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Urban and Groundwater Microplastic Contamination: Sources, Distribution, Impacts, and Remediation Technologies

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ABSTRACT: The presence of microplastics (MPs) in urban environments and groundwater systems has garnered significant global attention due to the critical role groundwater plays as a primary freshwater source. This review paper aims to comprehensively examine the sources, distribution, movement, and environmental impact of MPs, particularly focusing on urban areas and groundwater contamination. Special emphasis is placed on MPs originating from landfill leachate and their distribution along Malaysia's beaches. The paper also discusses the movement patterns of MPs, providing mathematical models for their migration. The environmental and health impacts of MPs, including soil degradation, toxicity in agricultural crops, and heavy metal adsorption, are analyzed. Additionally, current remediation technologies such as reverse osmosis, microbial exploitation, and ozonation are evaluated, with recommendations for combining different methods to enhance MP removal effectiveness. The involvement of the general public, socio-economic sectors, tourism, and waste management companies is highlighted as crucial for addressing this pervasive issue.

KEYWORDS: Environmental impact; groundwater contamination; landfill leachate; microplastic; remediation technologies; urban environments.

1. Introduction

Groundwater, stored in aquifers, is a vital resource that plays an essential role in the hydrological cycle. It serves as a primary source of drinking water, supports agriculture, and is one of the most widely used solvents in industrial processes. Additionally, aquifers are highly valuable for socio-economic development, particularly in arid and semi-arid regions where water scarcity is a significant challenge [1]. However, recent research highlights an alarming issue: the contamination of groundwater by microplastics (MPs), which poses serious risks to both groundwater resources and users. Microplastics, defined as small plastic particles typically less than 5 mm in size, have emerged as a global environmental concern due to their widespread presence in various ecosystems, including water bodies. These particles originate from the degradation of larger plastic waste through physical, chemical, and biological processes, eventually breaking down into tiny fragments [2]. MPs are introduced into the environment through various sources without adequate end-of-pipe treatment. Common sources include landfills, sewage treatment facilities, construction activities, industrial processes, and even household laundry [3]. Once released, MPs are incapable of natural decomposition and can persist in the environment for extended periods, often lasting hundreds of years [4].

The persistence of MPs in the environment has far-reaching consequences. They can infiltrate terrestrial ecosystems, where they contaminate groundwater systems and impose significant risks. These risks extend to human health and biodiversity, as MPs can be ingested by organisms, bioaccumulate in the food chain, and potentially harm both wildlife and humans. Groundwater contamination by MPs can have particularly detrimental effects on local communities that rely on this resource for drinking and irrigation, further exacerbating socio-economic and environmental challenges. Despite the severity of the issue, much of the scientific focus has been directed toward understanding the impacts of MPs in marine environments. Consequently, the effects of MPs on terrestrial ecosystems, particularly groundwater systems, have received comparatively less attention [4]. This oversight underscores the need for a more comprehensive understanding of how MPs impact groundwater resources and their broader implications for human health and the environment. This study aimed to address this gap by providing an overview of MPs in Malaysia's groundwater. It explores the sources of MPs, their distribution patterns, their potential impacts on human and environmental health, and the remediation technologies available to mitigate this growing problem.

2. Source, Distribution, and Movement.

The term microplastic was first introduced in 2004 and is defined as small plastic particles with sizes ranging from 1 μm to 5 mm [5, 6]. Microplastics (MPs) are generally categorized into two types: primary and secondary MPs. These categories originate from different sources, which will be discussed in detail in the following section. In general, conventional plastic products are highly resistant to natural degradation processes. The longevity of plastics can extend to thousands of years, although the exact duration depends on the chemical properties of the plastic and the environmental conditions it is exposed to [2]. While the degradation of plastic waste occurs very slowly, it is not entirely impossible. Environmental weathering processes can lead to the breakdown of plastics, resulting in the formation of smaller fragments over time. The breakdown of plastics involves changes in their polymer structure caused by both biological and abiotic processes. Biological processes include microbial activity, while abiotic processes encompass physical forces such as mechanical abrasion, as well as chemical reactions like photodegradation (UV exposure), oxidation, and hydrolysis [2]. These processes collectively contribute to the fragmentation and transformation of larger plastic waste into microplastic particles. A general overview of the degradation processes that plastics undergo is illustrated in Figure 1 below. This figure demonstrates how external factors such as sunlight, temperature, and mechanical forces interact with the properties of plastics, leading to their gradual decomposition into microplastic particles.

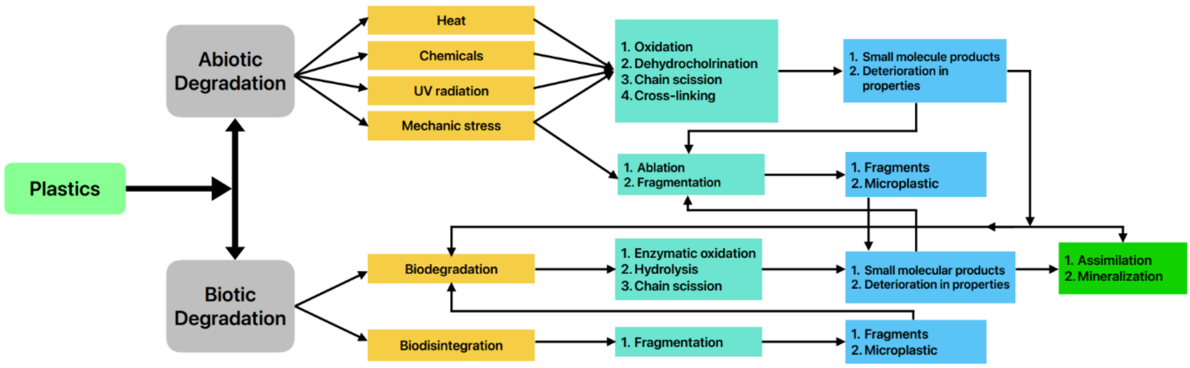

Figure 1. Plastic degradation process.

2.1.Source of microplastics.

are generally classified into two main categories: primary MPs and secondary MPs. Both types are typically discharged into water bodies, undergoing biological, chemical, and physical processes as they move through the environment. Primary MPs are directly manufactured for specific applications and originate from a wide variety of daily life activities. Examples include cosmetic products, the blasting of plastic products during industrial operations, and applications in medical science. These MPs are often discharged into urban sewage systems, particularly from products used in daily cleaning, such as facial scrubs and toothpaste, which contain microbeads. From there, they are transported to wastewater treatment plants (WWTPs) [7]. While WWTPs have proven effective at removing a significant portion of MPs, the removal is often insufficient when compared to the sheer volume of MPs entering the plants. As a result, a large number of MPs can still escape in the treated effluent, ultimately being released into the environment. The issue is even more severe in underdeveloped regions, where wastewater is often discharged directly into rivers or other water bodies without adequate treatment [7]. Consequently, these MPs can infiltrate nearby aquatic systems, including groundwater sources.

Secondary MPs, on the other hand, are formed through the degradation of larger plastic waste products. Common sources include industrial resin pellets, fishing equipment, landfill leachate, and other degradable plastic materials [7]. One of the largest contributors to secondary MPs is tire wear, a growing concern due to the rapidly increasing number of vehicles globally [8]. Frictional stresses are generated during the interaction between the tire, road surface, brake pad, and brake disk. These stresses cause fragments to tear off the rubber. Prolonged driving exacerbates this process, as the repeated stretching and abrasion fatigue the material, leading to the micro-cutting or scratching of tire treads. This produces elongated rubber particles, which are subsequently released into the environment [2]. Beyond these well-known sources, there is relatively little attention given to MP pollution originating from landfills. Landfills represent a major point source of MPs that pose significant threats to groundwater [9]. As a developing nation with a growing economy, Malaysia faces considerable challenges in managing its plastic waste. Most plastic waste ends up in landfills, which is the most widely adopted disposal method. Globally, landfilling accounts for approximately 21% to 42% of waste storage [10]. In Malaysia, it is estimated that 65% of waste was disposed of via landfilling in 2020 [11]. The abundance of landfill sites in Malaysia increases the production of leachate, an aqueous effluent formed when rainwater percolates through landfill waste. This leachate is a significant pathway for MPs to enter the environment, as they are frequently found in leachate samples [12]. Figure 2 illustrates the pathways through which MPs infiltrate and spread into the surrounding environment, highlighting the role of landfills as a critical source of contamination.

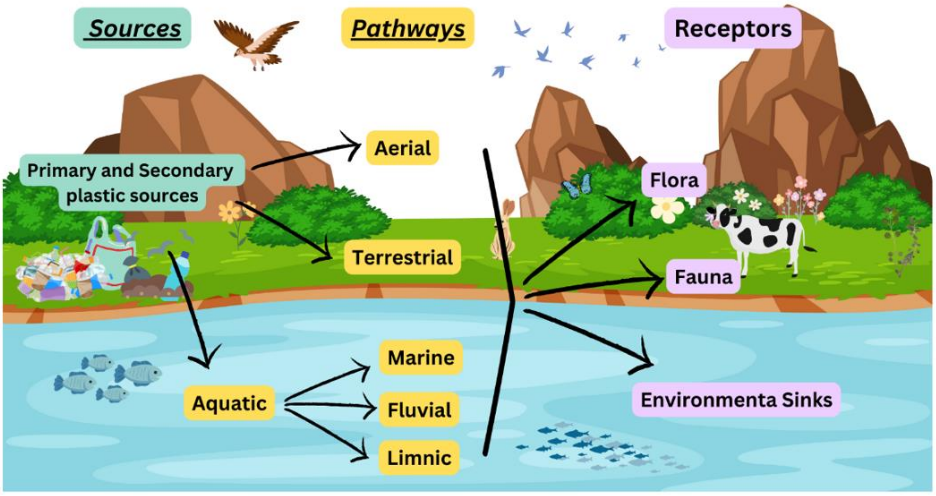

Figure 2. Pathway of MP into the environment.

2.2.Distribution.

As groundwater moves through different water regions, such as land surfaces, rivers, and oceans, microplastics (MPs) are also transported and distributed across these areas. Consequently, MPs can be found in various regions throughout Malaysia. Although research and data on the distribution of MPs across all Malaysian regions and states are limited, some studies have provided insights into their abundance in specific areas. For example, Fauziah et al [13] conducted a study in 2015 to evaluate the abundance of MPs in various coastal regions of Malaysia. The study measured the MPs collected in units of items per square meter. Sampling was conducted three times, in January, February, and March, with a consistent interval of 28 days between each sampling. The detailed abundances of MPs on the sampled beaches, along with their mean abundances, are summarized in Table 1. As seen from Table 1, it is hard to distinguish and conduct a comparison due to the inconsistency units being used in the data obtained. Nonetheless, when the mean values of the abundance are compared, Terengganu appeared to have the highest mean abundance of MPs at Seberang Takir Beach at 878.67 items/m^2. Tanjung Aru Beach, Sabah has the lowest abundance of MPs with a mean value of only 192 items/m^2. Apart from that, since the size of MPs plays an important role in determining the potential level of threat towards the aquatic ecosystem, their sizes are also determined in this research. The most commonly found size of the MPs found on the beaches was mostly more than 4.75mm [13]. There are several factors that are behind the fragmentation of plastic debris into smaller MPs, including prolonged exposure to UV light, physical abrasion and particularly photodegradation since the MPs on shorelines are more brittle due to the frequent wave action [14]. Other than that, there are also other factors that can cause plastic debris to undergo fragmentation not only on beaches but also in landfills, such as fluctuating temperature, microbial degradation, high salinity, physical stress, and the leachate pH [10].

Table 1. Abundance of MPs in Malaysia.

Source	Location	Sampling Techniques	Characterisation	Abundance	References
Sea	Teluk Kemang Beach, Negeri Sembilan	Shovel in a 50*50 cm^2 quadrate and 5 cm depth	Not mentioned	230.67 items/m^2	[13]
Sea	Pasir Panjang Beach, Negeri Sembilan	Shovel in a 50*50 cm^2 quadrate and 5 cm depth	Not mentioned	211.33 items/m^2	[13]
Sea	Batu Burok Beach, Terengganu	Shovel in a 50*50 cm^2 quadrate and 5 cm depth	Not mentioned	780.00 items/m^2	[13]
Sea	Seberang Takir Beach, Terengganu	Shovel in a 50*50 cm^2 quadrate and 5 cm depth	Not mentioned	878.67 items/m^2	[13]
Sea	Tanjung Aru Beach, Sabah	Shovel in a 50*50 cm^2 quadrate and 5 cm depth	Not mentioned	192.00 items/m^2	[13]
Sea	Teluk Likas Beach, Sabah	Shovel in a 50*50 cm^2 quadrate and 5 cm depth	Not mentioned	239.00 items/m^2	[13]
River	Skudai River, Johor	Box corner	(HSZ-600) Microscope with 40× - 45× magnification	Mean: 200 ± 80 particles/kg	[15]
River	Tebrau River, Johor	Box corner	(HSZ-600) Microscope with 40× - 45× magnification	Mean: 680 ± 140 particles/kg	[15]
River	Baram River, Sarawak	Ekman Grab sampler	Agilent ATR-FTIR spectroscopy	Range: 0.021 ± 0.002 to 0.057 ± 0.039 mg/g	[6]
River	Miri River, Sarawak	Ekman Grab sampler	ATR-FTIR Spectroscopy	Range: 283.75 ± 15.9 to 456.25 ± 33.6 particles/kg	[17]
Wetland	Setiu Wetland, Terengganu	229 × 229 mm Ponar grab (approximately 2–3 m water depth)	Olympus SZX-ZB7 microscope, ATR-FTIR spectroscopy (Perkin Elmer; Spectrum 65)	Range: 0.750 ± 3.838 to 14.25 ± 4.343 items/g	[18]

2.3. Movement.

It is crucial to understand the movement of contaminants, including the migration and transformation of such contaminants in different environments. This knowledge is essential for understanding their migration patterns and developing corresponding countermeasures to minimize any potential harmful and dangerous consequences[7]. Since landfills are a major contributor to groundwater pollution in Malaysia[19], treating leachate is of paramount importance. Leachate from landfills is often treated before being discharged into the environment to reduce harmful environmental impacts. However, microplastics (MPs) can still flow into the groundwater through landfill effluent due to various factors. Geomembranes, also known as landfill liners, are commonly used as barriers to contain leachate, ensuring that filtered waste solids are collected and treated to prevent pollution. While geomembranes are designed to be carefully manufactured and installed, there is still a possibility of defects, such as leaks. These defects can serve as pathways for leachates containing MPs to bypass the geomembrane and infiltrate the environment, particularly the groundwater[10]. Furthermore, even if leachates are filtered at the geomembranes and sent for treatment, MPs may not be fully removed or safely degraded. Leachates are collected in an equalization basin before being transferred to biological or physical/chemical treatments [10, 12, 20]. However, during these processes, MPs cannot be thermally, chemically, or biologically degraded. Instead, their distribution may change during the raw leachate treatment process[10]. As a result, MPs can still flow with the final treated effluent, eventually reaching the groundwater. Surface water flow, such as rain, plays a role in transporting MPs on the ground surface into water bodies. Rivers also carry MPs from their sources, such as landfills, into larger water systems. There have been reports of MPs present in the water column, seabed, and sediments of sea beaches[21–25], as the marine environment often serves as the final destination for MPs accumulating from groundwater and terrestrial environments [7]. While sea-water intrusion is a naturally occurring process where seawater mixes with groundwater, this event is often driven by human activities [21, 26–28]. Intensive groundwater extraction reduces the amount of freshwater flowing into the ocean, leading to the formation of drawdown cones and a deepened water table. This creates a high hydraulic gradient within the drawdown cones, causing seawater to flow into the aquifer, mixing with the groundwater. This intrusion has contributed to an increased concentration of MPs in groundwater aquifers near coastal areas.

3. Impact of Microplastics.

To understand why MPs are a global issue threatening the community and the environment, it is crucial to examine the potential health and environmental impacts of MPs. Hence, in this section, the evolution and health impacts of this contaminant on the environment and community was discussed.

3.1. Impact to environment.

Due to the nature of plastic, MPs are almost impossible to biodegrade or decompose on their own in most cases when they are abandoned in the environment, however when depending on several factors and conditions, they are still able to degrade under a longer period of time. Hence, when MPs stay in the environment for up to hundreds or thousands of years, consequential problems regarding the environment will arise. These MPs are dispersed in the environment and due to their tiny sizes with high surface area to volume ratio, with additional factors from ageing and weathering, they are more capable of absorbing heavy metals to themselves [29]. This is because smaller MP particles have larger specific surface area and are hydrophobic. Consequently, MP particles have been found to have around 10 to 100 times higher concentrations of heavy metals than any other substances in the immediate environment [29, 30]. There are only a few studies that have determined the potential toxic effects of MPs and heavy metals in both aquatic and terrestrial environments. Hence, the potential combined harmful effects of MPs and heavy metals are still yet to determine and study. On the other hand, there are still some known effects when these pollutants are transporting in the environment. For instance, MPs with contaminants adsorbed on them can release toxic substances when moving into the groundwater, potentially affecting the quality of soil nearby. In addition, when MPs are accumulated in the soil, it can affect the soil's physical properties, such as changing the soil bulk density, water holding capacity, soil aggregate stability, and soil porosity. The impact that causes the change in soil porosity could potentially increase the rate of water evaporating from the soil, thereby causing the soil to crack easily [31]. Moreover, the heavy metals contained in the MPs can also cause diverse effects on soil microflora and both the chemical and physical properties of the soil [29]. Ultimately, MPs are capable of polluting the environment with ease since they are very widely distributed across the ecosystem and constantly moving across different environments.

3.2. Impact to living organism.

MPs acquire access to human, territorial and aquatic life via different pathways, such as migration from the leakage of landfill leachate. Consequently, hundreds of species have been proven and documented to ingest MPs . At the same time, MPs have been discovered in the base of the food web in multiple varieties of zooplanktonic organisms, including organisms from higher trophic levels. As a matter of fact, both invertebrates and vertebrates such as Bivalvia and marine mammals have also been found to have been ingesting MPs, either through direct or lower trophic levels [18]. Micro and macro algae serve as the fundamental producers of food for a wide variety of zooplanktonic and crustacean organisms in the marine food chains. Phytoplanktons are known for responsible for around half of the photosynthesis activity in the environment. A good example of the effect of MP on these marine organisms was when chlorella was reported back in 2010 to be found to have MP accumulation, the consequences were oxidative stress and photosynthesis activity was affected and reduced [30, 32]. This was due to the accumulation of MP that has blocked the sun's radiation from the algal surfaces, hence causing the reduction of photosynthesis activity. In addition, an experiment that was conducted in a laboratory has also shown that MP particles that carry silver can significantly affect the root growth of duckweed, which is an important aquatic macrophyte that serves as a habitat and sustainable source of food for wildlife [30].

Apart from that, as mentioned in the previous part, MP particles are capable of contaminating soil, especially when they adsorbed other contaminants such as heavy metals. Subsequently, when the soil in a specific region is contaminated, both flora and fauna in the region will also be affected. This can be dangerous when MPs are bioaccumulated in foods and plants, particularly in agriculture. When the bioaccumulation of MP enters the roots of agricultural plants, the contamination can be transferred to multiple areas of the plant's systems. This can impose dangerous risks on the agricultural livestock that feeds on the contaminated plants because plants with edible roots like carrots are where the MPs and contaminants are accumulated before distributing to other parts of the plants [29].

3.3. Impact to community.

In fact, MPs suspended in groundwater can easily enter the human body. As mentioned in the previous section, MPs, along with other heavy metals, can accumulate in the roots of agricultural plants. This shows that they can also accumulate in the plants that humans consume daily. According to recent research, every human ingests an average of 5 g of MPs per week from various sources, including groundwater [21]. Therefore, it is crucial to understand the health impacts that MPs can cause upon accidental ingestion, so that preventive measures or countermeasures can be applied. Table 2 shows the different types of potential human health impacts when various types of MPs are ingested, either alone or in combination with other metals and/or chemicals.

Table 2. Health impact of direct ingestion of MPs.

Types of MP	Potential health impacts	References
PE and PS micro-particles	Cytotoxicity due to oxidative stress	[33]
PE particles	Immune activation of macrophages Production of cytokines	[34]
PS particles	Inflammatory effects	[35]
PS particles	Fast movement through endothelium in the bone marrow and uptake by phagocytizing cells	[36]

Table 3. Health impacts of ingestion of additives/plasticizers along with MPs.

Types of MP	Chemical(s)/metal(s) associated	Potential health impacts	References
Various plastics	Benzotriazoles	Respiratory tract irritant, Carcinogenic Genotoxic	[37]
PC plastics, epoxy resins	Bisphenol A (BPA)	Affects the development of the brain, causing loss of sex differentiation, Suspected endocrine-disrupting chemical	[38, 39]
PS for Styrofoam packaging	Styrene	Endocrine disrupting chemical	[38]
Various plastics	Benzophenone	Effects on childbirth weight and gestational age	[40]
Various plastics	Tri-isobutyl phosphate (TiBP)	Skin problems, Dermatitis, Reproductive abnormalities, Imbalanced hormonal levels	[41]
Various plastics	Tri-*n*-butyl phosphate (TnBP)	Skin problems, Dermatitis, Reproductive abnormalities, Imbalanced hormonal levels	[41]
Various plastics	Tris (2-chloroethyl) phosphate (TCEP)	Neurotoxic, Carcinogenic	[42]
PVC	Vinyl chloride	Angiosarcoma of liver	[43 44]
PVC (in medical tubing)	Phthalates (Di(2-ethylhexyl) phthalate (DEHP))	Prominent levels of BPA in infants Carcinogenic, Adverse effects on reproduction	[45]

Table 4. Health impact of ingestion of metals/metalloids accumulated over MPs or added as additives.

Type of MP	Chemical(s)/metal(s) associated	Potential health impacts	References
PET, PE, PVC	Aluminium	Breast cancer, Metal oestrogen	[46, 47]
Various plastics	Antimony	Breast cancer, Metal oestrogen	[46, 47]
PU foam and PVC	Tin	Breast cancer, Headache, Skin disease, Digestive problems	[46, 47]
PE, PVC, PES	Arsenic	Carcinogen	[46]
PE, PVC, PP	Chromium	Allergic reactions, Cardiovascular, Gastrointestinal, haematological, respiratory, and neurological effects	[48, 49]
PE, PP	Copper	Abnormalities at the genetic level	[46, 48]
PET, PE, PVC	Lead	Hypertension, anaemia, Effect on the brain Reproductive abnormalities, cell damage	[46–49]
PET, PE	Cadmium	DNA methylation, Metabolic changes Cellular apoptosis, Bone-related issues	[46–49]
PU	Mercury	Carcinogen, Brain dysfunction, Abnormalities at the genetic level	[48]

Based on the data in Table 2, Table 3 and Table 4 above, it is worth noticing that not only the MP particles but when other chemicals such as plasticizers and additives are ingested altogether can further adversely affect human health or even be lethal [21]. From causing organ damage and irritations to causing cancer and genetic abnormalities, these health impacts can be extremely detrimental and dangerous to the communities that rely on groundwater as their key source of water.

4. Remediation Technologies.

The health impacts and environmental impacts that can be brought about by the contamination of MPs in the groundwater have been discussed in previous sections, so the remediation technologies that can help counter this global issue will be discussed in the following section. To resolve this issue, complete elimination from the source of the pollutants is always the best solution. However, it is impossible to fully remove plastic from our daily life as humans still rely on plastic products due to its ease of production and low production costs. Hence, the best solution for primary MPs is to minimize production and usage, while safe disposal of used plastics and effective waste management is essential for reducing secondary MPs since they are one of the largest sources of plastic waste pollution [21]. Nonetheless, there will still be untreated plastic waste that is disposed into the environment, especially in landfills. For that reason, it is still possible to mitigate the amount of MP flowing into the groundwater by preventing the existing leachate from leaking into the ground or other water bodies such as rivers [19]. This can be done by extracting the contaminated groundwater at the downgradient of the landfill by installing pumping wells alongside the rivers. In the event of leachate is still unable to be completely prevented from leaking, another possible countermeasure is to limit and reduce the production of leachate. Besides that, treatment is also another method to mitigate the concentration of MPs in the effluent, depending on the treatment method, the treatment process can remove MP at a rate from 3% to even 100% [50].

4.1.Microbial remediation.

Microbes possess the ability to degrade MP polymers by utilizing the polymers as sources of carbon and energy, and this process is called biodegradation [51, 52]. Bacteria are typically very adaptive in all types of environments. There are also several bacteria that have been reported to be able to degrade plastic polymers [51]. By using the clear zone and weight loss technique of analysis, the microorganisms isolated from Andhra Pradesh and Telangana areas in Hyderabad were discovered to have the ability to degrade polyethylene, suggesting that these microorganisms could be potential MP degraders [53]. Thereafter, these microbes could be utilized as an environmentally friendly method to degrade MP. These microbes can then be applied to the treatment of landfill leachate or the extracted groundwater that contains MP, not to mention that it can also be exploited for treating an environment that is contaminated with MP. Regardless of the advantages, this method still has its disadvantages. This method of biodegradation has only been focused on screening the abilities of microbes to depolymerize one single type of plastic, it is not capable of biodegrading multiple types of plastics simultaneously [54].

4.2.Reverse osmosis.

Reverse osmosis (RO) is a treatment method that is typically used to purify water using nonporous or nanofiltration membranes that have pore sizes smaller than 2nm. This method works by exerting high pressure on a concentrated water solution so that this solution is forced to pass through a partially permeable membrane, leaving the substances of larger sizes in the concentrated water solution, hence effective in filtering out MP particles [55]. Moreover, there are possible ways to further increase the removal rate of MPs by combining the technologies, such as combining membrane bioreactor, nanofiltration and reverse osmosis. This combination can remove and capture MPs by biodegradation and membrane bioreactor respectively. Meanwhile, the rest of the MPs will be intercepted by the nanofiltration and reverse osmosis to make sure that the effluent will meet the standard of discharge [56]. In addition, there was also research that has proven when an extra physical filtration facility is added between the membrane filtration system and membrane bioreactor, it can greatly remove MP with a particle size of 10μm up to an effectiveness of 95%, thanks to the rich honeycomb structure and flakes that helps to trap the MPs [56, 57]. Biochar mixed sand or zeolite filtration are some of the examples of the extra physical filtration facility. However, there are still limitations to these technologies. The reverse osmosis membrane is sensitive to pH, temperature and certain types of chemicals from leachate; hence it has strict requirements for the quality of influent, making it not usable for all types of leachates. Additionally, membrane fouling is also another major issue since it increases the difficulty and costs of the treatment [56].

4.3. Ozonation.

Several chemical treatment methods can treat MPs, including ozonation, photo-catalytic degradation, coagulation, Fenton, and acid-alkali treatment. Ozone is recognized as a powerful oxidant from ancient times that can interact with different polymeric materials, including their unsaturated bonds and aromatic rings [61]. This method introduces the oxidant on the surface of MPs, causing it to become rougher, after that, the particle size is decreased. As a result, the MP hydrophilicity is increased, thus leading to further oxidative degradation, eventually producing other products like formic acid and phenol [62]. Although there are only a small number of studies on the influence of ozone in treating MPs, studies are reporting its effectiveness in influencing polymer degradations using high reactive secondary oxidant species, thus this process can be used as a direct treatment method for removing MPs [60]. For instance, a study has proven that when PE, PP and PET polymers are exposed to ozone, it reported a high polymer degradation rate that is higher than 90% at a temperature range of 35–45°C [63]. This method can be improved in several ways, such as by increasing the polymer surface tension, decreasing the melting points of the polymers and modifying mechanical properties. Therefore, ozonation is a possible method for treating MPs in wastewater, the biggest challenge, though, is the high production cost of ozone production and environmental problems [58, 60]. Table remediation technology is summarized in Table 5.

Table 5. Remediation technology: types of MPs treatment.

Remediation Method	Type of Treatment	Advantages	Disadvantages	Reference
Exploitation of Microbes	Biological	– Environmentally friendly, relying on natural processes. – Reduces the need for chemical interventions. – Effective in breaking down specific polymer types.	– Limited to biodegrading one type of plastic at a time. – Slow degradation rates compared to other methods. – - Requires optimal conditions for microbial activity.	[53]
Reverse Osmosis	Physical	– Highly effective in filtering microplastics (MP) smaller than 2 nm. – Can be combined with nanofiltration and membrane bioreactors to enhance removal efficiency. – When integrated with additional physical filtration facilities, it can achieve up to 95% effectiveness for MPs as large as 10 μm.	– Susceptible to membrane fouling, leading to reduced efficiency. – Membrane sensitivity to pH, temperature, and chemicals necessitates careful control. – High maintenance and operational costs.	[57, 58]
Ozonation	Chemical	– Achieves removal rates of up to 89.9%, making it a highly efficient tertiary treatment. – Enhances treatment processes by altering the physical and chemical properties of microplastics. – Facilitates the breakdown of MPs by modifying their morphologies for easier removal.	– Ozone production is complex and requires specialized equipment. – High operational costs due to energy requirements. – Potential environmental concerns, such as the formation of harmful by-products.	[59, 60]

5. Conclusions

The removal of MPs to protect natural water resources is key to a more sustainable future. MPs in groundwater remain a global issue that requires immediate and effective measures. The impacts of MP contamination in groundwater, as discussed above, prove that it is a global threat to both ecosystems and communities, since groundwater is one of the most reliable natural resources often consumed without specific treatment. In fact, some of the impacts can be lethal, including causing carcinogens, brain dysfunction, and breast cancer. Hence, prevention of plastic manufacturing or the search for plastic replacements should always be the first priority. This approach eliminates plastic products before they are even produced. However, due to the convenience that plastic has provided humanity for over a century, it is still impossible to completely halt plastic production. Therefore, reduction in plastic use is the next measure to take. By reducing plastic consumption and actively recycling plastic products, we can help reduce the concentration of MPs in groundwater. Although MPs will still flow into groundwater, solutions such as extracting or treating contaminated groundwater—using technologies like reverse osmosis—can be implemented. However, there are limitations to current technologies, such as membrane fouling, which reduces the effectiveness of filtering

MPs due to the blockage and wear and tear of the membrane. Intense research is still necessary to develop new remediation technologies to help mitigate the alarming concentration of MPs in groundwater today. Ultimately, this issue cannot be solved without involving the general public, socio-economic sectors, tourism, and companies specializing in waste management. For now, remediation technologies are not widely implemented, particularly in underdeveloped countries. Therefore, the best approach for remediation remains encouraging everyone to reduce plastic usage to minimize the possibility of MP formation.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Najib Mahmood Nawi made substantial contributions to the conception and design of the study, data acquisition, analysis, writing and drafting of the manuscript, and interpretation while Flavio Lopez-Martinez provided critical revisions and important intellectual content. Both authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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