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Review

Occurrence and Removal of Microplastics in Wastewater Treatment Plants: Perspectives on Shape, Type, and Density

Khumbelo Mabadahanye, Mwazvita T. B. Dalu and Tatenda Dalu *

School of Biology and Environmental Sciences, University of Mpumalanga, Nelspruit 1200, South Africa; mabadahanyek@gmail.com (K.M.); smazvita@gmail.com (M.T.B.D.)

* Correspondence: dalutatenda@yahoo.co.uk

Abstract: Microplastic (MP) contamination has grown to be a serious environmental issue in recent years. Microplastics are plastic particles, with a size of less than 5 mm, that are either produced specifically for use in a variety of products or emerge through the decomposition of larger plastic items. Data from prior research conducted in wastewater treatment plants (WWTPs) regarding the abundances of microplastics across different treatment stages of WWTPs in different countries were compiled using online scientific databases. This research found that although Turkey only managed to attain a removal rate of 48.0%, Iran and the United States were able to reach removal rates of over 90.0%. It was discovered that two plants in Morocco had relatively high removal efficiencies, with one achieving a remarkable 74.0% removal rate and the other an 87.0% removal rate. The predominance of fibers and fragments in the influent and effluent across all studied locations shows the difficulty in effectively removing them from wastewater. The widespread abundance of microplastic polymers from diverse sources poses a significant challenge for wastewater treatment facilities in efficiently managing and eliminating these pollutants. This research further demonstrated regional differences in the color composition of microplastics, with black, transparent, blue, and red being prominent colors in the influent and effluent of some regions. These color variations can influence the detection and identification processes, which are crucial for developing targeted removal strategies. In conclusion, it is essential to address the pervasiveness of microplastics in wastewater treatment plants. Improving treatment procedures, protecting the ecosystem, and conserving water quality for a sustainable future all depend on addressing the various sources of these contaminants.

Keywords: WWTPs; microplastics; influent; effluent; abundances

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1. Introduction

Every day, there is a greater risk of plastic pollution harming the environment [1]. Plastic products and materials are widely employed in both industry and daily life. China (30.0%), Europe (17.0%), and North America (18.0%) produce most of the raw materials used to make the nearly 360 million tons of plastic produced globally in 2018 [2]. Plastic output is anticipated to double by 2025 and quadruple by 2050 due to population growth, present plastic consumption, and waste [3]. According to Eerkes–Medrano et al. [4], plastic litter pollution is one of the most serious man–made hazards to the natural environment and is therefore a subject of growing concern. Due to their greater quantities and smaller sizes, microplastics are thought to be more common in the environment than macro– or mesoplastics [5]. Richard Thompson used the term "microplastics" in 2004 to refer to the very small plastic particles (less than 5 mm in size) that are found in surface waters and ocean sediment [6]. According to Estahbanati and Fahrenfeld [7], microplastics can either be produced accidentally by the breakdown of macroplastics (secondary MPs) or purposefully produced. Microplastics are a significant component of plastic pollution, which persists in the environment due to the extensive use of polymers, low recycling rates, and resistance to decomposition [1,8,9]. Microplastics are categorized into primary and secondary types.

Primary MPs are directly manufactured for various industrial and consumer applications, including packaging, vehicle construction, office equipment, personal care products, and air–blasting granules and pellets [10]. Secondary MPs result from the degradation of larger plastic items through biotic processes such as hydrolytic degradation, photolysis, weathering, UV radiation, and abrasion [11,12]. These MPs are predominantly composed of widely used plastic types such as polyethylene (PE), polypropylene (PP), polyester (PL), polyamide (PA), polystyrene (PS), and polyethylene terephthalate (PET), and have a high specific surface area that enhances their ability to adsorb contaminants [1,8]. They enter sewage systems primarily when plastic particles are discharged from garments during household washing and laundry due to synthetic fabric abrasion, and from personal care products [1,13]. Consequently, MPs are found in WWTPs and eventually in natural water bodies, posing risks to the environment and human health. Aquatic animals that consume microplastics may suffer from physical injuries including digestive tract obstructions and may be exposed to harmful compounds that are adsorbed on the MPs' surface. Heavy metals, persistent organic pollutants, and other dangerous chemicals are some of these substances [14]. Additionally, MPs can act as vectors for pathogens, further threatening aquatic life and potentially entering the human food chain through seafood consumption [15].

Wastewater treatment plants (WWTPs) play a crucial role in managing MP pollution. However, despite their significant capabilities, they still release a substantial number of MPs into the environment [16–18]. The MPs that enter WWTPs vary in polymer types, shapes, sizes, and colors [1]. Extensive research has been conducted on the detection and quantification of MPs in WWTP effluents and the removal efficiencies of these plants [16,19]. Although current technologies can remove large plastics from wastewater, they are not specifically designed to retain small MPs effectively [20]. Conventional WWTPs can achieve removal efficiencies of 64–99%, but this is insufficient given the volume of MPs discharged daily [21].

The purpose of this review is to thoroughly evaluate the prevalence, origins, disposition, and removal methods of MPs in wastewater treatment plants (WWTPs) in various global regions. This study aims to advance awareness of the difficulties and opportunities involved in managing microplastic pollution in WWTPs by synthesizing existing research and identifying knowledge gaps. Previous studies have focused on various aspects of microplastic removal in WWTPs, such as the efficiency of different treatment processes (primary, secondary, and tertiary treatments), the impact of operational parameters, and the fate of microplastics in sludge. However, significant gaps remain, particularly in understanding the long–term effectiveness of different removal technologies, the behavior of microplastics under different conditions, and the development of standardized methods for microplastic quantification and characterization in WWTPs.

2. Materials and Methods

The methodology used for this review, which examined the levels of microplastics in WWTPs, was produced to give a systematic and in–depth analysis of previous work. An internet search of mostly journal databases such as Google Scholar, Springer, ScienceDirect, Frontiers, and important institutional websites was used to compile the data [22]. A variety of keywords, including "microplastics", "WWTPs", and "prevalences and abundances", were used in the initial searches. A search was restricted to peer–reviewed articles from research written in English and published between 2015 and 2023. A total of 132 articles were screened, and 41 articles were used. Information about MP pollution, WWTPs, microplastic concentrations, microplastic per liter (MP/L), removal rates, types of microplastics, polymer types, and colors in the influents and effluents of WWTPs was extracted.

3. Results

3.1. Abundances of Microplastics and Removal Rates

The study found that Spain and Lithuania had high concentrations of MPs in the influent, with values of −796.05 MP/L and −2473 MP/L, respectively. In the effluent, the concentrations of MPs decreased to −994 MP/L and −38.55 MP/L. However, Iran was found to have low concentrations of MPs in the effluent, with 5.3 MP/L compared to Spain, while Thailand had low concentrations of MPs in both the influent and effluent with values of 0.4 MP/L and 0.05 MP/L (Table 1). Our analysis showed that the water treatment plants in Iran had high MP removal rates, with 99.1% of the MPs being removed from the influent. Treatment plants in Turkey only had a 48% MP removal rate, which suggests improvement is needed. The removal rate was unusually low in Lithuania, with high MP abundance, which was an interesting phenomenon given the country's significant microplastic contamination. The data show that MPs have been significantly removed in Morocco. In the first plant, influent concentration dropped from 188 MP/L to 50 MP/L, indicating a 74% removal rate. The second plant showed better performance, attaining an 87% removal rate where influent concentrations decreased from 519 MP/L to 86 MP/L (see Table 1).

Table 1. The abundance of microplastics in the influent and effluent and the removal rate of WWTPs in different countries in microplastic per liter (MP/L).

Location	WWTPs Unit	Influent (MP/L)	Effluent (MP/L)	Removal Rates (%)	References
China, Zhengzhou	Primary sedimentation, secondary sedimentation, filtration pool, dewatering	16.0	2.9	81.9	Ren et al. [23]
Finland	Screening, grit separation, primary clarification, biological treatment with activated sludge, final sedimentation, and disinfection	57.6	1.0	98.3	Lares et al. [24]
Iran, South of Tehran	Inlet, outlet, and anaerobic digested sludge	180.0	5.3	99.06	Oveisy et al. [25]
Iran, Sari City	Secondary settling tank	206.0	94.0	54.4	Yahynezhad et al. [26]
Kuwait	Reverse osmosis and ultrafiltration membranes, aeration tanks	120	1.5	98.8	Uddin et al. [27]
Kuwait	Oxidation ditch system, sand filtration, UV treatment, chlorination	226.5	11.5	94.9	Uddin et al. [27]
Kuwait	Vertically activated sludge process for biological treatment, Distributed Control system technology	132.0	5.0	96.2	Uddin et al. [27]
Lithuania	Screening, grit chambers, sedimentation tanks, aeration tanks, sludge dewatering system, nitrogen and phosphorus removal	2473 MP/L	994.0 MP/L	57.0	Uoginte et al. [28]
Morocco	Sedimentation, infiltration percolation, UV disinfection	188.0	50.0	74.0	Hajji et al. [29]
Morocco	Activated sludge treatment, aeration tanks, clarification tanks, mechanical filtration	519.0	86.0	87.0	Hajji et al. [29]
Spain, Chiclana de la Frontera	Pretreatment (grease trap, grit chamber, several screens), primary clarifiers, simultaneous nitrification and denitrification in a bioreactor, secondary clarifiers, anoxic tank, anaerobic digestion to treat solid fraction	796.1 MP/L	38.6 MP/L	84.0	Franco et al. [30]
Thailand	Equalization tank, grit chamber, aeration tanks, sedimentation tanks, sludge dewatering	0.4 MP/L	0.1 MP/L	86.5	Maw et al. [31]
Turkey	Screening, ventilated sand and an oil chamber, preliminary sediment tank biological and chemical phosphorus removal units, aeration tanks, and final sediment tank	3.1 MP/L	1.6 MP/L	48.0	Akarsu et al. [32]
Turkey	Screening, preliminary sediment, aeration tanks, and final sediment tanks	2.6 MP/L 1.5 MP/L	0.7 MP/L 0.6 MP/L	78.0 60.0	Akarsu et al. [32]
United Kingdom, East Midlands	Primary settlement, activated biological anoxic treatment, activated biological aerobic treatment	–	1.5 MP/L	–	Tagg et al. [33]
USA, South Caroline	Primary screening, primary clarifiers, activated sludge, secondary clarifiers, sludge handling, dewatering (rotary press), disinfection	2.5 MP/L	15.5 MP/L	97.6, 85.2, 85.5	Conley et al. [34]

3.2. Microplastic Types

Fibers and fragments were the most prevalent types of plastic pollution observed in influents and effluents in various global regions. For instance, plastic fibers make up over 70.0% of the influent and 68.0% of the effluent in Jakarta, Indonesia, while fragments make up ~24% of the influent and 26.0% of the effluent. Location affects how plastic contaminants in the influent are composed. Granules make up roughly 49.8% of the influent and 36.0% of the effluent in Xiamen, China, while microbeads make up roughly 1.0% of the influent and 2.0% of the effluent in Jakarta, Indonesia. Local elements and the sources of plastic waste in these areas, along with microplastics originating from remote areas through atmospheric deposition, are the main sources for these variations [35]. Large plastic objects like granules, pellets, and films are frequently reduced in quantity by wastewater treatment procedures. For instance, in Turkey, there is a little decrease in the percentage of plastic fibers from 87.7% in the influent to 86.5% in the effluent. The amount of small plastic fibers and fragments in the effluent after treatment usually remains constant or may even increase. For instance, in Korea, the fragment content significantly increased from 68.2% in the influent to 82.3% in the effluent. In South Tehran, Iran, plastic fragments increased slightly from 0.19% in the influent to 0.7% in the effluent, whereas in Korea, the fragments increased significantly from 68.2% in the influent to 82.3% in the effluent (Table 2).

Table 2. Types of microplastic found in the influent and effluent of WWTPs in different countries.

Location	Influent	Effluent	References
China, Xiamen	Pellet (2.5%), Fibers (17.7%), Fragments (30.0%), Granules (49.8%)	Pellet (5.6%), Fibers (30.4%), Fragments (28.0%), Granules (36.0%)	Long et al. [36]
Indonesia, Jakarta	Fibers (70.0%), Fragments (24.0%), Microbeads (1.0%), Film (3.0%), Foam (2%)	Fibers (68%), Fragments (26.0%), Microbeads (2.0%), Film (1.0%), Foam (3.0%)	Setiadewi et al. [37]
Iran, South of Tehran	Fibers (99.4%), Fragments (0.2%), Film (0.4%)	Fibers (98.95%), Fragments (0.7%), Film (0.3%)	Oveisy et al. [24]
Korea	Fragments (68.2%), Fibers (31.8%)	Fragments (82.3%), Fibers (17.7%)	Park et al. [38]
Iran, Sari City	Fibers (35.0%), Pellets (39.0%), Fragments (22.0%)	Fibers (34.0%), Pellets (22.0%), Fragments (38.0%)	Yahyanezhad et al. [26]
Turkey	Fibers (54.8%), Film (18.5%), Fragments (26.8%)	Fibers (44.4%), Film (30.2%), Fragments (25.4%)	Gundogdu et al. [39]
Turkey	Fibers (87.7%), Film (2.4%), Fragments (10.0%)	Fibers (86.5%), Film (2.5%), Fragments (10.8%)	Gundogdu et al. [39]
United States	–	Fibers (59.0%), Fragments (33.0%), Films (5.0%), Forms (2.0%), Pellets (1.0%)	Mason et al. [40]

3.3. Polymer Types

Region–specific variations in plastic waste composition and treatment effectiveness are highlighted by the many major polymer types that are present in different countries (Table 3). In several places, including Changzhou, China, and Turkey, polyethylene terephthalate (PET) is a predominant polymer type in both the influent and effluent. When compared to the influent, polypropylene (PP) dominates the effluent in Korea (63.3%), while the influent PP was 39.6%. Another important kind of polymer to consider is polyethylene (PE), which is present in both the influent and effluent in different countries. PE is persistent in the environment, as evidenced by its presence in the influent and effluent from different regions. Although PE is constantly present, the amount of it might fluctuate depending on the area and how well wastewater treatment systems remove it. The overall microplastic pollution in sewage systems is mostly caused by PE, along with other important polymers including PET and PP.

Table 3. Distribution of polymer types in the influent and effluent of WWTPs in different countries by percentages.

Location	Influent	Effluent	References
China, Changzhou	Rayon (41.8%), PET (27.6%), PP (15.52%), PE (6.1%), PS (3.4%), PE–PP (2.1%)	Rayon (43.5%), PET (29.2%), PP (14.5%), PE (6.28%), PS (2.12%), PE–PP (1.51%)	Xu et al. [19]
China, Xiamen	PE (26.9%), PP (30.2%), PS (10.3%), PE + PP (6.3%), PP + PE (5.1%), PES (3.3%), PET (7.5%), PA (9.9%)	PE (17.9 %), PP (34.8 %), PS (9.6%), PE + PP (4.7%), PP + PE (13.9%), PES (1.1%), PET (7.5%), PA (10.1%)	Long et al. [36]
Korea	PP (39.6%), PE (25.6%), PET (21.3%)	PP (63.3%), PE (13.8%), PET (13.3%)	Park et al. [38]
South Africa, Gauteng	–	PVC (47.8%), PET (17.4%), PA (13.1%), PE (4.3%)	Vilakati et al. [41]
Turkey	PE (29.2%), PET (50.8%), PP (13.8%)	PE (31.3%), Nylon–6 (6.3%), PET (43.8%), PP (18.8%)	Gundogdu et al. [39]
Turkey	PE (23.8%), PET (61.9%), PP (11.9%)	PE (18.8%), PET (68.8%), PP (12.5%)	Gundogdu et al. [39]

Notes: Abbreviations: Polypropylene (PP), Polyethylene (PE), Polystyrene (PS), Blend of Polyethylene and Polypropylene (PE + PP), Polyethylene Terephthalate (PET), Polyether Sulfone (PES), Polyamide (PA), Polyvinyl Chloride (PVC).

3.4. Microplastic Colors

Microplastics exhibit a wide range of colors influenced by environmental factors such as consumer habits, industrial activities, waste disposal methods, and local environmental conditions. Black and transparent MPs appear to be predominant in the influent and effluent across several studied locations, including China, Indonesia, and Iran. According to the collected data, black and transparent plastics are extensively used in various products and contribute significantly to microplastic pollution in these countries. White MPs dominate in Xiamen, China, and Thailand, comprising a substantial portion of MP composition in these regions. Additionally, red and blue MPs are notable in several areas, such as Indonesia, Iran, China, and Thailand, serving as potential indicators of MP sources (Table 4).

Table 4. Distribution of microplastic colors in the influent and effluent of WWTPs in different countries by percentages.

Location	Influent	Effluent	References
Beijing, China	–	Black (36.6%), Transparent (33.8%), Blue (11.9%)	Yang et al. [42]
Xiamen, China	Black (5.8%), Yellow (8.1%), Red (9.8%), Blue (9.1%), Green (12.1%), White (35.5%), Clear (19.6%)	Black (9.3%), Yellow (5.1%), Red (10.1%), Blue (8.0%), Green (17.2%), White (30.4%), Clear (19.9%)	Long et al. [36]
Jakarta, Indonesia	Transparent (36.0%), Blue (10.0%), Red (22.0%), Brown (3.0%), Green (1.0%), Yellow (2.0%), Black (26.0%)	Transparent (35.0%), Blue (13.0%), Red (21.0%), Brown (6.0%), Green (3.0%), Yellow (5.0%), Black (17.0%)	Setiadewi et al. [37]
South of Tehran, Iran	Transparent (69.8%), Red (5.3%), Blue (9.2%), Brown (0.3%), Gray (0.1%), Orange (0.4%), Yellow (0.3%), Green (1.1%), Black (13.3%)	Transparent (67.5%), Red (6%), Blue (6.574%), Black (17.6%), Green (1.3%), Brown (0.2%), Gray (0.2%), Orange (0.5%), Yellow (0.4%)	Oveisy et al. [24]
Thailand	–	White (57.0%), Blue (17.0%), Red (13.0%), Brown (8.0%), Black (5.0%)	Maw et al. [31]

4. Discussion

The investigation of MPs s in wastewater treatment plants (WWTPs) reveals that their presence in influent and effluent streams is influenced by various factors including the type and origin of microplastics, treatment processes used, the effectiveness of the removal technologies used in the WWTPs, and environmental conditions. Our analysis indicates significant microplastic contamination in influent waters, with varying levels of abundance observed across different geographical areas and WWTP types. Wastewater treatment plants in urban areas tend to have higher concentrations of MPs compared to those in rural areas, likely due to higher population density and greater industrial activities. This results in increased MP inputs from household wastewater, runoff, and industries [32]. The analysis further revealed that the success rate of WWTPs in reducing MP pollution varies significantly depending on the treatment methods employed. For instance, WWTPs in Finland, Iran, and Spain which use comprehensive treatment units, including grit separation, screening, biological treatment, sedimentation, and disinfection, exhibited removal rates ranging from 84.0% to 98.3%. This contrasts with WWTPs in Turkey, where simpler treatment designs showed lower removal rates between 48.0% and 78.0%. These findings show the importance of advanced and multi–stage treatment processes in enhancing the removal efficiency of MPs. Based on our analysis, a considerable number of MPs still persist in the effluent although the total concentration of MPs can be greatly decreased by WWTPs. Despite mechanical, chemical, and biological treatments achieving up to 99.0% MP removal, the remaining MPs in the effluent still pose environmental risks [43,44].

Primary and secondary treatment stages are crucial in the elimination of MPs. Murphy et al. [45] and Nafea et al. [46] found that 80.0–90.0% of MPs are removed during these stages. Heavier MPs are eliminated by sedimentation during primary treatment, while lighter MPs are skimmed off with fats, oils, and grease. Screening techniques are effective in removing solid particles, anticipating a removal of 50.0–70.0% of total suspended solids [47]. During secondary treatment, MPs may be biodegraded by bacteria and microorganisms. However, some studies report less than 90.0% removal efficiency [11,48]. Tertiary treatment technologies, such as biological aerated filters and gravity sand filtration, have shown varying levels of effectiveness in removing MPs [20,44].

Our analysis also noted the prevalence of fibers and fragments as the dominant types of MPs in both influent and effluent streams. The high presence of synthetic fibers, particularly polyester microfibers, is attributed to their extensive use in textiles and household products. These fibers are challenging to remove due to their flat surfaces and large length–to–width ratios, which make them difficult to capture during treatment processes [49]. As people wear more clothing in the winter than in the summer, Browne et al. [50] predicted that more microfibers would enter WWTPs during the winter.

The analysis of polymer types revealed that PP, PE, and PET are the most common in both influent and effluent streams. The widespread use of these polymers in household and industrial products explains their prevalence. For example, PET is commonly found in water bottles, food packaging, and synthetic clothing, contributing to its high presence in wastewater [51]. The color analysis of MPs provided insights into their potential sources. Transparent, white, black, red, and blue MPs were dominant, reflecting their diverse origins from industrial raw materials, personal care items, and household products [52]. Understanding the sources and behavior of these MPs is crucial for improving treatment designs and enhancing removal efficiency.

5. Conclusions

The data gathered from various regions about MPs in WWTPs show a diverse and varied situation. Various WWTPs use different treatment methods, exhibiting a broad variety of removal rates and efficiencies. Certain WWTPs, such as those in Finland, Iran, and Spain, demonstrate remarkable removal rates surpassing 98%, but other WWTPs such as one in Turkey struggle to efficiently reduce microplastic concentrations. In Iran and

Spain, effective removal is attributed to comprehensive inlet and outlet treatments along with anaerobic digested sludge, resulting in rates of 99% and 84%, respectively. These methods likely succeed due to their integrated approach combining physical, biological, and chemical processes adapted to local environmental conditions, contributing significantly to reducing microplastic pollution. Different MP types such as fibers, pieces, films, and pellets are found in different regions, which reflect regional differences in industrial activities and consumption patterns. Additional complexity is added by the existence of various polymers, including PS, PP, PE, and PET. The observed geographic variability highlights the impact of regional influences on the profiles of MPs. The environmental damage is further compounded by the colors of MPs, which range from translucent to blue and white to black. To further reduce the amount of microplastics in WWTP effluents, our review emphasizes the need for ongoing research into the efficiency of various treatment systems. The data also highlight areas for further investigation, such as missing data on color profiles and removal rates. To tackle the worldwide problem of MP pollution, continuous investigation and the creation of focused reduction plans according to the various obstacles presented by MP compositions in various areas are necessary.

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References

1. Acarer, S. Abundance and characteristics of microplastics in drinking water treatment plants, distribution systems, water from refill kiosks, tap waters and bottled waters. *Sci. Total Environ.* **2023**, *888*, 163866. [CrossRef]
2. Li, W.; Wang, S.; Wufuer, R.; Duo, J.; Pan, X. Microplastic Contamination in Urban, Farmland and Desert Environments along a Highway in Southern Xinjiang, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 8890. [CrossRef]
3. Freeman, S.; Booth, A.M.; Sabbah, I.; Tiller, R.; Dierking, J.; Klun, K.; Rotter, A.; BenDavid, E.; Javidpour, J.; Angel, D.L. Between source and sea: The role of wastewater treatment in reducing marine microplastics. *J. Environ. Manag.* **2020**, *266*, 110642. [CrossRef]
4. Eerkes–Medrano, D.; Thompson, R.C.; Aldridge, D.C. Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Res.* **2015**, *75*, 63–82. [CrossRef] [PubMed]
5. Karbalaei, S.; Hanachi, P.; Walker, T.R.; Cole, M. Occurrence, sources, human health impacts and mitigation of microplastic pollution. *Environ. Sci. Pollut. Res.* **2018**, *25*, 36046–36063. [CrossRef] [PubMed]
6. Thompson, R.C.; Olsen, Y.; Mitchell, R.P.; Davis, A.; Rowland, S.J.; John, A.W.; McGonigle, D.; Russell, A.E. Lost at Sea: Where is all the plastic? *Science* **2004**, *304*, 838. [CrossRef]
7. Estahbanati, S.; Fahrenfeld, N.L. Influence of wastewater treatment plant discharges on microplastic concentrations in surface water. *Chemosphere* **2016**, *162*, 277–284. [CrossRef] [PubMed]
8. Liu, W.; Zhang, J.; Liu, H.; Guo, X.; Zhang, X.; Yao, X.; Cao, Z.; Zhang, T. A review of the removal of microplastics in global wastewater treatment plants: Characteristics and mechanisms. *Environ. Int.* **2021**, *146*, 106277. [CrossRef]
9. Dalu, T.; Banda, T.; Mutshekwa, T.; Munyai, L.F.; Cuthbert, R.N. Effects of urbanisation and a wastewater treatment plant on microplastic densities along a subtropical river system. *Environ. Sci. Pollut. Res.* **2021**, *28*, 36102–36111. [CrossRef]
10. Mani, T.; Hauk, A.; Walter, U.; Burkhardt-Holm, P. Microplastics profile along the Rhine River. *Sci. Rep.* **2015**, *5*, 17988. [CrossRef]
11. Ziajahromi, S.; Neale, P.A.; Rintoul, L.; Leusch, F.D. Wastewater treatment plants as a pathway for microplastics: Development of a new approach to sample wastewater–based microplastics. *Water Res.* **2017**, *112*, 93–99. [CrossRef]
12. Arhant, M.; Le Gall, M.; Le Gac, P.Y.; Davies, P. Impact of hydrolytic degradation on mechanical properties of PET–Towards an understanding of microplastics formation. *Polym. Degrad. Stab.* **2019**, *161*, 175–182. [CrossRef]
13. Iroegbu, A.O.C.; Sadiku, R.E.; Ray, S.S.; Hamam, Y. Plastics in municipal drinking water and wastewater treatment plant effluents: Challenges and opportunities for South Africa—A review. *Environ. Sci. Pollut. Res.* **2020**, *27*, 22271–22291. [CrossRef]

14. Rochman, C.M.; Hoh, E.; Kurobe, T.; Teh, S.J. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Sci. Rep.* **2013**, *3*, 3263. [CrossRef]
15. Setälä, O.; Fleming–Lehtinen, V.; Lehtiniemi, M. Ingestion and transfer of microplastics in the planktonic food web. *Environ. Pollut.* **2014**, *185*, 77–83. [CrossRef]
16. Turan, N.B.; Erkan, H.S.; Engin, G.O. Microplastics in wastewater treatment plants: Occurrence, fate and identification. *Process Saf. Environ. Prot.* **2021**, *146*, 77–84. [CrossRef]
17. Dalu, T.; Ngomane, N.; Dondofema, F.; Cuthbert, R.N. Water or sediment? Assessing seasonal microplastic accumulation from wastewater treatment works. *H2Open J.* **2023**, *6*, 88–104. [CrossRef]
18. Dalu, T.; Themba, N.N.; Dondofema, F.; Cuthbert, R.N. Nowhere to go! Microplastic abundances in freshwater fishes living near wastewater plants. *Environ. Toxicol. Pharmacol.* **2023**, *101*, 104210. [CrossRef]
19. Xu, X.; Jian, Y.; Xue, Y.; Hou, Q.; Wang, L. Microplastics in the wastewater treatment plants (WWTPs): Occurrence and removal. *Chemosphere* **2019**, *235*, 1089–1096. [CrossRef]
20. Mintenig, S.M.; Int-Veen, I.; Loder, M.G.J.; Primpke, S.; Gerdts, G. Identification of microplastic in effluents of wastewater treatment plants using focal plane array–based micro–Fourier–transform infrared imaging. *Water Res.* **2017**, *108*, 365–372. [CrossRef]
21. Franco, A.A.; Arellano, J.M.; Albendin, G.; Rodriguez-Barroso, R.; Quiroga, J.M.; Coello, M.D. Microplastic pollution in wastewater treatment plants in the city of C'adiz: Abundance, removal efficiency and presence in receiving water body. *Sci. Total Environ.* **2021**, *776*, 145795. [CrossRef]
22. Tang, K.H.O. Interaction of microplastics with Persistent organic pollutants and the ecotoxicological effects: A Review. *Trop. Aquat. Soil Pollut.* **2021**, *1*, 24–34. [CrossRef]
23. Ren, P.; Dou, M.; Wang, C.; Li, Q.; Jia, R. Abundance, and removal characteristics of microplastics at a wastewater treatment plant in Zhengzhou. *Environ. Sci. Pollut. Res.* **2020**, *27*, 36295–36305. [CrossRef] [PubMed]
24. Lares, M.; Ncibi, M.C.; Sillanpaa, M.; Sillanpaa, M. Occurrence, identification, and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. *Water Res.* **2018**, *133*, 236–246. [CrossRef] [PubMed]
25. Oveisy, N.; Rafiee, M.; Rahmatpour, A.; Nejad, A.S.; Hashemi, M.; Eslami, A. Occurrence, identification, and discharge of microplastics from effluent and sludge of the largest WWTP in Iran-South of Tehran. *Water Environ. Res.* **2020**, *94*, 10765. [CrossRef] [PubMed]
26. Yahyanezhad, N.; Bardi, M.J.; Aminirad, H. An evaluation of microplastics fate in the wastewater treatment plants: Frequency and removal of microplastics by microfiltration membrane. *Water Pract. Technol.* **2021**, *16*, 782–792. [CrossRef]
27. Uddin, S.; Behbehan, M.; Habibi, N.; Faizuddin, M.; AI-Murad, M.; Martinez-Guijarro, K.; AI-Sarawi, H.A.; Karam, Q. Microplastics in Kuwait's Wastewater Streams. *Sustainability* **2022**, *14*, 15817. [CrossRef]
28. Uogintė, I.; Pleskytė, S.; Pauraitė, J.; Lujanienė, G. Seasonal variation and complex analysis of microplastic distribution in different WWTP treatment stages in Lithuania. *Environ. Monitor. Assess.* **2022**, *194*, 829. [CrossRef] [PubMed]
29. Hajji, S.; Ben-Haddad, M.; Abelouah, M.R.; De-la-Torre, G.E.; Alla, A.A. Occurrence, characteristics and removal of microplastics in wastewater treatment plants located on the Moroccan Atlantic: The case of Agadir metropolis. *Sci. Total Environ.* **2023**, *862*, 160815. [CrossRef]
30. Franco, A.A.; Martín-García, A.P.; Egea-Corbacho, A.; Arellano, J.M.; Albendín, G.; Rodríguez–Barroso, R.; Quiroga, J.M.; Coello, M.D. Assessment and accumulation of microplastics in sewage sludge at wastewater treatment plants located in Cadiz, Spain. *Environ. Pollut.* **2023**, *317*, 120689. [CrossRef]
31. Maw, M.M.; Boontanon, N.; Fujii, S.; Boontanon, S.K. Rapid and efficient removal of organic matter from sewage sludge for extraction of microplastics. *Sci. Total Environ.* **2022**, *853*, 158642. [CrossRef] [PubMed]
32. Akarsu, C.; Kumbur, H.; Gokdag, K.; Kiddeys, A.E.; Sanchez-Vidal, A. Microplastics composition and load from three wastewater treatments discharging into Mersin Bay, north eastern Mediterranean Sea. *Mar. Pollut. Bull.* **2020**, *150*, 110776. [CrossRef] [PubMed]
33. Tagg, A.S.; Sapp, M.; Harrison, J.P.; Sinclair, C.J.; Bradley, E.; Ju-Nam, Y.; Ojeda, J.J. Microplastic Monitoring at Different Stages in a Wastewater Treatment Plant Using Reflectance Micro–FTIR Imaging. *Front. Environ. Sci.* **2020**, *8*, 145. [CrossRef]
34. Conley, K.; Clum, A.; Deepe, J.; Lane, H.; Beckingham, B. Wastewater treatment plants as a source of microplastics to an urban estuary: Removal efficiencies and loading per capita over one year. *Water Res. X* **2019**, *3*, 100030. [CrossRef] [PubMed]
35. Xiao, S.; Cui, Y.; Brahney, J.; Mahowald, N.M.; Li, Q. Long–distance atmospheric transport of microplastic fibres influenced by their shapes. *Nat. Geosci.* **2023**, *16*, 863–870. [CrossRef]
36. Long, Z.; Pan, Z.; Wang, W.; Ren, J.; Yu, X.; Lin, L.; Lin, H.; Chen, H.; Jin, X. Microplastic abundance, characteristics, and removal in wastewater treatment plants in a coastal city of China. *Water Res.* **2019**, *155*, 255–265. [CrossRef] [PubMed]
37. Setiadewi, N.; Henny, C.; Rohaningsih, D.; Waluyo, A.; Soewondo, P. Microplastic occurrence and characteristics in a municipal wastewater treatment plant In Jakarta. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1201*, 012053. [CrossRef]
38. Park, H.J.; Oh, M.J.; Kim, P.G.; Kim, G.; Jeong, D.H.; Ju, B.K.; Lee, W.S.; Chung, H.M.; Kang, H.J.; Kwon, J.H. National Reconnaissance Survey of Microplastics in Municipal Wastewater Treatment Plants in Korea. *Environ. Sci. Technol.* **2020**, *54*, 1503–1512. [CrossRef] [PubMed]
39. Gundogdum, S.; Cevik, C.; Guzel, E.; Kilercioglu, S. Microplastics in municipal wastewater treatment plants in Turkey: A comparison of the influent and secondary effluent concentrations. *Environ. Monit. Assess.* **2018**, *190*, 626. [CrossRef]

40. Mason, S.A.; Garneau, D.; Sutton, R.; Chu, Y.; Ehmann, B.J.; Fink, P.; Papazissimos, D.; Rogers, D.L. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. *Environ. Pollut.* **2016**, *218*, 1045–1054. [CrossRef]
41. Vilakati, B.; Sivasankar, V.; Nyoni, H.; Mamba, B.B.; Omine, K.; Msagati, T.A.M. The Py—GC–TOF–MS analysis and characterization of microplastics (MPs) in a wastewater treatment plant in Gauteng Province, South Africa. *Ecotoxicol. Environ. Saf.* **2021**, *222*, 112478. [CrossRef] [PubMed]
42. Yang, L.; Li, K.; Cui, S.; Kang, Y.; An, L.; Lei, K. Removal of microplastics in municipal sewage from China's largest water reclamation plant. *Water Res.* **2019**, *11*, 175–181. [CrossRef]
43. Talvitie, J.; Heinonen, M.; Paakkonen, J.P.; Vahtera, E.; Mikola, A.; Setala, O.; Vahala, R. Do wastewater treatment plants act as a potential point source of microplastics? Preliminary study in the coastal Gulf of Finland, Baltic Sea. *Water Sci. Technol.* **2015**, *72*, 1495–1504. [CrossRef] [PubMed]
44. Carr, S.A.; Liu, J.; Tesoro, A.G. Transport, and fate of microplastic particles in wastewater treatment plants. *Water Res.* **2016**, *91*, 174–182. [CrossRef] [PubMed]
45. Murphy, F.; Ewins, C.; Carbonnier, F.; Quinn, B. Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. *Environ. Sci. Technol.* **2016**, *50*, 5800–5808. [CrossRef] [PubMed]
46. Nafea, T.H.; AI–Maliki, A.J.; AI-Tameemi, I.M. Sources, fate, effects, and analysis of microplastic in wastewater treatment plants: A review. *Environ. Eng. Res.* **2024**, *29*, 230040. [CrossRef]
47. Westphalen, H.; Abdelrasoul, A. *Challenges and Treatment of Microplastics in Water*; Glavan, M., Ed.; IntechOpen: London, UK, 2018; pp. 71–83.
48. Talvitie, J.; Mikola, A.; Koistinen, A.; Setala, O. Solutions to microplastic pollution—Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. *Water Res.* **2017**, *123*, 401–407. [CrossRef]
49. Talvitie, J.; Mikola, A.; Setälä, O.; Heinonen, M.; Koistinen, A. How well is microlitter purified from wastewater? A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. *Water Res.* **2017**, *109*, 164–172. [CrossRef] [PubMed]
50. Browne, M.A.; Crump, P.; Niven, S.J.; Teuten, E.; Tonkin, A.; Galloway, T.; Thompson, R. Accumulation of microplastic on shorelines worldwide: Sources and sinks. *Environ. Sci. Technol.* **2011**, *45*, 9175–9179. [CrossRef]
51. Ngo, P.L.; Pramanik, B.K.; Shah, K.; Roychand, R. Pathway, classification, and removal efficiency of microplastics in wastewater treatment plants. *Environ. Pollut.* **2019**, *255*, 113326. [CrossRef]
52. Zahra, S.I.; Iqbal, M.J.; Ashraf, S.; Aslam, A.; Ibrahim, M.; Yamin, M.; Vithanage, M. Comparison of ambient air quality among industrial and residential areas of typical South Asian city. *Atmosphere* **2022**, *13*, 1168. [CrossRef]