Hindawi
International Journal of Ecology
Volume 2023, Article ID 8826716, 21 pages
https://doi.org/10.1155/2023/8826716

Review Article

Microplastics in the Ecosystem: A Systematic Review of the Methods for Their Detection and Removal

Santiago L. Rubiños,[1] Juan H. Grados,[1] Juan T. Medina,[2] Eduardo N. Chávez,[1] Edwin Huarcaya,[1] Victor E. Rocha,[1] Herbert J. Grados,[1] and Milagros R. Neyra[2]

[1]*Faculty of Electrical and Electronic Engineering, Universidad Nacional del Callao, Juan Pablo II 306 Avenue, Bellavista, Callao 07011, Peru*
[2]*Faculty of Chemical Engineering, Universidad Nacional del Callao, Juan Pablo II 306 Avenue, Bellavista, Callao 07011, Peru*

Correspondence should be addressed to Eduardo N. Chávez; enchavezg@unac.edu.pe

Received 17 May 2023; Revised 30 November 2023; Accepted 8 December 2023; Published 31 December 2023

Academic Editor: Agoes Soegianto

Currently, research on microplastics (MPs) has increased due to their rapid distribution throughout the world and their harmful effects on the ecosystem. However, a detailed description of their dispersion and the methods for both detection and removal has not been given. The objective of this research is to carry out a bibliographic review that allows for a multidisciplinary analysis of microplastic contamination and current detection and removal methods. The method used is PRISMA in which articles from reliable databases such as Scopus, Web of science, and Google Scholar were collected and analyzed to finally provide details on the physical and chemical methods for detecting MPs, in addition to presenting the technologies for their removal. As a result of the analysis, critical information was obtained from the different studies on the impact of MPs on the ecosystem and the variation in detection and removal efficiency according to the type of pretreatment and methods applied to the sample. It is concluded that this research is essential to understand the consequences that MPs have on the ecosystem and provide tools to evaluate and improve current technologies, mainly detection and removal.

1. Introduction

The most frequently used polymers presently are polystyrene, nylon, polyurethane, polypropylene, and so on [1]. Polymers accumulate in various environments and break down into microplastics as they are exposed to environmental stressors [2]. Microplastics are primarily formed by the fragmentation of larger plastic items under various environmental factors, as well as fibers and particles from everyday objects such as clothing and personal care products [3]. Microbial degradation can cause plastic to fragment into tiny pieces, which has led to extensive research into microplastics. These are defined as plastics with a diameter of less than 5 mm. Plastic's chemical properties, such as its hydrophobicity and its ability to attract other hydrophobic particles, also contribute to this issue [4]. MPs found in urban wastewater typically originate from daily activities such as using toothpaste, cleaning products, and shower gels [5]. Microplastics are tiny pieces of plastic that are harmful to the environment. They can come from a variety of sources, including the shedding of synthetic fibers from clothing during washing [6, 7]. Disposable face masks used to protect against COVID-19 are another source of microplastics [8]. The COVID-19 pandemic has caused a massive surge in the use of masks and gloves, estimated to be around 129 billion and 65 billion, respectively, per month globally. As a result, the amount of plastics being released into the environment, including the oceans, has significantly increased. This has led to a rapid increase in MP production, making it crucial to evaluate methods for quantifying, removing, and distinguishing microplastics to better understand the impact of MPs on the environment [9].

Several review articles on MPs have been published, with most focusing on a single method, such as the study by Rani

et al. [10] which examined the vibratory spectroscopy method. Others focus on analyzing MP contamination in one type of ecosystem such as the one by Manzoor et al. [11] that focused on the Harike wetland or just on assessing the interactions of microplastics with existing pollutants [12]. However, very few bibliometric analyses have been carried out taking into account various methods for the quantification and removal of MPs and their impact on different ecosystems. Therefore, this research presents recent advances in the understanding of the impacts of MPs on the environment and humans, as well as the state of the art in the development of technologies for their quantification and proper disposal.

2. Methodology

The collection of articles in the Scopus, Web of Science, and Google Scholar databases published between January 2018 and May 2023 was performed to carry out a systematic review using the PRISMA method [13]. For best results, we used Boolean and key words as search criteria: TITLE-ABS-KEY (Microplastic) AND (TITLE-ABS-KEY (Water) OR TITLE-ABS-KEY (Rivers) OR TITLE-ABS-KEY (Remote) OR TITLE-ABS-KEY (Detection)). A total of 1261 articles were found, which are distributed in Web of Science, Scopus, and Google Scholar with 724, 424, and 113 articles, respectively. The first criterion used to filter the articles was to eliminate duplicates and articles that were not written in English. This led to the elimination of 447 articles. Next, 465 articles that had little relevance to the treatment of detection and elimination of microplastics were removed. After this, the remaining articles were evaluated based on the quality of their results, leading to the discarding of 241 articles. Finally, 8 complementary articles were incorporated to provide updated information that broadens the concepts in a relevant manner. In total, 116 articles were obtained for this review, of which 43 provided fundamental data on MPs in various water sources and their global effects, 35 addressed MP detection methods, and 38 focused on MP removal techniques (see Figure 1). Further details on these articles are available in Tables S1–S3, which can be found in the supplementary file.

3. Results and Discussion

3.1. Origin and Distribution of Microplastic. In recent years, the demand for plastics has increased globally which has translated into increased production of plastics, amounting to approximately 359 million tonnes per year. In addition, the COVID-19 pandemic in 2020 critically increased the production of plastic waste due to the use of face masks, face shields, and surgical gloves which were personal protective equipment (PPE) [14]. Among the countries with the highest production of plastics, China is with a production of 30% of the total produced, followed by the countries belonging to the North American Free Trade Agreement (NAFTA) such as the United States, Canada, and Mexico, which together produce 18% of the total plastics, followed by the African continent with 7%, Latin America with 4%, and the 9 countries that make up the Commonwealth of Independent States (CIS) with 3% of the total production [15]. These plastics due to poor recycling management end up being dumped in rivers and oceans; a global estimate estimates that this waste is between 1.15 and 241 million tonnes of plastic and that the majority of this material comes from Asian countries [16].

The durability of these plastics has led to a significant accumulation of plastic waste that after some time due to physical or chemical degradation gives rise to MPs, there are also microplastics that are produced directly for the make-up industry, medicine, and others, and these MPs are distributed in different environments such as public roads, businesses, restaurants, and marine ecosystems such as rivers, oceans, and seas around the world [17, 18]. It has been observed that the distribution of MPs is majorly influenced by either human activities or geographical conditions [19]. The reason behind this is the lightweight nature of MPs, which enables it to be carried to various locations through several means such as wind, water currents [20], precipitation, surface runoff, infiltration, and river transport. You can refer to Figure 2 for a visual representation of this phenomenon. Residues of MPs move extensively over large distances, evidenced by their occurrence in pristine and remote areas such as the poles [22], deep sea, and oceanic islands [23].

3.2. Type of Microplastics in the Environment. MPs, or microplastics, can be divided into primary and secondary categories. Primary MPs are produced by companies themselves, mainly in the cosmetic and healthcare industry, to market them as additives [24]. On the other hand, most MPs are of secondary origin. This is because plastic articles are often used in a disposable manner without considering that they can take over a hundred years to degrade in nature [25]. This degradation can occur due to several factors such as ultraviolet radiation, biodegradation, physical erosion, or chemical oxidation. As a result, smaller plastic particles are released into the environment from items such as textile fibers, toys, and car tires [26]. These particles, which have a diameter of less than 5 mm, are known as MPs. Secondary MPs are mostly moved to remote areas through tourism, to lakes and rivers through fishing, and to rivers, groundwater, and beaches through wastewater and urban runoff, as well as to residential areas through urban transport [27]. Table 1 shows the two main categories of MPs based on their origin and sources.

In Figure 3, the types of existing microplastics can be seen, including some captured in the depths of the sea that consisted mainly of colored pieces and the others in makeup microspheres that have already been prohibited in some countries such as England [38], which are the primary and secondary microplastics, respectively.

3.3. Route and Destination of Microplastics. MPs are found in different ecosystems and follow different transport routes on land, waterways, and rivers, accumulating in soils [39–41], urban areas, snow, ponds, groundwater [42], river channels,

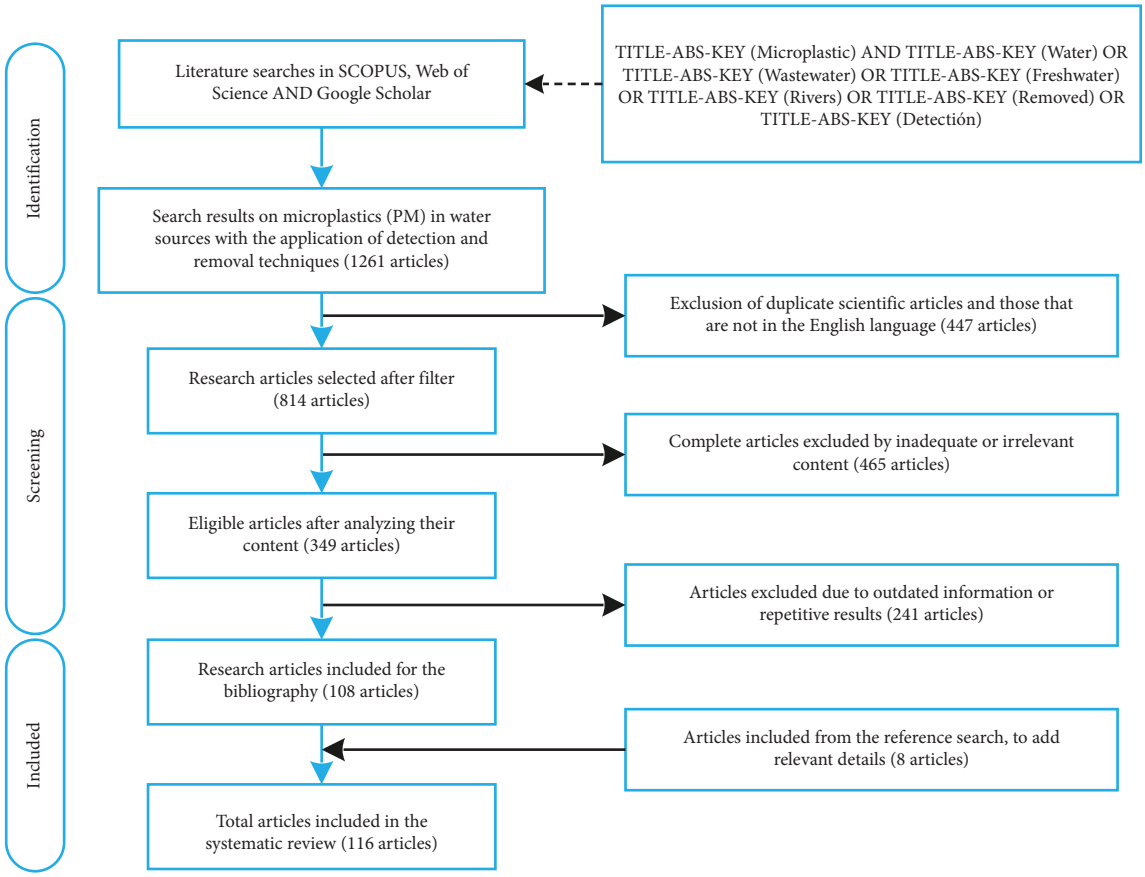

Figure 1: PRISMA flowchart. The flowchart presents the results and screening process of the original searches and the rerun of the searches.

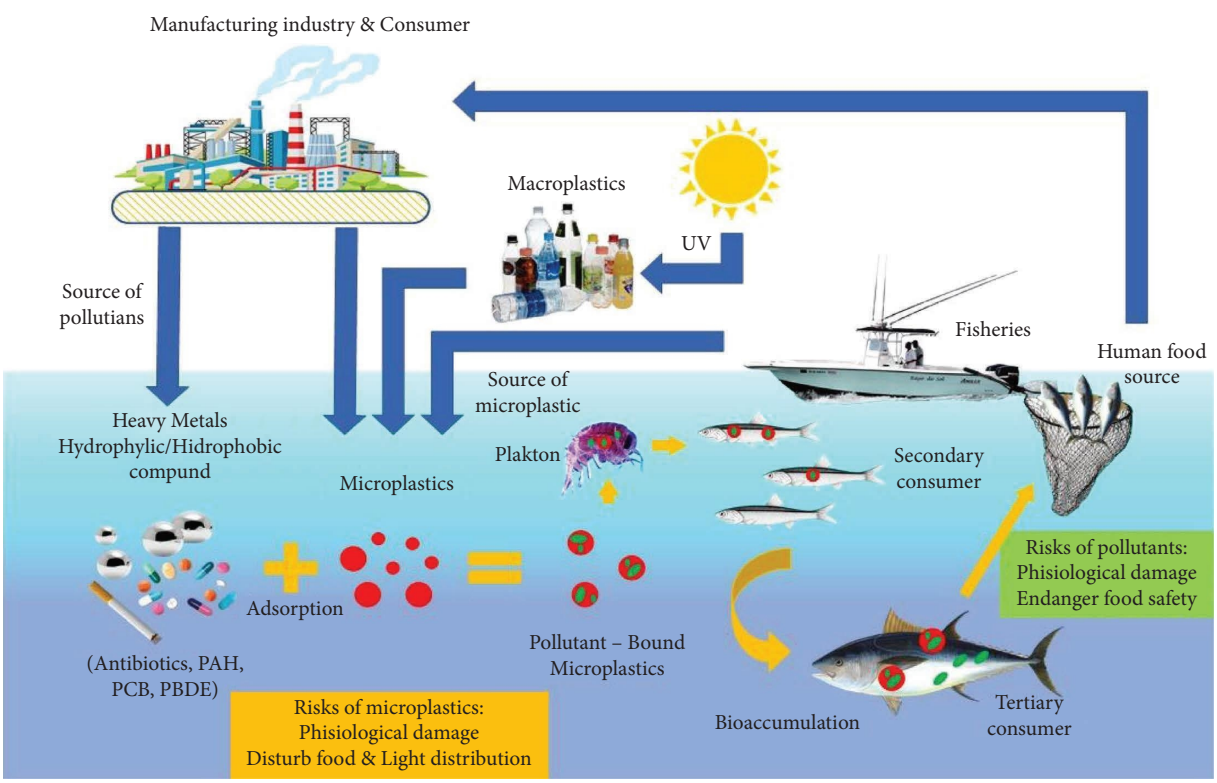

Figure 2: An illustration of the routes that microplastics follow and their global effect on the ecosystem and marine life [21].

Table 1: Proven origins of primary and secondary MPs.

Primary MPs	Secondary MPs
Fibers released during the production of textiles and clothing made of synthetic materials [28]	Toys, rubber, kitchen utensils, electrical wires, and interior paint [29]
Polyethylene (PE), polypropylene (PP), and polystyrene (PS) particles in cosmetic and medical products [30]	Textile fibers originating from clothing due to daily use or washing processes and released from textile manufacturing plants [31]
Cosmetic formulations often contain industrially produced microspheres and plastic particles [28]	It arises during the consumption and design of plastic products (for example, when plastic bottles degrade) or when macroplastics decompose into MPs [32]
Product of the industrial shot-blasting process using microplastics as an abrasive agent [31]	The marketing and use of disposable plastics, focus on straws and plastic bags [33]
Synthetic grass (turf) on the football pitch [34]	Material obtained from fishing nets [35]
Release of drilling fluids from oil and gas exploration activities, as well as in industrial abrasive processes [34]	LDP (low-density polyethylene) sheeting is commonly used in agriculture to maintain soil moisture, control weeds, and regulate temperature, a process known as plastic sheeting [34]

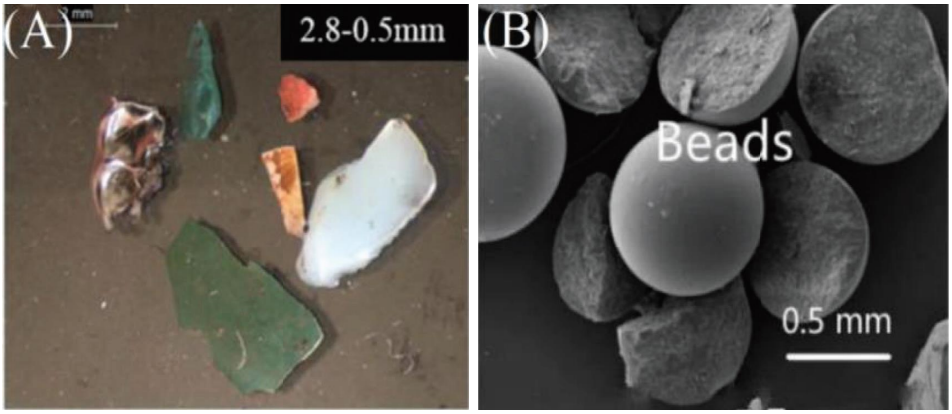

Figure 3: Examples of types of microplastics. Elements shown are primary microplastics (A) and secondary microplastics (B) [36, 37].

and supraglacial [43] wastes and eventually becoming widely distributed causing damage to biotic systems by entering the food chain through direct or indirect consumption, and indirect consumption occurs when food is consumed which transports the MP particles to places further away from their point of origin [44].

The occurrence and accumulation of MPs occur worldwide, although the highest production of secondary MPs occurs in developing and emerging countries; among the main factors are the lack of recycling policies to raise awareness among the population and poor wastewater treatment management [45]. The occurrence of MPs on agricultural land occurs due to the use of crop fertilizers made from sludge from wastewater treatment plants, as industrial, textile, and domestic wastewater flows into these plants and transports MPs [46]. In rivers, the main sources of MPs are the discharge of plastic waste directly into rivers, boil water discharges from urban areas, and surface runoff [47]. In aquaculture areas, the wear and tear of plastic materials that are part of working tools such as ropes, nets, cages, foam floats, and containers cause the appearance of MPs that pollute the waters of aquaculture ponds [48, 49]. In groundwater, MPs occur through leaching from the soil surface, percolation of wastewater through pores, and ground breaks.

3.4. Microplastic Toxicity. The toxicity of microplastics is related to the adhesion on their surface of pollutants and the release of phthalates, bisphenol A, and brominated flame retardants, the latter being used to enhance the properties of plastics which, when entering living organisms, have an impact on their health due to their intrinsic physical properties [50, 51]. In humans, the entry of MPs into the body can occur with primary and secondary MPs. Primary MPs can enter the body through the epidermis by the use of small plastic particles in cosmetics and orally employing some capsules and tablets that use MPs to enhance drug release [52]. In secondary MPs, entry into the body can occur through airborne particles and textile fibers or the consumption of contaminated food, with indirect consumption being the main form of MP entry [53]. Ingestion of MPs can occur through the consumption of fishery products [54] such as shellfish [55], agricultural products such as fruits and vegetables [56], condiments such as basil [57] and cooking salt [58], and other industrial and packaged products such as bottled water due to inadequate water treatment or the constant reuse of bottles [59, 60].

The health effects that MPs can have on the human body are still being studied, and it is not yet fully understood which diseases they can cause. However, some of the possible health impacts of the presence of MPs are discussed below. The presence of microplastics in the body can damage the intestinal epithelium, alter gene expression and hormone production, cause oxidative stress in the endocrine system, and contribute to skin conditions by entering through the capillary follicles [61]. The bronchioles may also be affected by the accumulation of MPs, as it can cause inflammatory injury, oxidative stress, cytotoxicity, translocation [62], and neurotoxicity which is associated with the release of chemical additives such as plasticizers and brominated flame retardants from MPs that interfere with the functioning of the nervous system, in addition to MPs possibly altering reproductive function by affecting fertility and embryonic and transgenerational toxicity [63] (see Figure 4).

3.5. Microplastic Identification Approaches. The identification of MPs has now become a priority. However, it remains a challenge due to the intrinsic properties and varied physicochemical characteristics of MPs that make accurate recognition difficult [23]. There are different methods to identify MPs, among which the physical method of visual inspection with the help of microscopes is not very accurate because MPs have a small size and a great variety of shapes, and in the samples, there is the presence of other materials that can generate confusion and an incorrect quantification; the use of this method is recommended when analyzing large plastic particles (>1 mm) [64]. Another method is the chemical method which presents more precise results such as the use of vibrational techniques used in Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy together with their microscopic variables (μFTIR or μRaman) for the identification of MPs based on the accessible references. Within the chemical method, we also have the technique of pyrolysis-gas chromatography/

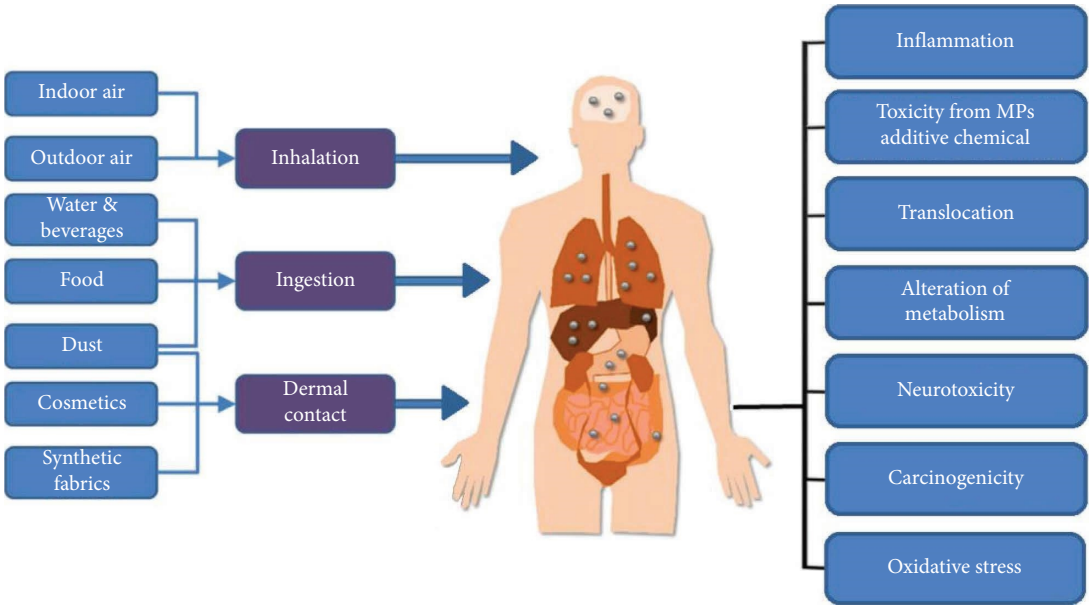

Figure 4: Schematic illustration of exposure of MPs to human health.

pyrolysis-mass spectrometry (Pyr-GC-MS), which combines two methodologies with pyrolysis [65]. Another technique to consider for the identification of MPs is scanning electron microscopy (SEM) which provides high-resolution images using the area to be studied to reveal morphological details; this study is usually complemented by energy-dispersive X-ray spectroscopy (EDS) which uses a high-energy electron beam to confirm the chemical composition of the particles, as each chemical element emits X-rays with specific energies [66]. Apart from traditional methods, various novel techniques have been developed for the detection of MPs. These techniques include thermogravimetry and differential scanning calorimetry (TGA-DSC) which analyze the properties and thermal responses of polymers in the sample, thermal extraction, desorption, gas chromatography, and mass spectrometry (TED-GC-MS) among others [67].

The integration of multiple methodologies can complement each other and help overcome the challenges associated with identifying microplastics [68] (see Figure 5). Table 2 shows a detailed overview of the primary analytical techniques used for the detection and quantification of MPs. The table focuses on various pretreatment methods and concentration techniques and highlights the advantages and disadvantages of each method.

3.5.1. Physical Method

(i) Visual inspection method: MPs can be detected through visual inspection or by microscopy to quantify their presence in the samples being analyzed. This method relies on the fact that MPs have distinct physical characteristics that make them distinguishable from other particles [82]. The evaluation of microplastics (MPs) usually involves identifying their color and shape, which can be performed without a complex analysis. This method has several advantages, such as not requiring extensive training, expensive equipment, or toxic materials. However, it may lack precision, especially when analyzing particles smaller than 500 μm [83]. Therefore, it is advisable to use this method for initial procedures or educational purposes only. It is worth noting that the margin of error can be as high as 70% due to the presence of contaminating particles in the sample that resemble MPs, making their distinction difficult [84].

3.5.2. Chemical Methods

(i) Pyr-GC/MS: At first, high-temperature thermal decomposition of polymers is carried out through pyrolysis, resulting in smaller particles [69]. The temperature range for this process can vary between 500 and 800°C. The material obtained from pyrolysis can then be separated by using a gas chromatography column based on their retention time, which can vary according to their chemical and physical properties. Finally, mass spectrometry is used to compare the results of the samples with the library of spectra to identify microplastic particles [85].

(ii) Fourier-transform infrared (FTIR): Fourier-transform infrared (FTIR) spectroscopy has three distinctive modes: transmittance, reflectance, and attenuated total reflection. Each mode is used to identify different aspects of the sample under test. In transmittance mode, the infrared spectrum is compared to identify the functional groups and chemical components present in the sample. Reflectance mode is used when the sample is too opaque for transmittance mode, and the signal cannot be measured. Finally, attenuated total

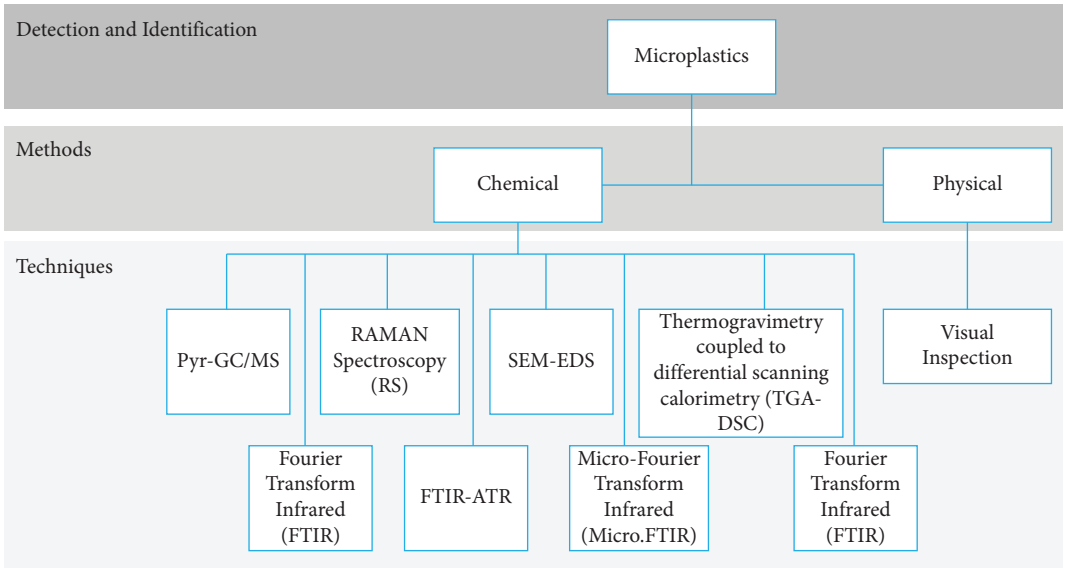

Figure 5: Methods for detection and identification of microplastics in aquatic systems.

reflection mode is used to provide a strong and easy-to-interpret signal [86]. FTIR is an invaluable tool that enables us to identify microplastics by analyzing the vibrations of the chemical bonds in their polymers and also provides us with crucial information regarding the aging of the material by analyzing the carbonyl, hydroxyl, and carbon oxygen groups. This makes FTIR an essential resource for any study or research concerning the characterization of plastic materials [87].

(iii) Raman spectroscopy (RS): This method is a powerful and noninvasive analytical technique that provides valuable information about complex molecular structures. It allows for the evaluation and identification of different types of materials without altering their integrity, as a high-energy laser with a specific wavelength used as the output source [88]. This makes it an important tool for analyzing polymers, as each polymer has its own unique Raman spectrum that can be used for identification and characterization purposes [89]. According to [90], this technique has been successfully utilized to quantify MPs with dimensions ranging from 20 μm to 50 nm even in low concentrations and complex environments.

(iv) Attenuated total reflection Fourier-transform infrared (FTIR-ATR): This technique is a relatively fast and nondestructive method that is primarily used for detecting the presence and characterization of MPs through molecular vibration analysis. To achieve better detection time and precision, it is recommended to apply a pretreatment tailored to the specific type of sample and analysis objective [91]. It is worth noting that despite the advanced technology used for detecting MPs, the method still faces several challenges. One such challenge is detecting tiny particles that are embedded in various groupings or concealed by a biological coating [92]. According to Aguirre's study [81], FTIR-ATR analysis revealed the presence of two primary types of polymers: polyester and polyethylene-vinyl acetate. The correlation rate was found to be between 0.89 and 0.96 for these polymers, indicating their identification with high accuracy.

(v) SEM-EDS: It is a highly effective analytical technique that combines scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) to identify and characterize microplastics (MPs). By using SEM to generate high-resolution images of the sample, this technique allows for the identification of the surface features and size of MPs, as well as other residues that may coincide in the sample. This information can be used to understand the degradation of MPs and to develop strategies for mitigating their harmful effects [75]. EDS is capable of providing valuable information on the chemical composition of microplastics, allowing for the identification of their types. This is made possible through the use of X-rays emitted by each element present in the sample. In addition, SEM-EDS is a powerful tool that enables visualization of both morphological and compositional data of inorganic elements with a significant amount of carbon [93].

(vi) Micro-Fourier-transform infrared (micro-FTIR): Infrared microscopy is a powerful technique that uses infrared radiation to analyze the molecular vibrations of chemical bonds. This approach allows for the identification and characterization of microscopic particles (MPs) in samples placed under observation, as each bond has its characteristic

Table 2: Table of microplastic detection methods.

Source	Identification method	Pretreatment	Concentration	Polymer type	Advantage	Limitation	Reference
Wastewater in Germany	Pyr-GC-MS	Filtration	100 μm, 50 μm, 10 μm	PE, PS	Recognition of compositions in samples; can simultaneously detect any additives present in the plastic	Destructive technology	[69, 70]
Plastic bottled water	FTIR	Sieve and wash with ethanol, freeze and oxidize with H_2O_2 or other chemicals, density separation, and sonication	6.5–100 μm	Polypropylene	Selective and reproducible (nondestructive) identification of polymer matrix, small sample quantities	It is not completely reliable with weathered samples, samples that have undergone degradation, or with samples containing mixed polymers	[23, 71]
Bottled mineral water	Raman spectroscopy	Cleaning with a 30% hydrogen peroxide (H_2O_2) solution, followed by filtration using a 47 mm diameter Whatman glass fiber filter and subsequent rinsing with deionized water	1–10 μm	PET, PE, PP	The Raman spectra of microplastics subjected to UV degradation remain virtually unchanged, and neither the shape nor the thickness of the particles affects the measurement	It is not entirely reliable on worn, colored, and degraded samples or on mixed polymer samples. Autofluorescence may mask the signal, and samples may be affected	[72, 73]
Marine mangrove	FTIR-ATR	Oxidation by density separation (30% H_2O_2)	<20 μm	PE, PP, PVC	It is primarily used to determine and describe MPs present in water and sediments. It is a cost-efficient method and does not require elaborate sample preparation or complex mathematical adjustments	The time required per particle is considerable (3 minutes per particle)	[70, 74]
Plastic water bottles	SEM-EDS	It needs to be deposited on an electrically conductive surface, using a thin layer of a conductive material, such as carbon (by vacuum evaporation) or gold and gold/palladium alloy (plasma sputter coating)	≥3 μm	PET, PE	It facilitates accurate identification of the size distribution, shape, and chemical composition of microplastic and nanoplastic particles	It can cause damage due to the electron beam and cause signs of degradation on the sample surface, resulting in high cost	[68, 75]
Water fountains in Qingdao	Micro-FTIR	Pass through a 0.45 μm nitrocellulose membrane using vacuum filtration	>10 μm	PVC, PE, PET	Particularly suitable for recognizing very small plastic particles	Measurement of irregularly shaped microplastic particles in environmental samples can generate spectra that are difficult to interpret due to refractive errors	[76, 77]
Wastewater	TGA-DSC	$ZnCl_2$ solution was added. Then, the biomass residues were oxidized using H_2O_2 (30%)	<12 μm	PE, PP	Cost-effective and straightforwardly allows determination of polymer-type concentrations and simultaneous analysis of polymer types and additives	It is only possible to identify PE and PP through destructive analysis	[78, 79]
Rivers	TED-GC-MS	Pretreated with H_2O_2 (20%) for 48 hours and 8 days	—	PE, PP, PS, PET, PA	It allows the analysis of significant amounts of samples, up to 100 mg. It is a potentially rapid and quantitative technique for the detection and identification of MPs	The absence of suitable calibration curves prevents the determination of the absolute mass content in the reference sample. If there is an overlap with another compound, certain mass fragments may be altered	[80, 81]

band in the IR spectra. By using a qualitative method, this technique enables the identification of chemical components on a microscopic scale in various ecosystems, making it a valuable tool for scientific research and analysis [94]. Micro-FTIR is a highly precise technique for detecting microplastics (MPs) with dimensions less than 100 mm. However, there is a need for further development of the technique to enable its use in large-scale studies.

(vii) Thermogravimetry coupled to differential scanning calorimetry (TGA-DSC): This technique utilizes thermal analysis and weight loss control in TGA or phase change in DSC to identify MPs. This approach facilitates the analysis of small samples and enables the identification of the thermal decomposition of parliamentarians [95]. In both scenarios, there is a possibility of errors when attempting to distinguish between different types of polymers. This is particularly true when there are polymers with similar properties, causing them to overlap and making it difficult to differentiate one from the other [96]. Majewski [78] has successfully employed this technique in various environments including wastewater. The study was able to accurately quantify PP and PE particles, but it proved challenging to distinguish other communes from MPs.

(viii) Thermal extraction desorption-gas chromatography-mass spectrometry (TED-GC-MS): The TED-GC-MS technique has proven to be a reliable method for analyzing large samples, with a weight of up to 100 mg, and accurately identifying the mass and type of MPs. This technique has the advantage of being both efficient and cost-effective as it does not require prior treatments that consume a lot of time and money. With these benefits, this method is a promising solution for identifying and analyzing MPs in various samples [97]. TED-GC-MS analysis is a powerful tool for characterizing polymers by determining the relative proportions of different types of polymers present in various environments. This information is used to identify and distinguish between different types of polymers with a high degree of accuracy [80].

3.6. Emerging Techniques for the Removal of Microplastics. Over the years, several techniques have been developed to eliminate particulate matter and contaminants from different environments. These techniques can be divided into physical, chemical, and biological methods, with each method having its own advantages and disadvantages based on the source of the particles to be removed. In this section, we will discuss the latest solutions in detail, including physical methods that use magnetic principles for water purification, such as the magnetic nanoparticle method [66]. Other physical methods include accelerated sand filtration (CAS) [98], microfiltration (MF), and ultrafiltration [99]. Moreover, various chemical methods have been proposed in the literature, including electrocoagulation [100, 101] and photocatalysis [102, 103], which have shown promising results in different applications. In this section, the biological methods used for removing microplastics are explained, with a focus on bacteria and fungi. While these eukaryotic organisms have been little studied, researchers continue to investigate their potential to efficiently remove microplastics. While this method may not be as efficient as others, ongoing research provides valuable information to enhance their effectiveness [104]. Figure 6 provides visual representations of each of the techniques used, and Table 3 offers expanded information to supplement the visuals.

3.6.1. Physical Methods of Removal. Physical removal techniques are an effective means of separating contaminants from a mixture without altering their chemical composition. These techniques leverage the physical properties of components, such as particle size, density, and morphology, to efficiently filter large amounts of pollutants. However, the effectiveness of these techniques may vary depending on the characteristics of the contamination source and the treatment method used [105]. When it comes to removing suspended solids from liquids, the sedimentation technique is commonly employed, relying on gravity to perform separation. However, particle retention-based methods such as ultrafiltration (UF) and rapid sand filtration (RSF) can also be used to remove MPs, with varying efficiency depending on their unique physical characteristics [109]. Last, the article highlights two additional methods: one that utilizes polyoxometalate magnetic absorbers and another that employs dissolved air flotation [68].

(i) Rapid sand filtration (RSF): The method exclusively relies on physical mechanisms to filter MPs by utilizing two types of force: the intermolecular van der Waals force and external forces that generate mechanical deformation. This approach ensures effective filtration and removal of MPs from the system [134]. RSF filtration involves the use of a sand layer that captures and retains solid particles. This system consists of a layer of coarse sand with a granular size ranging from 3 to 5 mm. The water passes through this layer and then goes through quartz with particles ranging from 0.1 to 0.5 mm, which effectively captures and retains the MP particles [109].

(ii) Dissolved air flotation (DAF): It is a highly effective method used for the purification of suspended particles, including MPs (particulate matter). The process involves introducing air microbubbles into water, which come into contact with the suspended particles and form a layer of sludge that can be easily removed. However, the effectiveness of the removal of MPs (microplastics) depends on various factors such as temperature, mixing speed, and air saturation. By analyzing these variables, the treatment system can be optimized to achieve better results

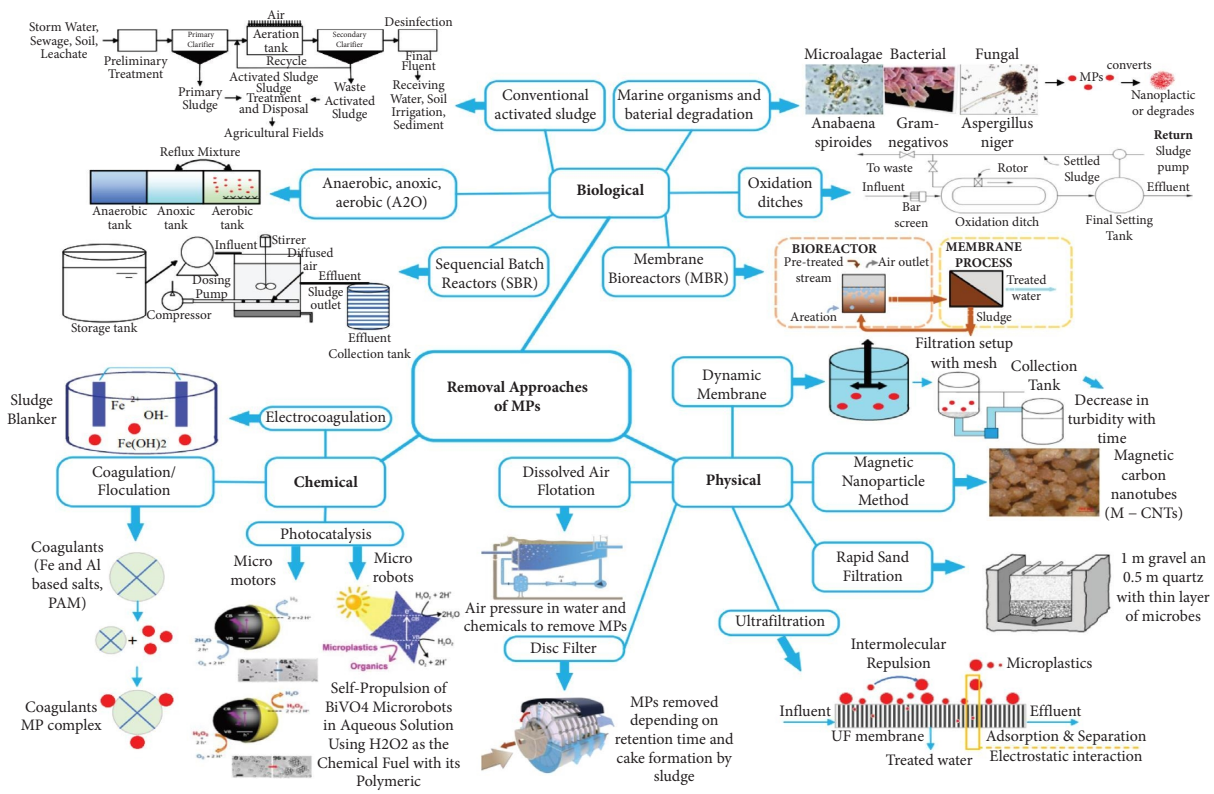

Figure 6: Microplastic removal approaches with physical, chemical, and biological methods [105–108].

[135]. The method is not only safe but also highly effective, as it eliminates the need for direct contact with toxic compounds. In addition, the DAF system is cost-effective due to its minimal maintenance requirements and energy-efficient operations [136].

(iii) Disc filter (DF): The filtration system comprises a series of circular discs, which are perforated and stacked in an airtight container. Typically, the meshes are made with high-quality polypropylene, polyester, or polyamide, which allow water to pass through while retaining any contaminating particles. The size of the pores ranges between 10 and 40 microns, making it highly effective in filtering out impurities. Numerous studies have proven the remarkable efficiency of this filtration system in producing clean and safe water. According to the research conducted by [110], the DF method demonstrated a remarkable retention rate of 89.7% for the particles, effectively capturing a significant portion of MP particles from wastewater. Over time, the surface of the filter may gradually accumulate sediment, which can lead to a decrease in filtration efficiency. To maintain optimal performance, it is recommended to periodically clean the filter by washing away any accumulated sludge using high-pressure counterflow or using sodium hypochlorite. This will help ensure that the filter continues to operate effectively and efficiently [111]. One key factor that impacts the efficiency of particle removal in a disc filter is the mesh size. A larger mesh size can filter a greater amount of particles, making it an important consideration for optimal filtration [137].

(iv) Ultrafiltration (UF): UF technology is a cost-effective way to purify water and remove contaminants without relying on expensive equipment or additives. Recent studies, such as the one mentioned by [112], have demonstrated high efficiency rates in the removal of MPs, ranging from 86% to 97.96%. The efficiency of UF depends on the size of pores, design, material, operating pressure, and maintenance carried out on the membrane used, since these factors intervene in the retention of MPs particles [138], facilitating their electrostatic interaction with each other and the membrane surface. Hence, the correct configuration of the system is of paramount importance [139].

(v) Dynamic membrane (DM): The DM method is designed to minimize the buildup of deposits in the primary membrane by utilizing a highly permeable mesh with tiny holes that are on the scale of micrometers or millimeters. This mesh aids in the formation of a sedimentary layer that functions as a secondary protective layer, thus reducing the pressure in the primary membrane [140]. An innovative approach to improve filtration efficiency involves using an additional membrane as a protective layer. This method is effective in filtering out remaining contaminant particles and MPs at a higher rate. Moreover, this system operates solely

Table 3: Methods applied in the removal of microplastics.

MP purification technologies	Removal efficiency	Advantages	Limitation	Reference
Physical methods of removal				
Rapid sand filtration (RSF)	97%	This filter removes suspended particles, microorganisms, and nutrients. It is effective in filtering small particles	It is necessary to add a coagulant to improve the adhesive ability	[109]
Dissolved air flotation (DAF)	95%	Low investment costs due to compact design, short retention time, and small dimensions of flocculation and flotation chambers	There are concerns about how interactions between bubbles/particles (aggregates), particularly in relation to adhesion through hydrophobic forces, work	[68]
Disc filter (DF)	89.7%	It has lower energy consumption, high resistance to various chemical contaminants, and is effective in reducing the presence of microplastics in wastewater effluents	Needs to be cleaned through high-pressure backwashing or using sodium hypochlorite to remove sludge buildup	[110, 111]
Ultrafiltration	86–97.96%	High retention capacity, optimal recovery rate, high-speed filtration, versatility in different application contexts, reduced cost, and absence of phase transfer	Water passing through the membrane forms a concentrated polarization layer, which negatively affects filtration efficiency due to fouling	[112, 113]
Dynamic membrane (DM)	99%	Low resistance to filtration, low transmembrane pressure, ease of operation, and absence of chemical treatment	Due to its oily nature, frequent cleaning is necessary to prevent excessive membrane fouling and sediment accumulation, which leads to high-energy consumption	[99]
Magnetic nanoparticle method	<92%	By removing organic, inorganic, microbial, and microplastic pollutants from water, the magnetic compound can be easily retrieved using a conventional magnet	It causes fragmentation of more fragile particulate matter and requires filtration suitable only for small water volumes	[103, 114, 115]
Chemical methods of removal				
Coagulation/flocculation	61%	Suitable for removing small microparticles, operating under adjustable conditions, and utilizing simple mechanical mechanisms	Chemicals must be added to the medium for small microplastics	[116]
Electrocoagulation	>90%	No risk of contamination, effective for small particle removal, cost-efficient, and flexible for automation while minimizing sludge	Repeated replacement of sacrificial anodes is necessary to prevent cathode passivation. In addition, this product is not suitable for use in areas without access to electricity	[100]
Micromotors	67%	Water is utilized as a nontoxic source for the effective removal of suspended particles and microplastics, while sunlight is harnessed as a renewable energy resource	It takes a chain of magnetic clusters to overcome obstacles and lacks selectivity	[117, 118]
Microsubmarines	70%	Sustainability is demonstrated through recycling and the elimination of oil and microplastic pollution	Microsubmarines have limited transportation capacity, thus requiring the combination of multiple microsubmarines in order to achieve sufficient capacity	[119, 120]
Biological methods of removal				
Oxidation ditches	97%	Compared to other biological treatment methods, sludge generation is reduced and less energy is consumed during the process	This method is highly efficient in smaller facilities but requires more space than traditional treatment plants	[108, 121]
Anaerobic, anoxic, and aerobic (A^2O)	72–98%	High organic loads can be handled with minimal sludge production	The anaerobic treatment process requires sufficient time to become effective	[104, 122]

Table 3: Continued.

MP purification technologies	Removal efficiency	Advantages	Limitation	Reference
Membrane bioreactors (MBR)	99.9%	It is capable of removing high levels of biological oxygen demand (BOD) and chemical oxygen demand (COD) from a variety of wastewater compositions	One of the major issues is the inability to eliminate contaminants that are resistant to removal	[123, 124]
Sequential batch reactor (SBR)	92.74%	It offers an affordable solution for achieving lower levels of effluent contaminants, allowing for easy expansion and simple operation with low capital costs	Effective aeration control is essential for optimal SBR efficiency, and the presence of sand can hinder this process	[125]
Conventional activated sludge (CAS)	95–99.9%	The treatment is cost-effective, adaptable to various tributary concentrations, and resistant to changes	The tank's long residence times, large settling surface, and high-energy consumption result in costly sludge processing and disposal	[98, 126]
Adsorption on green microalgae	94.5	The cut surfaces show a strong ability to attract small microplastic particles, and the selection is based on the surface charge of these microplastics	Nonreusable method, with microplastics that chemically adhere to the surface, potentially contaminating it	[127, 128]
Fungal degradation	59% of the weight of the MPs	Natural decomposition through enzymes produced by fungi	The removal of MPs takes a long period, as it only becomes significant after an incubation period of 280 days at a temperature of 25°C	[129, 130]
Bacterial degradation	20.4–97%	The application of bacteria is highly selective, reducing the likelihood of generating harmful byproducts. Furthermore, it consumes less energy and is more cost-effective than chemical procedures and applicable in a variety of contexts	Sometimes, the elimination of contaminants is not complete, and the process can be prolonged. Furthermore, it can be difficult to identify the right group of bacteria for efficient removal of MPs	[131–133]

on gravitational force, eliminating the need for bombs [141].

(vi) Magnetic nanoparticle method: Magnetic particle separation is a technique that enables the removal of MP fragments from water using magnetic particles. This makes it easier to treat large quantities of water, making it more advantageous than traditional filtration techniques. Magnetic particles, such as Fe nanoparticles, have a hydrophobic property, which makes it easy for them to adhere to their surface and facilitate their collection using magnetic methods [121]. According to recent research, magnetic carbon nanotubes (M-CNTs) have proven to be effective in adsorbing various polymers such as polyethylene (PE), polyethylene terephthalate (PET), and polyamide (PA). The tests carried out showed that the total removal of MPs was achieved in just 300 minutes using $5\,g{\cdot}L^{-1}$ of M-CNTs in a concentration of $5\,g{\cdot}L^{-1}$ of MPs [142]. A noteworthy study on this method was conducted by [126]. They utilized a superparamagnetic iron oxide core (Fe_2O_3, hematite) that was coated with silica (magPOM-SILPs) on the outer layer. This coating had a high affinity to interact with various contaminants such as organic and inorganic particles, germs, and MPs in aqueous solutions. The technique facilitated their extraction using a permanent magnet, making it easier to separate them from the solution.

3.6.2. Chemical Methods of Removal. Conglomerates can be formed through chemical reactions that transform the MPs in the chemical method. This process can also be utilized to decompose or make the surface of MPs adherent, which helps in extracting them from water using filters or other procedures [116]. When employing the chemical method, a common approach is to introduce certain chemicals that can interact with the polymer particles, leading to the formation of flocs. This process facilitates the filtration of MPs, but it may generate waste or sludge that needs to be collected afterwards [106]. Scientists are currently conducting studies to identify the optimal coagulants or parameters that need to be considered for efficient removal of MPs. These parameters include the type of coagulant, the appropriate dosage, and retention time [70].

(1) Coagulation/flocculation: Electrocoagulation is an effective method for removing microplastics from aquatic environments due to the negative charge of MPs. In various studies, the use of iron salts ($Fe_2(SO_4)_3.9H_2O$ and $FeCl_3.6H_2O$) and aluminum salts ($KAl(SO_4)_2.12H_2O$, $AlCl_3.6H_2O$, and $Al_2(SO_4)_3.18H_2O$) has been found to be effective in adhering to MPs. In addition, flocculants are used to facilitate the formation of globules that can be easily precipitated to the base of the coagulation tank [143]. The process of removing MPs from water before releasing them into the environment is imperative in water treatment plants. Recent tests conducted by [144, 145] have shown that coagulants containing aluminum and polyacrylamide are highly effective in removing MPs from water.

(2) Electrocoagulation: This is a potential technique to remove MPs and has the advantage that it does not leave sludge residues like coagulation, since it uses electric current in the sacrificial electrodes for the release of metal hydroxides, which precipitates MP particles, avoiding the use of chemical additives [146]. These electrodes can be made of various materials, but the most used ones are aluminum and iron, which after the electrochemical reactions produce metal ions from the anode and hydroxide ions from the cathode. The latter adhere to MPs, obtaining more voluminous conglomerates that can be filtered more easily [147].

(3) Photocatalysis: This technique for removing MP particles involves the use of solar energy to activate photocatalysts. These photocatalysts speed up chemical reactions that degrade and decompose MP particles through oxidation. The process of photocatalysis is cost-effective and does not have a negative impact on the ecosystem. Therefore, it is a promising technique for the removal of MPs [107]. One of the materials used for photocatalysis in the removal of particulate matter is titanium dioxide (TiO_2). Most studies on MP removal use TiO_2 since it can absorb light, particularly ultraviolet light, and generate pairs of electrons and holes in its crystalline structure. This occurs due to the difference in energy between the conduction and valence regions when TiO_2 is continuously exposed to light. As a result, the surface temperature rises, leading to the removal of contaminating particles from water [148], Examples of this are the micromotor and the microrobot, which will be detailed as follows:

Micromotor: These are materials capable of self-propulsion through the conversion of energy into mechanical motion. Photocatalytic activity can play a role in this process, as in the case of a study by [149], where the micromotor was made of titanium dioxide (TiO_2) and utilized the photocatalysis of hydrogen peroxide (H_2O_2) with visible light to move itself. In the absence of light, it used glucose oxidase (GOx) to continue moving. The movement of the micromotor is a result of photochemical reactions that occur in water and H_2O_2 due to electron holes [118]. In a recent study conducted by [117], TiO_2 was used as a base material, in combination with other elements, to eliminate microplastics (MPs) from water. The resulting material, called (Au@mag@TiO_2, mag = Ni, Fe), exhibited excellent mobility when exposed to UV radiation and H_2O_2 in water. When tested in river water, it demonstrated a 67% efficiency in MP removal.

Microrobots: They are a recently developed technique for eliminating MPs, based on self-propulsion using light, which allows them to interact with their surroundings. To

achieve the best results in terms of micromotor speed, various semiconductors must be tested to identify those most sensitive to light [150]. For example, the photocatalytic microrobot propelled by light, constructed with bismuth vanadate ($BiVO_4$) developed by [119], has the ability to move efficiently in aquatic environments under visible light stimulation, adhere to the surface of different polymer structures such as polylactic acid (PLA), polycaprolactone (PCL), polyethylene terephthalate (PET), and polypropylene (PP), and decompose MPs into small organic molecules and oligomers.

3.6.3. Biological Methods of Removal. The biological approach utilizes microorganisms like bacteria and fungi to break down MPs and organic substances in wastewater through aerobic and anaerobic processes. The research conducted by [151] suggests that aerobic processes are more efficient in degrading organic matter and MPs than anaerobic processes, which are primarily used for sludge stabilization. According to [152], after treatment, a total of 2.743 MP/kg (dw) are left in the sludge, indicating that microorganisms are capable of removing MPs when enzymatic activities occur [153].

(1) Oxidation ditches: The oxidation ditch treatment method is based on the principle of activated sludge. It is used for treating wastewater and involves aerobic biological processes that occur in the oxidation channel. During these processes, organic substances and MPs present in water are decomposed [154]. There are four generations in this method. In the first generation, oxidation ditches are used to combine oxygenation processes and gradual decantation of water intermittently. The second generation involves the addition of a vertical aerator with microorganisms that transform nitrogen compounds into different elements through nitrification and denitrification. Bacteria are used to transform nitrates into gaseous nitrogen (N2). The third generation achieves significant dephosphorization and denitrification, enabling the fourth generation to use a return system to improve MP removal efficiency [108]. Recent studies have demonstrated that this method is highly efficient, achieving a 97% removal rate of MPs [121].

(2) Anaerobic, anoxic, and aerobic (A^2O): The technique includes three phases: the first is anaerobic, which affects the organic load, followed by the anoxic phase, and finally the aerobic phase. Denitrification takes place during these phases, which helps in reducing the amount of nitrates in water, capturing phosphorus, and oxidizing organic material [142]. The study conducted by [126] demonstrated the effectiveness of this method in degrading microfibers, achieving a removal efficiency of 98.3%. Furthermore, another study conducted by [155] found that the method was highly efficient in removing MPs from wastewater, with a removal efficiency of 99.18%. The presence of these pollutants in the sludge further supports the potential of this technique for wastewater treatment.

(3) Membrane bioreactors (MBRs): To produce a high-quality treated effluent, a technique that uses membranes and microorganisms in an aerobic environment is employed to remove MPs. The process involves transferring the contaminated water to the bioreactor, which then filters MPs from the water flow through a membrane [156]. Filtering membranes can be classified as microfiltration or ultrafiltration depending on pore size. Most membranes have pores with a diameter of 0.1 micrometers, which easily retains MP particles and microorganisms [139]. This technique effectively eliminates MPs, but avoiding membrane fouling is crucial [157].

(4) Sequential batch reactor (SBR): It is a wastewater treatment system that is configured to work sequentially, allowing treated water to pass through all treatment phases to remove contaminating residues and fragments of MPs [158]. One of the main advantages of this system over conventional techniques is that it can perform the entire treatment in a single tank [159]. The SBR system has one inlet for wastewater and an aerator system that uses compressors with a stage for sludge renewal. Furthermore, it has an extraction mechanism to separate purified water and regulation systems to program the operating sequence [160].

(5) Conventional activated sludge (CAS): The system is designed to treat wastewater by utilizing microorganisms that break down organic matter. This system is composed of two phases. In the first phase, air is mixed with boiled water to facilitate the biodegradation of particulate matter by creating biofilms generated by microorganisms. In the second phase, decantation is performed to separate the biological sludge from the treated water, which effectively removes MPs [161]. This technology efficiently removes MPs with a 95 to 99.9% success rate, particularly from microfibers [126].

(6) Role of microalgae in the degradation of microplastics: There are certain organisms, such as the green alga *Scenedesmus dimorphus*, the diatom *Navicula pupula*, and the blue-green alga *Anabaena* that can decompose microplastics through biodegradation processes. Both high- and low-density polyethylene can be decomposed by these organisms. In fact, the degradation of low-density polyethylene (LDPE) has been noted to be particularly efficient [131]. Microalgae degrade polymeric substrates on plastic surfaces in wastewater using ligninolytic enzymes and exopolysaccharides [162].

(7) Fungal degradation of microplastics: Biodegrading plastics can be challenging due to their chemical and physical properties, which include a high molecular mass, hydrophobic nature, and low solubility.

However, using filamentous fungi in bioremediation processes presents a viable solution to tackle this issue [129]. Fungi possess the ability to trigger the creation of different chemical bonds in microplastics. These bonds include functional groups like carboxyl, carbonyl, and ester. Fungi's filamentous structures, called hyphae, are widely distributed and can penetrate the surface of polymeric materials effectively. As a result, they can establish connections and initiate the degradation process of plastics [163]. Fungi belonging to the genus *Aspergillus*, such as *Aspergillus niger*, *Aspergillus flavus*, and *Aspergillus oryzae*, are mainly used in biodegrading low-density polyethylene. This is because of their natural ability to be produced abundantly and grow extensively [164].

(8) Bacterial degradation of microplastics: Most of the bacteria that are capable of decomposing plastic materials through enzymatic processes belong to Gram-negative bacilli. Specifically, Pseudomonas bacteria have proven to be highly effective in biodegrading various plastics, including polyethylene variants of both natural and synthetic origins [165]. According to research conducted by [114], high-impact polystyrene emulsions containing nanometer-scale plastic particles showed a significant reduction in turbidity within four days of exposure to *Bacillus* spp. and *Pseudomonas* spp. strains. The study observed a decrease of 94.0% and 97.0%, respectively. According to a study conducted by [133], polyethylene sheets of 30 μm and 40 μm thickness were exposed to various types of bacteria including *Bacillus*, *Brevibacillus*, *Cellulosimicrobium*, *Lysinibacillus*, *Ochrobactrum*, and *Pseudomonas*. The study found that *Bacillus cereus* and *Brevibacillus borstelensis* had the highest biodegradation rates, with percentages of 35.7% and 20.4%, respectively.

4. Conclusions

The lack of policies that raise awareness among the population about the management of plastic waste and the poor recycling of products, together with the environmental factors that degrade them and the cosmetic and medical industry, have generated an increase in the production of MPs, which are distributed in the most remote places because they are easily transported through the air, sewage, and food, affecting the flora and fauna of the places where they are deposited. Strategies to reduce the impact of MPs on the ecosystem have focused primarily on wastewater treatment plants because the channels through which water passes make it easier to control the detection and removal of MPs. The technologies shown in this study for the detection and removal of MPs have limitations when applied, especially if applied individually, since efficiency could be reduced. So, a solution will be to combine different techniques based on their advantages and disadvantages to improve efficiency and their application in real situations, since if MP particles are too small or the water is too turbid, their identification or removal becomes more complex. Therefore, it is very important to focus on improving the detection and removal technologies of MPs, taking into account that in this study, with the aforementioned techniques, a higher concentration of MPs was detected in wastewater with concentrations that have reached up to 100 μm, and the technique with the best removal efficiency has been membrane bioreactors with an efficiency of 99.9%.

Data Availability

Data are included within the article or Supplementary Materials.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

S.L.R. and J.T.M. conceptualized the study. J.H.G. and H.J.G. proposed the methodology. J.T.M. and M.R.N. performed formal analysis. V.E.R. wrote the original draft. E.N.C. and E.H. edited and reviewed the manuscript. J.T.M. supervised the study. All the authors have read and agreed to the published version of the manuscript.

Acknowledgments

The authors would like to thank the Universidad Nacional del Callao and the Vice President for Research for their financial support for the publication of the article.

Supplementary Materials

The following supporting information can be downloaded at https://drive.google.com/drive/folders/1qR_Q8N6q7WwqTqgCxSWP9f_6z7I1aLAN?usp=sharing, Table S1: basic information on MPs in different water sources and their effects around the world. Table S2: MP detection methods. Table S3: MP removal methods. (*Supplementary Materials*)

References

[1] Y. Li, Y. Sun, J. Li, R. Tang, Y. Miu, and X. Ma, "Research on the influence of microplastics on marine life," in *Proceedings of the IOP Conference Series: Earth and Environmental Science*, vol. 631, no. 1, pp. 12006–12015, Xi'an, China, September 2021.

[2] K. Enders, R. Lenz, S. Beer, and C. A. Stedmon, "Extraction of microplastic from biota: recommended acidic digestion destroys common plastic polymers," *ICES Journal of Marine Science*, vol. 74, no. 1, pp. 326–331, 2017.

[3] T. A. Wagner, S. McLaughlin, K. Garg et al., "Proliferation of cells with HIV integrated into cancer genes contributes to persistent infection," *Science*, vol. 345, no. 6196, pp. 570–573, 2014.

[4] G. Casillas, B. C. Hubbard, J. Telfer et al., "Microplastics scoping review of environmental and human exposure data," *Microplastics*, vol. 2, no. 1, pp. 78–92, 2023.

[5] D. A. Gkika, A. K. Tolkou, E. Evgenidou et al., "Fate and removal of microplastics from industrial wastewaters," *Sustainability*, vol. 15, no. 8, p. 6969, 2023.

[6] A. L. Andrady, "The plastic in microplastics: a review," *Marine Pollution Bulletin*, vol. 119, no. 1, pp. 12–22, 2017.

[7] M. González-Hernández, C. Hernández-Sánchez, J. González-Sálamo, J. López-Darias, and J. Hernández-Borges, "Monitoring of meso and microplastic debris in Playa Grande beach (Tenerife, Canary Islands, Spain) during a moon cycle," *Marine Pollution Bulletin*, vol. 150, Article ID 110757, 2020.

[8] V. Pretell, L. Pinedo, W. Ramos, and E. Benites, "Evaluation and characterization of microplastics on three sandy beaches of Lima, Peru," in *Proceedings of the LACCEI International Multi-Conference for Engineering, Education and Technology, 2020*, Lima, Peru, March 2021.

[9] Y. Zhou, J. Wang, M. Zou, Z. Jia, S. Zhou, and Y. Li, "Microplastics in soils: a review of methods, occurrence, fate, transport, ecological and environmental risks," *Science of the Total Environment*, vol. 748, pp. 141368–141387, 2020.

[10] M. Rani, S. Ducoli, S. Federici, and L. E. Depero, "Influx of near-infrared technology in microplastic community: a bibliometric analysis," *Microplastics*, vol. 2, no. 1, pp. 107–121, 2023.

[11] S. Manzoor, H. Kaur, and R. Singh, "Existence of microplastic as pollutant in Harike wetland: an analysis of plastic composition and first report on ramsar wetland of India," *Current World Environment*, vol. 16, no. 1, pp. 123–133, 2021.

[12] M. Rai, G. Pant, K. Pant et al., "Microplastic pollution in terrestrial ecosystems and its interaction with other soil pollutants: a potential threat to soil ecosystem sustainability," *Resources*, vol. 12, no. 6, p. 67, 2023.

[13] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement," *British Medical Journal*, vol. 339, pp. 25355–b3336, 2009.

[14] M. T. Mehran, S. Raza Naqvi, M. Ali Haider, M. Saeed, M. Shahbaz, and T. Al-Ansari, "Global plastic waste management strategies (Technical and behavioral) during and after COVID-19 pandemic for cleaner global urban life," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–10, 2021.

[15] N. R. H. Aguiar and Y. J. O. Asencios, "Microplastics: characteristics, pollution, and technologies for their removal from water-a review," *Brazilian Journal of Development*, vol. 7, no. 8, pp. 78170–78199, 2021.

[16] L. C. M. Lebreton, J. Van Der Zwet, J. W. Damsteeg, B. Slat, A. Andrady, and J. Reisser, "River plastic emissions to the world's oceans," *Nature Communications*, vol. 8, pp. 15611–15710, 2017.

[17] A. L. Andrady, "Microplastics in the marine environment," *Marine Pollution Bulletin*, vol. 62, no. 8, pp. 1596–1605, 2011.

[18] B. Gewert, M. Ogonowski, A. Barth, and M. MacLeod, "Abundance and composition of near surface microplastics and plastic debris in the Stockholm Archipelago, Baltic Sea," *Marine Pollution Bulletin*, vol. 120, no. 1–2, pp. 292–302, 2017.

[19] H. K. Imhof, R. Sigl, E. Brauer et al., "Spatial and temporal variation of macro-meso- and microplastic abundance on a remote coral island of the Maldives, Indian Ocean," *Marine Pollution Bulletin*, vol. 116, no. 1–2, pp. 340–347, 2017.

[20] K. L. Law, "Plastics in the marine environment," *Annual Review of Marine Science*, vol. 9, no. 1, pp. 205–229, 2017.

[21] T. S. M. Amelia, W. M. A. W. M. Khalik, M. C. Ong, Y. T. Shao, H. J. Pan, and K. Bhubalan, "Marine microplastics as vectors of major ocean pollutants and its hazards to the marine ecosystem and humans," *Progress in Earth and Planetary Science*, vol. 8, no. 1, 2021.

[22] A. Kelly, D. Lannuzel, T. Rodemann, K. M. Meiners, and H. J. Auman, "Microplastic contamination in east Antarctic sea ice," *Marine Pollution Bulletin*, vol. 154, pp. 111130–111136, 2020.

[23] K. Waldschlager, "Microplastics in the aquatic environment," *Water and Waste*, vol. 20, no. 1–2, pp. 50–55, 2018.

[24] A. Lechner and D. Ramler, "The discharge of certain amounts of industrial microplastic from a production plant into the River Danube is permitted by the Austrian legislation," *Environmental Pollution*, vol. 200, pp. 159-160, 2015.

[25] R. Geyer, J. R. Jambeck, and K. L. Law, "Production, use, and fate of all plastics ever made," *Science Advances*, vol. 3, no. 7, 2017.

[26] A. Vianello, R. L. Jensen, L. Liu, and J. Vollertsen, "Simulating human exposure to indoor airborne microplastics using a Breathing Thermal Manikin," *Scientific Reports*, vol. 9, no. 1, pp. 8670–8712, 2019.

[27] F. Shahul Hamid, M. S. Bhatti, N. Anuar, N. Anuar, P. Mohan, and A. Periathamby, "Worldwide distribution and abundance of microplastic: how dire is the situation?" *Waste Management and Research*, vol. 36, no. 10, pp. 873–897, 2018.

[28] J. Wang, L. Zheng, and J. Li, "A critical review on the sources and instruments of marine microplastics and prospects on the relevant management in China," *Waste Management and Research*, vol. 36, no. 10, pp. 898–911, 2018.

[29] H. K. Ageel, S. Harrad, and M. A. E. Abdallah, "Occurrence, human exposure, and risk of microplastics in the indoor environment," *Environmental Sciences: Processes and Impacts*, vol. 24, no. 1, pp. 17–31, 2022.

[30] Z. Akdogan and B. Guven, "Microplastics in the environment: a critical review of current understanding and identification of future research needs," *Environmental Pollution*, vol. 254, pp. 113011–113034, 2019.

[31] S. Mhiret Gela and T. A. Aragaw, "Abundance and characterization of microplastics in main urban ditches across the bahir dar city, Ethiopia," *Frontiers in Environmental Science*, vol. 10, pp. 1–16, 2022.

[32] P. Pastorino, M. Prearo, E. Pizzul et al., "High-mountain lakes as indicators of microplastic pollution: current and future perspectives," *Water Emerging Contaminants and Nanoplastics*, vol. 13, 2022.

[33] Y. Picó and D. Barceló, "Analysis and prevention of microplastics pollution in water: current perspectives and future directions," *American Chemical Society Omega*, vol. 4, no. 4, pp. 6709–6719, 2019.

[34] A. Hasan Anik, S. Hossain, M. Alam, M. Binte Sultan, M. T. Hasnine, and M. M. Rahman, "Microplastics pollution: a comprehensive review on the sources, fates, effects, and potential remediation," *Environmental Nanotechnology, Monitoring and Management*, vol. 16, pp. 100530–100541, 2021.

[35] M. Papadimitriu and G. Allinson, "Microplastics in the Mediterranean marine environment: a combined bibliometric and systematic analysis to identify current trends and challenges," *Microplastics and Nanoplastics*, vol. 2, no. 1, 2022.

[36] C. Li, R. Busquets, and L. C. Campos, "Assessment of microplastics in freshwater systems: a review," *Science of the Total Environment*, vol. 707, Article ID 135578, 2020.

[37] R. M. Blair, S. Waldron, V. R. Phoenix, and C. Gauchotte-Lindsay, "Microscopy and elemental analysis characterisation of

microplastics in sediment of a freshwater urban river in Scotland, UK," *Environmental Science and Pollution Research*, vol. 26, no. 12, pp. 12491–12504, 2019.

[38] D. Xanthos and T. R. Walker, "International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review," *Marine Pollution Bulletin*, vol. 118, no. 1–2, pp. 17–26, 2017.

[39] M. Scheurer and M. Bigalke, "Microplastics in Swiss floodplain soils," *Environmental Science and Technology*, vol. 52, no. 6, pp. 3591–3598, 2018.

[40] S. Allen, D. Allen, V. R. Phoenix et al., "Atmospheric transport and deposition of microplastics in a remote mountain catchment," *Nature Geoscience*, vol. 12, no. 5, pp. 339–344, 2019.

[41] M. Rezaei, M. J. P. M. Riksen, E. Sirjani, A. Sameni, and V. Geissen, "Wind erosion as a driver for transport of light density microplastics," *Science of the Total Environment*, vol. 669, pp. 273–281, 2019.

[42] M. Bergmann, S. Mützel, S. Primpke, M. B. Tekman, J. Trachsel, and G. Gerdts, "White and wonderful? Microplastics prevail in snow from the Alps to the Arctic," *Science Advances*, vol. 5, no. 8, 2019.

[43] R. Ambrosini, R. S. Azzoni, F. Pittino, G. Diolaiuti, A. Franzetti, and M. Parolini, "First evidence of microplastic contamination in the supraglacial debris of an alpine glacier," *Environmental Pollution*, vol. 253, pp. 297–301, 2019.

[44] A. Cózar, E. Martí, C. M. Duarte et al., "The arctic ocean as a dead end for floating plastics in the North atlantic branch of the thermohaline circulation," *Science Advances*, vol. 3, no. 4, pp. 1–9, 2017.

[45] D. Ita-Nagy, I. Vázquez-Rowe, and R. Kahhat, "Prevalence of microplastics in the ocean in Latin America and the Caribbean," *Journal of Hazardous Materials Advances*, vol. 5, pp. 100037–100042, 2022.

[46] E. H. Lwanga, N. Beriot, F. Corradini et al., "Review of microplastic sources, transport pathways and correlations with other soil stressors: a journey from agricultural sites into the environment," *Chemical and Biological Technologies in Agriculture*, vol. 9, no. 1, p. 20, 2022.

[47] P. U. Iyare, S. K. Ouki, and T. Bond, "Microplastics removal in wastewater treatment plants: a critical review," *Environmental Science: Water Research and Technology*, vol. 6, no. 10, pp. 2664–2675, 2020.

[48] X. Xiong, Q. Liu, X. Chen, R. Wang, M. Duan, and C. Wu, "Occurrence of microplastic in the water of different types of aquaculture ponds in an important lakeside freshwater aquaculture area of China," *Chemosphere*, vol. 282, Article ID 131126, 2021.

[49] C. Wu, X. Xiong, A. H. Hamidian, Y. Zhang, and X. Xu, "A review on source, occurrence, and impacts of microplastics in freshwater aquaculture systems in China," *Water in Biological Systems*, vol. 1, no. 3, pp. 100040–100048, 2022.

[50] X. Guo and J. Wang, "The chemical behaviors of microplastics in marine environment: a review," *Marine Pollution Bulletin*, vol. 142, pp. 1–14, 2019.

[51] H. S. Ryu, J. Moon, H. Kim, and J. Y. Lee, "Modeling and parametric simulation of microplastic transport in groundwater environments," *Applied Sciences*, vol. 11, no. 16, pp. 7189–7200, 2021.

[52] K. Krishnan, "A systematic review on the impact of micro-nanoplastics exposure on human health and diseases," *Biointerface Research in Applied Chemistry*, vol. 13, no. 4, pp. 1–12, 2023.

[53] L. W. D. Van Raamsdonk, M. Van Der Zande, A. A. Koelmans et al., "Current insights into monitoring, bioaccumulation, and potential health effects of microplastics present in the food chain," *Foods*, vol. 9, no. 1, pp. 72–99, 2020.

[54] M. Smith, D. C. Love, C. M. Rochman, and R. A. Neff, "Microplastics in seafood and the implications for human health," *Current Environmental Health Reports*, vol. 5, no. 3, pp. 375–386, 2018.

[55] L. Van Cauwenberghe and C. R. Janssen, "Microplastics in bivalves cultured for human consumption," *Environmental Pollution*, vol. 193, pp. 65–70, 2014.

[56] G. Oliveri Conti, M. Ferrante, M. Banni et al., "Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population," *Environmental Research*, vol. 187, pp. 109677–109683, 2020.

[57] E. Mészáros, A. Bodor, E. Kovács et al., "Impacts of plastics on plant development: recent advances and future research directions," *Plants*, vol. 12, pp. 3282–3318, 2023.

[58] M. E. Iñiguez, J. A. Conesa, and A. Fullana, "Microplastics in Spanish table salt," *Scientific Reports*, vol. 7, pp. 8620–8627, 2017.

[59] M. F. Diaz-basantes, J. A. Conesa, and A. Fullana, "Microplastics in honey, beer, milk and refreshments in Ecuador as emerging contaminants," *Sustainability*, vol. 12, no. 14, p. 5514, 2020.

[60] M. Kedzierski, B. Lechat, O. Sire, G. Le Maguer, V. Le Tilly, and S. Bruzaud, "Microplastic contamination of packaged meat: occurrence and associated risks," *Food Packaging and Shelf Life*, vol. 24, pp. 100489–100495, 2020.

[61] B. Pandey, J. Pathak, P. Singh et al., "Microplastics in the ecosystem: an overview on detection, removal, toxicity assessment, and control release," *Water*, vol. 15, no. 1, pp. 51–81, 2022.

[62] A. Torres-Agullo, A. Karanasiou, T. Moreno, and S. Lacorte, "Overview on the occurrence of microplastics in air and implications from the use of face masks during the COVID-19 pandemic," *Science of the Total Environment*, vol. 800, pp. 149555–149563, 2021.

[63] C. G. Alimba and C. Faggio, "Microplastics in the marine environment: current trends in environmental pollution and mechanisms of toxicological profile," *Environmental Toxicology and Pharmacology*, vol. 68, pp. 61–74, 2019.

[64] S. Xiang, Y. Xie, X. Sun, H. Du, and J. Wang, "Identification and quantification of microplastics in aquaculture environment," *Frontiers in Marine Science*, vol. 8, pp. 1–10, 2022.

[65] A. R. Mccormick, T. J. Hoellein, M. G. London, J. Hittie, J. W. Scott, and J. J. Kelly, "Microplastic in surface waters of urban rivers: concentration, sources, and associated bacterial assemblages," *Ecosphere*, vol. 7, no. 11, 2016.

[66] J. W. Park, S. J. Lee, D. Y. Hwang, and S. Seo, "Recent purification technologies and human health risk assessment of microplastics," *Materials*, vol. 13, no. 22, pp. 5196–5217, 2020.

[67] R. Mansa and S. Zou, "Thermogravimetric analysis of microplastics: a mini review," *Environmental Advances*, vol. 5, Article ID 100117, 2021.

[68] Z. Zhang and Y. Chen, "Effects of microplastics on wastewater and sewage sludge treatment and their removal: a review," *Chemical Engineering Journal*, vol. 382, pp. 122955–122970, 2020.

[69] E. Hendrickson, E. C. Minor, and K. Schreiner, "Microplastic abundance and composition in western lake superior as determined via microscopy, pyr-GC/MS, and FTIR,"

Environmental Science and Technology, vol. 52, no. 4, pp. 1787–1796, 2018.

[70] H. Park and B. S. Park, "Review of microplastic distribution, toxicity, analysis methods, and removal technologies," *Water*, vol. 13, no. 19, pp. 2736–2764, 2021.

[71] S. Singh, M. Kalyanasundaram, and V. Diwan, "Removal of microplastics from wastewater: available techniques and way forward," *Water Science and Technology*, vol. 84, no. 12, pp. 3689–3704, 2021.

[72] M. I. Muhib, M. K. Uddin, M. M. Rahman, and G. Malafaia, "Occurrence of microplastics in tap and bottled water, and food packaging: a narrative review on current knowledge," *Science of the Total Environment*, vol. 865, no. 9, pp. 161274–165297, 2023.

[73] B. Nguyen, D. Claveau-Mallet, L. M. Hernandez, E. G. Xu, J. M. Farner, and N. Tufenkji, "Separation and analysis of microplastics and nanoplastics in complex environmental samples," *Accounts of Chemical Research*, vol. 52, no. 4, pp. 858–866, 2019.

[74] S. Veerasingam, M. Ranjani, R. Venkatachalapathy et al., "Contributions of Fourier transform infrared spectroscopy in microplastic pollution research: a review," *Critical Reviews in Environmental Science and Technology*, vol. 51, no. 22, pp. 2681–2743, 2021.

[75] A. V. Girão, "SEM/EDS and optical microscopy analysis of microplastics," *Handbook of Microplastics in the Environment*, Springer, Berlin, Germany, pp. 1–22, 2020.

[76] M. G. J. Löder, M. Kuczera, S. Mintenig, C. Lorenz, and G. Gerdts, "Focal plane array detector-based micro-Fourier-transform infrared imaging for the analysis of microplastics in environmental samples," *Environmental Chemistry*, vol. 12, no. 5, pp. 563–581, 2015.

[77] M. Zhang, J. Li, H. Ding et al., "Distribution characteristics and influencing factors of microplastics in urban tap water and water sources in qingdao, China," *Analytical Letters*, vol. 53, no. 8, pp. 1312–1327, 2020.

[78] M. Majewsky, H. Bitter, E. Eiche, and H. Horn, "Determination of microplastic polyethylene (PE) and polypropylene (PP) in environmental samples using thermal analysis (TGA-DSC)," *Science of the Total Environment*, vol. 568, pp. 507–511, 2016.

[79] G. Fytianos, E. Ioannidou, A. Thysiadou, A. C. Mitropoulos, and G. Z. Kyzas, "Microplastics in mediterranean coastal countries: a recent overview," *Journal of Marine Science and Engineering*, vol. 9, no. 1, pp. 98–113, 2021.

[80] S. I. Pathan, P. Arfaioli, T. Bardelli, M. T. Ceccherini, P. Nannipieri, and G. Pietramellara, "Soil pollution from micro-and nanoplastic debris: a hidden and unknown biohazard," *Sustainability*, vol. 12, no. 18, pp. 7255–7331, 2020.

[81] E. Dümichen, P. Eisentraut, C. G. Bannick, A. K. Barthel, R. Senz, and U. Braun, "Fast identification of microplastics in complex environmental samples by a thermal degradation method," *Chemosphere*, vol. 174, pp. 572–584, 2017.

[82] M. Jin, J. Liu, J. Yu et al., "Current development and future challenges in microplastic detection techniques: a bibliometrics-based analysis and review," *Science Progress*, vol. 105, no. 4, 2022.

[83] F. Zhou, X. Wang, G. Wang, and Y. Zuo, "A rapid method for detecting microplastics based on fluorescence lifetime imaging technology (FLIM)," *Toxics*, vol. 10, no. 3, p. 118, 2022.

[84] L. J. Zantis, E. L. Carroll, S. E. Nelms, and T. Bosker, "Marine mammals and microplastics: a systematic review and call for standardisation," *Environmental Pollution*, vol. 269, Article ID 116142, 2021.

[85] C. A. Peters, E. Hendrickson, E. C. Minor, K. Schreiner, J. Halbur, and S. P. Bratton, "Pyr-GC/MS analysis of microplastics extracted from the stomach content of benthivore fish from the Texas Gulf Coast," *Marine Pollution Bulletin*, vol. 137, pp. 91–95, 2018.

[86] Y. Chen, D. Wen, J. Pei et al., "Identification and quantification of microplastics using Fourier-transform infrared spectroscopy: current status and future prospects," *Current Opinion in Environmental Science and Health*, vol. 18, pp. 14–19, 2020.

[87] C. Campanale, I. Savino, C. Massarelli, and V. F. Uricchio, "Fourier transform infrared spectroscopy to assess the degree of alteration of artificially aged and environmentally weathered microplastics," *Polymers*, vol. 15, no. 4, p. 911, 2023.

[88] I. Chakraborty, S. Banik, R. Biswas, T. Yamamoto, H. Noothalapati, and N. Mazumder, "Raman spectroscopy for microplastic detection in water sources: a systematic review," *International journal of Environmental Science and Technology*, vol. 20, no. 9, pp. 10435–10448, 2022.

[89] G. Xu, H. Cheng, R. Jones et al., "Surface-enhanced Raman spectroscopy facilitates the detection of microplastics <1 μm in the environment," *Environmental Science and Technology*, vol. 54, no. 24, pp. 15594–15603, 2020.

[90] R. Gillibert, G. Balakrishnan, Q. Deshoules et al., "Raman tweezers for small microplastics and nanoplastics identification in seawater," *Environmental Science and Technology*, vol. 53, no. 15, pp. 9003–9013, 2019.

[91] J. Fojt, I. Románeková, P. Procházková, J. David, M. Brtnický, and J. Kučerík, "A simple method for quantification of polyhydroxybutyrate and polylactic acid microbioplastics in soils by evolved gas analysis," *Molecules*, vol. 27, no. 6, p. 1898, 2022.

[92] P. Mühlschlegel, A. Hauk, U. Walter, and R. Sieber, "Lack of evidence for microplastic contamination in honey," *Food Additives and Contaminants: Part A*, vol. 34, no. 11, pp. 1982–1989, 2017.

[93] H. A. Nel, A. J. Chetwynd, C. A. Kelly et al., "An untargeted thermogravimetric analysis-fourier transform infrared-gas chromatography-mass spectrometry approach for plastic polymer identification," *Environmental Science and Technology*, vol. 55, no. 13, pp. 8721–8729, 2021.

[94] Y. Zhong, Q. Bao, L. Yuan, J. Liu, Y. Cai, and X. Chen, "Analysis of microplastics in aquatic shellfish by pyrolysis–gas chromatography/mass spectrometry after alkali digestion and solvent extraction," *Polymers*, vol. 14, pp. 3888–3918, 2022.

[95] A. L. P. Silva, S. A. M. Silva, A. Duarte, D. Barceló, and T. Rocha-Santos, "Analytical methodologies used for screening micro(nano)plastics in (eco)toxicity tests," *Green Analytical Chemistry*, vol. 3, Article ID 100037, 2022.

[96] N. P. Ivleva, A. C. Wiesheu, and R. Niessner, "Microplastic in aquatic ecosystems," *Angewandte Chemie International Edition*, vol. 56, no. 7, pp. 1720–1739, 2017.

[97] K. Boyle and B. Örmeci, "Microplastics and nanoplastics in the freshwater and terrestrial environment: a review," *Water*, vol. 12, pp. 2633–2639, 2020.

[98] M. Lares, M. C. Ncibi, M. Sillanpää, and M. Sillanpää, "Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology," *Water Research*, vol. 133, pp. 236–246, 2018.

[99] L. Li, G. Xu, and H. Yu, "Dynamic membrane filtration: formation, filtration, cleaning, and applications," *Chemical Engineering and Technology*, vol. 41, no. 1, pp. 7–18, 2018.

[100] W. Perren, A. Wojtasik, and Q. Cai, "Removal of microbeads from wastewater using electrocoagulation," *American Chemical Society Omega*, vol. 3, no. 3, pp. 3357–3364, 2018.

[101] F. Miao, Y. Liu, M. Gao et al., "Degradation of polyvinyl chloride microplastics via an electro-Fenton-like system with a TiO2/graphite cathode," *Journal of Hazardous Materials*, vol. 399, pp. 123023–123031, 2020.

[102] T. S. Tofa, K. L. Kunjali, S. Paul, and J. Dutta, "Visible light photocatalytic degradation of microplastic residues with zinc oxide nanorods," *Environmental Chemistry Letters*, vol. 17, no. 3, pp. 1341–1346, 2019.

[103] F. Hooriabad Saboor, S. Hadian-Ghazvini, and M. Torkashvand, "Microplastics in aquatic environments: recent advances in separation techniques," *Periodica Polytechnica-Chemical Engineering*, vol. 66, no. 2, pp. 167–181, 2022.

[104] P. Masiá, D. Sol, A. Ardura et al., "Bioremediation as a promising strategy for microplastics removal in wastewater treatment plants," *Marine Pollution Bulletin*, vol. 156, pp. 111252–111258, 2020.

[105] A. Tursi, M. Baratta, T. Easton et al., "Microplastics in aquatic systems, a comprehensive review: origination, accumulation, impact, and removal technologies," *Royal Society of Chemistry Advances*, vol. 12, no. 44, pp. 28318–28340, 2022.

[106] N. Badola, A. Bahuguna, Y. Sasson, and J. S. Chauhan, "Microplastics removal strategies: a step toward finding the solution," *Frontiers of Environmental Science and Engineering*, vol. 16, no. 1, pp. 7–18, 2022.

[107] I. Nabi, A. U. R. Bacha, K. Li et al., "Complete photocatalytic mineralization of microplastic on TiO2 nanoparticle film," *iScience*, vol. 23, no. 7, pp. 101326–101365, 2020.

[108] S. M. Alramthi, G. H. Ali, A. M. Elthagafi, S. H. Eldosari, B. K. Zhu, and H. M. Safaa, "Oxidation ditches for recycling and reusing wastewater are critical for long-term sustainability—a case study," *Sustainability*, vol. 14, pp. 16737–16824, 2022.

[109] J. Talvitie, A. Mikola, A. Koistinen, and O. Setälä, "Solutions to microplastic pollution – removal of microplastics from wastewater effluent with advanced wastewater treatment technologies," *Water Research*, vol. 123, pp. 401–407, 2017.

[110] M. Simon, A. Vianello, and J. Vollertsen, "Removal of >10 μm microplastic particles from treated wastewater by a disc filter," *Water*, vol. 11, pp. 1935–1939, 2019.

[111] V. Fylypchuk, S. Induchny, P. Pearce, L. Fylypchuk, and S. Martynov, "Application of expanded polystyrene filter for tertiary treatment of domestic waste effluent in the UK," *Journal of Water and Land Development*, vol. 35, no. 1, pp. 41–47, 2017.

[112] J. González-Camejo, A. Morales, J. Peña-Lamas et al., "Feasibility of rapid gravity filtration and membrane ultrafiltration for the removal of microplastics and microlitter in sewage and wastewater from plastic industry," *Journal of Water Process Engineering*, vol. 51, pp. 103452–103461, 2023.

[113] L. Pittura, A. Foglia, Ç Akyol et al., "Microplastics in real wastewater treatment schemes: comparative assessment and relevant inhibition effects on anaerobic processes," *Chemosphere*, vol. 262, Article ID 128415, 2021.

[114] A. Misra, C. Zambrzycki, G. Kloker et al., "Water purification and microplastics removal using magnetic polyoxometalate-supported ionic liquid phases (magPOM-SILPs)," *Angewandte Chemie International Edition*, vol. 59, no. 4, pp. 1601–1605, 2020.

[115] J. Grbic, B. Nguyen, E. Guo, J. B. You, D. Sinton, and C. M. Rochman, "Magnetic extraction of microplastics from environmental samples," *Environmental Science and Technology Letters*, vol. 6, no. 2, pp. 68–72, 2019.

[116] B. Ma, W. Xue, Y. Ding, C. Hu, H. Liu, and J. Qu, "Removal characteristics of microplastics by Fe-based coagulants during drinking water treatment," *Journal of Environmental Sciences*, vol. 78, pp. 267–275, 2019.

[117] L. Wang, A. Kaeppler, D. Fischer, and J. Simmchen, "Photocatalytic TiO2 micromotors for removal of microplastics and suspended matter," *ACS Applied Materials and Interfaces*, vol. 11, no. 36, pp. 32937–32944, 2019.

[118] M. Padervand, E. Lichtfouse, D. Robert, and C. Wang, "Removal of microplastics from the environment. A review," *Environmental Chemistry Letters*, vol. 18, no. 3, pp. 807–828, 2020.

[119] S. M. Beladi-Mousavi, S. Hermanová, Y. Ying, J. Plutnar, and M. Pumera, "A maze in plastic wastes: autonomous motile photocatalytic microrobots against microplastics," *ACS Applied Materials and Interfaces*, vol. 13, no. 21, pp. 25102–25110, 2021.

[120] M. Sun, W. Chen, X. Fan, C. Tian, L. Sun, and H. Xie, "Cooperative recyclable magnetic microsubmarines for oil and microplastics removal from water," *Applied Materials Today*, vol. 20, pp. 100682–100692, 2020.

[121] X. Lv, Q. Dong, Z. Zuo, Y. Liu, X. Huang, and W. M. Wu, "Microplastics in a municipal wastewater treatment plant: fate, dynamic distribution, removal efficiencies, and control strategies," *Journal of Cleaner Production*, vol. 225, pp. 579–586, 2019.

[122] L. Yang, K. Li, S. Cui, Y. Kang, L. An, and K. Lei, "Removal of microplastics in municipal sewage from China's largest water reclamation plant," *Water Research*, vol. 155, pp. 175–181, 2019.

[123] J. Bayo, J. López-Castellanos, and S. Olmos, "Membrane bioreactor and rapid sand filtration for the removal of microplastics in an urban wastewater treatment plant," *Marine Pollution Bulletin*, vol. 156, pp. 111211–111219, 2020.

[124] J. Talvitie, A. Mikola, O. Setälä, M. Heinonen, and A. Koistinen, "How well is microlitter purified from wastewater?-a detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant," *Water Research*, vol. 109, pp. 164–172, 2017.

[125] P. N. Wakode and S. U. Sayyad, "Performance evaluation of 25MLD sewage treatment plant (STP) at kalyan," *American Journal of Engineering Research and Reviews*, vol. 3, no. 3, pp. 310–316, 2014.

[126] D. Sol, A. Laca, A. Laca, and M. Díaz, "Microplastics in wastewater and drinking water treatment plants: occurrence and removal of microfibres," *Applied Sciences*, vol. 11, pp. 10109–10121, 2021.

[127] I. Demir-yilmaz, N. Yakovenko, C. Roux et al., "The role of microplastics in microalgae cells aggregation: a study at the molecular scale using atomic force microscopy," *Science of the Total Environment*, vol. 832, pp. 155036–155079, 2022.

[128] F. Lagarde, O. Olivier, M. Zanella, P. Daniel, S. Hiard, and A. Caruso, "Microplastic interactions with freshwater microalgae: hetero-aggregation and changes in plastic density appear strongly dependent on polymer type," *Environmental Pollution*, vol. 215, pp. 331–339, 2016.

[129] M. E. E. Temporiti, L. Nicola, E. Nielsen, S. Tosi, and S. Tosi, "Fungal enzymes involved in plastics biodegradation," *Microorganisms*, vol. 10, no. 6, pp. 1180–1206, 2022.

[130] R. Y. Krishnan, S. Manikandan, R. Subbaiya, N. Karmegam, W. Kim, and M. Govarthanan, "Recent approaches and advanced wastewater treatment technologies for mitigating emerging microplastics contamination – a critical review," *Science of the Total Environment*, vol. 858, Article ID 159681, 2023.

[131] M. Miloloža, M. Cvetnić, D. Kučić Grgić et al., "Biotreatment strategies for the removal of microplastics from freshwater systems. A review," *Environmental Chemistry Letters*, vol. 20, no. 2, pp. 1377–1402, 2022.

[132] K. C. Omidoyin and E. H. Jho, "Effect of microplastics on soil microbial community and microbial degradation of microplastics in soil: a review," *Environmental Engineering Research*, vol. 28, no. 6, pp. 220716–220720, 2023.

[133] C. N. Muhonja, H. Makonde, G. Magoma, and M. Imbuga, "Biodegradability of polyethylene by bacteria and fungi from Dandora dumpsite Nairobi-Kenya," *PLoS One*, vol. 13, no. 7, 2018.

[134] E. Sembiring, M. Fajar, and M. Handajani, "Performance of rapid sand filter – single media to remove microplastics," *Water Supply*, vol. 21, no. 5, pp. 2273–2284, 2021.

[135] E. Wisniowska and M. Kowalczyk, "Recovery of cellulose, extracellular polymeric substances and microplastics from sewage sludge: a review," *Energies*, vol. 15, no. 20, pp. 7744–7754, 2022.

[136] Y. Wang, Y. Li, L. Tian, L. Ju, and Y. Liu, "The removal efficiency and mechanism of microplastic enhancement by positive modification dissolved air flotation," *Water Environment Research*, vol. 93, no. 5, pp. 693–702, 2021.

[137] K. Nielsen, A. Mørch-Madsen, P. S. Mikkelsen, and E. Eriksson, "Effect of disc filtration with and without addition of flocculent on nano-and micro-particles and their associated polycyclic aromatic hydrocarbons in stormwater," *Water*, vol. 7, no. 12, pp. 1306–1323, 2015.

[138] J. Zhang, G. Li, X. Yuan et al., "Reduction of ultrafiltration membrane fouling by the pretreatment removal of emerging pollutants: a review," *Membranes*, vol. 13, no. 1, pp. 77–126, 2023.

[139] W. Liu, J. Zhang, H. Liu et al., "A review of the removal of microplastics in global wastewater treatment plants: characteristics and mechanisms," *Environment International*, vol. 146, Article ID 106277, 2021.

[140] Y. J. Lim, S. M. Lee, R. Wang, and J. Lee, "Emerging materials to prepare mixed matrix membranes for pollutant removal in water," *Membranes*, vol. 11, no. 7, pp. 508–532, 2021.

[141] L. Li, G. Xu, H. Yu, and J. Xing, "Dynamic membrane for micro-particle removal in wastewater treatment: performance and influencing factors," *Science of the Total Environment*, vol. 627, pp. 332–340, 2018.

[142] H. Lee and Y. Kim, "Treatment characteristics of microplastics at biological sewage treatment facilities in Korea," *Marine Pollution Bulletin*, vol. 137, pp. 1–8, 2018.

[143] A. Abomohra and D. Hanelt, "Recent advances in micro-/nanoplastic (MNPs) removal by microalgae and possible integrated routes of energy recovery," *Microorganisms*, vol. 10, no. 12, pp. 2400–2419, 2022.

[144] T. K. Dey, E. Uddin, and M. Jamal, "Detection and removal of microplastics in wastewater: evolution and impact," *Environmental Science and Pollution Research*, vol. 28, no. 14, pp. 16925–16947, 2021.

[145] R. Triebskorn, T. Braunbeck, T. Grummt et al., "Relevance of nano- and microplastics for freshwater ecosystems: a critical review," *TrAC, Trends in Analytical Chemistry*, vol. 110, pp. 375–392, 2019.

[146] D. N. Tito, P. Krystynik, and P. Kluson, "Notes on process and data analysis in electro-coagulation-The importance of standardisation and clarity," *Chemical Engineering and Processing: Process Intensification*, vol. 104, pp. 22–28, 2016.

[147] D. Elkhatib, V. Oyanedel-Craver, and E. Carissimi, "Electrocoagulation applied for the removal of microplastics from wastewater treatment facilities," *Separation and Purification Technology*, vol. 276, Article ID 118877, 2021.

[148] J. Arun, S. Nachiappan, G. Rangarajan, R. P. Alagappan, K. Gopinath, and E. Lichtfouse, "Synthesis and application of titanium dioxide photocatalysis for energy, decontamination and viral disinfection: a review," *Environmental Chemistry Letters*, vol. 21, no. 1, pp. 339–362, 2023.

[149] W. Noh, S. Jo, J. Kim, and T. S. Lee, "Visible-light-driven asymmetric TiO2-based photocatalytic micromotor hybridized with a conjugated polyelectrolyte and glucose oxidase," *Langmuir*, vol. 37, no. 20, pp. 6301–6310, 2021.

[150] K. Villa, L. Děkanovský, J. Plutnar, J. Kosina, and M. Pumera, "Swarming of perovskite-like Bi2WO6 microrobots destroy textile fibers under visible light," *Advanced Functional Materials*, vol. 30, no. 51, pp. 1–10, Article ID 2007073, 2020.

[151] Y. Li, "Technology review and selection guide for industry wastewater treatment," *Computational Water, Energy, and Environmental Engineering*, vol. 9, no. 2, pp. 22–35, 2020.

[152] D. Harley-Nyang, F. A. Memon, N. Jones, and T. Galloway, "Investigation and analysis of microplastics in sewage sludge and biosolids: a case study from one wastewater treatment works in the UK," *Science of the Total Environment*, vol. 823, Article ID 153735, 2022.

[153] J. P. Harrison, M. Sapp, M. Schratzberger, and A. M. Osborn, "Interactions between microorganisms and marine microplastics: a call for research," *Marine Technology Society Journal*, vol. 45, no. 2, pp. 12–20, 2011.

[154] W. Wang, C. Shi, J. Yang, M. Zeng, Z. Dai, and Z. Zhang, "Modelling performance of oxidation ditch in wastewater treatment plant by STOAT software," *IOP Conference Series: Earth and Environmental Science*, vol. 300, no. 3, Article ID 032065, 2019.

[155] A. Nur, P. Soewondo, A. S. Setiyawan, and K. Oginawati, "Microplastics in the continuous biofilm reactor: occurrence, fate, and removal," *IOP Conference Series: Earth and Environmental Science*, vol. 1065, no. 1, Article ID 012012, 2022.

[156] A. O. Adeniji, K. Okaiyeto, J. N. Mohammed, M. Mabaleha, E. B. Tanor, and M. J. George, "A mixed method assessment of research productivity on microplastics in various compartments in the environment," *International journal of Environmental Science and Technology*, vol. 20, no. 11, pp. 12847–12874, 2023.

[157] T. U. Rahman, H. Roy, M. R. Islam et al., "The advancement in membrane bioreactor (MBR) technology toward sustainable industrial wastewater management," *Membranes*, vol. 13, no. 2, p. 181, 2023.

[158] S. Sathian, M. Rajasimman, G. Radha, V. Shanmugapriya, and C. Karthikeyan, "Performance of SBR for the treatment of textile dye wastewater: optimization and kinetic studies," *Alexandria Engineering Journal*, vol. 53, no. 2, pp. 417–426, 2014.

[159] H. A. Aziz, N. N. A. Puat, M. Y. D. Alazaiza, and Y. T. Hung, "Poultry slaughterhouse wastewater treatment using submerged fibers in an attached growth sequential batch

reactor," *International Journal of Environmental Research and Public Health*, vol. 15, no. 8, pp. 1734–1812, 2018.

[160] D. R. Prajapati and N. Kaur, "Process capability in terms of TSS in waste water treatment technology," *International Journal of Environment and Waste Management*, vol. 19, no. 3, pp. 203–215, 2017.

[161] A. Mohammad R and A.-A. Qusay, "Eco-friendly microplastic removal through physical and chemical techniques: a review," *Annals of Advances in Chemistry*, vol. 7, no. 1, 2023.

[162] U. Anand, S. Dey, E. Bontempi et al., "Biotechnological methods to remove microplastics: a review," *Environmental Chemistry Letters*, vol. 21, no. 3, pp. 1787–1810, 2023.

[163] C. Li, B. Jiang, J. Guo et al., "Aging process of microplastics in the aquatic environments: aging pathway characteristic change, compound effect, and environmentally persistent free radicals formation," *Water*, vol. 14, no. 21, pp. 3515–3543, 2022.

[164] G. C. DSouza, R. S. Sheriff, V. Ullanat et al., "Fungal biodegradation of low-density polyethylene using consortium of Aspergillus species under controlled conditions," *Heliyon*, vol. 7, 2021.

[165] S. Thakur, S. Mathur, S. Patel, B. Paital, and B. Paital, "Microplastic accumulation and degradation in environment via biotechnological approaches," *Water*, vol. 14, no. 24, pp. 4053–4073, 2022.