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New Management Strategy Framework for Effectively Managing Microplastic in Circular System Form Plastic Product Manufacturing to Waste Treatment Facility

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Abstract: In recent years, concerns regarding the environmental impact of microplastics (MPs) have led to increased international attention on these pollutants. Although the initial focus was largely directed toward marine environments, land-based pollution sources, including MP release, have been recognized to directly affect marine ecosystems. Therefore, soil-, atmosphere-, groundwater-, and river-based research is ongoing. However, when considering sources of MP, it is necessary to examine the circular system of plastic in terms of raw materials, production, consumption, discharge, and disposal (recycling). Accordingly, the present study proposes a strategy to effectively manage MPs using this circular system. First, the factors influencing MPs in the circular system were identified, and MPs at the system's final stage, i.e., at the waste treatment facility, were subsequently investigated. Using the concept of MP waste (MPW), strategies were then developed for effective MP management within the circular system. Applying the proposed theoretical strategy to the Korean waste management system revealed that the new policy framework improves the current MP management system. Overall, this study provides fundamental data for establishing new or improved MP management schemes from a waste sector perspective.

Keywords: microplastic; policy framework; circular system; theoretical strategy; waste management

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1. Introduction

Microplastics (MPs) are artificially or naturally fragmented micro-sized plastics in the range of 1 nm to 5 mm. MPs comprise a mixture of polymers and additives and are typically acknowledged to pose a threat to ecosystems [1–3]. MPs can be categorized into primary and secondary MPs based on their origin [4]. Primary MPs are intentionally manufactured at sizes < 5 mm, such as microbeads and plastic pellets. Secondary MPs are generated via the fragmentation of plastics in the environment, including textile fibers and tire dust, to sizes < 5 mm through processes such as photodegradation, abrasion, and decomposition [2,5].

In recent years, numerous studies have reported the harmful effects of MPs on ecosystems, highlighting their physicochemical properties, bioaccumulation, and toxicity. Smaller MPs can be ingested by marine organisms, with their impact extending to birds and marine mammals [6–8]. Hydrophobic substances, such as polychlorinated biphenyls, persistent organic pollutants, and heavy metals, likely adhere to MP surfaces and bioaccumulate through the food chain, affecting the overall ecosystem, including seawater, freshwater, and soil [9]. Furthermore, additives used in plastic manufacturing, such as plasticizers and flame retardants, may leach into the environment, acting as toxic agents [10,11]. In terms of harmful effects on human health, MPs can affect all organs, potentially traversing cellular barriers, such as the blood–brain barrier, leading to cerebral ischemia and reperfusion injury [12,13].

The UN Environment Assembly has adopted a resolution on marine plastic waste and MPs; accordingly, they recommend investigating the origins of MPs entering the oceans, developing management measures to minimize their entry, and creating international, national, and regional management strategies to strengthen international coordination [14]. Discussions on implementation are underway at the international level, involving the establishment of groups of experts from various countries, aiming for concrete measures and internationally binding agreements to reduce marine waste. The Organization for Economic Cooperation and Development has suggested conducting national surveys to identify MP sources in land and oceans as well as developing policies to minimize plastic use in each country [15,16]. At the G7 Summit, the G20 Action Plan on Marine Litter was discussed, a plan aiming to investigate marine litter (including MPs) impacts on the environment, develop measures to protect the environment from marine litter, and apply these measures in a circular system considering the life cycle of plastics [17,18].

Although initial international concern over MP pollution focused primarily on marine environments, the lack of land-based plastic management is now recognized as one of the major direct contributors to marine pollution [19]. Specifically, waste plastics, the source of MPs, are discharged directly into the ocean from land, or MPs generated on land are washed into the ocean [20]. The direct impact of land-generated MPs on marine environments as well as terrestrial flora and fauna, nature overall, and humans, is particularly concerning. Consequently, investigations are underway in many countries, generally prioritizing research on MP contamination throughout the environment, including soil, air, coast, and rivers [21–29]. However, when considering sources of MP, a circular system approach is required for investigation, including examining the industrial system producing plastic products from raw plastics, the household system consuming and discharging the plastic products, and the waste treatment system collecting and processing waste [30]. The present study aimed to identify the causes of MP pollution in the circular system, from plastic product manufacturing to waste processing, with the objectives of reducing MP occurrence and effectively managing generated MPs.

2. Factors Influencing MPs in the Circular System: From Plastic Product Manufacturing to Waste Management

With the increasing use of plastic, considerable plastic waste is generated, threatening the environment and human life. Thus, one possible solution is to consider the concept of circular economy. This concept aims to protect the environment from plastic pollution and promote the growth and innovation of industry and humans through overall changes in every step of designing, producing, using, and recycling plastic. Considering that plastics are the origin of MPs, the flow of plastic in a circular system also has a high impact on the generation, movement, accumulation, and diffusion of MPs into the surrounding environment. Therefore, understanding MPs in this circular system of plastic can be an effective management strategy for MPs. In this section, to understand the factors influencing MPs within the circular system, a schematic diagram of the cyclical system, beginning from the manufacturing of plastic products to waste treatment, was examined (Figure 1). Within the circular system, seven material factors (MFs) potentially causing MP pollution were identified. First, the raw material (MF-1) required for plastic product manufacturing is supplied for production. The manufactured plastic product (MF-2) is then supplied for human use or economic gain, and the waste generated during production (MF-3) is transferred to the waste treatment facility. Discarded plastic products (MF-4), as well as sewage, rainwater, groundwater, and other waters containing plastic substances from human usage or economic activities (MF-5), are disposed of through sewage treatment facilities. Recyclable waste may be separated and incorporated back into the product manufacturing process (MF-6). Finally, the risk of plastic materials leaking from each part of the circular system into the environment must be considered (MF-7).

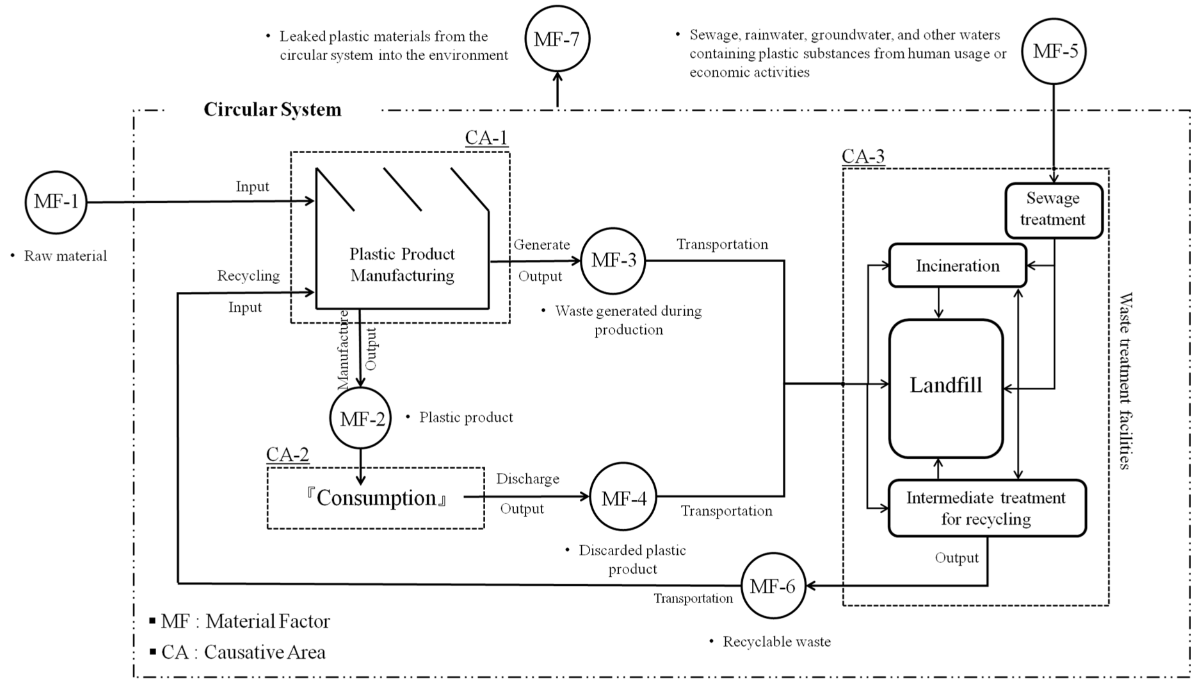

Figure 1. Factors influencing MPs within the circular system range from plastic product manufacturing to waste treatment facilities. (MF-1: raw material (raw plastic), MF-2: plastic product, MF-3: waste generated during production, MF-4: discarded plastic product, and MF-5: sewage, rainwater, groundwater, and other waters containing plastic substances from human usage or economic activities, MF-6: recyclable waste, MF-7: leaked plastic materials from the circular system into the environment; CA-1: manufacturing plastic products, CA-2: using plastic products, and CA-3: disposing of waste).

The areas where MFs are provided and where they may occur or cluster are called causative areas (CAs). We categorized the CAs into manufacturing plastic products (CA-1), using plastic products (CA-2), and disposing of waste (CA-3). Depending on the nature of the plastic product, CA-1 includes intentional MP production through crushing, grinding, and screening of solid plastic raw materials as well as unintentional generation during manufacturing, with all being especially relevant to businesses producing plastic beads and pellets, make-up products, synthetic rubber and tires, and plastic fibers, among other products [31–34]. When MPs are generated, they are also present in the dust in the capture facility or in sludge and wastewater from the process. CA-2 includes products that contain or comprise MPs, making them an important MP source, given the ease with which they wear, corrode, or degrade. Products containing MPs include skin exfoliators, cosmetics, face washes, body scrubs, toothpaste, lip balms, moisturizing creams, makeup, and detergents, among others [32,35]. Products comprising MPs include plastic bead products, antislip powder products, and fillers [32,36,37]. Products with potential (stealth) MPs include tires, synthetic clothing, tennis balls, laundry and dishwasher pods/tablets, cigarette butts, glitter, wet wipes, tea bags, paints, and takeaway cups [32,38–42]. Regarding CA-3, MPs may be generated during waste processing at recycling facilities, incinerators, and sewage treatment facilities [34,43–45]. Additionally, MP generation may occur artificially or naturally during landfilling, or they may be introduced from external sources [46–48].

3. Investigation of MPs in Waste Treatment Facilities

MPs at CA-1 and CA-2 can be effectively controlled if management practices are improved at specific manufacturing steps as well as in the use, discharge, and collection of certain products. In contrast, managing MPs at CA-3 is challenging as various nonplastic waste types are processed at treatment facilities along with plastic waste. Therefore, before addressing strategies to effectively manage MPs (Section 4), this section examines MPs at representative facilities relevant to CA-3, i.e., landfill sites and incineration, sewage treatment, and recycling facilities.

3.1. Materials and Methods

To investigate MPs at the waste treatment facilities, the facilities were selected and sampled based on their representativeness, types of substances treated, main processes, throughput, and characteristics and amount of waste discharged following treatment (Table 1). One incineration facility that incinerates municipal waste (Facility A) and another that incinerates waste from recyclers (Facility B) were selected, both handling a high proportion of plastic waste. For sewage treatment, two facilities (Facilities C and D), one located in Seoul and one in Busan, two of South Korea's largest cities, were selected, considering the size of the city, the amount of sewage, and the generation of sewage sludge. Landfill sites were selected based on the processing scale. For recycling, four facilities (Facilities E–H) were selected, considering facilities primarily recycling waste plastic products (e.g., household products, automobiles, and construction sites) and waste tires. Overall, samples were prepared from 14 waste types from 8 facilities. More details can be found in the Supplementary Information, Figure S1.

Table 1. Characteristics of the four facility types.

<table>
<tr><th colspan="2" rowspan="2">Facility Type</th><th rowspan="2">Material Carried into Facility</th><th rowspan="2">Main Process</th><th colspan="3">Waste Generated After Process</th></tr>
<tr><th>Type</th><th>Particle</th><th>Sample Code</th></tr>
<tr><td rowspan="5">Incineration</td><td rowspan="3">A facility [(1)]</td><td rowspan="3">Plastic waste and waste plastic products 20 (wt.%), rubber 1.3 (wt.%), fiber 5 (wt.%)</td><td rowspan="3">Incinerator with grate combustion furnace</td><td>Bottom ash</td><td>Various</td><td>IAB</td></tr>
<tr><td>Fly ash</td><td>Very fine (<0.1 mm)</td><td>IAF</td></tr>
<tr><td>Fly ash (medicated)</td><td>Very fine (<0.1 mm)</td><td>IAFm</td></tr>
<tr><td rowspan="2">B facility [(2)]</td><td rowspan="2">Plastic waste and waste plastic products > 30 (wt.%)</td><td rowspan="2">Incinerator with fluidized bed furnace</td><td>Bottom ash</td><td>Various</td><td>IBB</td></tr>
<tr><td>Fly ash</td><td>Very fine (<0.1 mm)</td><td>IBF</td></tr>
<tr><td rowspan="4">Sewage treatment</td><td rowspan="2">C facility [(3)]</td><td rowspan="2">Sewage [(9)]</td><td>Dewatering process with polyacrylamide coagulant</td><td>Sludge</td><td>Usually fine (<5 mm)</td><td>SCW</td></tr>
<tr><td>Drying process with polyacrylamide coagulant</td><td>Sludge</td><td>Usually fine (<5 mm)</td><td>SCD</td></tr>
<tr><td rowspan="2">D facility [(4)]</td><td rowspan="2">Sewage [(9)]</td><td>Dewatering process with polyacrylamide coagulant</td><td>Sludge</td><td>Usually fine (<5 mm)</td><td>SDW</td></tr>
<tr><td>Drying process with polyacrylamide coagulant</td><td>Sludge</td><td>Usually fine (<5 mm)</td><td>SDD</td></tr>
<tr><td colspan="2">Landfill</td><td>Mixture of municipal solid waste and construction waste</td><td>Landfill sites</td><td>Landfilled waste</td><td>Various</td><td>LW</td></tr>
<tr><td rowspan="4">Intermediate treatment</td><td>E facility [(5)]</td><td>Waste plastic products</td><td>Melting, electric heater, and cutting processes</td><td>Process residues</td><td>Various</td><td>RE</td></tr>
<tr><td>F facility [(6)]</td><td>Waste plastic products</td><td>Melt mixer process</td><td>Process residues</td><td>Various</td><td>RF</td></tr>
<tr><td>G facility [(7)]</td><td>Waste plastic products (scrap cars)</td><td>Crushing, cutting process</td><td>Process residues</td><td>Various</td><td>RG</td></tr>
<tr><td>H facility [(8)]</td><td>Waste tire</td><td>Crushing, cutting process</td><td>Process residues</td><td>Various</td><td>RH</td></tr>
</table>

[(1)] A facility for incineration of municipal solid waste. [(2)] B facility for incineration of residues generated from intermediate treatment facilities. [(3)] C facility located in Seoul metropolitan city. [(4)] D facility located in Busan metropolitan city. [(5)] E facility manufacturing plastic chipping. [(6)] F facility manufacturing plastic popcorn. [(7)] G facility manufacturing plastic flake. [(8)] H facility manufacturing recyclable tire raw material. [(9)] Sewage with wastewater, rainwater, groundwater, etc., containing plastic materials in human life or economic activities.

Prior to MP analysis, all samples were pretreated to separate foreign substances (nonplastic) and remove organic materials (Figure 2) [49–53]. Samples weighing 0.1–2.0 g (Table S1) were subjected to a float–sink process using a separatory funnel to separate foreign substances. Given that typical plastics have a density of approximately 1.41 g/cm^3 (Table S2), $ZnCl_2$ was used as it has a density of 1.6 g/cm^3 (Table S3). Following density separation, primary filtration was conducted using a 20 µm diameter metal filter (Table S4), and residual organic matter was removed using H_2O_2 solution (30%) (Table S5). Following acid treatment, samples were subjected to second filtration under the same conditions as the first filtration and subsequent drying. MPs were then analyzed via Fourier transform infrared spectroscopy (FT-IR; LUMOS II, Bruker, USA) (Figure S2) [54,55]. Analytical results were obtained through focal plane array mapping, and MP components were confirmed if the concordance rate with library data exceeded 70%.

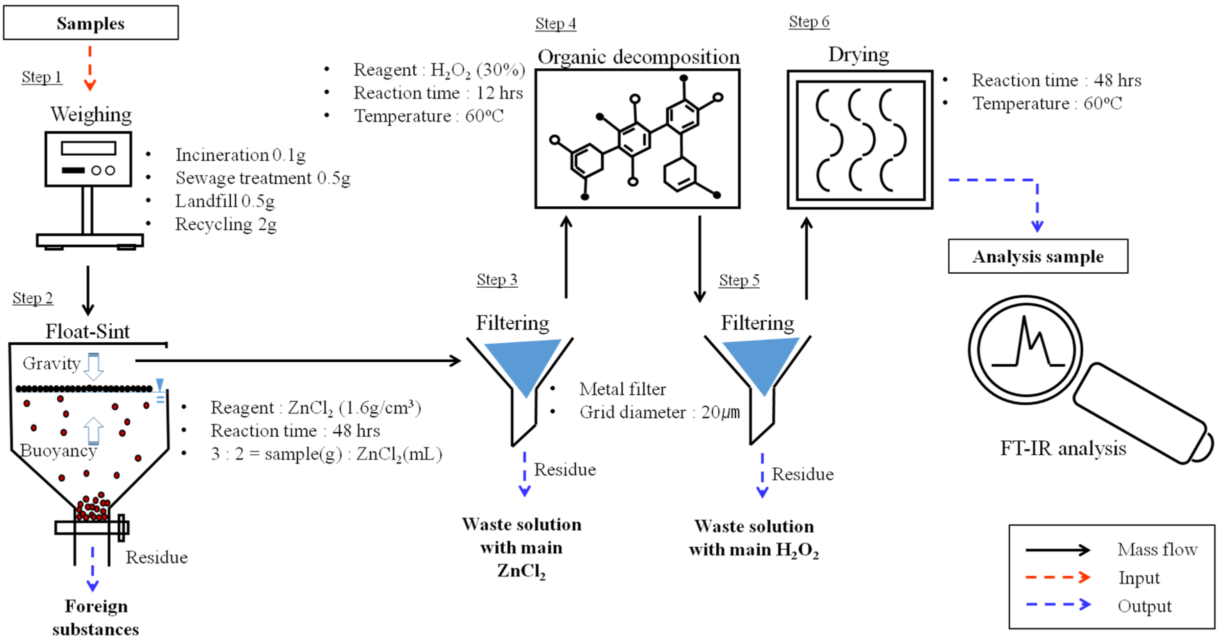

Figure 2. Schematic flow diagram for preparing samples for FT-IR analysis.

3.2. MPs in Landfill Sites, Incineration, Sewage Treatment, and Recycling Facilities

Table 2 shows the number of MPs (≤5 µm) in the samples from each facility. High levels of polypropylene, polyethylene, and polyethylene terephthalate were detected, along with polyvinyl chloride, polyamide, polyurethane, and polymethyl methacrylate. Fly ash (sample code: IBF) from municipal incinerators with a high plastic waste proportion presented with the highest MP levels, and process residues (sample codes: RF and RG) from facilities involved in intermediate treatment for recycling had higher levels compared with samples from other facilities. The average value for all samples was 333.5 ea/g. The FT-IR spectrum and image in Figure 3 support the results provided in Table 2.

In Table 3**,** the results of this study are compared with those of previous studies conducted in various suspected contamination areas [45,56–62]. Our findings have revealed higher MP levels, partly because most previous studies were conducted before the coronavirus pandemic of 2019; increased plastic waste generated from packaging and disposable products during the pandemic likely affected the results of our study [63–66]. Additionally, differences in MP conditions, sample pretreatment methods, analysis methods, particle size ranges, target facility or region characteristics, and environmental factors (e.g., climate and season) may also have contributed to these discrepancies. Table 3 includes results from investigations conducted in specific soils, coasts, rivers, oceans, and air with suspected MP contamination [21–29]. Comparing these data reveals that MPs from waste treatment facilities can contaminate the environment through external runoff.

Table 2. Number of MPs (≤5 µm) in the samples from incineration, sewage treatment, landfill facility, and intermediate treatment. The experiments were repeated. Each data point was determined in triplicate, and standard deviations of the data were estimated for each case (Table S6).

Sample Code		ea/g							
		PP [(1)]	PE [(2)]	PET [(3)]	PVC [(4)]	PA [(5)]	PU [(6)]	PMMA [(7)]	Total
Incineration	IAB	40	10	30	-	-	-	-	80
	IAF	-	12	-	-	-	-	-	60
	IAFm	40	130	10	-	-	-	-	180
	IBB	80	140	20	-	-	20	-	260
	IBF	270	720	30	-	10	-	10	1040
Sewage treatment	SCW	232	142	6	-	-	-	-	380
	SCD	38	6	62	-	-	3	1	114
	SDW	160	66	16	-	46	-	-	288
	SDD	12	-	-	-	-	-	-	12
Landfill	LW	208	138	22	12	8	12	12	412
Intermediate treatment	RE	116	21	2	-	1	2	-	142
	RF	5	1	850	-	-	-	-	856
	RG	497	32	4	-	-	-	-	533
	RH	309	1	2	-	-	-	-	312

[(1)] PP: polypropylene. [(2)] PE: polyethylene. [(3)] PET: polyethylene terephthalate. [(4)] PVC: polyvinyl chloride. [(5)] PU: polyurethane. [(6)] PA: polyamide. [(7)] PMMA: polymethyl methacrylate.

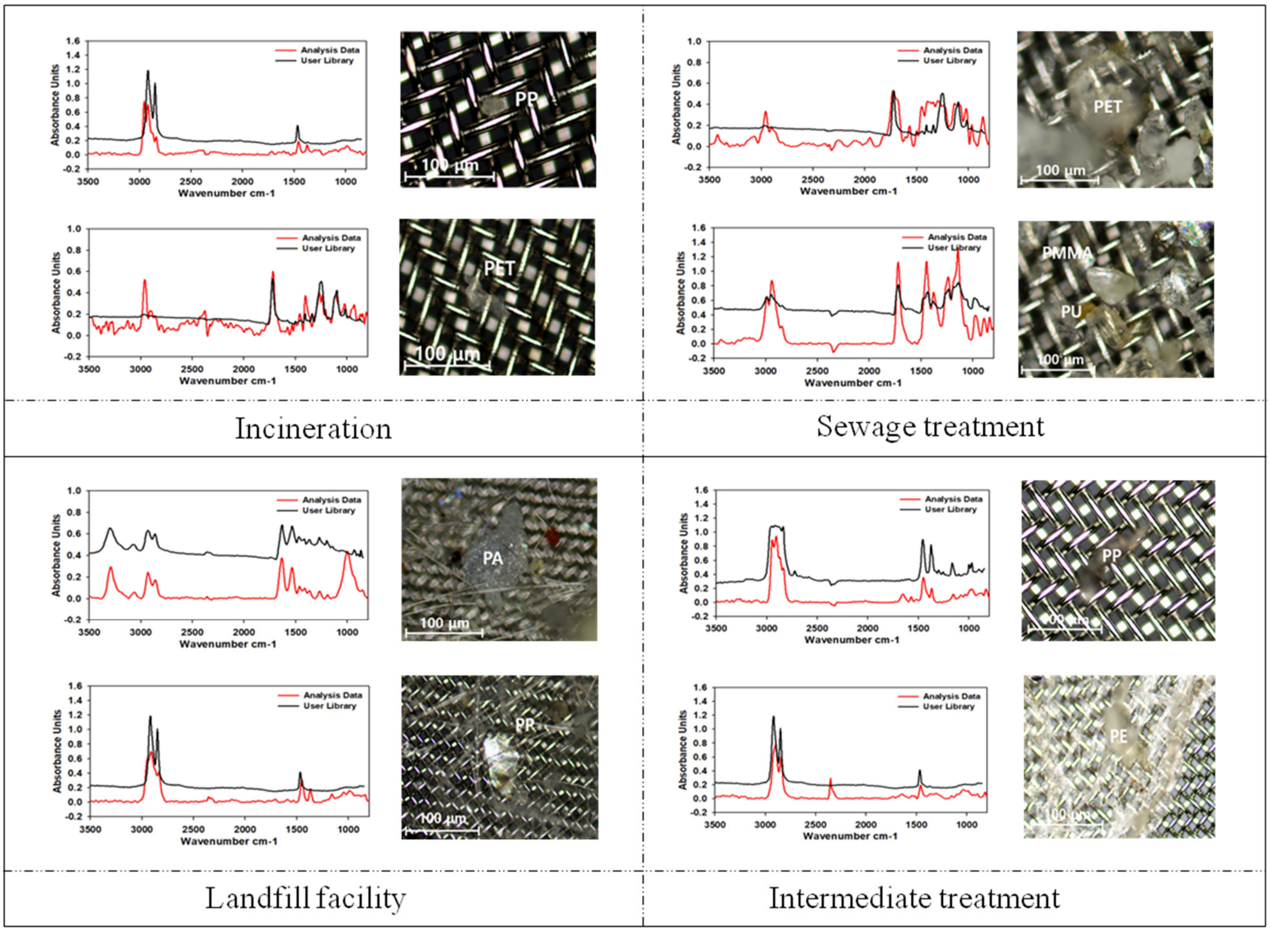

Figure 3. FT−IR spectrum and image of MPs.

Table 3. Abundance of MPs in various suspected contamination areas.

	Location	Particle	Plastic Type	Abundance Range	References
Incineration	Seoul, Korea Wuhan, China Eight different cities in China	<5 mm <5 mm 50 um–1 mm	PA, PE, PET, PMMA, PP, PU PA, PE, PMMA, PP, PS, PVC PE, PET, PP, PS, ABS	60–1040 ea/g 11.2 ± 0.5 ea/g 0.6 ± 0.2 ea/g	This paper [56] [45]
Sewage treatment	Seoul and Busan, Korea Northern Italy Oldenburg and Holdorf, Germany 11 provinces of China	<5 mm 10 um–5 mm <500 um 37 um–5 mm	PA, PE, PET, PMMA, PP, PU AN, PE, PET PE, PET, PP PA, PE, PO, PS	12–380 ea/g 113 ea/g 1–24 ea/g 1.6–56.4 ea/g	This paper [58] [59] [57]
Landfill	Incheon, Korea Shanghai, China 11 landfill sites in Thailand	<5 mm 0.23–4.97 mm <330 um	PA, PE, PET, PMMA, PP, PU, PVC EPM, PE, PEUR, PP, PS PE, PET, PP	420 ea/g 20–91 ea/g 0.1–2.3 ea/g	This paper [62] [60]
Coastal soil	Shandong, China	<5 mm	PE, PEU, PP, PS	<0.1–14.7 ea/g	[28]
Floodplain soil	Swiss	<5 mm	PE, PP, PS, PVC	0.59 ea/g	[24]
Typical soil	Beijing, Shandong, and Xinjiang, China	<5 mm	PA, PE, PP, PS, UF	18.3–40.2 ea/g	[23]
River	Beijing, China Seoul, Korea	<2 mm 0.1–5 mm	PE, PET, PP, PS PE, PFTE, PTEE	0.1–0.6 ea/g 0–234.5 ea/m^3, 1–48 ea/fish	[27] [22]
Coastal	South India Southeast Iran Xiangshan Bay, China	0.3–6.7 mm 0–4.75 mm <330 um	PET, PTFE, PVE, PVDF PE, PET, PTE RY, PE, PET, PP, PS, PVC	Wet sediment 0.1–1.6 ea/g, Dry sand < 0.1–1.5 ea/g 0.2 ea/g Water 0.17 ea/m^3, Sediment 0.1 ea/g	[25] [21] [26]
Airborne	Beijing, Tianjin, Shanghai, Nanjing, and Hangzhou, China	<0.1–9.6 mm	RY, PAA, PAN, PE, PES, PET	Northern 358 ± 132 ea/m^3, Southeast 230 ± 94 ea/m^3	[29]

4. Theoretical Strategy for Effective Management of MPs

To minimize the impact of MPs on the surrounding environment from the circular system (Figure 1) encompassing plastic product manufacturing and waste treatment, three key measures should be implemented. First, the input of plastic raw materials (MF-1) should be reduced; this can be achieved by maximizing recycling systems to reduce landfilling and using plastic alternatives or minimizing production volumes to reduce the total amount of plastic within the circular system.

Second, microplastic leakage (MF-7) from the circular system into the environment should be curbed. For example, generated MPs may leak from the system during production. During consumption and discharge, MPs may leak when products comprising or containing them are dumped by users or disposed of illegally or unintentionally. In the disposal phase, the current processing system often overlooks MP management, leading to unintentional losses due to inadequate MP processing methods, facility limitations, and lack of management awareness.

Third, a strategic plan to effectively manage MPs within the circular system must be enforced. To this end, certain wastes or waste products impacting MPs were categorized as MP waste (MPW). The concept of MPW was applied to each part of the circular system, as shown in Table 4. During production, specific plastic manufacturing processes with high MP generation rates are targeted; waste from the processes is denoted as MPW-1. The consumption and discharge phases target specific products that comprise, contain, or exhibit a high potential to generate MPs. Moreover, MPW-2 is defined as the state in which such products are disposed of after use. During disposal, dedicated landfill facilities manage MPW-1 and MPW-2 separately from general waste, as shown in Figure 4. Waste managed at dedicated landfill facilities is referred to as MPW-3. For incinerators, sewage treatment plants, and intermediate treatment plants, regular MP analysis should be monitored to determine the extent of MP contamination. If MP levels exceed a certain threshold, the waste should be transferred to a dedicated landfill facility for disposal. If monitoring at a general landfill facility reveals high MP content, a separate treatment method for MP management should be considered, or the establishment of a dedicated management facility should be considered.

Table 4. Applying the concept of MPW to each part of the circular system.

Circular System	Range	Related Factors		Type of MPW
		Material Factor (MF)	Causative Area (CA)	
Production	• Field: production field of plastic product • Input: raw material and recyclable waste • Output: manufactured plastic products and waste generated during production	MF-1, MF-2, MF-3, MF-6, and MF-7	CA-1	During production, waste from specific plastic manufacturing processes with high MP generation rates is denoted as MPW-1.
Consumption and Discharge	• Field: consumption and discharge fields of plastic product • Input: manufactured plastic product • Output: discarded plastic product	MF-2, MF-4, and MF-7	CA-2	MPW-2 is defined as the state in which specific products are disposed of after use; such products comprise, contain, or exhibit a high potential to generate MPs.
Disposal	• Field: disposal field of waste or waste product • Input: waste generated during production, discarded plastic products, and sewage • Output: recyclable waste	MF-3, MF-4, MF-5, MF-6, and MF-7	CA-3	Waste, including MPW-1 and MPW-2, managed at dedicated landfill facilities is referred to as MPW-3.

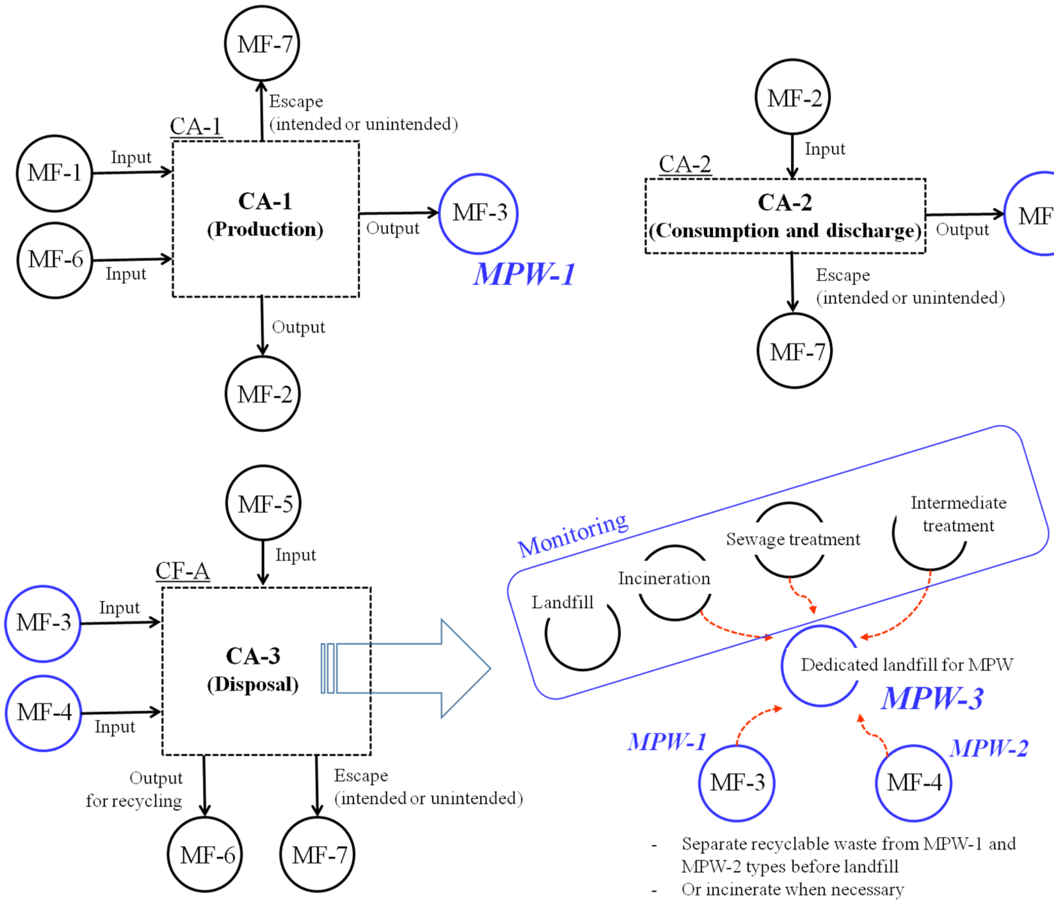

Figure 4. Flows of MPW-1, MPW-2, and MPW-3 in each part of the circular system. The red rotted arrows indicate "landfilled".

5. Applying the Theoretical Strategy: A Case Study in South Korea

As a case study, the theoretical strategy associated with the MPW concept presented in Section 4 was applied to the Korean waste management system to confirm the feasibility of the MP management approach in a circular system. To apply MPW-1, a total of three separate steps can be implemented (Figure 5). First, the industries that intentionally and directly produce MPs are identified, including those with high waste plastic emissions and specific MP-generating processes (e.g., shredding, grinding, and cutting). To achieve this, the Korean Standard Industrial Classification, which categorizes and codes industrial activities for all companies in South Korea according to their nature and can be uniformly applied to compile various industry-related statistics, can be used [67]. Korean industrial sectors are categorized in the classification table as sections (21 types), divisions (77 types), groups (232 types), classes (495 types), and sub-classes (1196 types), with the industrial sectors generating MPW-1 also identified in this table. In the second step, the waste types generated by the industries identified in the first step are determined using the “List of Waste Types” stipulated in the Korean Wastes Control Act [68]. In the third step, data from the first and second steps are used to provide industry guidelines and determine waste types defined as MPW-1.

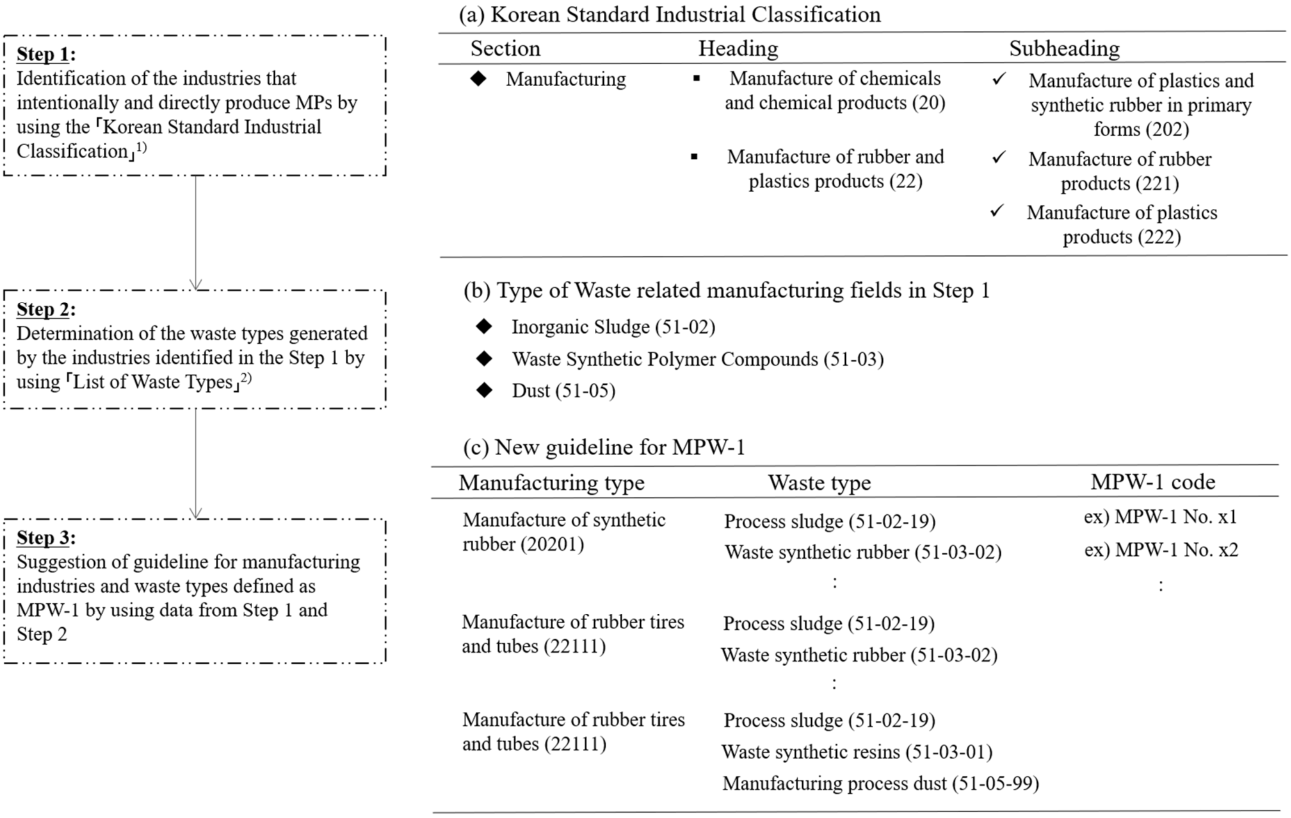

Figure 5. Implementation of three separate steps for applying MPW-1 in the Korean waste management system.

MPW-2 can be categorized into three waste product types: waste products containing MPs, those composed of MPs, and those with a potentially high incidence of MPs (the products categorized into each type are described in Section 3.1). Therefore, it is necessary to list the waste products for each of the three MPW-2 types and provide guidelines for separating them from other waste products during discharge [69]. Figure 6 presents the flow chart from waste discharge to treatment, illustrating the route for MPW-2-type waste separation and discharge to an MPW-dedicated landfill facility. If MPW-2 types are recyclable or more suited to incineration, they may be exempt from MPW-dedicated landfills.

To effectively manage MPs in landfills, several factors should be considered. First, the decomposition of buried MPs must be accelerated. Typically, plastic in the surroundings decomposes through a process from aerobic biodegradation of organic waste to methane fermentation [46,47,70]. Taking this into account, using various indigenous microorganisms, such as bacteria and fungi, can help accelerate MP degradation [71–75]. Second, MP-specific filtration must be installed to prevent MPs from escaping through leachate treatment facilities [46,76]. Third, various physical sorting techniques, including flotation, air flotation, and magnetic separation using hydrophobic Fe nanoparticles, should be applied to separate and recover MPs [77–85]. Recovered MPs can be reused as a plastic raw material or converted into hydrocarbon feeds through thermochemical processing techniques or as an adsorbent for polyaromatic hydrocarbons and heavy metals [86–90]. In South Korea, over 300,000 tons of waste plastics are sent to landfills annually [91]. As shown in Table 2, a substantial amount of MPs will be generated in landfills over time due to weather (e.g., wind, rain, and snow), seasonal changes, and diverse waste types [46,47]. Furthermore, all landfills have the risk of leakage as they do not account for MPs [92]. Hence, monitoring is required to determine MP contamination levels, and, if necessary, facilities should be reinforced for MP management. Most importantly, implementing dedicated MP management landfills is crucial.

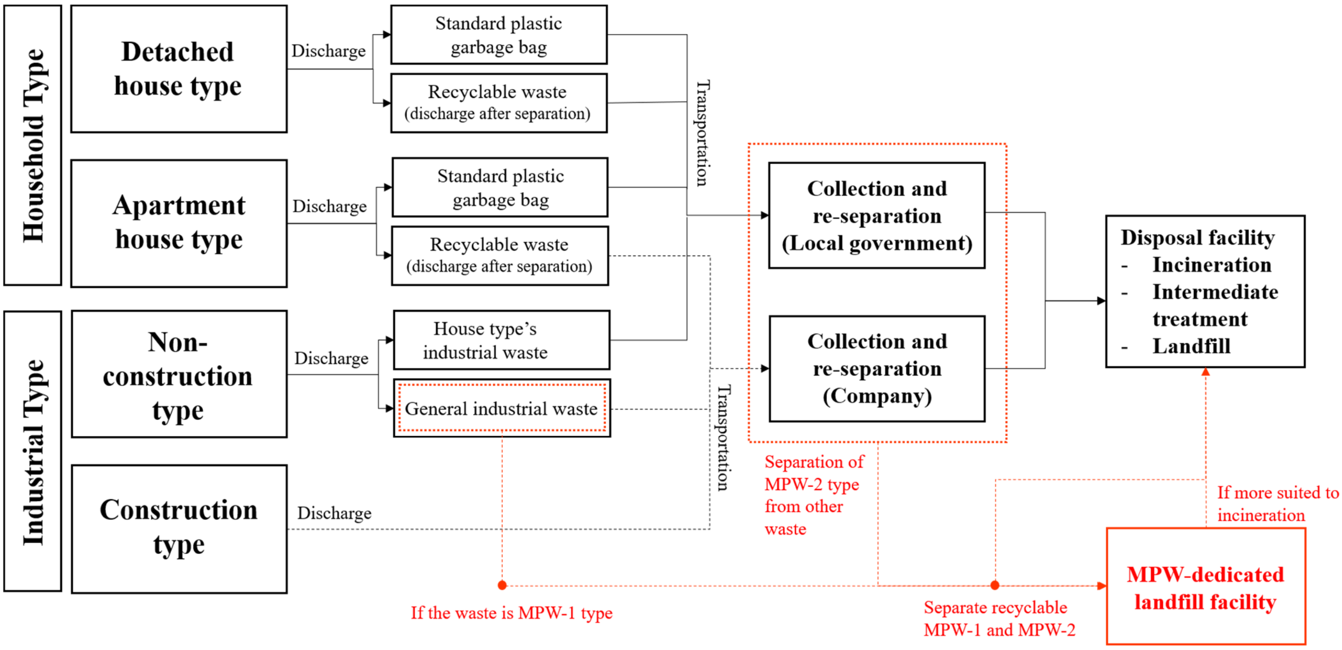

Figure 6. Illustration of the route for MPW-2 type waste separation and discharge to an MPW-dedicated landfill facility.

6. Conclusions

There is still considerable debate regarding the direct impact of MPs on human health. Because plastics are generally inert, the mechanisms underlying their absorption into animals or humans are difficult to determine. Moreover, indications suggest that overall environmental contamination from plastic dust remains relatively low. However, the urgency of addressing MPs is underscored by several factors, which does not exempt them from the general rules: Large amounts of plastics in the environment contribute to their continued generation; the additives used in plastic product manufacturing are extractable and toxic chemicals; MPs can become contaminated by their surroundings and turn into a source of pollution if present in the environment improperly; MPs can gradually enter leachate after landfilling and affect groundwater; and inhalation of MPs can cause lung disease. Considering these factors, a new national MP management system is necessary. This may include institutionalizing MP management, establishing new regulations, improving existing versions to prevent MP release into the environment, and identifying and controlling MP sources. To this end, the present study explored a new policy framework to manage MPs effectively in the circular system, from plastic product manufacturing to waste treatment. We proposed a theoretical strategy to establish a management system for MPs and confirmed its feasibility through its application to the Korean waste management system. Notably, tracking MPs throughout the circular system facilitates effective MP management in waste management systems. Governments, industry managers, and researchers in other countries can use this theoretical approach to evaluate and modify their own management systems as necessary.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su162210054/s1, Figure S1: Waste treatment facilities with incineration, sewage treatment, landfill, and intermediate treatment; Figure S2: Particle mapping and MP compound analysis of FT-IR (LUMOS II, Bruker, USA); Table S1: Weighing the samples according to waste type; Table S2: Density values for each major plastic type; Table S3: Specific gravity of general reagents for density separation; Table S4: Characteristics of filter papers according to filtration type; Table S5: Conditions of each general solution type used for organic decomposition; Table S6. Average and standard deviations of the data determined in triplicate.

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