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Factors Influencing the Three-dimensional Distribution of Microplastics on Sandy Beaches: A Case Study from the Turkish Coast of the Black Sea

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Abstract

Microplastic pollution stands as an emerging threat to sandy beach ecosystems, globally. However, beaches are three-dimensional systems, and only a limited number of studies investigated the vertical and horizontal distribution of microplastics in these systems. Furthermore, the causative drivers behind the three-dimensional distribution of microplastics on sandy beaches have not been well understood. Therefore, 7 potential factors including total organic content, sand grain size, beach length, and width, the proximity of the study site to the closest city center (a proxy for the tourism influence), cleaning frequency of the beaches, and road type next to the beach on nine sandy beaches of the Turkish Coast of the Black Sea were collectively investigated as causative drivers. Microplastic abundance, size, and compositions were examined in sand samples collected at different depths between 0 and 105 cm. While microplastic abundance was evenly distributed horizontally, it showed a gradual decline with increasing depth. The abundance of microplastics varied between 21.18±0.98 item/kg^{-1} (at the beach surface) and 2.78±0.93 item/kg^{-1} (at the deepest sampling point). Potential factors examined here explained 84.7% of the variation in microplastic abundance with the highest relative influence by wave actions. Microplastic size showed a seaward decline on the beach surface with 1045.11±274.36 µm, but it seemed similar between depths. Other characteristics (color, shape, and polymer type) significantly differed between depths and tidal heights. The majority of the microplastics were fragments (38.4%) and foams (37.8%). White was the most available microplastic color with 30.23%. Microplastics detected on these sites were dominated by polystyrenes. The factors examined here explained their variations of microplastic characteristics between 84.25% and 89.14%. This study provides important insights into the current literature by examining multiple causative drivers for the three-dimensional microplastic distribution on sandy beaches, which should be useful for management strategies to reduce the impact of these contaminants on organisms.

Introduction

Plastics are considered one of the most emerging threats to ecosystems. Plastic pollution has gradually increased in all kinds of ecosystems since its industry started in the 1950s. The annual plastic production reached 367 million tonnes in 2020 (PlasticsEurope, 2021). It is expected to increase with the increase in the human population and plastic demand (PlasticsEurope, 2021), suggesting that the threat will worsen if appropriate and efficient precautions are not taken. Plastic materials are preferred over other materials such as wood and metals due to their lightweight, durable, and cost-effective nature (GESAMP, 2019), which makes them utilized for various purposes including transportation, fishing, packaging, construction, etc. (Andrady, 2011; Akdogan & Guven, 2019).

Microplastics are defined as the smaller particles of plastic items with a size of smaller than 5 mm (Andrady, 2011; GESAMP, 2019). 2 major sources of microplastics

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in nature have been defined, which are primary and secondary microplastics (GESAMP, 2019; Gaylarde *et al*., 2021). Primary microplastics are particles produced smaller than 5 mm and often do not experience further breakdown processes, including mostly microbeads in personal care products and medicines (Andrady, 2011; GESAMP, 2019). Specifically, single-use plastic products including sorption of drugs, syringes, bags and containers (Gopinath *et al.,*2022) and microbeads in personal care and cosmetic products are commonly exploited in health applications and considered and important source for microplastic in nature (Bashir *et al.,* 2021). On the contrary, secondary microplastics are the products of larger plastic items after a breakdown process, including fishing nets, laundry discharge, packaging, construction materials, etc. (Jiang, 2018; Akdogan & Guven, 2019).

Sandy shores are three-dimensional ecosystems with a variety of terrestrial, semi-aquatic, and aquatic organisms (McLachlan & Brown, 2006; Davis & FitzGerald, 2010). While some of those organisms live on the surface (e.g., plants, crabs, etc.), others either live underwater primarily in the tidal zone or bury themselves in the sand (McLachlan & Brown, 2006; Davis & FitzGerald, 2010). Besides their ecological features, sandy shores have been defined as the sink of microplastics on the coastal systems (Cauwenberghe *et al*., 2015). Seward and landward physical and chemical forces (e.g., waves, winds, floatings, etc.) transport microplastics to the sandy shores from the areas in the vicinity (Balthazar-Silva *et al*., 2020), and those particles often accumulate on the sand (Rochman, 2018). Furthermore, those physical and chemical forces help those contaminants to descend into the deeper points in the sand. Additionally, burrowing organisms on the beaches contribute to microplastic occurrence at depths in the sand (Capparelli *et al*., 2022).

Most studies that examined microplastic occurrence on sandy shores have often investigated surface pollution as it is considered to be a reliable indicator of the beach microplastic contamination profile (Besley *et al*., 2017). However, several reports investigating three-dimensional microplastic occurrence on sandy shores have suggested that a more detailed methodology should be utilized by combining microplastic data collected at various depths to have a more accurate contamination profile (Turra *et al*., 2014; Moreira *et al*., 2016; Chubarenko *et al*., 2018; Pervez & Wang, 2022; Pham *et al*., 2023), which could be more helpful in revealing adverse effects of these contaminants on sandy shore organisms. Although those studies examined the three-dimensional distribution of microplastic occurrence and some characteristics on sandy shores, the research conducted on causative drivers behind this distribution pattern is limited to a few potential forces such as oceanographic variables (Turra *et al*., 2014; Chubarenko *et al*., 2018). Therefore, this study was carried out to fill that gap by collectively examining total organic content (TOC hereafter), sand grain size, beach length, and width, the proximity of the study site to the closest city center (a proxy for the tourism influence), cleaning frequency of the beaches, and road type next to the beach as an indicator of terrestrial microplastic contribution as causative drivers for the three-dimensional microplastic distribution on sandy shores. The research question of this study stands as to whether microplastic abundance, size, and other characteristics varied between depths and tidal heights and whether this three-dimensional distribution of microplastics on sandy shores was the consequence of collective impacts by several factors. The abundance, size, and characteristics of the microplastics on sandy shores were hypothesized to vary between tidal heights and depths. Further, examined factors were hypothesized to collectively explain the three-dimensional distribution of microplastics on sandy shores. The results of this study could potentially be used for more accurate conservation applications to reduce the adverse effects of microplastics on sandy shores.

Materials and Methods

Study Sites and Sample Collection

To understand the potential causative drivers for the three-dimensional distribution of microplastics, 675 sand samples on 9 beaches were collected between the 2nd and 28th of April 2021 on the Turkish Black Sea Coast (Figure 1). Sampling occurred just before the beginning of regular tourism season and beach cleaning as these factors influence the microplastic characteristics on sandy shores (Gül, 2023). Sampled beaches had various distances to city centers and thus experienced different degrees of human disturbance.

Three 100 m long lines parallel to the sea were examined. The lower line was placed on the water's edge and the upper line was selected on the edge of the beach vegetation or the first hard structure on the sand. The middle line was placed between the upper and lower lines at an equal distance. The distance between lines varied according to the beach width. 5 sampling areas of 0.25 m^2 spaced at approximately 25 m intervals were selected on each line (a total of 15 sampling areas on each beach) (Besley *et al*., 2017). Sand samples were collected at 5 different depths at 20 cm intervals from 0 cm to 105 cm (0- 5 cm, 25- 30 cm, 50- 55 cm, 75- 80 cm, 100- 105 cm) using a metal shovel. Sand samples within approximately 5 cm depth were sampled at each sampling depth. Overall, 75 sand samples were collected from each beach. Sand samples were kept and transported in separate zip-lock bags to the laboratory for further analysis (Eo *et al*., 2018; Gül, 2023). Visually detected possible plastic items because of their color and shape were placed in the bags, as well.

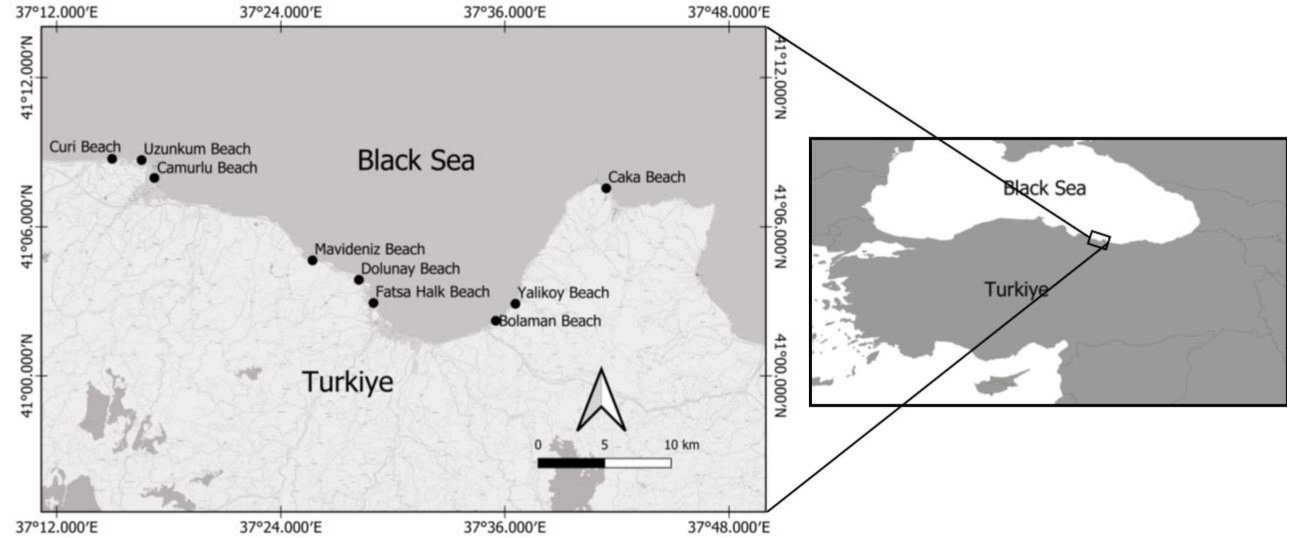

Figure 1. Map of the study sites on the Turkish Coast of Tükiye.

Explanatory Variables

To understand the causative drivers behind the variations in abundance, size, color, shape, and polymer type of microplastics at different depths and tidal heights on sandy shores, a total of 7 explanatory variables were considered including total organic content (TOC hereafter), sand grain size, beach length, and width, the proximity of the study site to the closest city center (a proxy for the tourism influence), cleaning frequency of the beaches, and road type next to the beach as an indicator of terrestrial microplastic contribution.

To obtain the TOC of the sand (% loss), 3 replications of 5 g sand samples were collected from each beach on the lower line. The TOC of the sand was examined by combustion at 550 °C for 12 h (Cambardella *et al*., 2001). For sand grain size analysis, 3 replications of 500 g sand samples were collected on the middle line. Dried sand at 70 °C for 24 h was passed through a series of sieves (0.941 mm, 0.505 mm, 0.25 mm, 0.13 mm, 0.061 mm, 0.043 mm). Folk & Ward method using GRADISTAT v.9.1 was employed to determine the mean grain size (Blott & Pye, 2001). Further, beach width was measured three times on each beach as the distance between the high-water mark and the edge of the backshore vegetation or the edge of the first hard structure on the sand. Beach length was measured using Google Earth Pro. Like beach length, data on the proximity of the study sites to the closest city center were obtained via Google Earth Pro. Data on the cleaning frequency of the beaches were gathered from local municipalities as this is an efficient method to minimize microplastic abundance on sandy shores (Gündoğdu & Çevik, 2019; Gül, 2023). Finally, the road type next to the beaches was noted as follows; arterial, street, or highway. The road type might be an important factor as a type source of microplastics on sandy shores due to demonstrating the volume of traffic and the use of the number of people, because the majority of the terrestrial input in the microplastic contamination on sandy shores is the result of the water runoff (Willis *et al*., 2017), which washes all the coastal area including the roads close to beaches.

Sample Processing

For sample processing, the method developed by Besley *et al*. (2017) was followed with slight modifications. Shortly, all sand samples were sieved through a metal sieve with a mesh size of 5 mm after drying at 60°C for 48 h in an oven. Following, sand samples and fully saturated salt (NaCl) solution (500 g sand and 1 L salt solution) were mixed in an aluminum tray (30×24×4 cm, L×W×H) (Maynard *et al*., 2021). NaCl solution was preferred due to its environmentally friendly and cost-effective nature, which is a highly efficient methodology in detecting approximately 85% of the microplastic particles (Quinn *et al*., 2017). After stirring approximately for two minutes three times, the mixture was left to rest overnight. The liquid layer of the mixture was sieved using a metal sieve with a pore size of 50 µm to obtain the supernatant. The supernatant was washed under tap water for approximately two minutes to remove the remaining salt. All samples were placed in separate aluminum boxes and dried at 60 °C for 24 h. For a more detailed description, please see Gül (2023).

Quality Control

Some quality control criteria were used to avoid the potential risk of contamination and erroneous results. To prevent potential contamination from the environment and the clothes of the researcher, zip-lock bags made up of transparent polyethylene were used.

When the collected sand samples were placed, the bags were locked immediately. All microplastic samples were examined to see whether they contained any piece of transparent polyethylene bags. Further, the laboratory where the samples were processed had no ventilation and least visitors. Additionally, during the laboratory processes washed glass or metal tools were preferred. Finally, 3 blank samples were prepared identically with the sand samples to examine potential airborne contamination. The results demonstrated the validation of the applied methodology as no microplastic particles in the blank samples and no piece of transparent polyethylene bags were detected in the samples.

Microplastic Identification

To identify microplastics, the particles prepared after laboratory processes were placed in a 35-mm glass Petri dish. Organic matter and particles were visually separated under a microscope (Nikon Eclipse 80i equipped with a Nikon DS-Fi1 digital camera and a NIS-Elements D3.0 image analysis system), because digestion using hydrogen peroxide (H_2O_2) is not efficient in removing organic particles (Hurley *et al.*, 2018). Detected organic particles were removed from the Petri dish using a metal tweezer. Three criteria were considered during the visual examination: 1) whether items had a cellular or organic structure, 2) whether the thickness of the fibers varied throughout the entire length, and 3) whether items had clear and homogenous color (Hidalgo- Ruz *et al.*, 2012). To validate the visual separation, 5 particles from 5 different samples were identified as microplastics and were examined by FTIR, initially. All particles were identified as microplastics, and thus all samples were separated and identified visually. The morphological characteristics of each microplastic particle including shape, color, and size in its longest dimension were stated and noted, separately. One of five shape categories namely pellet, foam, fragment, fiber, and film were assigned for each microplastic (McCormick *et al.*, 2014). Regardless of their shape (spheres or fragments), polystyrene particles were categorized as foam. Microplastic particles were grouped into the following five size categories: <1000 µm, 1001-2000 µm, 2001-3000 µm, 3001-4000 µm, and 4001-5000 µm. Both microplastic abundance and sizes were reported as average±S.D. in the Results section.

For verification of visual identification and determination of polymer composition of microplastic particles, Fourier Transform Infrared spectroscopy (FTIR hereafter) was used. Particles in similar shape and color were considered the same type, and therefore 18 particles representing all particles were examined under FTIR spectroscopy (Bruker Vertex 70) (McCormick *et al.*, 2014). The spectra range was 400- 4000 cm^{-1}. 32 repetitive scans with a resolution of 4 cm^{-1} were applied. OPUS software controlled the whole process.

Data Analysis

To understand whether microplastic abundance varied between tidal heights and depths on sandy shores, a generalized linear mixed-effects model (GLMM) with a Poisson distribution was applied. Tidal heights and depths were treated as fixed factors. The model included the site as a random factor to control for the potential influence of spatial variations across sites. Similarly, a linear mixed-effects model (LMER) was employed to determine if microplastic particle size varied between tidal heights and depths. In the model, tidal heights and depths were used as fixed factors and the site was a random factor. These two models were followed by Tukey's HSD tests for multiple comparisons between depths and tidal heights ("lsmeans" package in R, Lenth & Hervé, 2018).

To see the variations in the color, shape, and polymer type of microplastics between tidal heights and depths, separate permutational analyses of variance (PERMANOVAs) were used based on Bray-Curtis coefficient. Further, to assess the average dissimilarities of color, shape, and polymer type of microplastic particles, separate SIMPER analyses were employed.

Separate Redundancy Analyses (RDA) were used to evaluate the explanatory matrices for the variation in abundance, shape, color, and polymer type of microplastics between tidal heights and depths (Legendre & Legendre, 2012). All 7 explanatory variables were included in the models (i.e., TOC, sand grain size, beach length and width, proximity of the study site to the closest city center, cleaning frequency of the beaches, and road type next to the beach). Further, to obtain the relative importance of the explanatory variables for the abundance of microplastics between tidal heights and depths, a Generalized Boosted Regression Model (GBM hereafter) (Elith *et al.*, 2008) was employed using the gbm package in R (Ridgeway *et al.*, 2013) with a Poisson distribution. For the GBM model, the default values for the formula were used. As the size of microplastics did not vary between tidal heights and depths, no further analysis was performed for this characteristic. All statistical analyses were performed in the statistical software R version 3.6.2 (R Core Team) and PAST version 4.09 (Hammer *et al.*, 2001).

Results

Variation in Microplastic Abundance

A total of 2876 microplastic items from 675 sand samples at various tidal heights and depths over 9 beaches were examined. Microplastics were found at all beaches, tidal heights, and depths. The most polluted beach seemed to be Mavideniz Beach with an abundance of 13.68±11.72 items/kg^{-1}, which was followed by Bolaman Beach (9.33±7.88 items/kg^{-1}), Çamurlu Beach (8.43±8.41 items/kg^{-1}), Dolunay Beach

(8±7.6 items/kg^{-1}), Yalıköy Beach (7.92±5.56 items/kg^{-1}), Uzunkum Beach (7.76±7.27 items/kg^{-1}), Fatsa Halk Beach (7.71±6.53 items/kg^{-1}), Cüri Beach (7.47±7.09 items/kg^{-1}), and Çaka Beach (6.43±5.29 items/kg^{-1}). While microplastic abundance was similar between tidal heights, it showed a gradual decline with increasing depth (Figure 2). Microplastic abundance was highest at the surface (21.18±0.98 items/kg^{-1}) and lowest at the deepest sampling point (2.78±0.93 items/kg^{-1}). The microplastic abundance was slightly different at deeper sampling points between tidal heights with lower abundance at sampling lines closer to the seawater, though this difference was not statistically significant (Figure 2).

The Redundancy Analysis indicated that potential causative drivers included in the model explained 84.7% of the overall variations in microplastic abundance between sampling depths and tidal heights. The first and second RDA axes explained 55.78% (RDA 1) and 9.38% (RDA 2) of the variations in the three-dimensional distribution of the microplastics on sandy shores (Figure 3a). Further, GBM model indicated that wave actions (variations in TOC+sand grain size) were the most important variable explaining the distribution of microplastics on sandy shores at different depths by approximately 46% (Table 1). Wave actions were followed by the beach morphology (variations in beach length + beach width) by explaining approximately 37%

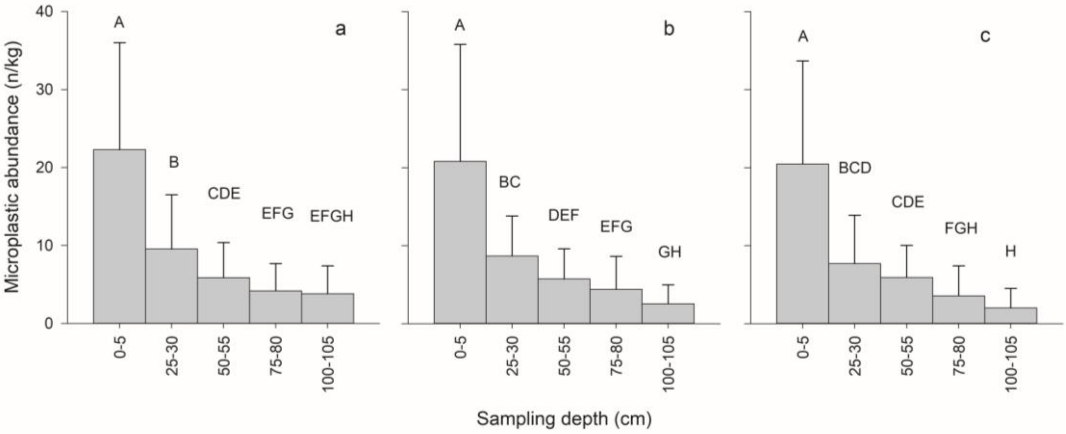

Figure 2. Mean of microplastic abundance (± S.D.) between sampling depths of a) upper line, b) middle line, and c) lower line. Letters above the bars indicate the significant difference based on Tukey's HSD test.

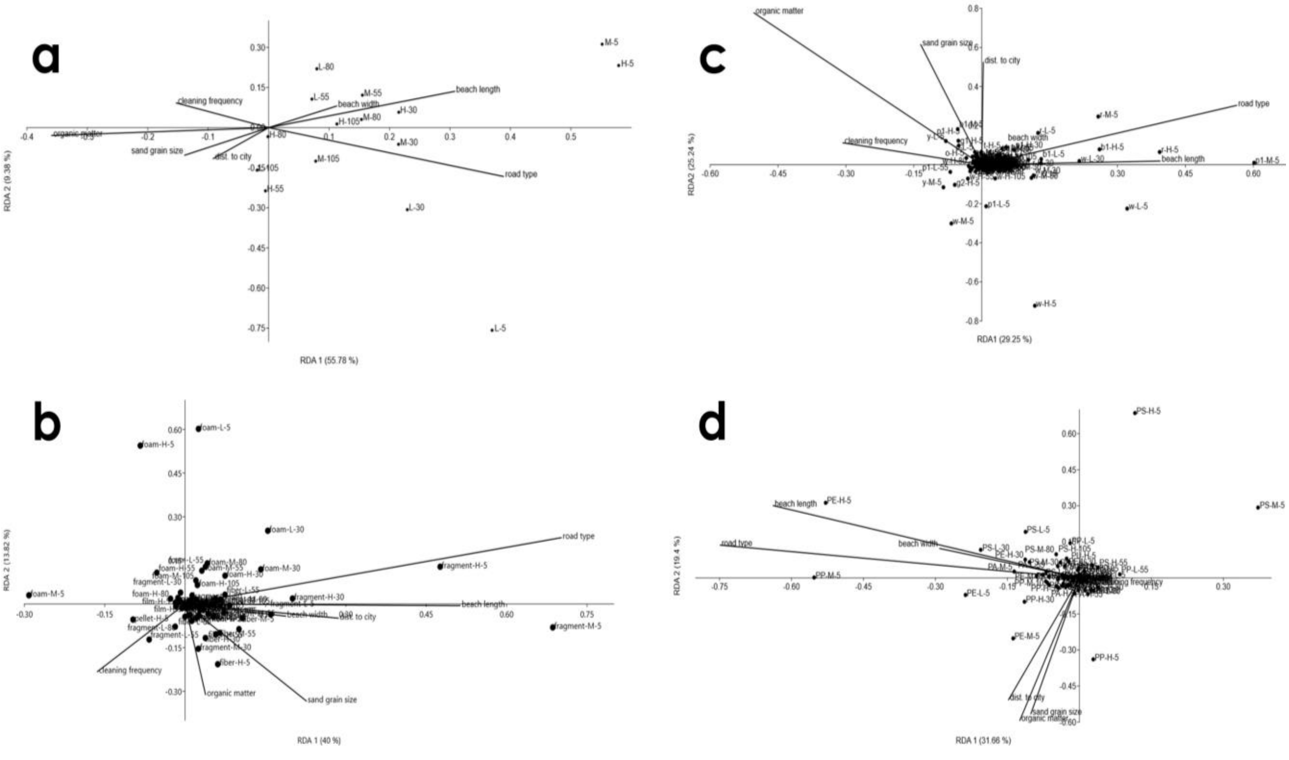

Figure 3. Ordination diagrams showing the results of RDA analyses of model parameters and a) microplastic abundance, b) microplastic shape, c) microplastic color, and d) microplastic polymer type.

of the variations in microplastic abundance between depths. Finally, the cleaning frequency of the beaches was the least influential variable for the distribution of the microplastics on sandy shores (Table 1).

Variation in Microplastic Size

The size of all microplastic particles significantly varied between tidal heights with the accumulation of larger particles on the upper line (Figure 4). Tukey's HSD test indicated that the size of all microplastic particles was higher at the upper line (1045.11±274.36 µm) compared to the microplastic size on the middle (935.34±375.79 µm) and lower lines (844.27±180.07 µm) (Figure 4). No difference in microplastic size between the middle and lower lines, and between the upper and middle lines was found. Additionally, the size of microplastics did not vary between sampling depths (Figure 4).

Shape of Microplastics

Fragments (38.4%) and foams (37.8%) were the most common shapes at all tidal heights and depths. The least available shape for the sampled microplastics was film (accounted for 1.2%) at all tidal heights and depths

Table 1. The relative importance of the model variables explaining variations in microplastic abundance

Variables	Relative importancen(%)
TOC	31.02
Beach length	22.22
Sand grain size	15.43
Beach width	14.49
Roady type next to the beach	10.28
proximity of the study site to the closest city center	5.02
Beach cleaning frequency	1.54

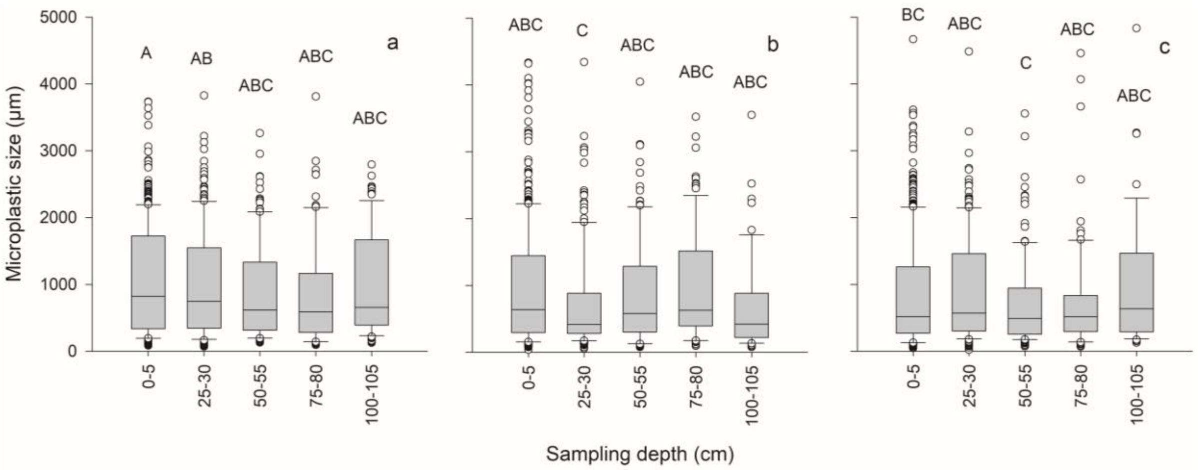

Figure 4. Average microplastic size (µm ± S.D.) between sampling depths of a) upper line, b) middle line, and c) lower line. Letters above the bars indicate the significant difference based on Tukey's HSD test.

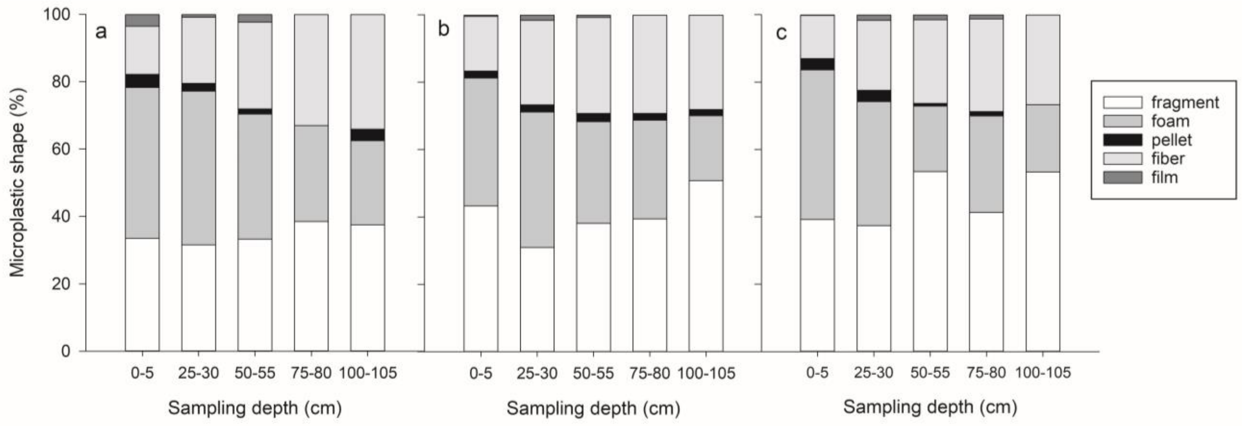

Figure 5. Assessment of microplastic shape (%) between sampling depths of a) upper line, b) middle line, and c) lower line.

(Figure 5). The shapes of microplastic particles significantly varied between depths (PERMANOVA, F=21.49, P<0.001) with a 53.83% of dissimilarity (SIMPER test). No difference was found in the shape of microplastics between tidal heights (PERMANOVA, F=1.83, P=0.07). Further, the interaction term between tidal heights and depths was not significant (PERMANOVA, F=0.84, P=0.71). RDA showed an overall explanation of the variations in the microplastic shape between tidal heights and depths by 84.2%. RDA 1 explained 40% and RDA 2 explained 13.82% of the variations in microplastic shapes between tidal heights and depths (Figure 3b).

Color of Microplastics

A total of 11 different microplastic colors were determined. The most and the least available microplastic colors were white (accounted for 30.23%) and gray (accounted for 0.69%) at all tidal heights and depths (Figure 6). The color of microplastic particles significantly varied between tidal heights (PERMANOVA, F=1.98, P=0.019) and between depths (PERMANOVA, F=11.022, P<0.001) with a 62.19% and 63.16% of dissimilarity (SIMPER), respectively. No significant interaction term between tidal heights and depths in terms of variations in microplastic color was obtained (PERMANOVA, F=1.124, P=0.256). RDA showed an overall explanation of the variations in microplastic color by 89.14% with an explanation of RDA1 by 29.25% and RDA2 by 25.24% (Figure 3c).

Polymer Type of Microplastics

A total of 5 different polymer types were detected by FTIR analysis, which are polystyrene (PS), polypropylene (PP), polyethylene (PE), polyamide (PA), and polyurethane (PU). While PS was the most available polymer type (accounted for 37.07%), PU was the least abundant polymer type (accounted for 1.87%) at all tidal heights and depts (Figure 7). Variations in the polymer type of microplastics were influenced by the tidal heights (PERMANOVA, F=1.911, P=0.044; SIMPER, 54.47% of dissimilarity), and depths (PERMANOVA, F=17.113, P<0.001; SIMPER, 56.32% of dissimilarity). The interaction between the tidal heights and depths showed no significant influence on the variations in polymer type of microplastics (PERMANOVA, F=0.086, P=0.824). RDA indicated that variables in the model explained a total of 87.45% of the variations in the polymer type of microplastics. Variations in the polymer type of microplastics were explained by RDA 1 and RDA 2 by 31.66% and 19.4%, respectively (Figure 3d).

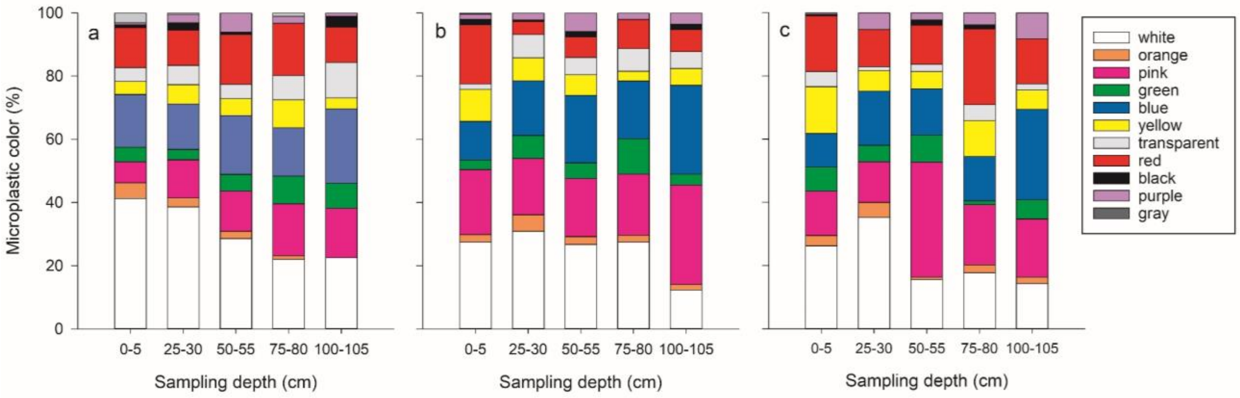

Figure 6. Assessment of microplastic color (%) between sampling depths of a) upper line, b) middle line, and c) lower line.

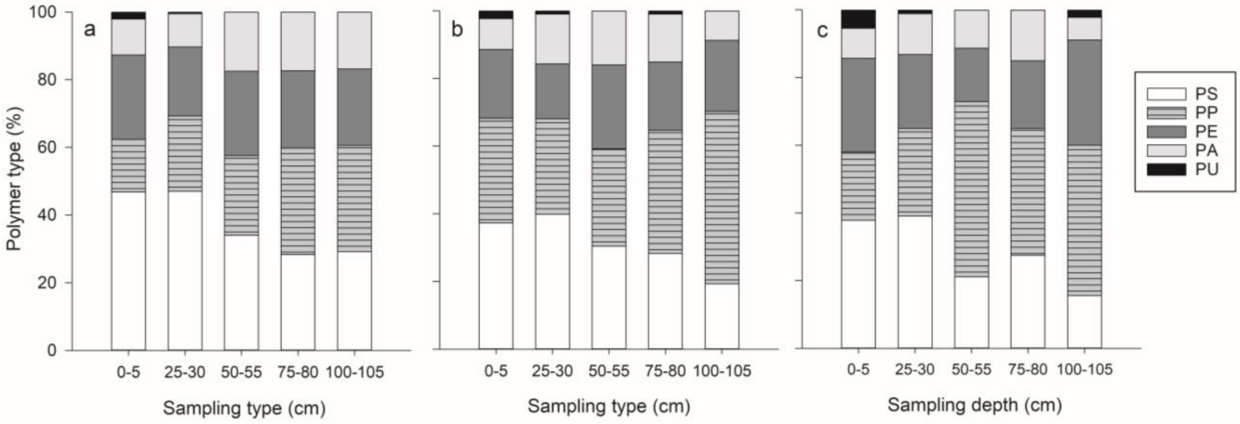

Figure 7. Assessment of microplastic polymer type (%) between sampling depths of a) upper line, b) middle line, and c) lower line.

Discussion

The findings of the current study indicated that microplastics showed an uneven three-dimensional distribution pattern on sandy shores, which was largely explained by wave actions and beach morphology. Further, while the size of the microplastics was similar at sampling depths, it showed a gradual decline between tidal heights. Other characteristics of microplastics including color, shape, and polymer type varied between tidal heights and sampling depths. As sandy shores are three-dimensional ecosystems with crucial services (McLachlan & Brown, 2006; Davis & FitzGerald, 2010), the findings of this work by investigating the potential factors determining the microplastic variations at different depths and tidal heights provide important insights that could be useful for the conservation implications to reduce the possible adverse effects of these contaminants in these systems.

Variation in Microplastic Abundance

Most studies investigating microplastic occurrence on sandy shores have often focused on surface contamination because examining these areas has been reported as a good indicator of the beach contamination profile (Besley *et al*., 2017). Only a few studies have investigated the three-dimensional microplastic contamination profile of the sandy shores whose results suggest that the abundance of microplastics obtained from different depths should be pooled for a more accurate estimation as the quantity of the buried microplastic particles may be large enough to influence the overall microplastic contamination profile (Turra *et al*., 2014; Moreira *et al*., 2016; Chubarenko *et al*., 2018).

Most of the previous studies investigating the three-dimensional distribution of microplastics on sandy shores found an increase in the microplastic density at depths approximately between 30 cm and 60 cm (Turra *et al*., 2014; Chubarenko *et al*., 2018; Pervez & Wang, 2022; Pham *et al*., 2023). The exception for these findings was reported from the sandy beaches of Cyprus in which a gradual decline in the microplastic density from the surface to deeper cores was detected (Duncan *et al*., 2018), which is in agreement with the findings of this work. This consistency between these two studies is not surprising as the beaches sampled in those studies are on the coasts of the semi-enclosed non-tidal marine systems (e.g., East Mediterranean and the Black Sea), however other studies were conducted on the ocean beaches where these sites are open to stronger oceanographic processes and tidal influences (but see Chubarenko *et al*., 2018).

Factors explaining the microplastic occurrence on the coastal systems that are influential for beach surface have also been of interest to various studies. Those include river input, fishing, wind influence, agricultural activities, tidal influence, recreational activities, and short-term and long-term tourism (Ballent *et al*., 2013; Kim *et al*., 2015; Stolte *et al*., 2015; Aytan *et al*., 2016; Cheung & Fok, 2016; Terzi & Seyhan, 2017; Willis *et al*., 2017; Dowarah & Devipriya, 2019; Gündoğdu & Çevik, 2019; Terzi *et al*., 2020; Aydın *et al*., 2023; Gül, 2023; Şener & Yabanlı, 2023). However, the causative drivers behind the vertical distribution of microplastics on sandy shores have only been examined by a limited number of studies. Previous studies identified the oceanographic processes (e.g., coastal currents, wave heights, tidal influence, etc.,) as the causative drivers (Turra *et al*., 2014; Moreira *et al*., 2016; Chubarenko *et al*., 2018). As stated above, all other studies investigated the three-dimensional distribution of microplastic particles on oceanic beaches (Turra *et al*., 2014; Pervez & Wang, 2022; Pham *et al*., 2023, but see Chubarenko *et al*., 2018). However, Chubarenko *et al*. (2018) conducted their research on the Russian coast of the Baltic Sea which is a non-tidal semi-enclosed marine system similar to the research sites of this study (the Black Sea) and of Duncan *et al*. (2018) (the Eastern Mediterranean Sea). They found a similar vertical microplastic distribution pattern with other oceanic beaches and their findings are not in agreement with the findings of this work and Duncan *et al*. (2018). This is obviously because of the variations in the wave energy between the Baltic Sea and the Black Sea (Loughlin *et al*., 2021; Jin *et al*., 2024). The sites Chubarenko *et al*. (2018) sampled experience strong winter waves that can reach up to 10 m in height, which causes a sea level rise of more than 2 m (Chubarenko *et al*., 2018). However, the coasts of neither the Eastern Mediterranean nor the Black Sea do not experience such strong waves in any season.

This study revealed 7 potential causative drivers that help to explain the three-dimensional distribution of microplastics on sandy shores. Similar to other studies, oceanographic processes (i.e., sand grain size and TOC used as indicators) were the most influential factors, which was followed by the beach morphology (e.g., beach width and length). It seems reasonable to conclude that beach morphology possibly interacts with other oceanographic processes. Shorter and narrower beaches are expected to be impacted by oceanographic processes greater than longer and wider beaches.

Other explanatory factors examined in this work include the level of terrestrial microplastic input (e.g., road type next to the beach), visitor frequency (e.g., the proximity of the beach to the closest city center), and cleaning frequency. Results indicated that the terrestrial input is one of the important drivers of the buried microplastics on sandy shores, which could be explained by the dynamism of the sandy beaches as these areas are under strong terrestrial and oceanographic influences that determine the frequency of the sand turn over time (McLachlan & Brown, 2006). Further, visitor frequency was found to be another moderately impacting factor in the three-dimensional distribution of microplastic particles, which could be related to the visitor frequency-related density of microplastic particles on beaches (Gül, 2023). Surprisingly, the cleaning frequency, which is an efficient way to diminish microplastic abundance on sandy shores (Gül, 2023) had the least influence on the three-dimensional distribution of microplastics. This study was conducted just before the tourism season when the beaches had not been cleaned for at least 4 months, which could reduce the overall efficiency of the cleaning frequency. This should be investigated by further studies.

Variation in Microplastic Size

A seaward gradual reduction in microplastic sizes on the surface of the beaches was detected, which could have at least two different explanations. First, larger plastic items often accumulate at the higher parts of the beaches and smaller pieces of those (e.g., microplastic particles) move seaward (Critchell & Lambrechts, 2016). Second, a similar number of larger plastic items stay between tidal heights, but the wave actions collect the plastic particles from the lower parts of the beaches at a higher rate compared to higher parts of the beach (Ballent *et al*., 2013). Further studies should be conducted to clear up these controversial possibilities.

Unlike the surface accumulation, no significant variation in microplastic size between various depths was detected. Products after a continual breakdown process have been defined as the largest source of microplastics in aquatic environments (Jiang, 2018). Solar ultraviolet radiation and high temperatures (Sun *et al*., 2022) and complex physical and chemical forces (McLachlan &Brown, 2006) synergistically influence larger plastic items and substantially increase the degradation speed on sandy shores (Corcoran *et al*., 2009). Given that information, similar vertical size distribution of microplastics on sandy shores could be the consequence of the variations in degradation speed at various depths. Exposure to direct solar radiation, high temperature, and other physical and chemical forces likely causes a faster degradation in the plastic items accumulated on the beach surface compared to the buried ones. Considering the low energy waves in the Black Sea, the turnover time of the sand should be quite long, as well (Jin *et al*., 2024). Therefore, it seems reasonable to conclude that the particles detected at various depths spent much longer time on the beaches compared to those on the surface (Thompson *et al*., 2009; Loughlin *et al*., 2021). Further studies are needed to test the age hypothesis proposed here.

Variations in Microplastic Characteristics

Microplastic characteristics (e.g., color, shape, and polymer type) have been utilized to understand processes, origins, and sources of those contaminants. For example, microplastics in white and transparent colors are often considered originated from the fishing industry (Wang *et al*., 2011), personal care products are considered sources of microbeads (Gaylarde *et al*., 2017), and polyethylene and polypropylene are thought as packaging materials (Hidalgo-Ruz *et al*., 2012). Therefore, understanding these characteristics of microplastics is an important component of the protection plans for coastal systems. However, no study is available, which examined the relationship between microplastic characteristics and their three-dimensional distribution. Further, different types of characteristics may have different possible explanations.

Microplastics with different polymer types have various densities (Frias *et al*., 2016). These variations in the density of different polymer types could influence their retention time in sand with higher transportation rates of the particles with lower densities by waves (Feng *et al*., 2022). Further, particles with higher density could penetrate to relatively deeper points in the sand, but the overall influence of the particle density is low (Waldschläger and Schüttrumpf, 2019). Indeed, microplastic particles detected at deeper sampling points in this study consist of heavier materials such as PP and PE rather than PS. Furthermore, the size of the particles are important determinant of their descending depth. Previous studies indicated that particles with smaller sizes descending to deeper points (O'Connor *et al*., 2019; Waldschläger & Schüttrumpf, 2019; Jin *et al*., 2024), which might be considered as further evidence for the potential variation in the ages of microplastics at different depths as proposed above. Moreover, the shape of the microplastic particles influences their descending speed and depth. Microplastics in spherical shape can reach to deeper point in sand compared to fragments and fiber (O'Connor *et al*., 2019; Waldschläger & Schüttrumpf, 2019; Feng *et al*., 2022). The results of this study indicated that PS particles in white color are more scarce at deeper sampling points compared to PP and Pa particles with various colors. However, further studies are required to understand the relationships between the descending rate and depth of microplastic particles and the influence of potential explanatory variables on these behavior as strongly suggested by Waldschläger & Schüttrumpf (2019).

Explanatory variables examined in this study worked in concert to explain the three-dimensional distribution of the microplastics with different shapes, colors, and polymer types by more than 84%, suggesting that these forces have different influential effects on these particles with different characteristics. However, no previous data is available to explain these interactions, therefore this is left to further studies.

Limitations

Detection of microplastic characteristics from environments still lacks a standardized global methodology. Therefore, weaknesses including limitations of applied methodology and used instruments should be clearly stated by the authors. Similar to counterpart studies, this work has some limitations related to separation techniques and instruments. Various measures, on the other hand, were taken to minimize the limitations. First, a limited number of particles compared to the overall sample size were validated by FTIR, which might lead to an overestimation of the overall microplastic contamination profile. To prevent this, a simple pre-validation technique was applied by examining five visually identified microplastic items retrieved from five different sand samples. Second, sand samples from various depths were collected using metal shovels, which may cause contamination of the sand samples with microplastic items from different depths and therefore may lead to erroneous results. To minimize the erroneous due to this potential contamination, the data were analyzed using mixed models. Overall, the same sampling technique was applied throughout the study. Therefore, any potential erroneous results, if there were any, should be similar for all samples, and with the combination of mixed models, this should not change the general frame of the results.

Conclusion

The causative drivers of the three-dimensional distribution of microplastic particles were examined on nine sandy beaches along the Turkish Coast of the Black Sea. For this purpose, 7 factors including TOC, sand grain size, beach length, and width, the proximity of the study site to the closest city center (a proxy for the tourism influence), cleaning frequency of the beaches, and road type next to the beach as an indicator of terrestrial microplastic contribution were examined just before the regular tourism season. The abundance of microplastic particles significantly varied between tidal heights and sampling depths, which was explained by 84.7% of the explanatory variables. The most influential variables were oceanographic processes (e.g., TOC and sand grain size) at 46.44% and beach morphology (e.g., beach length and width) at 36.7%. While there was a seaward decline in the microplastic size on the surface, no difference in particle sizes between depths was detected, suggesting that different factors may shape the microplastic size variations on the beach surface and at different depths. Other microplastic characteristics (shape, color, and polymer type) substantially varied between tidal heights and sampling depths. Those factors examined in this study explained at least 84% of variations in those characteristics, suggesting that those factors influence microplastics differently concerning the characteristics. Consequently, as a first detailed attempt to understand the causative drivers behind the three-dimensional distribution of the microplastics on sandy shores, this study suggests that microplastic distribution on beaches at various tidal heights and sampling depths cannot be explained by a sole factor. Instead, different factors work in concert to shape the distribution of these contaminants on beaches, which should be considered by the beach managers and local authorities responsible for coastal cleaning.

Ethical Statement

This article does not include any organisms and, therefore does not need ethical approval.

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No funding was received for this study.

Author Contribution

The author is solely responsible for conducting this research and preparing the article.

Conflict of Interest

The author declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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