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Presence, Spatial Distribution, and Characteristics of Microplastics in Beach Sediments Along the Northwestern Moroccan Mediterranean Coast

Soria Azaaouaj [1], Noureddine Er-Ramy [1], Driss Nachite [1] and Giorgio Anfuso [2,*]

[1] Laboratory of Applied and Marine Geosciences, Geotechnics and Geohazards (LR3G), Faculty of Sciences, University of Abdelmalek Essaadi, Tetouan 93000, Morocco; soriaazaaouaj@gmail.com (S.A.); ramy.nourdin@gmail.com (N.E.-R.); dnachite@uae.ac.ma (D.N.)

[2] Department of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, 11510 Puerto Real, Spain

* Correspondence: giorgio.anfuso@uca.es

Abstract: Microplastics (MPs) (<5 mm) are recognized as an emerging global problem in all oceans and coastlines around the world. This paper provided the quantification and characteristics of microplastics found on fourteen beaches along the northwestern Moroccan Mediterranean coast. A total of 42 samples were gathered at a depth of 5 cm along the shoreline using a quadrant of 1 m × 1 m. Microplastics were detected in all sediment samples. The average abundance was 59.33 ± 34.38 MPs kg^{-1} of dry weight (median: 48.33 MPs kg^{-1}), ranging from 22 ± 7.21 to 135.33 ± 38.80 MPs kg^{-1}. Statistical analyses revealed significant differences between sampling sites. All observed microplastics were classified according to their shape, color, and size. The microplastic shapes comprised fibrous MPs (77.61%), fragments (15.65%), films (4.49%), foams (1.85%), and pellets (0.40%). Microplastic particles in the sediment samples ranged from 0.063 to 5 mm in length and were composed of small (54.3%, <1 mm) and large sizes (45.7%, 1–5 mm). The size fractions with the greatest percentage of MPs were 1–2 mm (24.9%). The dominant color of the microplastics was transparent (43.2%), followed by black (15.8%) and blue (13.3%), with shapes that were mainly angular and irregular. The present results indicate a moderate level of microplastic contamination on the beaches throughout the northern Moroccan Mediterranean coast, and tourism, fishing activities, and wastewater discharges as the most relevant sources.

Keywords: beach pollution; marine debris; fishing activities; wastewater

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1. Introduction

Plastic pollution represents one of the most widespread environmental problems affecting all ecosystems. The global production of plastic products has risen considerably, from 2 million metric tons (in 1950) to around 400 million metric tons (in 2022) [1,2], and between 5 and 12 million tons of plastic litter are discharged into coastal environments each year [3,4]. Plastic macro-debris in the environment gradually breaks down into smaller particles through mechanical abrasion, UV radiation, and biological processes, leading to the formation of a particular type of marine plastic known as microplastics (MPs, <5 mm) [5,6]. Depending on their source, they can be divided into primary and secondary microparticles. Primary microplastics consist of microscopic, manufactured plastic particles and are commonly used in household and industrial applications [7,8]. Secondary microplastics are formed by the complex fragmentation and weathering of larger

plastic objects in nature [9]. Numerous investigations have demonstrated the widespread presence of microplastics in all environmental compartments [10–12] and in a variety of aquatic organisms. Therefore, they constitute a serious problem [13–15].

The Mediterranean Sea is one of the world's most polluted places even though it is a hotspot for biodiversity [4]. The local coastal population (around 512 million in 2018 [16]) and tourism (around 400 million overnight stays per year as estimated in 2019 [17]), combined with its semi-enclosed nature, are believed to be the main causes of the substantial accumulation of marine debris, essentially consisting of plastics [18,19]. Recent studies demonstrated microplastic pollution on beaches [5,6,20], the seabed [21,22], and the surface waters of the Mediterranean Sea [23–25], and their concentrations are comparable with those reported for the five regions of floating plastic particle accumulation in the open ocean [19].

In Morocco, as in all Mediterranean countries, the presence of microplastics on beaches represents a challenge. The Moroccan Mediterranean coast is a region of great economic and environmental relevance and a critical area for the protection of threatened and endangered species in the Alboran Sea [26]. However, this area is affected by intensive fishing and tourism activities, high population density, and discharges from extremely contaminated rivers, contributing to a significant risk of microplastic pollution [27]. An in-depth study of the distribution and prevalence of microplastics has been carried out along all the beaches of the entire eastern Moroccan Mediterranean coast, from Saïdia to Al Hoceima [28]. However, on the northwestern coast, apart from a few localized studies [27,29], no research has tackled microplastics over the whole area, and this is the main objective of this paper. The objective of the present work is to determine the abundance, type (fragment, pellet, foam, etc.), size, color, and spatial variability of microplastic debris stranded on the beaches of the northwestern Moroccan Mediterranean coast.

2. Materials and Methods

2.1. Study Area

The present paper represents the first investigation on the prevalence and characteristics of microplastics, ranging in size from 63 µm to 5 mm, in 14 beaches located along the northwestern part of the Moroccan Mediterranean coast, between Al Hoceima and Tangier (Figure 1). The beaches selected are representative of the characteristics of the Moroccan Mediterranean coastline. They cover some of the most popular and frequented sites during the summer period, thus reflecting the dynamics of beach use. They also include sites close to the main rivers outflowing in the northwestern Moroccan Mediterranean coast. In addition, these sites encompass all beach typologies—rural (4), village (3), urban (4), and resort (3)—as defined by the classification of Williams and Micallef [30], which allows a complete and balanced study of the coastline studied.

The study area, which covers 300 km of coastline, is characterized by sandy beaches, coastal wetlands, rocky coasts, coves, dunes, and cliffs [31,32]. The tide is microtidal and semi-diurnal, with a tidal range that decreases from west to east. The prevailing wind in the region is mainly from the west to the east [33]. Tourism activity, marine traffic, and fishing practices are the potential sources of microplastic pollution in this area.

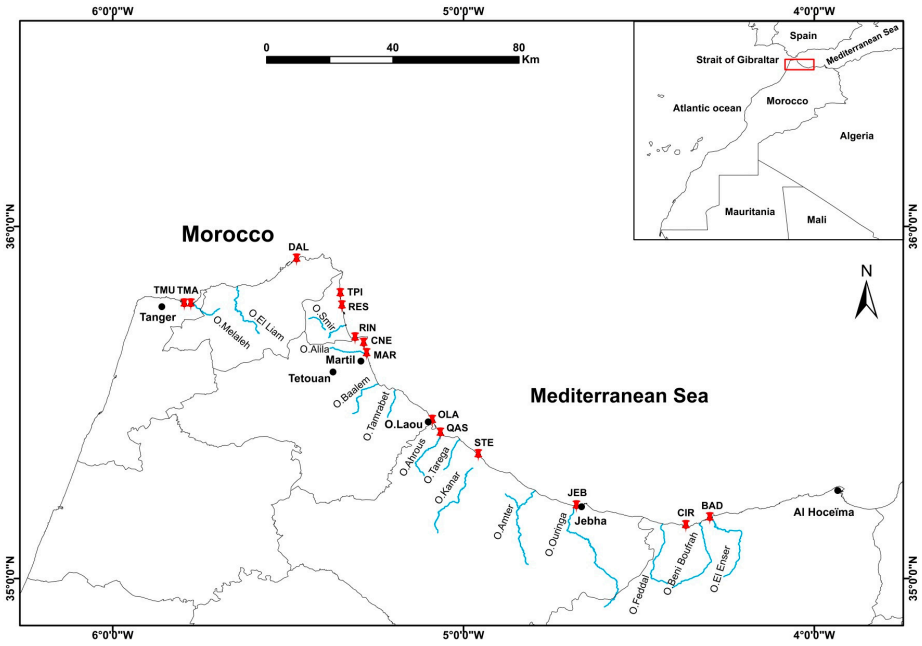


Figure 1. Location of the surveyed beaches along the study area. ((BAD) Bades, (CIR) Cala Iris, (JEB) Jebha, (STE) Stehat, (QAS) Quaa Assrasse, (OLA) Oued Laou, (MAR) Martil, (CNE) Cabo Negro, (RIN) Rincon, (RES) Restinga, (TPI) Tres Piedras, (DAL) Dalia, (TMU) Tangier Municipal, and (TMA) Tangier Malabata.

2.2. Sampling and Analysis

Microplastics sampling in beach sediments was carried out in accordance with the European MSFD program [34]. A total of 42 sediment samples were taken in November 2021, before the arrival of relevant winter rains and marine storms, from 14 beaches between Al Hoceima and Tangier on the northern Mediterranean coast of Morocco. Within each beach, 3 beach sediment samples (replicates) from the top 5 cm of sediment were collected along the shoreline using a 1 m^2 wooden quadrant. A gap of 25 m was maintained among the three sampling sites. Each sample consisted of ca. 4 kg of sediment and was stored in an aluminum container and transported to the laboratory. To avoid contamination, sampling was conducted using a stainless steel spoon, latex gloves, and cotton clothing [35]. In the laboratory, sediment samples were oven-dried at 60 °C for 48 h. For the sample analysis, 1 kg of dry beach sediment was sieved through a cascade of stainless steel sieves of 5, 1, and 0.063 mm. Mesoplastics (particles $\geq$ 5 mm) and their fraction < 0.063 mm were excluded from this study. Larger MPs (5–1 mm) were identified by visual recognition and binocular microscope observation, while smaller MPs (<1 mm) were extracted using a flotation method developed by Thompson et al. [36], Ng and Obbard [37], Claessens et al. [38], and Mohamed Nor and Obbard [39], with some slight modifications. A salt solution was prepared by dissolving 280 g of sea salt in 1 L of distilled water. The sediment fraction <1 mm was placed in a 2 L glass beaker with 1 L of saturated sea salt solution. The mixture was stirred with a magnetic stirrer for 30 min at 1000 rpm and then left to stand for 2 h. Finally, once this time had elapsed, the supernatant supposed to contain the samples' microplastics was filtered using Whatman filters (Whatman, Maidstone, Kent, UK), and this operation (shaking, settling, and filtration) was repeated twice for each sample. To avoid the ambient deposition of airborne filaments and fibers, aluminum foil was placed over every beaker used for separation. The filters were then placed in glass Petri dishes and dried at 60 °C in an oven for 24 h. The dried filter papers were inspected under a binocular microscope (Nikon SMZ800N, Nikon, Tokyo, Japan).

The identification criteria described by Mohamed Nor and Obbard [39] and Hidalgo-Ruz et al. [40] were followed in order to distinguish plastic particles from those that occur naturally. Microplastic particles were categorized based on their shape, which included fibrous MPs (fibers and filaments), fragments, films, pellets, and foams (expanded polystyrene particles or other foams), and color (white, transparent, red, orange, blue, black, gray, brown, green, pink, yellow, and violet). Plastic particles were also classified into nine size classes: 0.063–0.2; 0.2–0.4; 0.4–0.6; 0.6–0.8; 0.8–1; 1–2; 2–3; 3–4, and 4–5 mm.

2.3. Data Analysis

The microplastic particles collected were counted for each replicate sample, and their abundance (average value of the 3 replicates) was defined as the number of items per kilogram of dry sediment (items kg^{-1} d.w.). Their associated standard deviation (SD) was also obtained. Data were presented as the average ± standard deviation (SD). Microplastic graphs were created using Microsoft Excel 2010 (Microsoft, Redmond, WA, USA). Statistical analyses were carried out using the SPSS Version 20.0 statistics software package (IBM, Armonk, NY, USA). Shapiro–Wilk tests (SPSS version 20.00) were used to investigate the normality of data. Furthermore, one-way analysis of variance (ANOVA) was used to compare the microplastic concentrations among sampling sites. Statistical significance with *p*-values (<0.05) was used for all statistical analyses. The geographical location of the beaches studied was depicted using ESRI ArcGIS 10.3 (ESRI, Redlands, CA, USA).

3. Results and Discussion

3.1. Abundance of Microplastics

A total amount of 2492 microplastic particles, varying from 0.063 to 5 mm, were collected and characterized. Considering all sampled sites, the average abundance of microplastics was 59.33 ± 34.38 MPs kg^{-1} (median: 48.33 MPs kg^{-1}) and varied from 22 ± 7.21 MPs kg^{-1} at Dalia to 135.33 ± 38.80 MPs kg^{-1} at Tres Piedras (Table 1). The average abundance of microplastics (59.33 ± 34.38 MPs kg^{-1}) recorded in the present was compared with values obtained by similar previous studies based on the same methodological protocols for sampling and laboratory analyses as the ones used in the present paper, and was used to essentially characterize microplastics related to tourism and fishing activities. The results observed in this paper were similar to values recorded in other regions such as Murcia in Spain (53.1 ± 7.6 MPs kg^{-1}, [41]), the Persian Gulf (61 ± 49 MPs kg^{-1}, [42]), Indonesia (70.91 ± 23.88 MPs kg^{-1}, [43]), and China (72 ± 27.2 MPs kg^{-1}, [44]), but significantly greater than those found at beaches in Russia (1.3 to 36.3 MPs kg^{-1}, [45]), Granada in Spain (20–48 MPs kg^{-1}, [46]), Bangladesh (8.1 ± 2.9 MPs kg^{-1}, [47]), Vietnam (0 to 6.58 MPs kg^{-1}, [48]), the Caribbean Islands (7 ± 6 MPs kg^{-1}, [49]), and the coastline of Gujarat (1.4 ± 1.14 to 26 ± 28.15 MPs kg^{-1}, [50]) (Table 2).

The average concentration of MPs in beach sediments reported in this paper was lower than that of the eastern Mediterranean coast of Morocco (99.79 ± 44.19 MPs kg^{-1}, [26]). This average is still significantly lower than the findings of studies conducted on the beaches of the Atlantic coast of Morocco (15720 MPs kg^{-1}, [51]), on the southern coast of the Baltic Sea (3267 MPs kg^{-1}, [52]), England (from 40 to 560 MPs kg^{-1}, [53]), the northern coast of Mississippi (590 ± 360 MPs kg^{-1}, [54]), the Port of Charleston, South Carolina, USA (4515 MPs kg^{-1}, [55]), Mexico (135 ± 92 MP kg^{-1}, [56]), the Galapagos Islands in Ecuador (3300 MPs kg^{-1}, [57]), Karnataka (664 ± 114 MPs kg^{-1}, [58]) and the Pondicherry coast (720.30 ± 191.60 MPs kg^{-1}, [59]) in India, Thailand (338.89 ± 264.94 MPs kg^{-1}, [60]), Shandong in China (664 ± 80 MPs kg^{-1}, [61]), and Taiwan (200 MPs kg^{-1}, [12]) (Table 2).

Table 1. The abundance of MPs (items kg^{-1} dry weight) for each surveyed beach (±SD: standard deviation).

Code	Beach	Coordinate System		Total MPs	Fibers	Filaments	Films	Fragments	Foams	Pellets
BAD	Bades	35.171017	−4.297218	24.97 ± 13.32	0	21.33 ± 13.32	0.67 ± 1.15	2.67 ± 2.31	0	0
CIR	Cala Iris	35.148218	−4.365325	25.33 ± 11.02	0.67 ± 1.15	19.33 ± 11.37	1.33 ± 1.15	0.67 ± 1.15	3.33 ± 3.06	0
JEB	Jebha	35.204896	−4.679614	44.67 ± 17.24	0.67 ± 1.15	36.67 ± 11.02	0.67 ± 1.15	6.67 ± 5.77	0	0
STE	Stehat	35.348361	−4.956083	83.33 ± 32.52	2.67 ± 3.06	66 ± 21.63	0.67 ± 1.15	14 ± 12.49	0	0
QAS	Qaa Assrasse	35.413112	−5.067114	113.33 ± 20.82	4 ± 6.93	74.67 ± 29.14	6 ± 10.39	26.67 ± 36.30	2 ± 3.46	0
OLA	Oued Laou	35.449611	−5.090361	50 ± 57.17	4 ± 4	36 ± 39.85	2 ± 2	7.33 ± 12.70	0	0.67 ± 1.15
MAR	Martil	35.625944	−5.272194	51.33 ± 14.19	6 ± 5.29	30 ± 9.17	7.33 ± 2.31	4.67 ± 5.03	3.33 ± 3.06	0
CNE	Cabo Negro	35.664347	−5.284090	79.33 ± 39	0	39.33 ± 26.03	9.33 ± 9.45	27.33 ± 21.20	1.33 ± 2.31	2 ± 3.46
RIN	Rincon	35.687500	−5.323167	44 ± 18.33	3.33 ± 4.16	28.67 ± 20.53	3.33 ± 3.06	6.67 ± 7.02	2 ± 3.46	0
RES	Restinga	35.775306	−5.346250	31.33 ± 7.57	1.33 ± 2.31	28 ± 8	0	2 ± 3.46	0	0
TPI	Tres Piedras	35.810000	−5.351139	135.33 ± 38.80	7.33 ± 6.11	110.67 ± 29.14	4.67 ± 3.06	12.67 ± 7.02	0	0
DAL	Dalia	35.905583	−5.477278	22 ± 7.21	2 ± 2	20 ± 6.93	0	0	0	0
TMU	Tangier-Municipal	35.777532	−5.793753	79.33 ± 22.48	9.33 ± 9.45	56.67 ± 8.08	1.33 ± 2.31	11.33 ± 6.11	0	0.67 ± 1.15
TMA	Tangier-Malabata	35.777500	−5.779306	46.67 ± 12.22	13.33 ± 6.11	22.67 ± 11.72	0	7.33 ± 3.06	3.33 ± 4.16	0
	Mean			59.33 ± 34.38	3.90 ± 3.90	42.14 ± 26.25	2.67 ± 3.03	9.29 ± 8.62	1.10 ± 1.42	0.24 ± 0.56
	Median			48.33	3	33	1.33	7	0	0

Table 2. Comparative study of microplastic abundance in various beach sediments.

Region	Range (Min–Max) (MPs kg^{-1})	Mean Abundance (MPs kg^{-1})	Size Range (mm)	Predominant Shapes	Reference
Coastal area of the Mar Menor lagoon, Spain	8.2 ± 0.6–166.3 ± 1.7	53.1 ± 7.6	0.17–5	Fragments and Fibers	[41]
Aveiro, Portugal	15–320	100	0.3–5	Fibers	[62]
Mexico	16 ± 4–312 ± 145	135 ± 92	0.032–5	Fibers	[56]
Brazil		398 items	1–5	Foams and Fragments	[63]
Puerto Rico	3 ± 3–17 ± 4	7 ± 6	0.3–4.75	Fibers and Fragments	[49]
South Aegean Sea coasts, Turky	117.33 ± 79.95–360.00 ± 237.66 (Summer) 76.00 ± 49.52–358.33 ± 297.24 (Winter)	177.11 ± 121.29 (Summer) 170.53 ± 168.87 (Winter)	N.D	Fibers and Fragments	[64]
Virginia and North Carolina, USA	2224–596	1410 ± 810	0.5–5	Fibers	[65]
North Mississippi, USA	950 ± 100–270 ± 30	590 ± 360	N.D	Fibers and fragments	[54]
Karnataka coast, India	264 ± 62–1002 ± 174	664 ± 114	0.1–5	Fibers and films	[58]
Puducherry Coast, India		720.30 ± 191.60	0.3–5	Fragments and fibers	[59]
Gujarat state, India	1.4 ± 1.14–26 ± 28.15		1–5	Threads and films	[50]
Phuket coast, Thailand		188.3 ± 34.5	N.D	Fibers	[66]
Rayong coast, Thailand	80 ± 38.73–582.22 ± 319.29	338.89 ± 264.94	0.1–5	Fragments and fibers	[60]
Northern coastal waters of Surabaya, Indonesia	50.74 ± 5.45–111.93 ± 5.82	70.91 ± 23.88	0.2–1	Fragments and Fibers	[43]
Hengchun Peninsula, Taiwan	80–480	200	N.D	Fibers	[12]
Da Nang, Vietnam		9238 ± 2097	0.3–5	Fibers	[67]
Cox's Bazar, Bangladesh		8.1 ± 2.9	0.3–4.5	Fragments and Fibers	[47]
Shandong, China	900 ± 180–172 ± 12	664 ± 80	N.D	Fibers	[61]
Qingdao, China	9.08 ± 8.99–30.02 ± 2.49	17.88 ± 5.18	0.1–1	Filaments and Films	[68]
Persian gulf, Iran	36.0 ± 7.2–125 ± 25	61 ± 49	0.8–4.6	Fibers and films	[42]
Bizerte Lagoon, Tunisia	141.20 ± 25.98–461.25 ± 29.74	316.03 ± 123.74	0.1–5	Fibers and Fragments	[69]
Bizerte Lagoon, Tunisia	2340 ± 227.15–6920 ± 395.97		0.2–5	Fibers and Fragments	[70]
Agadir, Morocco	7680–34,200	15,720	N.D	Fibers and fragments	[51]
Eastern Mediterranean coast, Morocco	40 ± 7.48–230 ± 48.69	99.79 ± 44.19–86 *	0.063–5	Fibrous and fragments	[28]
Northern Mediterranean coast, Morocco	22 ± 7.21–135.33 ± 38.80	59.33 ± 34.38–48.33 *	0.063–5	Fibrous and fragments	Present study

Note: * indicates the median.

The ANOVA F test revealed that there were significant differences in the abundance of MPs among the 14 beaches (F = 5.12, ddl = 13, $p = 0.00$). This great spatial heterogeneity was in line with the findings of previous research on microplastics pollution in beach sediments [28,37,71].

The greatest concentration of microplastics was found in the samples from Tres Piedras beach, with a mean abundance of 135.33 ± 38.80 MPs kg^{-1}, which was significantly greater than that of the other sites along the northwest Mediterranean coast of Morocco ($p < 0.05$). This can be attributed to the high level of tourist activity at this sample site, i.e., a large number of visitors per day, which can reach a maximum of 20,000. Many studies around the world have demonstrated a strong correlation between tourism and high concentrations of microplastic debris. For example, a greater prevalence of microplastics in the sand of the beaches of Huatulco Bay, located on the Pacific coast of southern Mexico, has been associated with the strong influence of water from parked cruise ships, hotels, and tourist activities facing the bay of Huatulco [72]. A strong correlation was also found between tourist activities and the abundance of MPs in sand and sediment in a protected coastal area located in the southeast of Spain: the Mar Menor lagoon [41]. In this paper, high concentrations of MPs have also been found on the beach at Quaa Asserasse (113.33 ± 20.8 MPs kg^{-1}), located in the province of Chefchaouen. MPs pollution at Quaa Asserasse may be preferentially linked to artisanal fishing, which is the main economic activity in this region. High concentrations of microplastics have been reported at the Firma and Arekmane beaches, located on the eastern Moroccan Mediterranean coast, and were linked to a combination of tourism and fishing activities carried out in these areas [28]. In addition to fishing activity, high levels of MPs observed at Quaa Asserasse beach are likely related to the discharges of the Ahrous River, as observed by several studies that have attributed high levels of microplastics to river discharges [6,38,73]. The lowest MPs abundance was found in Dalia (22 ± 7.21 MPs kg^{-1}), probably due to the rural nature of the beach, limited anthropogenic activities, and the absence of rivers flowing into this area [56,69] (Table 1).

3.2. Microplastic Types, Colors, and Sizes

Microplastic samples were categorized into different types based on their morphology, including fibrous MPs (filaments and fibers), fragments, films, foams, and pellets. Examples of different types of microplastics collected from the 14 beaches are shown in Figure 2. Fibrous MPs were the most prevalent type, accounting for 77.61% (1934 items) of the total MPs detected (filaments: 71.03%, fibers: 6.58%), followed by fragments (15.65%, 390 items), films (4.49%, 112 items), foams (1.85%, 46 items), and pellets (0.40%, 10 items) (Table 1 and Figure 3). These results are comparable to those reported on other Moroccan beaches, i.e., in the eastern part of the Mediterranean [28] and in the central part of the Atlantic [51].



Figure 2. Examples of microplastic types found in the sediments of the studied beaches. ((**A**–**F**) Filaments, (**G**) fibers, (**H**–**M**) fragments, (**N**–**P**) films, (**Q**–**S**) pellets, and (**T**) foam). Scale bar: 1 mm.

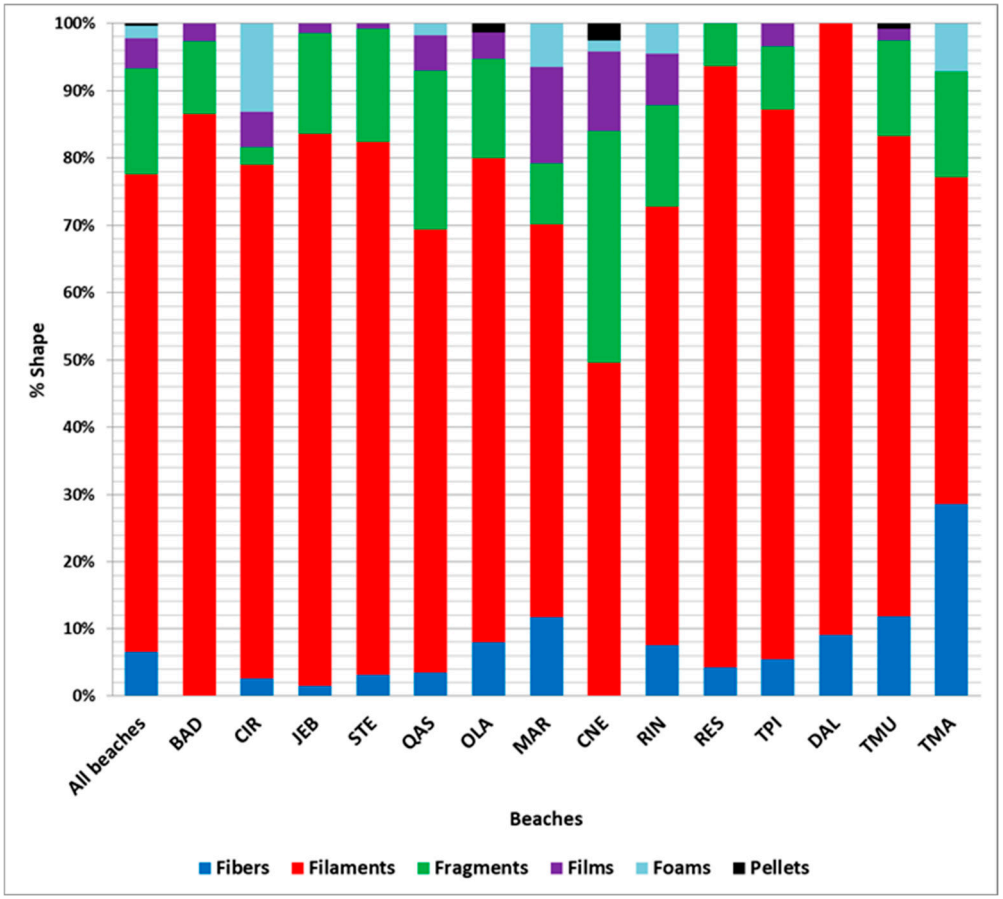


Figure 3. Distribution of MP shapes at each site.

High proportions of fibrous microplastics were also observed in other regions, such as in Algeria [74], Tunisia [69,70], the Gulf of Lion in the NW Mediterranean Sea [75], Slovenia [5], the Baltic Sea [76], Turkey [64], Portugal [62], the Persian Gulf [42], Dubai in the United Arab Emirates [77], India [78], Indonesia [79], Thailand [66], Vietnam [67], Taiwan [12], China [68], New Zealand [71], South Africa [80], Virginia and North Carolina, USA [65], the Gulf of Mexico [81], and the Baja California Peninsula, Mexico [56] (Table 2). The coefficient of variation (CV) for the abundance of fibers, fragments, films, foams, and pellets was >1.0, implying that their abundance in sediments was highly variable. However, the coefficient of variation for filaments was <1.0, indicating low variation compared with other MP types. Low filament spatial variation was also observed on sandy beaches along the eastern Moroccan Mediterranean coast [28]. To further understand the variability of different types of microplastics in beach sediments, a future study should attempt to increase the sample size and extend it to new geographical areas, including beaches with different environmental and anthropogenic characteristics, as well as to monitor the evolution of microplastics pollution over time. This would provide a better understanding of the factors that influence the distribution and variability of microplastics in beach sediments.

The abundance of microplastic types varied spatially and was assessed by means of an ANOVA F test. There was a significantly different proportion of filaments ($p = 0.00$) and fibers ($p = 0.042$) in beach sediments between sampling sites at the $p < 0.05$ level, while there was no significant difference in fragments ($p = 0.243$), films ($p = 0.135$), foams ($p = 0.269$), and pellets ($p = 0.561$).

The predominance of secondary microplastics, mostly angular (63% of fragments and 52% of foams had angular or subangular shapes) and irregular (96% of films had irregular shapes) on beaches compared to pellets indicates that the source of microplastics is related to the degradation of large plastic items.

According to Nachite et al. [82], 68.7% of macro-debris found on Moroccan Mediterranean beaches were plastic items and included bottle caps, plastic bags, bottles, food containers, and pieces of plastic, among others. The results of this paper are in line with the study carried out on the eastern Mediterranean coast of Morocco by Azaaouaj et al. [28], which reported that most of the MP particles detected were angular and irregular in shape, resulting from the decomposition of larger materials into smaller pieces. Cordova et al. [43] and Priya et al. [83] revealed that irregular microplastics are the most prevalent type found in nature.

In the present paper, the MPs identified showed different colors, which is consistent with other MP studies [28,58,66,84,85], indicating that microplastic particles come from a variety of sources [20]. Transparent (43.1%) and black (16%) were the dominant MP colors, followed by blue (13.3%), white (9.3%), red (6.3%), and pink (5.9%). The remaining 6% was made up of green, orange, brown, yellow, and violet particles (Figure 4).

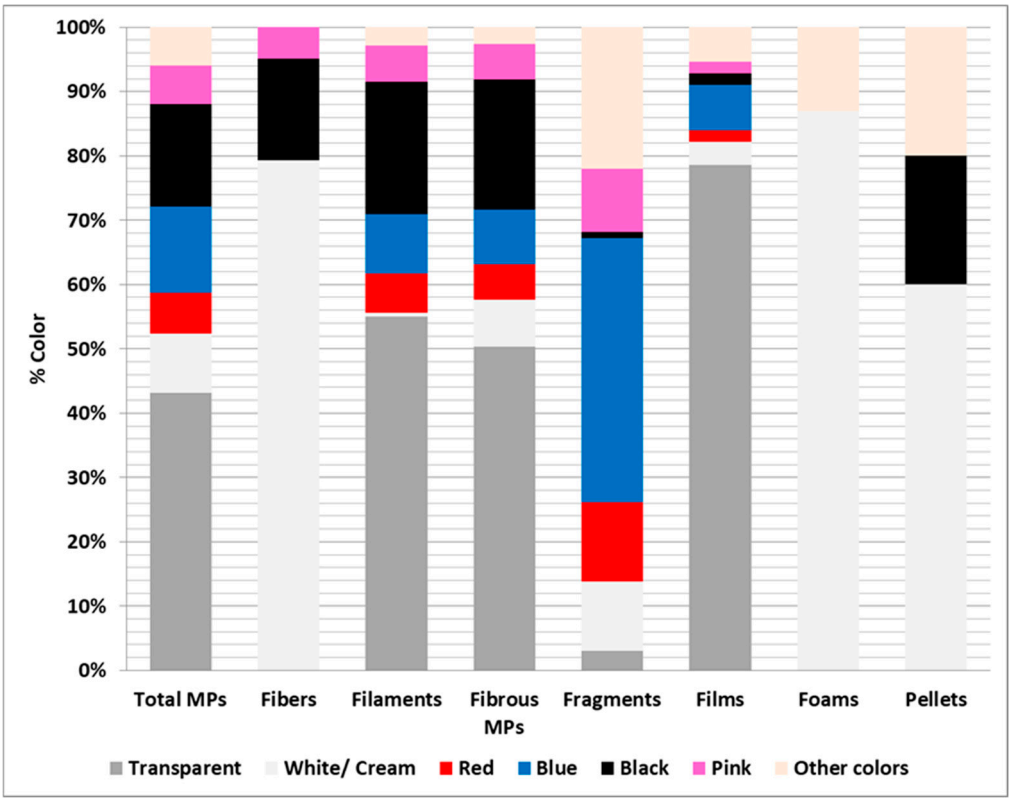


Figure 4. Colors (in percentages) observed for each different shape of microplastic investigated.

The results of the ANOVA F test revealed that only transparent and black microplastics showed a significant difference between the beaches examined (ANOVA F test, $p = 0.02$; $p = 0.01$). It can be deduced from the above findings that light-colored microplastics (white and transparent particles) represented 52.4% of the microplastics analyzed. The most abundant colors of microplastics reported on the eastern beaches of the Moroccan Mediterranean coast were white/transparent (60%) [28], which is consistent with the current findings. The larger percentage of white/transparent MPs recovered in the present research is mainly attributed to fishing gear [28,62,66]. These colors may also be the result of the aging process, such as weathering and degradation over extended periods of time [9,86]. Microplastic particles of similar colors have been detected in other places, such as on the Portuguese coast [62], where 51% of the microplastics were white and translucent. A study carried out in India revealed that white/transparent MPs accounted for 70.57% of the total amount [87]. Similarly, Bissen and Chawchai [88] discovered that 39.6% of the microplastics detected on the beaches of Chonburi province, Thailand, were white/transparent. Nonetheless, other investigations have indicated a significant occurrence of colored microplastics [6,39,89–91]. The color of microplastics may potentially contribute to the likelihood of ingestion due to prey item resemblance [92]. Boerger et al. [93] showed that white/transparent (75%) and blue (11.9%) plastics were primarily ingested by planktivorous fish from the North Pacific central gyre. Shaw and Day [94] found that seabirds have a tendency to eat light-colored plastic pellets because of their similarity with common food sources, such as fish eggs and crustaceans. Neves et al. [95] revealed that the ingestion of microplastics by fish could cause internal injuries or obstruction of the gastrointestinal tract and lead to death. MP ingestion can also damage the cells and tissues of organisms such as zebrafish (*Danio rerio*) [96] and blue mussels [97] and affect their reproductive function, as observed for Pacific oysters (*Crassostrea gigas*) [98].

The MPs detected in this paper were mainly categorized into nine subcategories based on their size (Figure 5), with an overall average size of 1.42 ± 1.14 mm. Pellets had the

largest average major dimension (3.70 ± 1.07 mm), followed by foams (2.99 ± 1.31 mm), films (2.66 ± 1.31 mm), fragments (1.48 ± 1.42 mm), filaments (1.31 ± 0.98 mm), and fibers (1 ± 0.89 mm). The findings of the ANOVA F test indicated that there was a statistically significant variation ($p < 0.05$) between sampling sites for size fractions of 0.2–0.4 ($p = 0.073$), 0.8–1 ($p = 0.004$), 1–2 ($p = 0.001$), and 2–3 mm ($p = 0.000$); however, there was no statistical difference ($p > 0.05$) for sizes of 0.063–0.2 ($p = 0.633$), 0.4–0.6 ($p = 0.003$), 0.6–0.8 ($p = 0.245$), 3–4 ($p = 0.261$), and 4–5 mm ($p = 0.073$). Large MPs (LMPs: 1–5 mm) accounted for 45.7% (1138 items), while small MPs (SMPs: <1 mm) accounted for 54.3% (1354 items).

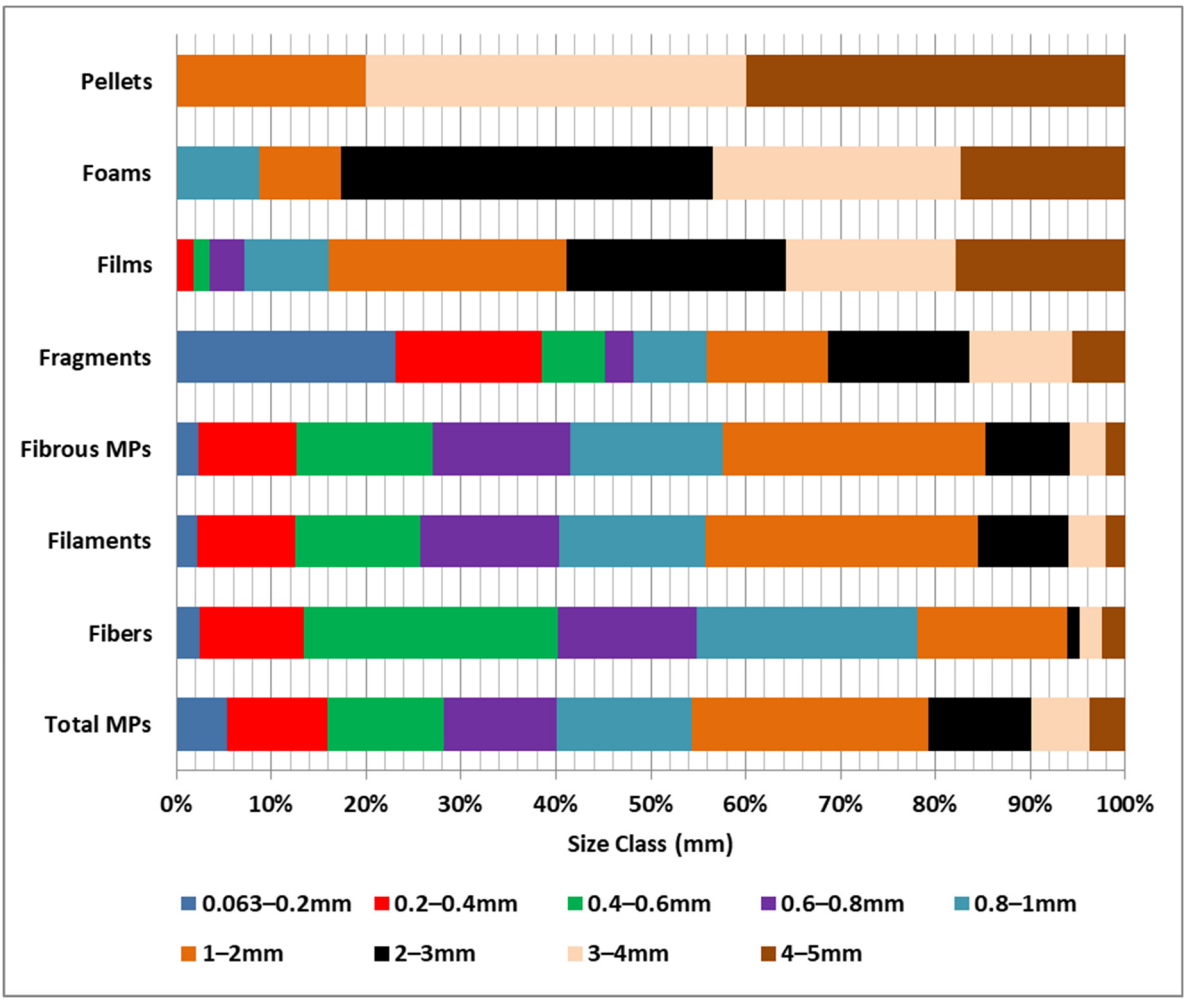


Figure 5. Size of different shapes of microplastics investigated.

The largest percentage of microplastics (24.9%) was identified in the 1–2 mm size range, followed by 14.2% (0.8–1 mm), 12.3% (0.4–0.6 mm), and 12% (0.6–0.8 mm). The present results are consistent with research in the northwest Pacific Ocean [9], the Tuticorin coast in India [99], the Bohai Sea in China [100], and the Praia da Barra beach in Aveiro, Portugal [62]. However, this pattern was different from many other previous studies, including those conducted in the Persian Gulf [101], Bangladesh [73], Slovenia [5], and Indonesia [79], where microplastics >1 mm were predominantly found. Additionally, contrary to the present findings, the abundance of LMPs on the beaches of the eastern Mediterranean coast of Morocco was more dominant than SMPs [28]. The prevalence of small microplastics can be attributed to the decomposition and degradation of larger plastic items [60] due to the fact that the plastic aging process and climate forcing contribute to breaking large marine plastic litter into smaller particles, resulting in a reduction in the size of microplastics [9]. Because of their small size, microplastics can be ingested by a

wide variety of marine organisms. Microplastics could be mistaken as prey by various benthic and pelagic marine organisms, such as fish [102], amphipods [36], mussels [103], and zooplankton [7], since their size range is similar to that of sand grains and planktonic organisms [104]. Lusher et al. [105] demonstrated that the small size of MPs facilitates intake by organisms compared to macroplastics.

Fibrous MPs were detected and were the predominant form at all sites, representing 77.6% of the total amount of microplastics (Table 1 and Figure 3). In order to shed light on the origin of fibrous particles in the area studied, fibrous MPs were separated into two subcategories in this paper: filaments (fishing materials) and fibers (degraded textiles). Fibers were relatively low in abundance (6.58%, 164 items) and were observed on eleven out of the fourteen beaches studied. Their average concentration was 3.9 ± 3.9 fibers kg^{-1} (Table 1 and Figure 3). They were predominantly (98.8%) composed of single fibers and appeared in all size fractions, but most frequently in the 0.4–0.6 mm fraction, which represented 26.8% of the total fibers (Figure 5). The fiber colors found were white, black, and pink, which accounted for 79.3%, 15.9%, and 4.9% of the total fibers, respectively (Figure 4). Anthropogenic sources, such as synthetic textiles, may be principally responsible for the high quantity of colored fibers in the examined area [85]. The highest values were observed at the Tangier Malabata and Tangier Municipal beaches, where the overall averages were 13.33 ± 6.11 and 9.33 ± 9.45 fibers kg^{-1}, respectively, which are higher than the average for the study area (Table 1). Most of the fiber-shaped MPs found on these beaches may be linked to sewage resulting from washing clothes that are made from synthetic materials. Previous studies have suggested that the washing process can release 1900 to 700,000 fibers per 6 kg of clothing into the marine environment [106,107]. Manbohi et al. [85] and Prata et al. [108] reported that the major fiber pollutants present in the environment came from domestic waste resulting from clothes-washing activities. The existence of fibers in this area is consistent with an earlier study that demonstrated the presence of fiber microplastics on the eastern Mediterranean coast of Morocco from wastewater resulting from the laundering of synthetic clothing [28].

The majority of microplastics found in all beaches were filaments, which accounted for 71% of the total particles identified and an overall average of 42.14 ± 26.25 filaments kg^{-1} (Table 1 and Figure 3). Single filaments accounted for 99.9% of all filaments detected and were found in all size fractions, with the highest prevalence in the 1–2, 0.8–1, and 0.6–0.8 mm size classes, accounting for 28.8%, 15.4%, and 14.6% of the total filaments (Figure 5). Transparent filaments were mainly observed (55.2% of the total filaments) in this paper (Figure 4), which concurs with the findings obtained by Prarat and Hongsawat [60], who discovered that 51% of the filaments in Rayong province, Thailand, were transparent. A high abundance of filaments, with above-average values, was detected at Tres Piedras (110.7 ± 29.1 filaments kg^{-1}), Quaa Asserasse (74.7 ± 29.1 filaments kg^{-1}), and Stehat (66 ± 21.6 filaments kg^{-1}) (Table 1). The high proportion of microplastic filaments found on the beach of Tres Piedras was probably due to the tourist activities, as reported in other areas by Chen and Chen [12] and Hossain et al. [73]. The main activity regularly practiced on the beaches of Quaa Asserasse and Stehat is artisanal fishing, and many abandoned fishing net fragments have been found on these beaches. Therefore, the likely source of the high concentrations of filaments at those sites was the fragmentation of ropes, lines, and fishing nets. According to Bissen and Chawchai [88], thousands of tons of waste are discarded each year by fishing activities (e.g., broken fishing nets and plastic ropes), which supports the role of fishing as a potential source of MPs. They also reported that filaments resulting from the wear and tear of fishing nets and plastic ropes show colors different from the color of the original product, which can explain the larger percentage of transparent microfilaments observed in the present study.

After fibrous MPs, fragments were the second most common type of particles. Fragments were found on all beaches except Dalia, representing 15.65% (390 items) of all microplastics and with an average of 9.3 ± 8.6 fragments kg^{-1} (Table 1 and Figure 3). Fragments were present in all size fractions with varying quantities, but were more frequent in the 0.063–0.2, 0.2–0.4, and 2–3 mm size classes, accounting for 23.1%, 15.4%, and 14.9% of the total fragments (Figure 5). The majority of fragments found in the study area were angular (45.6%), and the remaining were subangular (17.4%), rounded (20.5%), and sub-rounded (16.4%). Microplastic fragments presented blue (41%), green (14.9%), red (12.3%), white (10.8%), pink (9.7%), orange (4.6%), transparent (3.1%), violet (2.1%), black (1%), and yellow (0.5%) colors (Figure 4). The largest number of microplastic fragments, with above-average values, was recorded in Cabo Negro (27.3 ± 21.2 fragments kg^{-1}), Quaa Asserasse (26.7 ± 36.3 fragments kg^{-1}), and Stehat (14 ± 12.5 fragments kg^{-1}) (Table 1). On these three beaches, the majority of those fragments were more angular than subangular and showed bright, fresh colors (blue: 39.2%, red: 16.7%, and pink: 12.7%), indicating the short residence time of these particles [9]. The fragmentation of hard plastic products such as packaging materials, containers, and toys could be the main source of fragments, as observed in other areas by Alomar et al. [109] and Xu et al. [110].

Films, with an average value of 2.7 ± 3 kg^{-1}, were found on eleven out of the fourteen beaches studied, representing 4.5% of the total (Table 1 and Figure 3). Most of these films were irregular in shape (96.4%) and had sizes > 0.2 mm, being more frequent in the larger size fractions (84% were >1 mm), with higher percentages in the 1–2 and 2–3 mm class sizes (25% and 23.2%, respectively) (Figure 5). The most common color of film was transparent (78.9%), followed by blue (7.1%), yellow (5.4%), white (3.6%), red (1.8%), black (1.8%), and pink (1.8%) (Figure 4). The high proportion of transparent films implies the degradation and alteration of plastic waste over a longer period in the study area. The beaches with values exceeding the average were Cabo Negro (9.3 ± 9.5 films kg^{-1}), Martil (7.3 ± 2.3 films kg^{-1}), and Quaa Asserasse (6 ± 10.4 films kg^{-1}) (Table 1). Plastic bags and packaging materials, which are thinner and more flexible, may become the main sources of films at the study sites [79,111]. The use of plastic mulch in agriculture and farming activities is also a likely source of films [36,39].

In contrast to previous studies [45,84,112], foams were poorly represented in the research area and were only observed at six beaches, with an average density of 1.1 ± 1.4 foams kg^{-1} (Table 1 and Figure 3). Furthermore, small amounts of foam were reported from the east part of the Moroccan Mediterranean coast [28], the Mar Menor lagoon in southeast Spain [41], Charleston Harbor, South Carolina, USA [55], Pondicherry, India [59], and Turkey's recreational beaches along the Aegean Sea [64]. All foams were >0.8 mm, with higher ratios in the 2–3 and 3–4 mm classes (39% and 26%, respectively) (Figure 5). The majority were subangular (39.13%) and rounded (34.78%), with angular and sub-rounded foams accounting for just 13% each. They were found only in white (87%) and orange (13%) colors (Figure 4), which is in good agreement with the findings published by Azaaouaj et al. [28], Leads et al. [55], and De-la-Torre et al. [84]. The higher proportion of white foams is not surprising as white foams, particularly expanded polystyrene, are very common. The highest concentrations were recorded at Cala Iris (3.3 ± 3.1 foams kg^{-1}), Martil (3.3 ± 3.5 foams kg^{-1}), and Tangier Malabata (3.3 ± 4.2 foams kg^{-1}) (Table 1). Foam-shaped microplastics could come from food packaging, household, electronic, cosmetic, transport, and construction (insulation) materials, among others. Foam floats or buoys used for fishing may also be a potential source of foams, as observed in other areas by Wang et al. [113]. The low abundance of foams in the study area should be taken into consideration, as this type of marine debris has been shown to adsorb the mercury present in the environment.

Pellets were found on only three beaches, with an average value of 0.2 ± 0.6 pellets kg^{-1} (Table 1 and Figure 3). A low abundance of pellets has also been reported previously on sandy beaches along the eastern Mediterranean coast of Morocco [28], China [110], India [58], Tunisia [69], Thailand [60], and Bangladesh [73]. However, other investigations have shown a high concentration of pellets [108,114,115]. All pellets were >1 mm, with higher frequencies in the 3–4 (40%) and 4–5 mm (40%) size fractions (Figure 5). The vast majority of pellets were cylindrical (60%), with spherical and lenticular shapes accounting for only 20% each. White (60%) was the most common color, representing 60% of total pellets (Figure 4), suggesting a longer residence time in the marine environment. This finding is in line with other studies that have reported that most of the plastic pellets found in sediments are white [28,69,114,115]. The very low proportion of pellets observed was probably due to the lack of nearby sources (e.g., petrochemical and plastic production plants, etc.). Industrial pellets were found in small quantities on the beaches of Cabo Negro (60%), Tangier Municipal (20%), and Oued Lao (20%) and were likely carried onto the beach by sea currents, as observed at other areas [116] (Table 1).

Plastic polymers are manufactured from a wide range of compounds. Azaaouaj et al. [28] report that the FTIR analysis of microplastic particles on Moroccan Mediterranean beaches showed that polyethylene (PE) was the most commonly identified polymer, followed by polystyrene (PS), polypropylene (PP), and polyvinyl chloride (PVC). Microplastic fragments were identified as PE, PS, and PVC polymers. Microplastic films were identified as comprising PE, PP, and PVC. All filaments were identified as PP polymers, all pellets were identified as PE polymers, and foams were identified as PS polymers.

PE is used in a wide variety of applications, including adhesive tapes, plastic bags and containers, and drain pipes. PP is broadly used in ropes, clothing fabrics, diapers, bottle caps, fishing nets, and strapping. PS is used in cool boxes, containers, and float buoys for fishing and aquaculture. PVC is used in pipes and containers [28,59].

Comparable outcomes were noted for other Mediterranean coastlines. For example, Frère et al. [117] identified three polymer types, namely PE (53.3%), PP (30%), and PS (16.7%), in marine microplastics from French coasts. Using FT-IR, four different MP polymers were defined on Grenada beaches, with a high proportion of PE (36%) [46]. Recently, Bouadil et al. [118] studied the type of polymers present in the surface waters of Al Hoceima Bay using Raman spectroscopy analysis. The results confirmed the presence of four different types of polymers: polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalates (PET), with PE polymers accounting for the majority (67.4%).

4. Conclusions

The present paper describes the abundance and characteristics of microplastic contamination on 14 beaches of the northern Moroccan coast and reveals a moderate abundance (59.33 ± 34.38 MPs kg^{-1}) of such items compared to those identified on other beaches worldwide. Microplastics were detected in all sediment samples collected on the beaches studied, and great variability in microplastic abundance was recorded in the investigated area. The MPs in all sampling sites were dominated by fibers (77.61%), followed by fragments (15.65%) and films (4.49%), and the majority of microplastic particles were angular and irregularly shaped. The predominance of secondary microplastics such as fragments, fibers, films, and foams on beaches compared to pellets suggests that they were essentially linked to the breakdown of large plastic items. The main colors of MP particles were transparent (43.2%), black (15.8%), and blue (13.3%). Small microplastics (<1 mm) accounted for 54.3% of the total microplastics, while large microplastics (1–5 mm) accounted for 45.7%. The size fractions with the highest prevalence of microplastics were 1–2 mm (24.9%). Further, this study allowed us to suppose that land-based sources, including tourism activities, fishing

activities, domestic wastewater discharges, and rivers, are most likely the primary cause of MP pollution in the study area. Finally, this paper provides a baseline assessment of the MP contamination in the research area and can serve as supporting evidence for comparisons with future data available on the decrease or increase of MPs in beach sediments along the Mediterranean coast of Morocco.

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Abbreviations

The following abbreviations are used in this manuscript:

FTIR	Fourier-Transform Infrared Spectroscopy
PE	Polyethylene
PS	Polystyrene
PP	Polypropylene
PVC	Polyvinyl chloride
PET	Polyethylene Terephthalates

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