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Anthropogenic Microparticles Abundance in Sandy Beach Sediments along the Tetouan Coast (Morocco Mediterranean)

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Abstract: Despite the widespread presence of anthropogenic microparticles (AMs) in beach sediments, research on their occurrence on Moroccan Mediterranean beaches is still limited. This study is the first report on AM pollution in four sandy beaches along the Tetouan coast (Morocco Mediterranean). The findings reveal an average AM concentration of 483.12 ± 157.04 AMs/kg of beach sediment. The most common AM types were fibers (75.54%) and fragments (24.06%). AMs were predominantly black, red, and blue, measuring between 0.1 and 1 mm. The evaluation of the anthropogenic microparticles pollution index (AMPI) and the coefficient of anthropogenic microparticles impact (CAMI) for the study area indicated a "very high abundance" of AMs and an "extreme" level of impact. The polymers identified in these areas included PS, PE, PP, and PET. Tourism, fishing, domestic activities, and poor solid waste management practices are the primary sources of AM pollution in this region. To protect Moroccan beaches, the implementation of a consistent plastic waste management strategy is recommended.

Keywords: plastic pollution; beach sediments; impact assessment; coastal conservation; management strategies

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1. Introduction

Due to their significant benefits, plastics are extensively and widely utilized by society [1]. Plastic production has risen drastically during the past 70 years, increasing from 1.7 million tons in 1950 to 370 million tons in 2019 [2]. It is expected that this quantity will triple by 2040 [3]. However, due to inappropriate disposal practices, a considerable portion of plastic waste ends up in marine ecosystems via rivers, landfills, incineration, household materials, sewage treatment plants, and industrial discharge [4]. This has led to a significant increase in plastic litter in the oceans worldwide [3,5,6]. The MPs pollution affects coastal and open waters, the deep sea, coral reefs, and mangroves [7–10].

Microplastics (MPs), as defined by Browne et al. [11], are plastic particles smaller than 5 mm. MPs can be intentionally produced at a microscopic scale for use in personal care products, detergents, etc., known as primary microplastics; or they can result from the breakdown of larger plastic items (macroplastics) in aquatic ecosystems due to environmental factors, which are called secondary microplastics [12]. The main sources of environmental MPs pollution include accidental discharge of plastic pellets, improper disposal of plastic items, tire wear, loss of fishing gear, discharges from wastewater treatment plants, runoff from stormwater, and fibers released during the washing of fabrics/textiles [13]. The concentration of MPs in a marine environment is influenced by various factors, including proximity to urban centers, marine currents, wind direction, tides, and waves [13]. Among the microparticles that contaminate the marine environment, microfibers (MFs) are the predominant type [14–16]. MFs mainly come from the production, use, washing and drying of textiles, which can continue to release MF even after disposal. The primary route for MFs to reach the marine ecosystems is via sewage systems [16–18]. Furthermore, the presence of MFs in oceans is linked to the fabrication and utilization of nets and ropes in the fishing and aquaculture sectors [19]. Consequently, these multiple sources contribute to a complex assortment of MFs, encompassing different sizes, colors, and compositions (both natural and synthetic), collectively contributing to marine pollution. It is important to recognize that fibers made from natural materials, often treated with dyes, additives, and flame retardants [20], become as durable as synthetic fibers [21] and pose an equal threat to marine ecosystems [15,22]. Moreover, textile dyes can enter the food chain, undergoing bioaccumulation and biomagnification [23,24]. From this perspective, the analysis of anthropogenic microparticles (hereafter AMs), including MPs and MFs (synthetic, semi-synthetic and anthropogenically modified cellulose), might allow the environmental assessments and the comparison of concentrations across different studies [14,25–28].

Due to their similarity to natural prey and small sizes, AMs can be rapidly ingested by a wide range of marine animals, including fish, invertebrates, mammals, sea turtles, and seabirds [29–34]. Several studies shown that ingested AMs can lead to movement restrictions, weight loss, decreased food intake, reproductive dysfunction, stress, increased mortality rates, growth deceleration, and accumulation in soft tissues of marine organisms [35–40]. Moreover, AMs serve as vectors for the transport of toxic chemical pollutants, including heavy metals, organic pollutants, and pharmaceuticals [41,42], thereby increasing the bioavailability of these chemicals in the food chain [43].

Marine debris and plastics are major problems for Morocco [44,45]. Morocco has been classified as eighteenth on a list of countries, in terms of the quantity of plastics entering marine environments [46]. Annually, around 0.31 million metric tons of plastics enters the Moroccan marine environment [46]. The Moroccan Mediterranean is an area of high environmental and economic importance and a key area for the protection of marine biodiversity and endangered biota in the Alboran Sea [47,48]. This area is impacted by intensive tourism and fishing activities, high population density, and discharge from heavily polluted rivers, contributing to a considerable risk of microplastic (MP) pollution [47,49]. Despite the evident issue of plastic pollution on Moroccan beaches, the assessment of AMs abundance along the Moroccan coastline has not received the attention it deserves, with only a few studies addressing MPs in the Moroccan coastal environment [47,49].

To our knowledge, no studies have been conducted to date on the presence of AMs in Tetouan beach sediments. To fill these knowledge gaps, our research focused on the micro-litter across four beaches along the Tetouan coast (Morocco Mediterranean). This study is of considerable scientific importance, as it represents the first investigation about beached AMs in this region of Morocco. Therefore, the aims of the study are: (i) to assess the accumulation of AMs in beach sediments along the Tetouan coast; (ii) to quantify, for the first time, the abundance of the AMs in the sediments of these four beaches, and (iii) to characterize the items in terms of size, shape, color, and polymer type. The findings of this study will provide new insights into AMs pollution and support the development of national strategies to mitigate this type of pollution in Morocco.

2. Materials and Methods

2.1. Study Area and Sample Collection

The study was conducted along the Tetouan coast of the Moroccan Mediterranean, an area notable for its high levels of human activity, including industrial and tourist operations, alongside fishing and agricultural practices [50]. The tidal pattern in this region is generally semi-diurnal, characterized by two high tides and two low tides each day [47]. For the purposes of this research, four sampling sites were selected: Fnideq (35°50′23.462″ N, 5°21′1.607″ W), M′diq (35°41′16.341″ N, 5°18′41.121″ W), Martil

(35°37′37.266″ N, 5°16′8.886″ W), and Kaa Asrasse (35°25′6.242″ N, 5°2′38.012″ W). The choice of these beaches was based on varying factors such as population density, levels of tourist activity, and the presence of rivers (Table 1).

Table 1. Location and general characteristics of the investigated sites.

Beach	Coordinates	Type	Port/Harbor	Wastewater Treatment Plant (WWTP)	River
Fnideq	35°50′46″ N/5°21′07″ W	Urban	Artisanal fishing	Yes	Yes
M'diq	35°41′34″ N/5°18′12″ W	Urban	Industrial and Artisanal	No	No
Martil	35°37′26″ N/5°16′88″ W	Urban	Artisanal fishing	Yes	Yes
Kaa Asrasse	35°25′24″ N/5°2′12″ W	Rural	Artisanal fishing	No	Yes

Fnideq, M'diq, and Martil represent the most densely populated coastal cities along the Tetouan coast, characterized by their extensive tourism, a significant number of hotels, restaurants, and active fishing industries. The beaches Martil and Fnideq are situated within the basins of the Oued Martil and Negro rivers, respectively. Finally, Kaa Asrasse encompasses smaller and less populated fishing villages. The river in Kaa Asrasse is identified as having a high potential for pollution in the area. Beach sample sediments were collected from 14 to 16 October 2022, across the mentioned locations along the Tetouan coast (Figure 1).

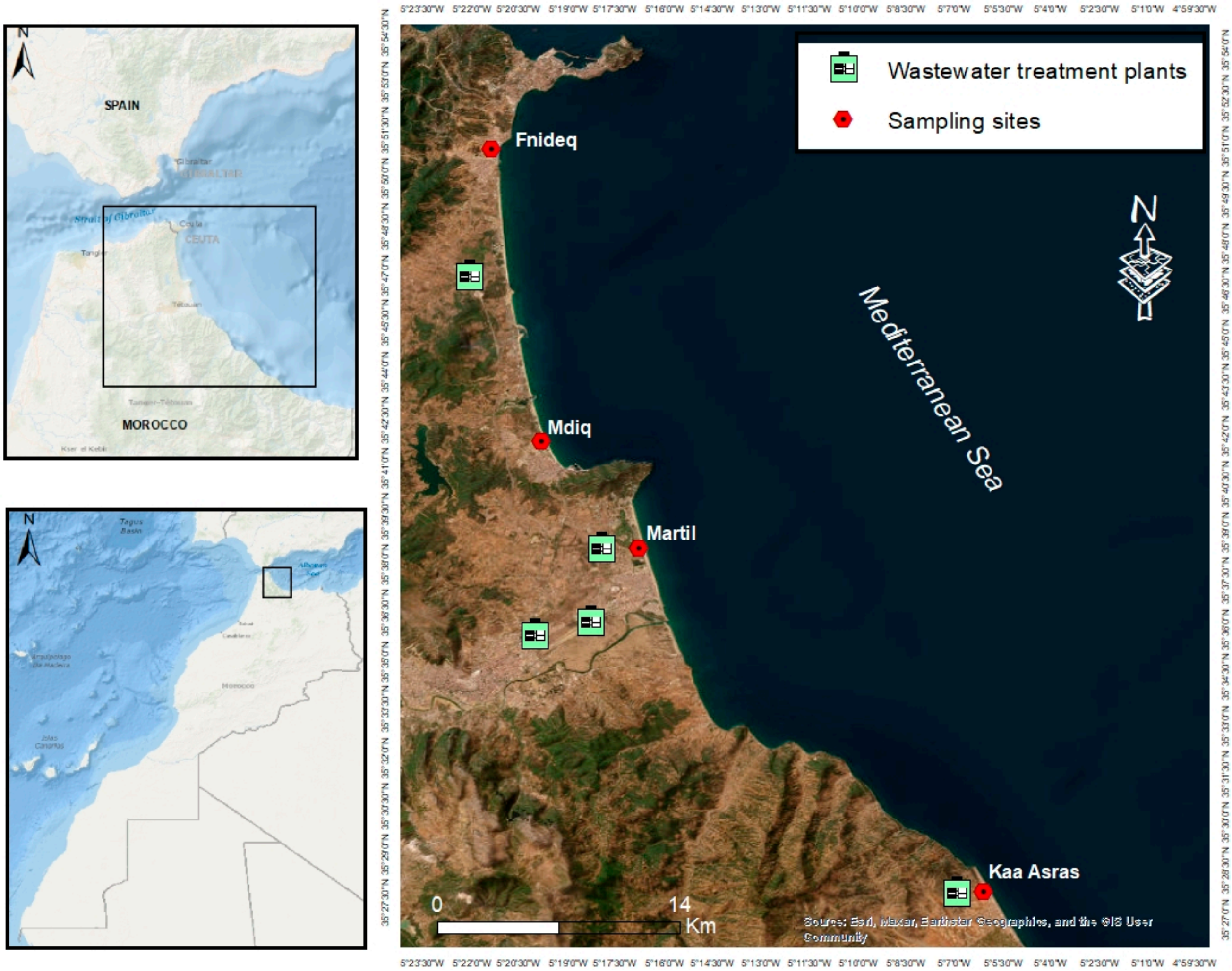

Figure 1. Geographical location of the four sampling sites.

On each of the four sites studied, a sampling area of 100 m^2 was established. These sampling areas were situated between the low and high tide marks, occupying each beach's central zone.

Eight sediment samples were collected from the four beaches surveyed. The first 5 cm of surface sediment was collected using a 50 cm × 50 cm quadrant, with two quadrants positioned at each sampling site and separated by 50 m. Approximately 400 g of sand was collected from each quadrant using a pre-cleaned stainless steel shovel. All sediment samples were wrapped in aluminum foil, stored in a pre-cleaned cooler at 4 °C and transported to the chemistry laboratory of the National Institute of Fisheries Research, Tangier (Morocco) for analysis.

2.2. AMs Extraction

The extraction of AMs from beach sediment samples was carried out following the protocol described by Masura et al. [51], with slight modifications. First, sediment samples were dried at 90 °C until completely dry (24–48 h). Then, the samples were transferred to clean glass beakers. For the total decomposition of organic matter, including diatoms, 20 mL of a 0.05 M aqueous solution of Fe (II) (Sigma-Aldrich, Steinheim, Germany), and a significant amount of 30% hydrogen peroxide (H_2O_2, Solvachim, Morocco) were added to each sample, followed by a subsequent drying phase at 75 °C lasting for 1 h. Subsequently, a concentrated saline solution (1.15 g/mL) was prepared by dissolving sodium chloride (Sigma Aldrich, Oakville, ON, Canada) in Milli-Q water. This solution was introduced into the beakers and stirred using a magnetic stir bar for 15 min as part of the flotation process. The supernatant was transferred to separating funnels, where it settled for 24 h prior to being filtered through a Whatman filter paper (pore size 1 µm, 47 mm, Whatman, Germany), previously dried at 50 °C. The filtrate was processed using a filtration system equipped with a stainless steel funnel (YT-330B, Winteam, Hangzhou, China), then rinsed with Milli-Q water. Finally, the filters were rinsed with distilled water, dried at 40 °C, and then placed in glass Petri dishes to avoid any potential contamination, ready for subsequent analysis.

2.3. Visual Identification

AMs were counted and photographed using a stereomicroscope. AM items were visually identified, and they had to satisfy specific criteria as outlined by Hidalgo–Ruz et al. [52]: (1) the particle exhibited a consistent color throughout, (2) the particle resisted deformation or breaking when manipulated with forceps, and (3) the particles were free of cellular and tissue structures.

The AMs were sorted based on their physical characteristics, including shape (such as fragments, spheres, fibers, and films), size (categories included less than 0.1 mm, 0.1–1 mm, 1–2 mm, and 2–5 mm), and color. Undyed microfibers, for which a natural composition cannot be excluded, were not considered for this study. Suspected particles were isolated using forceps on glass slides, then stored for further analysis, namely polymer identification through Raman spectroscopy.

2.4. Quality Control

During the samples analysis, rigorous steps were taken to minimize the risk of airborne microplastic contamination. During the samplings, no plastic tools and materials were used. Additionally, the laboratory contamination was assessed by placing a moist filter over an opened Petri dish [53]. To prevent cross-contamination, all the materials used were rinsed with ethanol and distilled water, and work surfaces were cleaned with ethanol. Operators were required to wear cotton coats to further reduce the risk of contamination. Prior to use, the filters were meticulously inspected under a microscope to ensure they were free from any airborne microplastic particles. When handling sediment samples, latex gloves and stainless steel forceps were used to maintain the integrity of the samples. A total of 29 microparticles were found on the procedural blanks. The same number of items was eliminated from the corresponding samples based on shape, color, and size.

2.5. Polymer Characterization

A random sub-sample of 18 AMs was selected for analysis by Raman spectrometry, following the method used by Bouzekry et al. [53]. This method is gaining ground in the analysis of the composition of MPs, particularly due to its high spatial resolution that permits the study of very small plastic particles. AMs extracted from the sediments were identified and quantified using an HR Evolution micro-confocal Raman system (Horiba Scientific, Kyoto, Japan) with a DXR 532 nm laser diode and a 10× Olympus objective (Thermo Scientific, Waltham, MA, USA). Spectra were recorded with wavenumbers of 600 to 4000 cm^{-1}, while the cumulative number of spectra and exposure time ranged from 2 to 20 and from 5 to 20 s, respectively, based on the specific dye in the AMs. The laser power of the Raman spectrometer was fixed at 5 mW, which is critical to avoid damaging or degrading the sample. The final spectra obtained were compared with those available in the SLoPP and SLoPP-E spectral libraries.

2.6. Impact Assessment

The assessment of AMs impact within the study area was conducted using two novel environmental indices.

The first index was calculated modifying the Microplastic Pollution Index (MPPI), [54] as AMPI (anthropogenic microparticles pollution index), which quantifies the presence of AMs in beach sediments. It achieves this by evaluating the ratio of the quantity of AMs to the area surveyed. The AMPI for the four beaches under study was determined used the formula below:

$$\text{AMPI} = \frac{\sum \text{AMs}}{\text{Surveyed area}}$$

Using this index, the four beaches were categorized into five levels reflecting the extent of anthropogenic microparticles (AMs) presence, ranging from “very low presence” to “very high presence”. To evaluate the impact of various forms AMs, the Coefficient of Microplastic Impact (CMPI; [54]) was modified.

The novel index calculates the relationship between the total amount of specific AM shapes (such as fragments and fibers) and the overall quantity of AMs found in a sample. The CAMI for the four beaches studied was calculated using the formula provided below:

$$\text{CAMI} = \frac{\text{Specific AMs}' \text{ Shape}}{\text{Total AMs}'}$$

The impacts of different AM forms will be classified in four categories from minimum to extreme. For instance, minimum; if CAMI is 0.0001–0.1, average; if CAMI is 0.11–0.5, maximum; if CAMI is 0.51–0.8, and extreme when CAMI is 0.81–1 [54].

2.7. Data Analysis

The AMs found were expressed as number of identified AMs per kg of sediment. Abundance data were tested for homoscedasticity and normality using the Levene and Shapiro–Wilk tests. The one-way analysis of variance (ANOVA) test was used to assess if there were differences between beaches. Statistical tests were applied using SPSS (version 20). All results were considered significant when $p < 0.05$.

3. Results

3.1. Abundance of AMs in Beach Sediments

In this study, 990 microparticles were isolated. Of these, 78.80% were anthropogenic microparticles. The remaining 21.20%, which were represented by undyed MFs, were excluded from data analysis and the calculation of final concentrations.

AMs were detected in all the sediment samples collected from the four beaches (Figure 2).

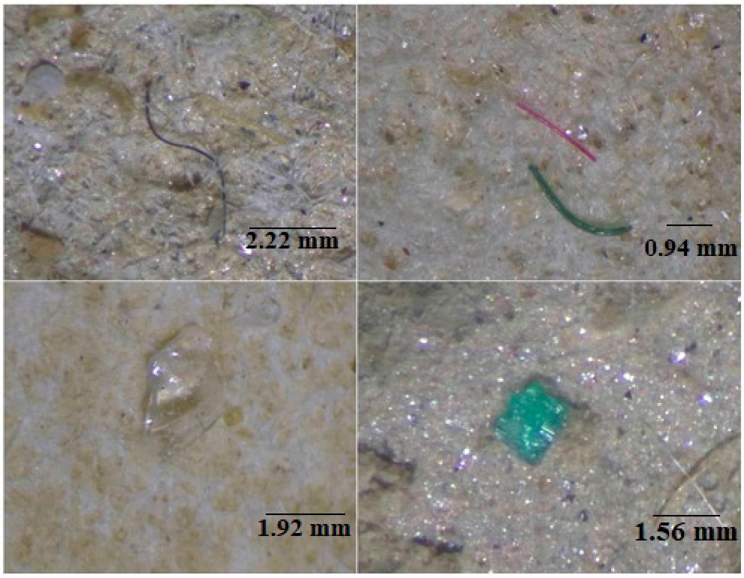

Figure 2. Examples of AM types found in beach sediments.

A total of 773 AMs were found in all the sediment samples from the four beaches investigated, distributed as follows: 254 AM items on Fnideq beach, 235 items on Kaa Asrasse beach, 166 items on Martil beach and 118 items on M'diq beach. The average abundance of AMs was 483.12 ± 157.04 AMs/kg, with the highest average AM number observed in Fnideq (635 AMs/kg) followed by Kaa Asrasse (587.5 AMs/kg), Martil (415 AMs/kg), and M'diq (295 AMs/kg) (Figure 3). The ANOVA test showed no statistically significant difference in AMs abundance between the four beaches.

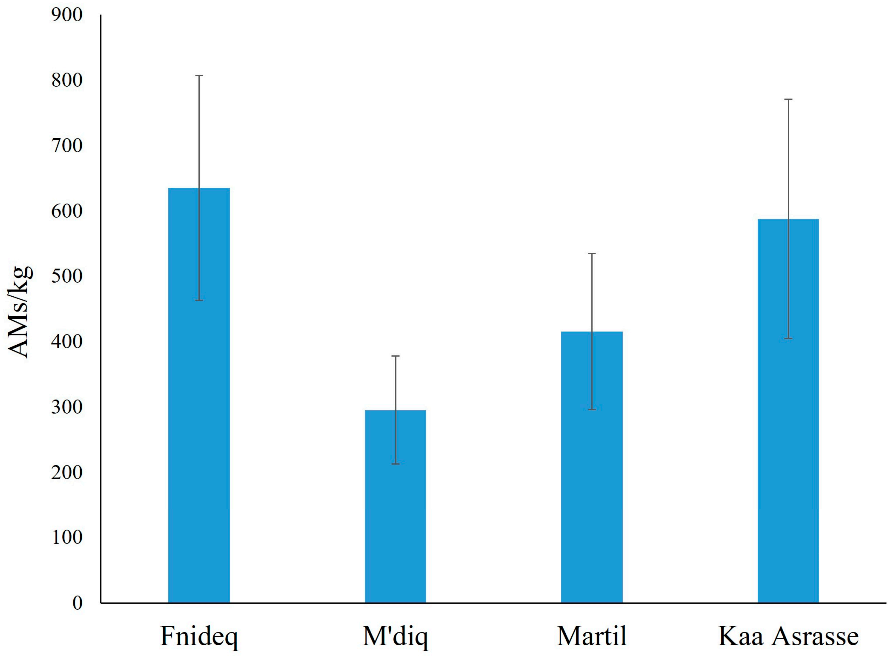

Figure 3. Abundance of AMs (with error bars) in the sediments of the four beaches sampled.

3.2. Morphological Characteristics of AMs in Beach Sediment

AM particles of different shapes, sizes, and colors were sampled and analyzed on the four beaches in this study. The samples obtained were classified according to their morphology into different types. The three shapes of AM identified were fiber, fragment, and foam (Figure 4).

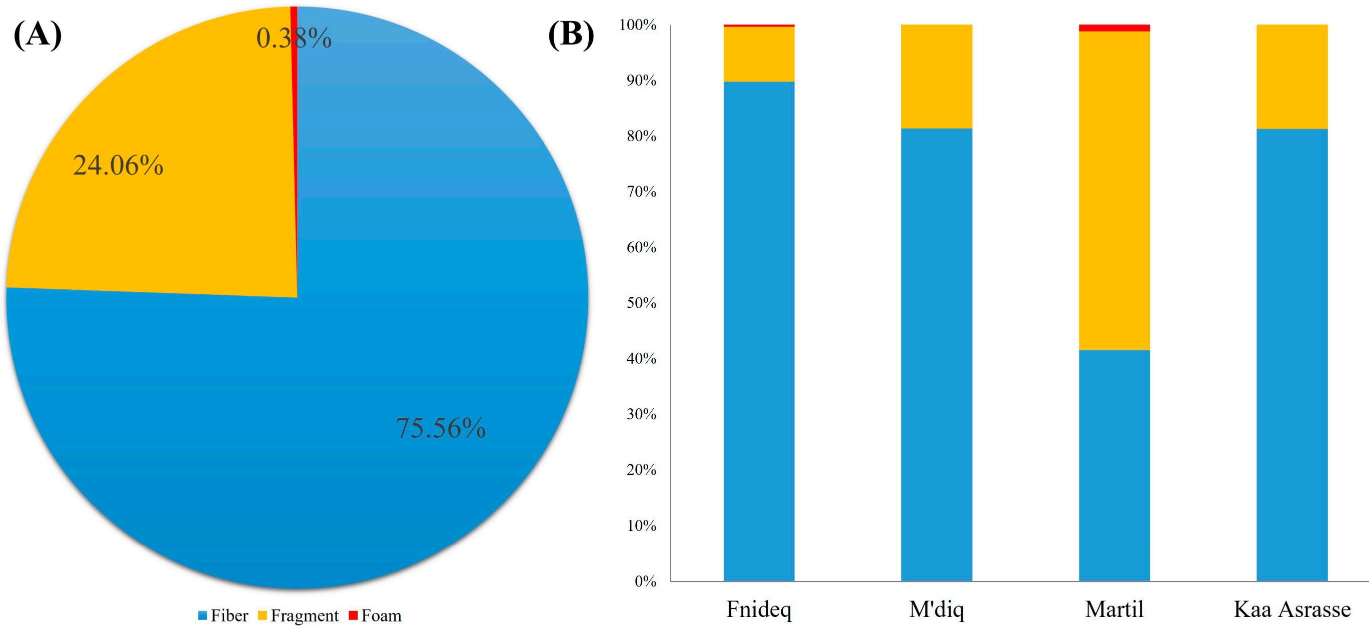

Figure 4. Percentage of AM shapes representing all sediment samples (**A**) and among sites (**B**).

Overall, fiber was the most frequent shape (75.56%) in the sediments of the four beaches. Fibers were the most common shape type in Fnideq, Kaa Asrasse, and M'diq (89.76%, 82.27%, and 81.35% respectively) (Figure 4). Martil beach showed anthropogenic fragments as the most abundant shape, accounting for 57.22%. In this study, AM sizes ranged from 0.002 to 5 mm, with an average size of 1.33 mm (Figure 5).

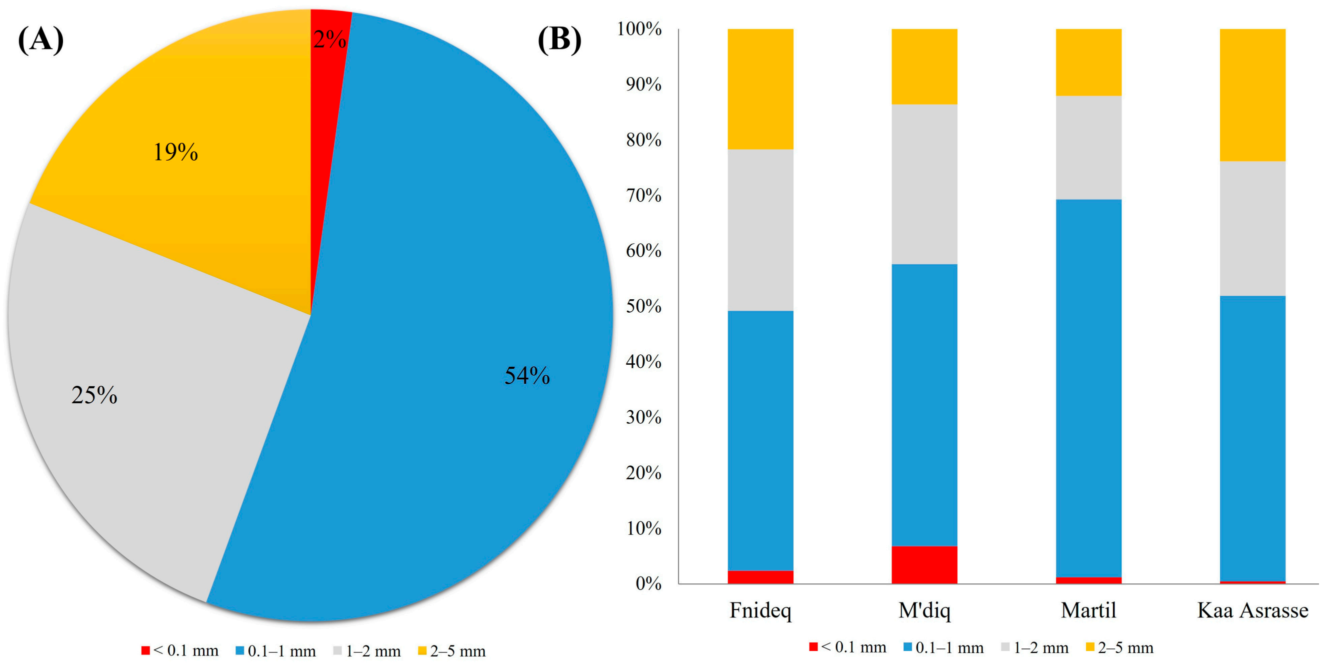

Figure 5. AM size (%) in sediment samples (**A**) and in each site (**B**).

The fibers varied in size from 0.002 to 5 mm and the fragments from 0.19 to 5 mm. The average fiber size was 1.20 mm, while the average fragment size was 1.46 mm. In order to understand the size distribution, the AMs were categorized based on their size into four classes: <0.1, 0.1–1, 1–2, and 2–5 mm. AMs in the size class of 0.1–1 mm (53.42%) were the most common in the sediment samples at four sampling sites (Figure 5), following by sizes 1–2 mm (25.35%), 2–5 mm (19.01%) and <0.1 mm (2.19%). The most common colors were black, red, and blue, representing 39.98%, 34.29%, and 14.76%, respectively (Figure 6).

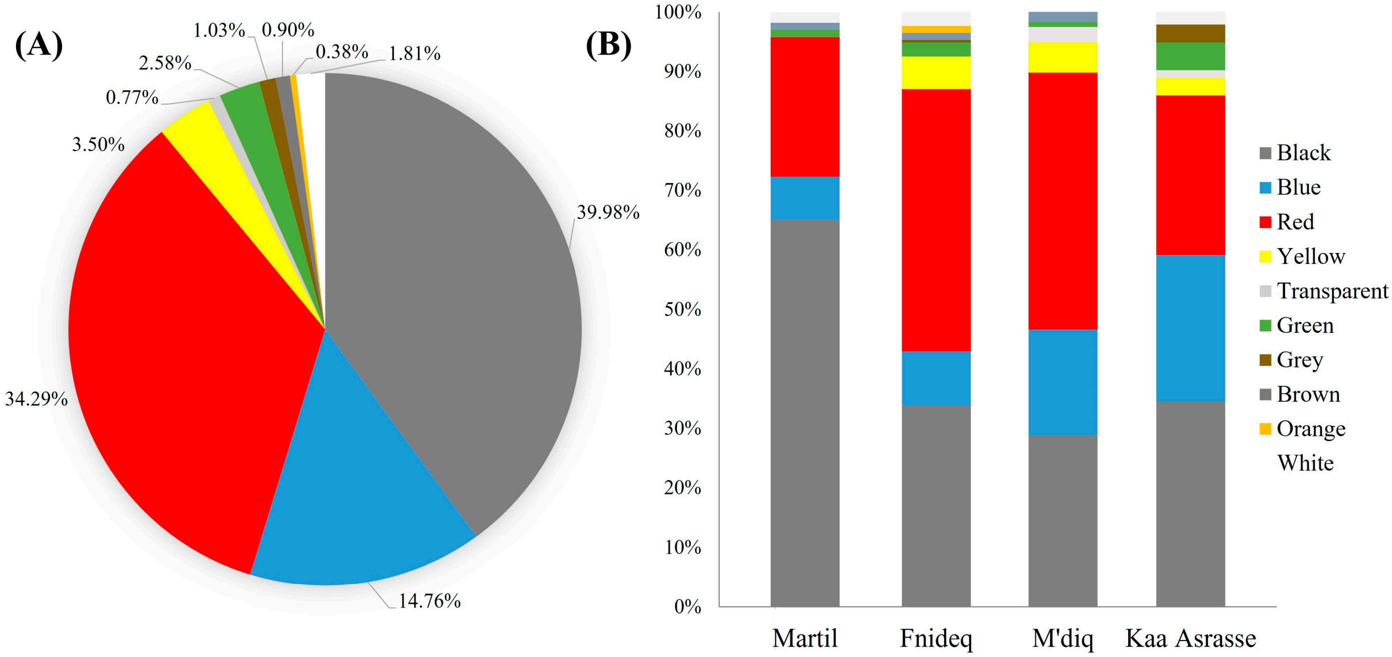

Figure 6. Percentage of AM colors representing all sediment samples (**A**) and among sites (**B**).

Other colors, such as yellow, green, gray, brown, and orange, were found in minor proportions, accounting for 11.03% of the total (Figure 6). At Martil beach, black was the predominant color (65.06%), followed by red (23.49%), blue (7.22%), green (1.20%), and brown (1.20%) (Figure 6). At Fnideq beach, red was the most abundant color (44.09%), followed by black (33.8%), blue (9.05%), yellow (5.51%), green (2.36%), and brown (1.18%). At Kaa Asrasse beach, black (34.46%) and red (26.80%) were the dominant colors, whereas at M'diq beach, red (43.22%), and black (28.81%) were most prevalent (Figure 6). Among fibers, the most common colors were black, red, and blue. For fragments, the majority were black, followed by blue, and red.

3.3. Polymer Identification

Eighteen microparticles were analysed to identify their polymeric nature. The assay, conducted by Raman spectroscopy, identified four types of plastic polymers. Most of the polymers collected were polystyrene (PS, 44%), followed by polyethylene (PE, 22%), and polypropylene (PP) and polyethylene terephthalate (PET), 17% for both types (Figures A1 and 7).

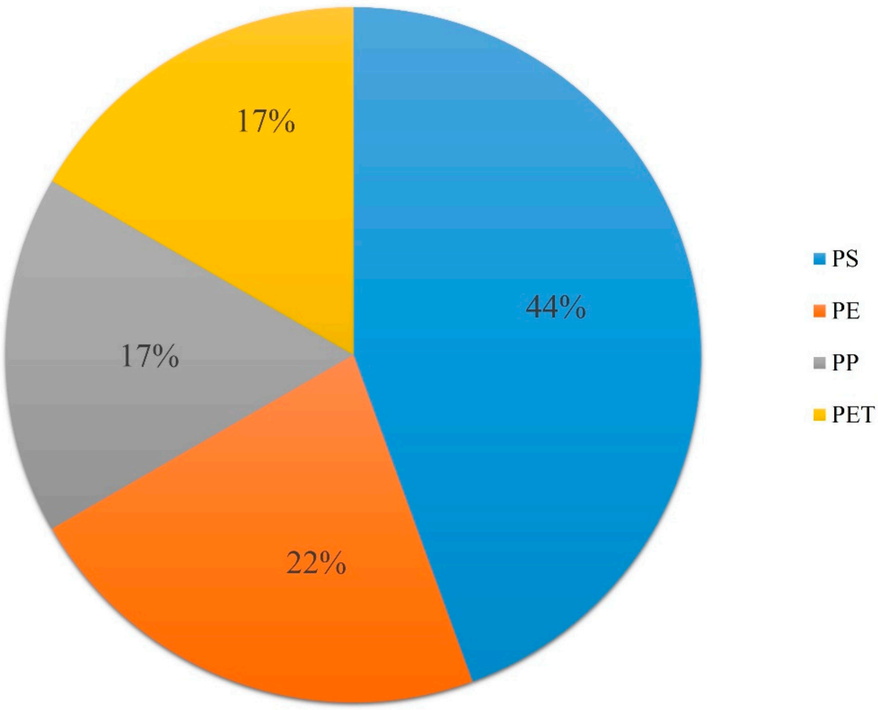

Figure 7. MP polymers recorded in sediments.

3.4. Beach Quality Assessment

The four beaches surveyed were assessed through the application of two novel environmental indices. The AMPI (anthropogenic microparticles pollution index), calculated for each location surveyed, revealed a very high presence of anthropogenic microparticles across all beaches as shown in Table 2.

Table 2. Classification of beaches according to the anthropogenic microparticles pollution index (AMPI) and coefficient of anthropogenic microparticles impact (CAMI).

Site Name	AMPI Fiber	AMPI Type	AMPI Fragment	AMPI Type	CAMI-Fiber	CAMI Type	CAMI Fragment	CAMI Type
Fnideq	114	Very High Abundance	12.5	Moderate Abundance	0.89	Extreme	0.09	Minimum
M'diq	48	Very High Abundance	11	Moderate Abundance	0.81	Extreme	0.18	Average
Martil	34.5	Very High Abundance	47.5	Very High Abundance	0.41	Average	0.57	Maximum
Kaa Asrasse	95.5	Very High Abundance	22	High Abundance	0.82	Extreme	0.17	Average

The AMPI of the entire study area registered a value of 96.62. This value places Mediterranean beaches into the "very high abundance" category of AMs. The highest fiber densities were reported in the Fnideq beach (570 AMs/kg), while the lowest densities were observed in the Martil beach (172.5 AMs/kg). The coefficient of fibers impacts for the entire study area is 0.75 which classifies these beaches with a "extreme" impact (Table 2). By beach, CAMI-fibers revealed three beaches (75%) had an "extreme" impact and one beach (15%) had an "average" impact. In the study area, no beach has a "minimum" impact on the fibers (Table 2).

The average fragment density was 116.25 AMs/kg, but these densities vary between the four beaches. The highest fragment densities were observed on Martil (237.5 AMs/kg), while the lowest densities were reported on M’diq (55 AMs/kg). The general coefficient of fragments impact for the entire study area was 0.24 (average impact), while by location, two beaches (50%) can be categorized with an “average” impact, one beach (25%) has a “maximum” impact, and one beach (25%) has a “minimum” impact (Table 2). There are no sites with “extreme” fragments impact.

To comprehensively assess the situation, CAMI and AMPI metrics were combined in a sector analysis. For each beach, a dynamic table was created by assigning AMPI values to rows and CAMI values to columns. This table was segmented into three distinct zones based on the percentile technique [55]. The green area indicates beaches where the presence of AMs is very low, highlighting a good environmental status. The orange area includes beaches with a low to moderate presence of AMs, reflecting a mediocre environmental status. Such areas necessitate cleaning operations to improve their condition. Finally, the red area represents zones with a high to very high presence of AMs, indicating unsatisfactory and poor environmental conditions. These areas call for urgent interventions and possibly even restoration efforts to mitigate the impact. The combination of CAMI and AMPI using sector analysis is showed in Table 3.

Table 3. Sector Analysis Approach: Integration of the anthropogenic microparticles pollution index (AMPI) and coefficient of anthropogenic microparticles impact (CAMI) for the four surveyed sites.

		AMPI (Fibers)					
		Very Low Abundance	**Low Abundance**	**Moderate Abundance**	**High Abundance**	**Very High Abundance**	
CAMI (Fibers)	Minimum						0
	Average					1	1
	Maximum						0
	Extreme					3	3
		0	0	0	0	4	4
		AMPI (Fragments)					
		Very low abundance	Low abundance	Moderate abundance	High abundance	Very high abundance	
CAMI (Fragments)	Minimum			1			1
	Average			1	1		2
	Maximum					1	1
	Extreme						0
		0	0	2	1	1	4

Regarding the found fibers, all sampled beaches fall within the red area, indicating a very high abundance of AMs. In contrast, when considering fragments, three beaches are situated in the orange zone, signifying a low to moderate presence, while only one beach falls within the red zone. It is noteworthy that none of the beaches are classified within the green zone for either type of AM.

4. Discussion

In this study, we have conducted the first evaluation of anthropogenic microfibers (AMs) in four beach sediments along the coast of Tetouan, Mediterranean Morocco. Comparisons with other studies should be undertaken cautiously due to the absence of standardization in sampling and analysis methods. Microfibers typically comprise 80–90% of microplastic counts, despite their synthetic nature being rarely confirmed. Many studies likely classify cellulosic fibers (natural) as synthetic, leading to an overestimation of microplastic quantities in sediments.

4.1. Abundance of AMs in Beach Sediments

The abundance of AMs in the sediments of the study area is comparable to those found in France (33–798 MPs/kg, [56]), Algeria (182.66–649.33 MPs/kg, [57]), and Egypt (480–766 MPs/kg [58], 165–714 MPs/kg [59]) (Table S1).

Our results were higher than MP abundances reported in Morocco Mediterranean from Azaaouaj et al. [60] (40–230 MPs/kg) (Table S1), as well as those found in Tunisia (316.03 MPs/kg, [61]; 2.46 MPs/kg, [62]), in Algeria (7.66–66.0, [63]; 73, [64]; and 43.62–72.0, [65]), in Spain (32.8 MPs/kg, [66]; 10.7 MPs/kg, [67]; 19.37 MPs/kg, [68]), in Portugal (100 MPs/kg, [69]), Slovenia (0–82.1 MPs/kg, [70]), in France (12–187 MPs/kg, [56]), and in Italy (12.1 MPs/kg, [71]).

The observed MP abundances were lower than the values recorded on Moroccan Atlantic beaches (7680–34.200 MPs/kg, [72]; 915–1448 MPs/kg [73]), as well as European beaches (1512 MPs/kg, [74]), in Italy (1069 MPs/kg, [75], 672–2175 MPs/kg, [76]), and in Spain (3125.25 MPs/kg, [77]) (Table S1).

The abundance of AMs varied between sites. There are many possible explanations for the varying quantities of AMs between the four beaches, with some of the most influential factors including the human activities, the position of the beach, the ocean currents in the zone and whether it is influenced by the presence of rivers [78]. Additionally, the concentration of AMs on beach sediments can be highly variable and influenced by natural processes such as wind, wave height, tide, precipitation, and river flow [78]. This difference in the concentration of AMs per beach can be explained principally by the activities conducted along the four beaches. The high presence of AMs in the sediments of urban beaches (Fnideq, M'diq and Martil) is consistent with expected findings, given that they constitute tourist destinations, are characterized by intensive fishing activity and high population density, and have substantial wastewater effluents [78]. Martil beach is adjacent to the Martil River, which discharges the wastewater of the city into the coast. River discharges could be one of the sources of AM pollution in the study area [13,78]. As this site is very highly used by local populations and tourists in all four seasons of the year, the degree of littering is higher than at the other four beaches that we surveyed. Browne et al. [11] reported that up to 80% of microplastics detected in sediments comes from the disposal of waste in coastal environments. The higher abundance of AMs in the sediment of Kaa Asrasse beach (587.5 AMs/kg) was surprising, because it is a rural beach with low human activity. The observed results may be linked to fishing activities and the direct disposal of waste on the beach by the local community. Furthermore, Kaa Asrasse beach receives freshwater inputs from the Kaa Asrasse river, which might transport AMs into the region's coastal environment. Rivers act as vectors for AMs, especially during the rainy months, and AM can quickly transport to the marine environment [79]. This beach has an issue with management and disposal of plastic litter, which can significantly affect the quality of sediments and contribute to AMs contamination in the region [45]. Finally, M'diq beach has a far lower tourist activity and is less densely populated, which explains the lower concentration of AMs at this site compared with other urban beaches.

4.2. Morphological Characteristics of AMs in Beach Sediment

The high percentage of fibers recorded in the study area aligns with findings from other studies in Morocco, which also reported a high prevalence of anthropogenic microfibers along both the Mediterranean and Atlantic coasts [49,72,73].

This result agrees also with the results reported in other studies in the Mediterranean and throughout the world [80,81]. On six continents, a study performed in marine sediments from 18 coasts showed that the most abundant shape of MPs was fiber [11]. This was also the case in sediment samples from Tunisia, as reported by Abidli et al. [61]. Bentaallah et al. [65] reported similar observations in sediment samples from the Algerian coast. Anthropogenic microfibers were the predominant shape of particles found on the beaches of Spain [68] and Egypt [58]. The dominance of microfibers in the beaches of the Moroccan Mediterranean is due to their smaller size compared to other types of AMs.

Due to their small size, they can rapidly penetrate the pore spaces and can be trapped in sediments, which facilitates their accumulation and sediments simultaneously act as a sink for AMs [82]. The shape of AMs can be linked to their sources of production (primary or secondary). The high number of fibers on Fnideq beach is due to the presence of wastewater treatment plants in the area. The fibers are also primarily generated by the breakage of fishing lines, domestic effluents and from textile/fabric industrial production. The low number of fragments in this study is because these AMs are large and do not move easily across sediment voids. Therefore, they stay on the surface for a long time, becoming more exposed to distribution by winds and ocean currents [82]. Our results aligned with the results of a study performed on Spanish beaches, recording the highest prevalence of smaller MPs [68]. In addition, a study of Algerian beaches observed a higher prevalence of smaller MPs [65]. In Bangladesh, 59% of the MPs in sediment samples were 1–5 mm in size [83]. The high concentration of smaller AMs in the four beaches studied may be due to bigger AMs breaking into smaller pieces in the marine environment under the effect of several degradation agents [11]. Smaller AMs were often found to have fragmented from larger pieces. Several processes such as ablation, abrasion, and collision due to the turbulent effects of waves, wind, and river produce the secondary AMs that enter the marine ecosystem [84]. This situation raises concerns about the potential risks of AMs for marine biota in the Moroccan Mediterranean [53]. As the size of microparticles decreases, their capacity to accumulate in marine biota may increase [85]. The different colors found in this study may be due to their origin from various sources. On European beaches, blue and black were the most common colors, and with red account for the highest proportion (77.5–82.9%) [74]. The findings of this work are consistent with Bayo et al. [68] who studied MPs near the harbor of Cartagena (Spain). MPs with similar colors were observed in other studies, such as in Tunisia [61] in which 60% of the MPs were blue and black. Red, blue, and transparent are also a frequent color detected in sediments in Egypt [58], while blue (40.46%) and white/transparent (24.75%) were two abundant colors on Turkish beaches [86]. The diversity of the colors of AMs reflects the diversity of their sources of pollution. It is probable that the colored AMs we detected derived from colored plastic products widely employed in daily life, such as commodity packaging, disposable plastic bags and clothing [86]. This is a factor can affect the potential bioavailability of AMs/MPs for marine biota, particularly for species foraging on olfactory or visual cues [85]. Colored particles of MPs are very attractive to fauna and similar to natural prey, so are often ingested in their place [87].

4.3. Polymer Identification

Our results highlight that PS (44.4%) was the most-found polymer followed by PE, PP and PET, in line with the results of Bouadil et al. [88] which indicated that PE, PP, PS, and PET are the most commonly found polymers.

In Italy, Munari et al. [71] and Vianello et al. [76] found PE and PP, PS and PET as prevalent polymers. In France, Constant et al. [56] found PP, PE, PS. In Morocco Mediterranean, Azaaouaj et al. (2024) [60] found PE, PS, PP, and PVC, while Ghani et al. [59] found PE, PA, PP, PET, and PS (Egypt) (Table S1).

Abelouah et al. [72] reported a predominance of PE, PP and PS in Moroccan Atlantic beaches. Similar polymers were recorded by Bošković et al. [89] in beach sediment from the Montenegrin coast (PP and PET). The study of Bayo et al. [68] indicated a dominance of PP and PE in Spanish beach sediments. These results are related to the global dominant production and use of these polymers. Due to their lower density, PE and PP polymers generally float and can be easily transported by several environmental drivers, which could also favor the distribution of these polymers [90].

Field observations revealed a high level of plastic pollution in the studied area (Figure 8). The waste observed primarily consists of food packaging, containers, bags, bottles, and other packaging materials (Figure 8). The polymers commonly used in these packaging applications include polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET), among others. The dominance of these polymers in the AMs analyzed in this study is underscored by the prevalence of packaging plastics groups in the beaches studied. Packaging waste is commonly used daily by the local population and is either discharged from domestic activities or left behind by visitors coming to the beach for recreational purposes. The concentration of MPs in coastal environments is likely to increase as packaging plastics degrade into smaller particles, growing the potential for harm to the health of coastal ecosystems.

Figure 8. Direct discharge of sewage and waste on Moroccan Mediterranean beaches (primary/secondary sources of MPs).

4.4. Beach Quality Assessment

The AMPI values observed in this study aligned with those reported by Abelouah et al. [72] and Ben-Haddad et al. [73] on the central Atlantic coast of Morocco. Regarding AMPI classification, Pervez et al. [91] categorized beaches in southern Shandong as "moderate" to "high" while Rangel-Buitrago et al. [54] classified beaches in the central Colombian Caribbean as having a "very high abundance" category of MPs. The AM concentration found on Moroccan beaches is concerning, especially since it is relatively high in comparison to other Mediterranean regions.

The levels of AMs on the Moroccan Mediterranean beaches represent a direct threat to the local marine wildlife, as highlighted by Bouzekry et al. [53] and Krikech et al. [92].

The significant pollution from AMs in the sediments of the studied beaches underscores the need for implementing management strategies to reduce the presence and impact of AMs. This highlights the importance of understanding not only the concentration of AMs in the marine environment, but also their sources. Mitigating the influx of AMs into Moroccan beaches is essential for the sustainability of these environments [47].

Public education, coupled with awareness, is the key strategy for reducing the production and mismanagement of plastic litter on Moroccan beaches [93]. Adopting the principle of the circular economy of plastic waste can minimize the quantity of such waste, including MPs [93]. Ongoing monitoring and research along the Mediterranean coast of Morocco are crucial to fully understanding and mitigating MP sources and impact, and thus contributing to the management of this issue.

This article presents the baseline data concerning AM concentration in beach sediments, highlighting the need for further studies to better understand the risks posed by the ingestion of AMs by marine organisms.

4.5. Research Limitations

Our application of Raman spectrometry was specifically designed to detect potential pollution by microplastics (MPs); however, the number of samples analyzed was relatively small. The analysis itself, particularly the use of the 532 nm line in Raman spectrometry, is more suited for identifying PE, PP, and PS than other polymers. The chemical characterization of these particles is crucial for understanding potential sources and toxicological impacts. Given the concentration of microfibers in the environment, a chemical composition analysis is crucial for toxicological assessments.

To overcome these limitations, further research is necessary to validate the findings of this study and provide a more comprehensive assessment of AM abundance in the coastal areas of the Moroccan Mediterranean. Such research is crucial for developing more effective strategies to combat plastic pollution.

5. Conclusions

This study evaluated, for the first time, the presence of AMs in four beach sediments along the coast of Tetouan (Mediterranean Morocco). In addition, for the first time, two novel indexes for anthropogenic microparticles were applied. Our results showed that the examined Moroccan beaches are heavily impacted by AMs pollution, suggesting that these beaches are a sink for these contaminants. Three of the four beaches studied were dominated by anthropogenic microfibers, whereas one was characterized by microfragments of anthropogenic origin. The high concentrations reported suggest contributions from local communities, ship traffic, river inputs, as well as environmental conditions such as sea currents and winds that can facilitate AM deposition on the beach surface. Furthermore, these findings highlight the need for immediate measures to improve environmental quality. This study provides important data that should be used to initiate environmental protection policy and support initiatives aimed at effective territory management. Such initiatives include beach clean-up and restoration efforts, as well as the recycling of plastic wastes. Further studies are needed to assess the influence of temporal and seasonal patterns on the distribution and abundance of AMs on Mediterranean Moroccan beaches.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments11040083/s1, Table S1: Beach contamination by microplastics along the Mediterranean basin.

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Appendix A

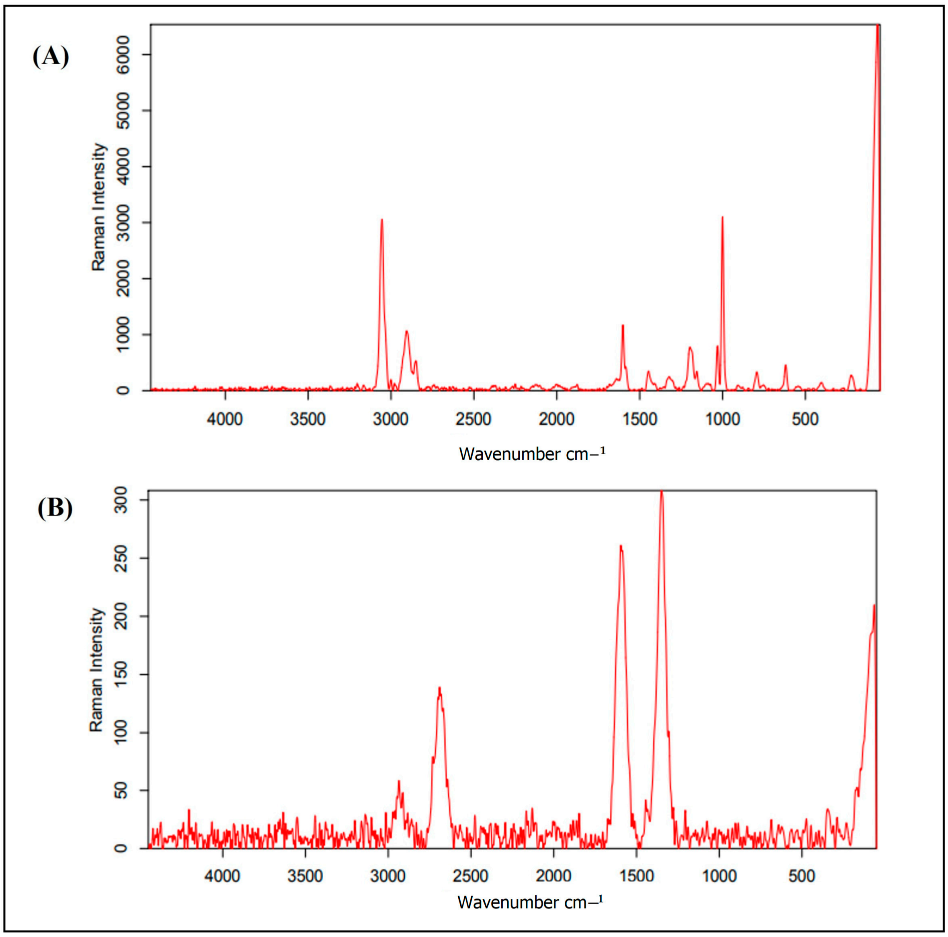

Figure A1. Examples of Raman spectra of samples analyzed. (**A**) Polystyrene and (**B**) Polypropylene.

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