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Methodology for Analysis of Microplastics in Fine Fraction of Urban Solid Waste

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Abstract: This study addresses the pressing need for standardized methodologies to quantify microplastics (MPs) within the fine fraction of municipal solid waste (MSW), often overlooked despite its potential environmental impact. Five extraction protocols were evaluated to identify the most effective method for isolating MPs in fine waste. These were specifically applied to samples from the Universidad Autónoma Metropolitana and one transfer station in Mexico City. A potassium hydroxide digestion protocol with subsequent flotation and centrifugation steps achieved optimal results, ensuring complete organic matter degradation and high microplastic recovery. Subsequent analyses revealed notable concentrations of MPs, primarily fragments and fibers, with higher abundance at the university site. Statistical tests confirmed significant differences between the sample sites. These findings highlight the vulnerability of MSW fine fractions to microplastic contamination and underline the importance of targeted waste management strategies. This research contributes to understanding microplastic behavior in waste management systems and emphasizes the need for mitigation efforts to prevent environmental contamination.

Keywords: collection center; fragments; dust; plastics; small waste

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Academic Editors: Chenyang Zhang, Fujing Pan, Xiaoyu Gao, Weiqi Fu, Anxu Sheng, Zhiqiang Kong, Lei He, Sining Zhong and Jie Chen

Received: 14 November 2024
Revised: 20 December 2024
Accepted: 31 December 2024
Published: 4 January 2025

Citation: Avila-Escobedo, K.P.; Moctezuma-Parra, K.Y.; Alvarez-Zeferino, J.C.; Espinosa-Valdemar, R.M.; Sotelo-Navarro, P.X.; Vázquez-Morillas, A.; Cruz-Salas, A.A. Methodology for Analysis of Microplastics in Fine Fraction of Urban Solid Waste. *Microplastics* **2025**, *4*, 2. https://doi.org/10.3390/microplastics4010002

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1. Introduction

Plastic pollution, a global crisis of the 21st century, is a staggering reality. With over 400 million tons of plastic produced annually, a substantial portion finds its way into the environment, impacting the equilibrium of terrestrial and aquatic ecosystems [1–4]. Among the various types of plastic pollution, microplastics (MPs), defined as plastic particles smaller than 5 mm, are a mounting concern due to their widespread presence and potential to infiltrate the food chain [5–7]. These tiny plastic particles are the result of the breakdown of larger plastic products and the direct release of microparticles, such as those found in cosmetics and cleaning products [8–10].

Municipal solid waste (MSW) management worldwide faces significant challenges in relation to plastic waste. Plastics are estimated to represent between 10 and 12% of the total composition of MSW, varying by region [11,12]. Among the most common types of plastic waste are low- and high-density polyethylene (used in bags and wrappers), polypropylene (in containers and caps), polyethylene terephthalate (common in bottles),

and expanded polystyrene (in food packaging and containers). These materials, due to their low biodegradability, can persist for centuries in landfills and ecosystems, contributing to increased environmental pollution [13–15].

A critical fraction within MSW is the so-called fine fraction, a subset of waste that is defined primarily by the size of its particles, which are usually smaller than 20 mm, although some studies consider even smaller sizes, such as 10 mm or 5 mm. This fraction includes a mixture of organic, inorganic, and contaminant materials that are not easily segregated in conventional separation processes. In some cases, it contains a high concentration of MPs, metal fragments, artificial minerals and other fine waste that is difficult to recycle or manage [9,16–18]. Although traditionally considered harmless, this fraction can contain a high concentration of MPs and other contaminants [17]. A notable aspect of fine fraction is its potential contamination, as it can accumulate heavy metals, MPs, and other toxic elements [9]. Furthermore, it is often a problematic fraction in waste management systems, as its size means it cannot be easily processed in traditional facilities, resulting in its disposal in landfills [16]. However, some studies have proposed its possible reuse, for example, as filling material at construction sites, although this use is still in the experimental phase and requires further research to assess environmental risks [9,18].

Studies conducted in Mexico and other regions of the world have revealed that fine fraction can account for up to 5% of total MSW and is often disposed of in landfills without proper treatment [19]. This practice poses a significant risk, as the accumulation of MPs in landfills can lead to the contamination of nearby soils and water bodies [16,18,20]. It is difficult to stop generating fine fraction in USW, but once generated, it is ideal to deposit it at a controlled final disposal site to prevent it from being transported to other sites and ecosystems by wind or rain. In the case of larger plastic waste found at such sites, it would be ideal not to send it there and instead subject it to co-processing to prevent it from fragmenting in the presence of biotic and abiotic factors and giving rise to microplastics.

In countries like Mexico, where waste management is still facing significant challenges, the lack of specific management for fine waste underscores the urgent need for more in-depth research and the development of effective mitigation strategies [21]. This work, therefore, aimed to establish a methodology for analyzing microplastic contamination in fine fraction from urban solid waste (USW); this methodology was applied to fine fraction of waste produced in the Universidad Autónoma Metropolitana campus (UAM-A), and that received at the transfer station and segregation plant (TESPA), both located in Azcapotzalco, in Mexico City.

2. Materials and Methods

This section describes the methodology of the five protocols tested for the extraction of MPs and the selection of the best one for application to samples from UAM-A and TESPA.

2.1. Contamination Prevention

Throughout the development of the methodology, various measures were implemented to avoid cross-contamination by plastic particles present in the air. These measures included wearing cotton clothing and a gown; using glass and metal materials and utensils; washing and drying the material in an oven before use; cleaning the work area, before use, with absorbent paper and alcohol; using blanks during sample processing; using lighters during the extraction process to burn MPs found in the surrounding air; and performing part of the processing in a laminar flow hood [22,23].

2.2. Description of Five Protocols for Microplastic Extraction

Five protocols, selected from studies published in the ScienceDirect database, were tested to develop the methodology. These protocols addressed the analysis of MPs in which the digestion of organic matter was implicit. Before testing the five protocols on waste samples, virgin MPs were put in contact with oxidizing reagents to evaluate whether they damaged the particles and, from there, we decided which ones were worth continuing to work with. The added MPs were five pieces of each of the following types: polyethylene terephthalate (PET) from beverage bottles, high-density polyethylene (HDPE) obtained from yogurt bottles, polyvinyl chloride (PVC) manufactured from medicine blisters, low-density polyethylene (LDPE) obtained from carrier bags, and expanded polystyrene balls (EPS) purchased at a stationery store.

Since virgin MPs did not present alterations in any of the cases, the testing of all protocols was applied to a sample of USW obtained from TESPA in October 2021. In addition, the same quantity and types of virgin MPs were added as in the previous step. The objective of this stage was to evaluate the behavior of the different oxidizing reagents and the digestion conditions in the presence of the sample and the MPs. Table 1 shows the conditions applied to each of the tested protocols.

Table 1. Relevant information about the five tested protocols.

Protocol	Oxidant	Conditions	Filtration	Comments	References
Protocol 1	Step 1: 10% KOH Step 2: 30% H_2O_2 Step 3: Fe(II) 0.05 M	Mass of sample: 50 g. Step 1: 40 °C 24 h Step 2: 40 mL 3 times every 20 min at 60 °C Stage 3: 40 mL once	Vacuum on cellulose filter (Ø = 47 mm and pore size of 8 µm)	Stirring for 10 s when adding each reagent	[24]
Protocol 2	180 mL of 10% KOH plus 20 mL of 30% H_2O_2	Mass of sample: 50 g. 60 °C for 24 h with stirring every 6 or 8 h	Vacuum on cellulose filter (Ø = 47 mm and pore size of 8 µm)	Covering the sample with aluminum foil and stirring with a glass rod	[25,26]
Protocol 3	20 mL of Fe(II) 0.05 M plus 20 mL of 30% H_2O_2	Mass of sample: 50 g. Room temperature for 5 min and then 75 °C for 30 min with stirring with magnetic bar	After flotation: vacuum on cellulose filter (Ø = 47 mm and pore size of 8 µm)	The sample was sieved with a 3 and a 5 mm mesh. After digestion, the sample was subjected to flotation with saturated NaCl with stirring for 2 min with a glass rod and left to rest for 24 h	[27,28]
Protocol 4	10% (*m*/*v*) KOH in a ratio of 1:10 (sample mass/solution volume)	Mass of sample: 10 g. 40 °C for 72 h (until presence of clear solution, without traces of organic matter)	After digestion: vacuum on a cellulose filter (Ø = 47 mm and pore size of 8 µm).	During digestion, the sample was stirred once a day with a glass rod, rinsed with deionized water before and after, and dried with adsorbent paper. After the first filtration, the filter paper with the sample was rinsed with deionized water	[29–31]
Protocol 5	10% (*m*/*v*) of KOH in a ratio of 1:5 (sample mass/solution volume)	Mass of sample: 62 g. 60 °C for 24 h (with stirring)	Vacuum on cellulose filter (Ø = 47 mm and pore size of 8 µm)	Heating on a grill and stirring with a magnetic bar	[32–36]

After all the protocols were tested, the best one was chosen. The assessment parameters were as follows: (a) the organic matter was completely or mostly digested; (b) the sample was not thick and could be filtered without complications; (c) the process to digest the samples was safe and did not cause accidents; (d) the filters with MPs were more accessible to observe under the microscope, that is, they did not have a high content of organic matter that would prevent the MPs from being seen; (e) the virgin MPs had not suffered damage (color changes or cracks); and (f) the MPs' recovery percentage was greater than 90%. Of all

the protocols, the best was protocol 4, which, after obtaining the results, was adjusted by conducting flotation tests with NaCl saline solution (1.1 g/mL) followed by centrifugation of the sediment, coming from the flotation tests, with $CaCl_2$ saline solution (1.6 g/mL) at a higher speed, that is, at 2300 units of relative centrifugal force (RCF), for 5 min to ensure correct sedimentation when the organic matter load was higher; finally, after centrifugation, filtration was conducted with a Millipore system with a cellulose ester mixture membrane (Ø = 47 mm and pore size of 0.45 µm).

2.3. Application of the Best Protocol

This section describes the study sites from which samples of thin waste originating from USW were obtained to be analyzed using the best protocol.

2.3.1. Study Sites

The first site was the Universidad Autónoma Metropolitana, Azcapotzalco Unit (UAM-A), located in the northern area of Mexico City. Since 31 October 2003, it has implemented a Solid Waste Management Program titled "Separacción por un mejor UAMbiente" [37]. Every year, at least three studies are conducted on the generation and composition of the solid waste produced by UAM A. The average waste generation between 2004 and 2007 was 1430 kg/day. From 2008 to 2022, waste generation decreased to 782.7 kg/day and fluctuated between 612.9 kg/day and 832.1 kg/day, except in 2014, when it increased to 961 kg/day. In 2022, it dropped to 505.4 kg/day. Of all the waste generated at UAM, mixed plastics predominate, with 23%, then sanitary waste and paper, with 20%, and fine fraction, with 5%. On the other hand, recoverable waste such as aluminum cans accounted for 1.17%, glass 4%, and textiles 2%; these represent the lowest proportion of waste generated [38].

The second site was TESPA, which performs mechanical separation by waste type, organic and inorganic, as well as by size. Plastics, PET, aluminum, and containers, among others, are recovered in a system of conveyor belts by manual sorting [39]. TESPA is equipped with technology such as automatic sprayers that capture odor particles during operational hours, a misting system that applies bactericide and fragrance, and roofs designed to prevent waste dispersion and with soundproofing to reduce noise propagation [39,40]. TESPA has a reception capacity of 1400 tons of solid waste daily and a daily processing capacity of 1000 tons from the Azcapotzalco, Cuauhtémoc, Gustavo A. Madero, and Miguel Hidalgo boroughs [39,40].

2.3.2. Obtaining Samples of Thin Waste

On 10 August 2023, two pre-samples of USW were obtained from TESPA as follows: waste from 10 collection trucks from different randomly selected origins was stored in 200 L containers, one for each truck. Each pre-sample was obtained later, mixing five containers' content. For UAM-A, USW samples were obtained from the generation study developed in April 2024, according to the national standard NMX-AA-61-1985 [41]. The masses of the pre-samples were 208.2 kg and 231.7 kg for TESPA, and 576.9 kg and 633.7 kg for UAM-A. The quartering method was applied for each pre-sample, based on the NMX-AA-15-1985 standard [42]. On a flat surface of 4 m × 4 m, the USW from each pre-sample was poured and homogenized with shovels, and then, the mound of USW was divided into four equal quadrants to eliminate opposing parts. This process was repeated with the quadrants not removed until representative samples of 30 kg were obtained.

Each representative sample obtained from the quartering method was placed on a table, and the USW was separated and classified into different categories using an adaptation of the Mexican standard NMX-AA-22-1985 [43]. The waste classification comprised nine categories, including 21 secondary types of waste (Table 2).

Table 2. Categories for urban solid waste classification.

Category	Type of Waste	Category	Type of Waste
Organic	Food waste	Paper and cardboard	Paper
	Pruning waste		Cardboard
	Napkins and sanitary paper		Tetra Pak
Sanitary	Disposable nappies	Textiles	Textiles
	Sanitary towels	Special management waste (SMW)	Potentially hazardous
	Other sanitary		Construction
Glass	All types of glass	Plastics	All plastics
Metals	Aluminum cans	Others	Wood
	Other cans		Semi-fine fraction
	Other metals		Fine fraction
			Other

Each by-product was placed in a pre-labeled polyethylene bag; the most considerable waste was stored first, and then the remaining fragmented waste was passed through a sieve with a 5 mm mesh opening to obtain the fine fraction of USW. Each by-product was weighed, and the percentage in terms of mass was obtained by dividing its mass by the total mass of the sample using Equation (1):

$$P_p = \left(\frac{M_1}{M}\right)100 \quad (1)$$

where the equation elements are defined as follows:

P_p = The mass proportion of the specific waste.

M_1 = The mass of the type of waste, in kg, minus the weight of the used bag.

M = The total mass of the sample, in kg.

Finally, the fine fraction of the USW was transported to the laboratory and stored in a refrigerator at 3 °C until its analysis.

2.3.3. Extraction of Microplastics

The extraction of MPs from the fine fraction samples obtained in the classification of by-products was carried out in the laboratory using protocol 4, which allowed us to extract and observe MPs from 0.03 to 5.00 mm. Five replicates of 10 g on a wet basis were analyzed for each of the four fine residue samples. All replicates, contained in aluminum trays, were oven-dried at 100 °C for 24 h to remove the moisture and obtain the dry mass.

Subsequently, 100 mL of 10% potassium hydroxide (KOH) solution was added to each replicate of fine residues to degrade organic matter; this mixture was stirred with a clean, dry glass rod. The samples were covered with aluminum foil and incubated at 40 °C to 50 °C for 72 h. After this time, 300 mL of sodium chloride (NaCl) solution with a density of 1.1 g/mL was added to each sample, stirred for 5 min, and allowed to stand for 24 h to 96 h. The supernatant was vacuum-filtered on filter paper with an 8 µm pore size, and the filters with sample were stored in glass Petri dishes at room temperature. To the sediment remaining after filtration, 40 mL to 70 mL of calcium chloride solution ($CaCl_2$) with a density of 1.6 g/mL was added and centrifuged at 2300 revolutions per minute (rpm) for 5 min; the supernatant obtained was vacuum-filtered on cellulose ester blend membranes with a pore size of 0.45 µm. The membranes were stored in glass Petri dishes at room temperature.

2.3.4. Microplastic Classification and Statistical Analysis

Subsequently, all filter paper samples and cellulose ester blend membranes were placed on clean glass slides, in order to have a flat surface that allowed easy manipulation, and were observed directly under an optical microscope A.KRÜSS Optronic, MBL2000 (A. Krüss Optronic GmbH, Hamburg, Germany) at 5× and 10× magnifications.

An external camera EUROMEX, CMEX DC.5000 (Euromex, Duiven, The Netherlands) was connected to the microscope and to a computer. Using the camera and with the help of Image Focus software 2.4.9.0 version, all the membranes and filter papers were carefully examined to discard non-MP items, such as dust, stones or organic fibers. All the particles of MPs, such as fragments (which are rigid and cannot be folded), films (which are easy to fold and shine in the presence of light), foams (which can be distinguished by their easy compression), and fibers (thin filaments), were counted, and their shape, size (the diameter of spherical particles and the width of the fibers were measured, and the fragments and films were measured crosswise), and color were determined. The type of polymer was analyzed with FTIR Agilent, Cary 630 (Agilent, Santa Clara, CA, United States).

A statistical analysis of the concentrations of MPs found in the fine residues of each of the four samples for dry mass was carried out using Statgraphics Centurion XV, Version 15.2.06. First, a normality test was run using the Shapiro–Wilk method to see how the data behaved, that is, whether the data did or did not have a normal distribution. Since the data had a non-normal distribution, the non-parametric Kruskal–Wallis test was chosen to analyze whether there were or were not statistically significant differences in the concentrations of MPs in the fine residues of the different samples analyzed.

3. Results

This section shows the relevant results of this research.

3.1. Evaluation of Five Protocols

After the five protocols were implemented, observations were made for each one, which allowed the best one to be selected for application in samples of thin waste from TESPA and UAM-A. The relevant findings of each protocol are summarized in Table 3.

Table 3. Results of all tested protocols.

Protocol	Degradation of Organic Matter	Virgin MP Recovery Percentage	Other Comments	Conclusion
Protocol 1	After 24 h, the sample was not completely digested.	It could not be calculated	When adding H_2O_2, there was a significant loss of sample due to the fact that it spilled. Filtration was not possible	Protocol not suitable for digestion of organic matter
Protocol 2	After 24 h of treatment, organic matter was still observed, and the sample was too thick	It could not be calculated	Filtering to retrieve virgin MPs could not be performed	Protocol not suitable for digestion of organic matter
Protocol 3	After 20 min, the sample was not completely digested, but much of the matter was destroyed	It could not be calculated	When H_2O_2 was added, there was a large amount of foam. The treatment did not last 30 min, since after 20 min, the reagents had already evaporated, and the entire sample adhered to the glass	Protocol moderately suitable for digestion of organic matter

Table 3. *Cont.*

Protocol	Degradation of Organic Matter	Virgin MP Recovery Percentage	Other Comments	Conclusion
Protocol 4	After digestion, the sample had good degradation	100%, no color changes or presence of cracks	The filters were clearly visible as there was very little presence of organic matter. However, flotation tests with NaCl (1.1 g/mL) and centrifugation with $CaCl_2$ (1.6 g/mL) and at a higher speed are recommended	Proper protocol
Protocol 5	The sample changed color, but did not degrade	It could not be calculated	Filtration was not possible because the organic matter had not degraded	Protocol not suitable for digestion of organic matter

The results showed that the best protocol was number 4 since its recovery percentage of virgin MPs was 100%, and there was good degradation of organic matter. This level of degradation, in turn, after filtering the samples, allowed the MPs contained in the filters to be clearly observed, and an easy count and classification of the MPs present in the fine fraction sample could be performed.

3.2. Classification of Urban Solid Waste

Figure 1 shows the composition of USW at the two study sites. It can be observed that the categories that, on average, presented the highest percentage were organics (48.82%), plastics (19.57%), and paper and cardboard (13.90%). Regarding the fine fraction, this, on average, had a percentage of 1.35% (TESPA 1, 1.76%; TESPA 2, 1.04%; UAM-A 1, 1.17%; UAM-A 2, 1.44%).

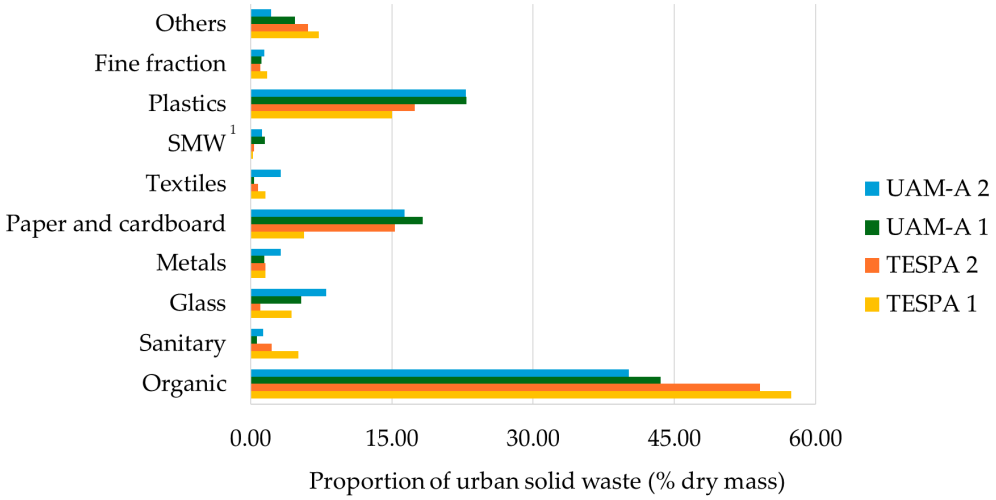


Figure 1. The proportion of different urban solid waste at the two study sites. SMW [1] = special management waste.

3.3. Abundance, Characteristics, and Statistial Analysys of Microplastics in Fine Fraction

The abundances of MPs were 10.4–36.9 #MP/g of dry mass, with the sample from UAM-A 2 having the highest value and the sample obtained from TESPA 2 having the lowest value (Table 4).

Table 4. The central tendency and dispersion values of the abundance of microplastics in the four samples analyzed, #MP/g of dry mass.

Site	Mean ± Standard Deviation	% Variance	Median
TESPA 1	15.1 ± 2.7	17.8	14.9
TESPA 2	10.4 ± 1.6	15.4	10.1
UAM-A 1	28.4 ± 12.6	44.2	22.2
UAM-A 2	36.9 ± 4.8	13.2	36.0

Figure 2 shows a box-and-whisker diagram for the abundance of MPs in the four samples. This could be related to the percentage of macroplastics, as samples from UAM-A had a higher mass proportion of plastics (22.92 and 22.89% for UAM-A 1 and UAM-A 2, respectively), compared to those obtained from TESPA (15.00 and 17.46%).

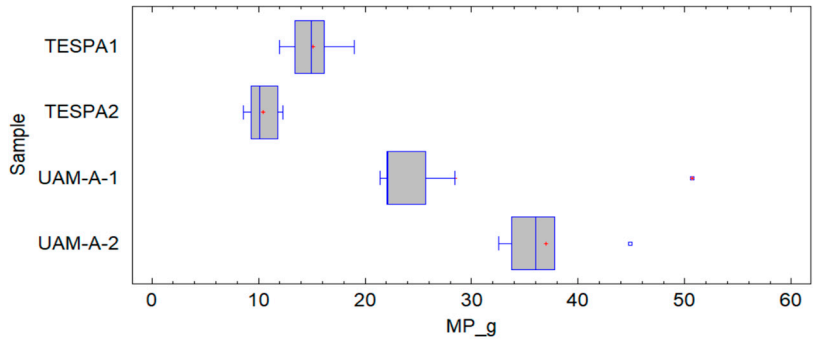


Figure 2. Box-and-whisker diagram of the four sampled sites. The vertical blue line inside the box represents the median, while the red cross is the mean. Data outside the graph represents outliers.

UAM presented the highest concentrations of MPs with a median value of 33.1, 2.7 times higher than the TESPA samples (Table 5).

Table 5. The central tendency and dispersion values of the two sites analyzed, #MP/g of dry mass.

Site	Mean ± Standard Deviation	% Variance	Median
TESPA	12.8 ± 3.2	25.4	12.1
UAM-A	32.7 ± 10.1	30.8	33.1

Figure 3 shows a box-and-whisker diagram of the abundance of MPs at the two study sites, showing that the highest concentration of MPs was at UAM-A.

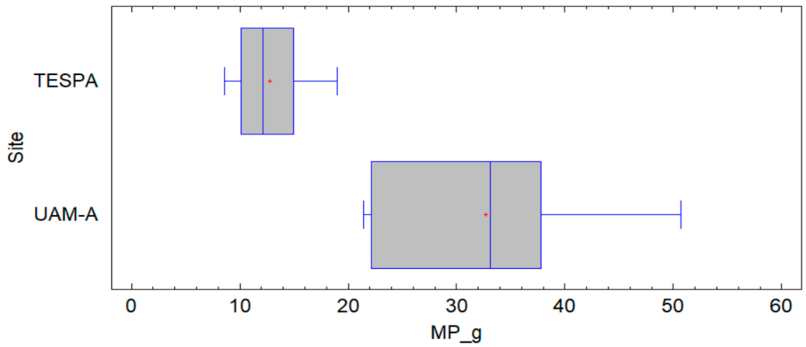


Figure 3. Box-and-whisker diagram for the abundance of microplastics in the fine fraction of the two sampled sites. The vertical blue line inside the box represents the median, while the red cross is the mean. Data outside the graph represents outliers.

Regarding the characteristics of MPs, Figure 4 shows the classifications by size, type, color, and polymer. For size, the MPs studied ranged from 0.03 to 5.00 mm; the most common were those smaller than 1.0 mm, with percentages ranging from 38.63 to 80.81%. At the same time, the lowest values were in the range of 3.1–4.0 and 4.1–5.0 mm (Figure 4a). For shape, fragments were the most abundant MPs, with percentages ranging from 36.12 to 74.81%, followed by fibers with 10.81 to 40.75% (Figure 4b). Regarding the color of MPs, there was no trend toward a specific color; together, black and white represented high values between 33.27 and 75.06% (Figure 4c). Finally, the three most common polymers were PE, PP, and nylon, with a mean of 22.5% each.

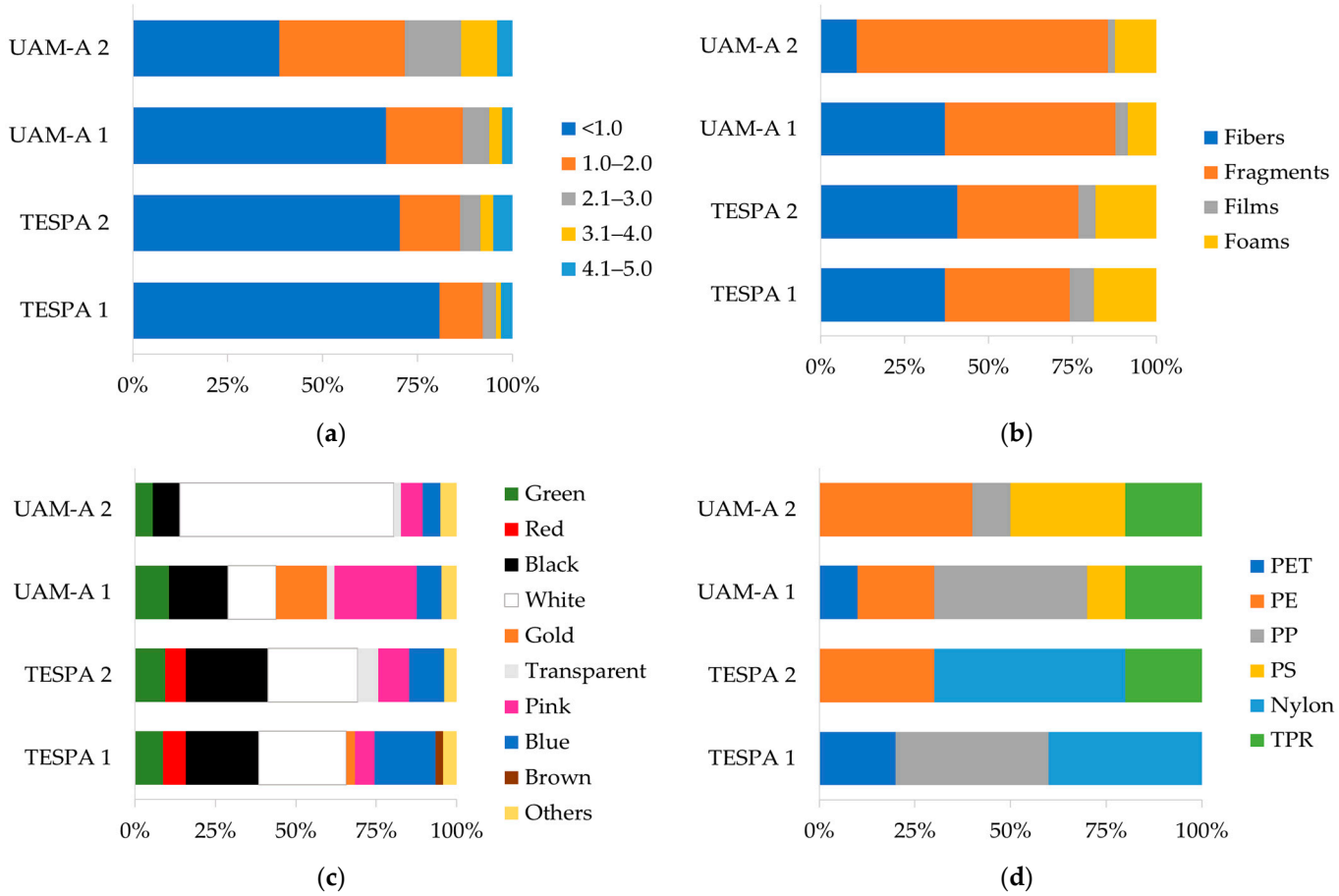


Figure 4. Classification of microplastics: (**a**) size in millimeters, (**b**) shape, (**c**) color, and (**d**) polymer.

Figure 5 shows some examples of microplastics found in the fine fraction of urban solid waste from TESPA 1. From left to right, we can see a foamed Styrofoam particle, which may come from fast food disposables, and three fragments, the last of which shows alterations (apparently has cracks).

On the other hand, Figure 6 illustrates some MPs found at TESPA 2, UAM-A 1, and UAM-A 2.

In the case of films, they are characterized by being thin, the shine they generate in the presence of light, and their flexibility. It is also noted that in UAM-A 1, there was apparently a red film which seemed to come from painting remains, and this is related to the workshops of the SAD division courses where these types of supplies are used by the subjects to carry out different works. On the other hand, in the first photo of UAM-A 2, there is a plastic fragment in which organic remains were embedded.

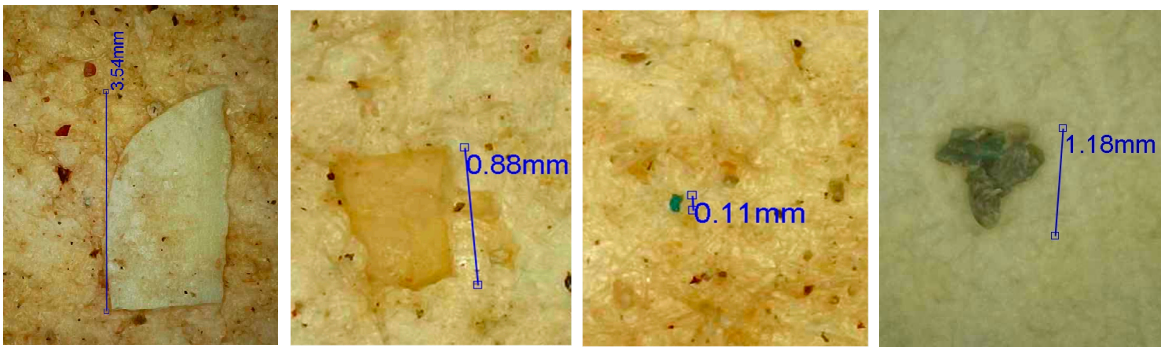
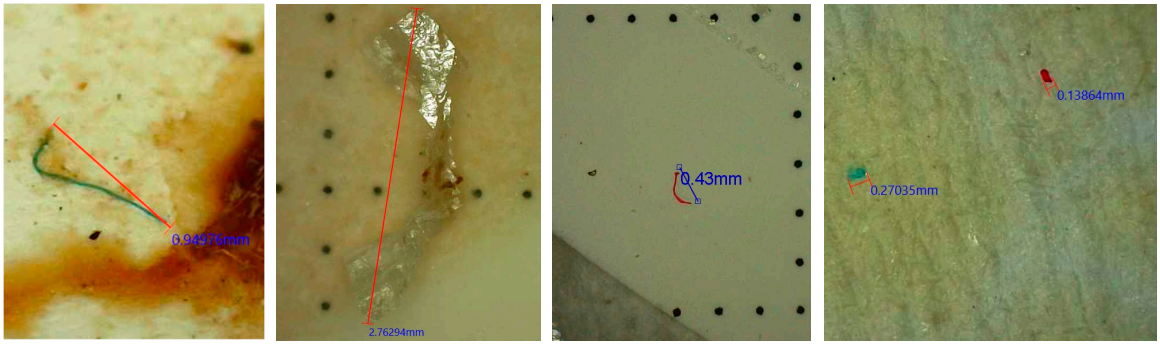
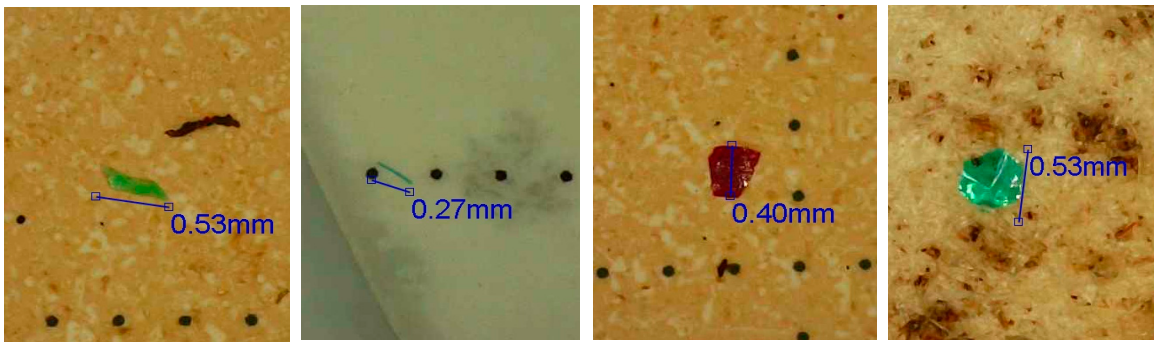


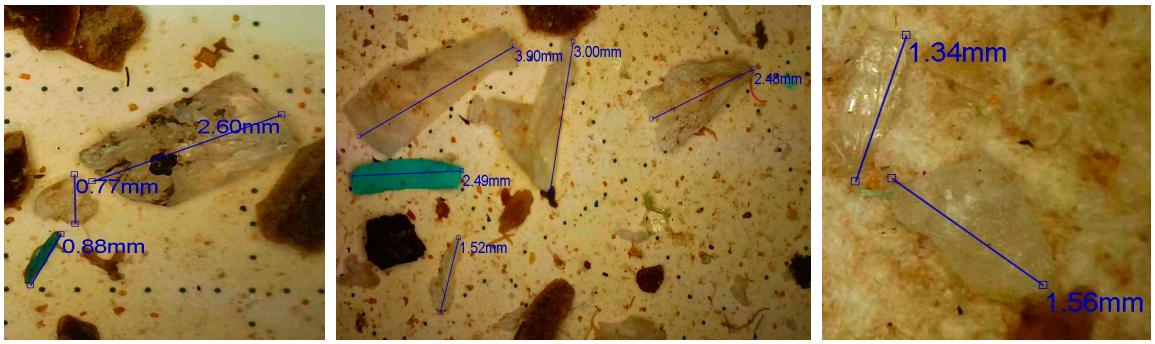
Figure 5. Examples of microplastics from TESPA 1.



(**a**)



(**b**)



(**c**)

Figure 6. Examples of microplastics from (**a**) TESPA 2, (**b**) UAM-A 1, and (**c**) UAM-A 2.

4. Discussion

The analysis of waste composition is crucial for developing effective waste management infrastructure and valorization strategies. However, the lack of standardized methods for sampling, analysis, and classification, particularly for the fine fraction of municipal solid waste (MSW), poses a significant challenge. This fraction, variably defined

as particles < 10 mm or <5 mm [44] and sometimes limited to specific components like sand, ash, dust, and street sweepings [45–48], hinders comparative analyses across studies. Table 6 illustrates this variability, with reported fine fraction proportions ranging from 0.2% to 15.27% by weight, depending on the region, waste category, and definition employed.

Table 6. Studies around world about fine fraction in urban solid waste.

Region or Country	Category of Waste	% in Weight	Reference
Germany	Fine waste (0–10 mm)	6.3 of household waste	[44]
China's eastern coastal regions	Dust	0.0–15.27 of municipal solid waste	[45]
Bangalore, India	Dust and sweeping	6.53, average of domestic, markets, trade, slums, and street sweeping	[46]
Three municipalities in Denmark	Gravel, stones, and sand	0.3–0.2 of residual waste	[47]
Mexico	Fine waste (<2 mm)	2.25 of urban solid waste	[48]

While research on fine fraction has predominantly focused on legacy waste in landfills for mining purposes [19,49–51], or on specific inputs/outputs of treatment processes [52,53], there is limited information on its composition in collected MSW or at transfer stations. Understanding this fraction in the early stages of waste management is crucial for improving waste characterization, enabling a more accurate assessment of the overall waste stream composition. Furthermore, it facilitates predicting waste behavior in different scenarios, including landfilling, biological, and thermal treatment. This understanding also aids in developing improved material separation techniques for enhanced resource recovery and the identification of valuable resources.

Analyzing MPs in fine fraction presents challenges due to its heterogeneity, influenced by waste composition, management practices, and the presence of organic matter, requiring careful removal to avoid the underestimation of microplastic content. Although standardized methods for microplastic analysis in MSW are lacking, this research employed a sequence of sieving, digestion, density separation, filtration, and visual and/or chemical analysis, similar to approaches used in other studies [54]. This methodology proved effective in extracting, measuring, and classifying MPs within the 0.03 to 5.00 mm size range, providing clear evidence of this emerging pollutant in the fine fraction of MSW.

This study investigated the presence of MPs within the fine fraction of MSW, an area of growing concern due to the potential for environmental contamination and human health risks. Fibers and rigid fragments constituted over 70% of the identified MPs, highlighting their contribution to microplastic contamination in the waste stream. The detected microplastic quantities (10–37 MP/g of dry mass), when extrapolated to daily waste generation [48], could amount to an estimated 27 thousand to 100 thousand million microplastic items in the fine fraction generated in Mexico. The predominance of MPs smaller than 1 mm (80%) indicates a high propensity for these particles to leak from waste management systems and become incorporated into environmental matrices, such as agricultural soil [55,56].

Regarding the statistical analysis by site, the *p*-value was 0.000157053, which, being less than 0.05, indicates that there are statistically significant differences between the medians of both sampling sites. This can be corroborated in the box-and-whisker plot in Figure 3, where it can be observed that the medians of both sites (vertical line in the middle of the box) are far apart from each other and that the highest concentrations of microplastics were found at UAM-A.

The high presence of MPs in the samples from UAM-A could be due to the fact that within the university, there are different potential sources (such as laboratories or workshops of the different departments, gourmet and subsidized cafeterias, classrooms, warehouses, and green areas for recreational and sports uses, among others) where different plastic articles are used that, after being discarded, can become microplastics. In addition to this, various festivities and events are often held at the university in some subjects, especially in the division of Sciences and Arts for Design (SAD), that involve the use of single-use plastic articles and even microplastics present in materials used for crafts such as foam. Likewise, UAM-A also has a synthetic grass soccer field, which is a potential source of MPs, since plastic fragments are released from the grass when used.

On the other hand, solid waste from homes arrives at the transfer station, which, even when it contains plastic waste, is collected so that the presence of these, as well as their fragments and MPs, is less.

This study highlights the need for standardized methodologies to characterize fine fraction, including microplastic analysis. It also emphasizes the importance of future research to investigate the fate and transport of MPs in waste management systems and the environment. Finally, it points to the necessity of mitigation strategies to reduce microplastic contamination in the waste stream and prevent their release into the environment. By addressing these needs, waste management systems can move towards greater sustainability and minimize the environmental and health impacts of microplastic pollution.

5. Conclusions

The findings of this research identified an efficient methodology for extracting MPs from the fine fraction of municipal solid waste, establishing a process that minimizes particle loss and ensures complete organic matter degradation. The selected protocol is not only replicable and safe but also provides a high recovery rate of MPs, which is essential for research in waste management and emerging contaminant monitoring. This methodological advance could serve as a foundation for future standards and standardized procedures in microplastic analysis in residual fractions.

The significant presence of MPs in the fine fraction of municipal solid waste suggests that current waste management systems should address these contaminants, which, though not visible to the naked eye, pose a latent threat to the environment. The high concentrations found at the university site, compared to the transfer stations, highlight the influence of local consumption patterns and waste handling types. Waste management programs must include specific mitigation strategies for this fraction, especially in urban contexts with high waste generation.

This study emphasizes the urgency of developing more stringent and specific control policies for MPs in solid waste. Although in different states and municipalities of Mexico, the commercialization, distribution, and/or delivery of single-use plastic articles has been prohibited, only Mexico City has included products containing microplastics; however, there is no certainty that compliance is verified in all supermarkets, markets, stores, and other points of sale, and above all, that the corresponding sanctions are applied. Therefore, it is necessary to reinforce this part to reduce or avoid the presence of MPs coming from larger plastic waste in USW.

Another very important aspect is the use of plastic articles made from biodegradable materials for which, if not treated under the processes and conditions for which they were created, there is a risk that they will only fragment, but not completely biodegrade. In this sense, if biodegradable plastics are disposed of in USW and, at the final disposal sites, the conditions are not suitable for them to degrade, there is a probability that they will generate microplastics.

Finally, it is also considered that it is necessary to increase the level of control at the final disposal sites in Mexico, since many of them do not have a leachate collection system, geomembrane, or cover after burying the waste, which is essential to avoid the dispersion of MPs in the environment.

The information obtained herein on the quantity, characteristics, and diversity of MPs in fine fraction opens the door to new research on their behavior and persistence in waste management systems and their eventual impact on soil and water. Future studies should explore not only the mechanisms of microplastic release into the environment, but also the implementation of technologies that facilitate their separation and treatment, promoting a transition to more sustainable and less polluting waste management practices.

Author Contributions: Conceptualization, J.C.A.-Z., A.A.C.-S. and A.V.-M.; methodology, R.M.E.-V., K.P.A.-E. and A.A.C.-S.; formal analysis, J.C.A.-Z. and K.P.A.-E.; investigation, P.X.S.-N. and A.V.-M.; resources, K.Y.M.-P. and K.P.A.-E.; data curation, J.C.A.-Z., K.P.A.-E. and K.Y.M.-P.; writing—original draft preparation, P.X.S.-N., J.C.A.-Z., R.M.E.-V., K.P.A.-E., A.V.-M. and A.A.C.-S.; writing—review and editing, A.V.-M., P.X.S.-N. and A.A.C.-S.; project administration, A.V.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors thank the transfer station and segregation plant of Azcapotzalco and the collection center of the Universidad Autónoma Metropolitana, Azcapotzalco, for the support provided for this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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