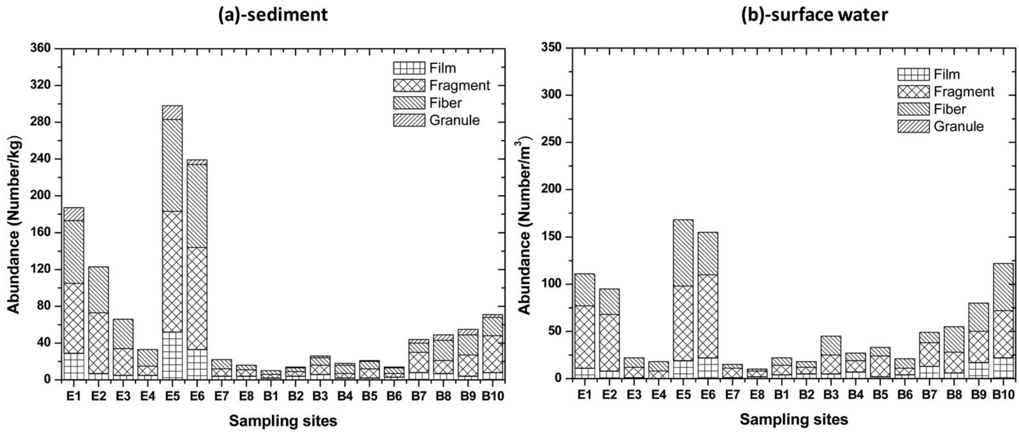

Figure 3. Type and number of microplastics in sediments and surface water.

ports (Izar et al. 2019; Moreira et al. 2016; Turra et al. 2014). However, there were no granules present in the water samples, probably because microplastics may be deposited in the sediments due to the action of wind, tides, and deposition. Collignon et al. (2012) reported that the number of microplastics in the Northern Mediterranean before strong wind events was five times higher than after these events. In addition, the distribution of microplastics in surface water may vary depending upon the density of the plastic. The addition of bio-encrustation and suspended solids on the surface may alter the microplastic density, changing the sinking/floating properties (Browne et al. 2011; Wang et al. 2016).

The abundance of microplastics in water and sediments did not show a direct relationship with size (Figure 4(a,b)). Unlike some literature studies, greater abundance with a reduction in the size of microplastics was observed (Barnes et al. 2009; Leads and Weinstein 2019; Zhao et al. 2014). A higher abundance of larger microplastics (1 to 5 mm) were present at site E5 compared to the other locations. This size range is more abundant compared to sizes from 0.5 to 1 mm with a predominance of microplastics between 0.1 and 0.5 mm at the same site. Meanwhile, microplastics $<$ 0.1 mm were present at lower abundances in all sediment samples and were absent in some surface water samples. Sites E1, E2, and E6 showed similar abundances to location E5 and the other points. The size distributions were similar in these samples.

The presence of smaller microplastics implies longer residence times, in which continuous fragmentation into smaller and smaller particles occurs due to salinity, light, temperature, humidity, and microbiological degradation (Andrady 2017; Doyle et al. 2011; Wang et al. 2016). Conversely, the presence of larger microplastics suggests that the plastic particles have been in the environment for shorter periods, as for sewage that is constantly discharged at locations E1, E2, E5, and E6.

Gimiliani et al. (2020) showed the number of smaller plastic particles was inversely proportional to sediment grain size in estuarine samples. In other words, the smaller the size, the higher the quantity of microplastics (Gimiliani et al. 2020). However, in this study, the abundance of microplastics from 0.5 to 1 mm was higher than for $<$0.1 mm. Nor and Obbard (2014) reported more microplastics between 0.5 and 1 mm

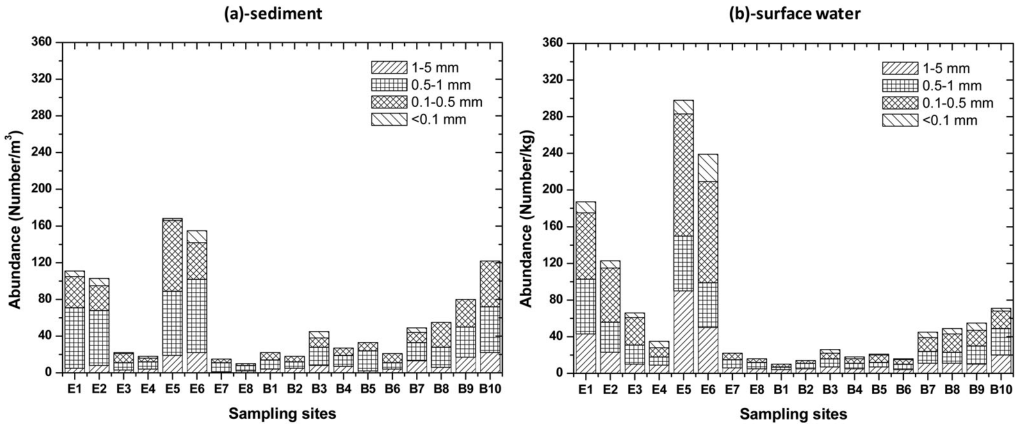

Figure 4. Number and sizes of microplastics in sediments and surface water.

and lower abundances for those <0.1 mm in sediments. These results suggest that the measurements were made near the source before degradation occurred.

Sediments with a higher proportion of grains with fine fractions (<250 µm) are more cohesive and flocculate regularly. The microplastics are expected to be retained in the sediments during flocculation of the particles (Nor and Obbard 2014) which likely affects the suspension and deposition (Pohl et al. 2020). Since smaller mesh size microplastics accumulate more, the risk of benthic and epibenthic organism exposure may increase with the number of microplastics (Gimiliani et al. 2020).

In beaches on the Atlantic Coast, although considered environments under moderate to low energy conditions and containing sediments with fine fractions between 200 and 63 µm, microplastics are susceptible to transport by winds, waves, and ocean currents (Browne, Galloway, and Thompson 2010). The beach environment is considered to be dynamic (Turra et al. 2014) which justifies the lowest microplastic abundance compared to the Sebou Estuary, whose sediments are fractions of very fine sand to clay (<125 µm). In the vicinity of the mouth, where site E1 is located, there is a predominance of very fine sand that decreases toward location E2. A gradual increase is observed from silt to clay sediments for sites E2–E8. The gradual decrease in energetic conditions of fluvial regime occurs upstream (Haddout et al. 2021).

Based on the characteristics of the sediments from the estuary, relatively high abundances were anticipated at all sample sites. However, a direct relationship between the size of the sediments and the abundance of microplastics at locations E1, E2, E5, and E6 was not observed. However, the microplastic abundances were proportional to population density because the cities of Mehdia and Kenitra with 497,282 inhabitants were in the vicinities. The literature has shown that over 90% of the variation in the abundance of plastic debris is explained by the population density where the samples were collected (Browne, Galloway, and Thompson 2010). Fewer microplastics were observed in remote regions where human activities are limited (Jiang et al. 2019). Microplastics have been identified in water and sediments in rivers around the world (Klein, Worch, and Knepper 2015; Rodrigues et al. 2018; Tibbetts et al. 2018). Many studies have shown that elevated microplastics in river water and sediments are associated with proximity to highly populated areas, industry, wastewater treatment plants, and tributaries.

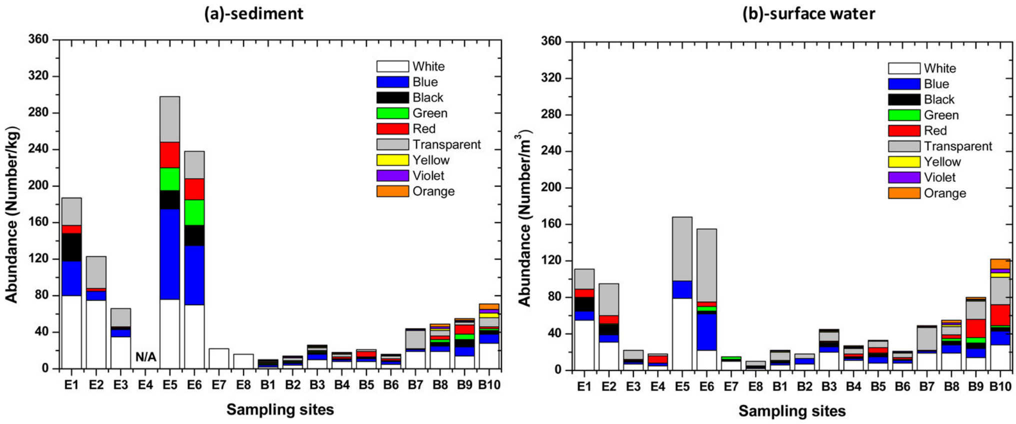

Figure 5. Number and colors of microplastics in sediments and surface water.

The colors of the microplastics in the water and sediment samples (Figure 5(a,b)) were employed to identify their sources. The microplastics at sites E1–E3 were probably from a different origin than those at locations E5 and E6. The water samples had few green microplastics, probably transported from the E5 and E6 sites. The estuary drains to the beach may explain why the beach samples match the colors in the estuary. Sites B8–B10 had yellow, violet, and orange microplastics that were not found in the estuary, suggesting they were derived from other sources.

Previous studies have reported the presence of microplastics on the Atlantic Coast (Fytianos et al. 2021; Maaghloud et al. 2020), especially in fish consumed by humans. Pollution originating in the Sebou Estuary may be contribute to microplastics (Loulad et al. 2019) in water and fish.

The reduction of microplastics may be achieved by the efficient management of solid waste by minimizing the disposal of plastic waste by recycling and reduction in plastic packaging, especially single use materials. It has been estimated that 63% to 97% (Chiu et al. 2020; Galgani et al. 2013) of marine waste is plastic waste that eventually becomes microplastic.

Conclusions

This study has characterized microplastics in surface water and sediments of selected stations in the Sebou Estuary and Atlantic Coast of Morocco. The estuarine water and sediments were contaminated with more microplastics than the beach samples. Sewage from the cities of Mehdia and Kenitra is the main source of pollution, which introduces large quantities of microplastics into the estuaries. The determined types, sizes, and colors of the microplastics suggests that these microplastics originated from the Sebou Estuary, were transported to the coastal zone, and distributed along the beach, with a focus at Oulad Berjal Beach on the Atlantic Coast by tides and currents. The presence of point and diffuse sources in the estuary identifies it to be a microplastic contamination hotspot. The microplastics are transported along the Sebou River to the beaches near the estuary, contributing to the marine litter. Understanding the sources of microplastics, as well as their distribution and destination, may contribute to the development of future programs for monitoring and management of plastic waste in the Sebou Estuary. Actions must be initiated at the source to reduce the formation of plastic contamination.

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that influenced the results reported in this paper.

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