

Article

Review and Analysis of Methods for Separating Plastic Micro-Particles from Pipe Systems, Taking into Account Efficiency and Automation Potential

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Abstract

The issue of microplastics in the aquatic environment has become one of the key topics in contemporary environmental engineering, chemical engineering and materials technology. Plastic microparticles are found not only in natural waters, but also in industrial and municipal piping systems, process installations and even in drinking water, posing a growing threat to public health, ecosystem stability and the reliability of technical equipment. Due to its chemical resistance, hydrophobicity and variety of sizes and shapes, microplastics are difficult to remove using traditional separation methods, and their harmful impact is part of a broader analysis of the life cycle of plastics, from their production and use to the waste phase and their impact on the environment. In response to the scale of the phenomenon, a number of liquid–solid separation methods have been developed, including approaches based on physical, chemical and biological principles. These methods vary in their scope of application, operational requirements and the way they interact with the particles present in the flow. The scientific literature describes mechanical techniques, chemical reactions and the interaction of biological organisms in a controlled environment as the main groups of separation. Each group has specific limitations resulting from the properties of microplastics, flow conditions and medium characteristics, which means that the choice of separation technology must take into account the specific nature of the system in question. The development of advanced measurement methods, monitoring systems and control techniques enables more accurate observation and analysis of particle movement, as well as the study of the relationship between device operating parameters and the behaviour of contaminants in the flow. The increasingly widespread use of measurement data, predictive algorithms and pattern recognition techniques makes it possible to describe the phenomena accompanying microplastic separation in greater detail and to formulate new concepts for devices and flow systems based on analytical methods, computational tools and adaptive control systems is in line with current trends in process engineering and automation, as well as with the concept of Industry 4.0. Taking the above information into account, the aim of this work is to analyse selected liquid–solid separation methods in order to identify the most optimal in terms of the effectiveness of removing plastic microparticles, with the assumption of the greatest possible number of features indicating the possible future automation of a given process.



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1. Introduction

Materials based on synthetic polymers are finding increasingly widespread applications both in industry and in domestic environments. Their ubiquity, while beneficial from an economic and functional perspective, is simultaneously associated with the emission of waste of varying scales—from nanoparticles and microfibrils to larger macro-sized elements. This phenomenon poses a real threat to the natural environment. As demonstrated by M. Brown et al., water samples with a volume of 250 mL contained, on average, approximately 20 polyester or acrylic fibres, with values depending on the sampling region [1]. In recent years, plastic microparticles have infiltrated both marine and freshwater ecosystems, exerting a significant negative impact on local fauna and flora. The degradation of macroplastic elements, induced among others by UV radiation, salinity, or biofouling, leads to the gradual fragmentation of material and the successive formation of macro-, meso-, micro-, and nano-plastics. During a NOAA conference, it was established that microplastics should be defined as particles with diameters ranging from 333 μm to 5 mm, regardless of their visibility to the naked eye [2]. According to commonly accepted classifications, microplastics are divided into primary and secondary types. Primary plastic particles include elements intentionally manufactured for industrial purposes, such as microbeads used in cosmetics, granules, or microfibrils released during the washing of synthetic textiles. Secondary microplastics, in contrast, are generated through the fragmentation of larger polymer waste, including plastic bags, bottles, fishing nets, and structural components. Studies by D. Cooper and P. Corcoran indicate that the highest accumulation of microplastic fibres is observed in highly urbanised and industrialised regions, where daily deposition rates may reach up to 400 fibres [3,4]. These findings reinforce the hypothesis of a strong correlation between the degree of anthropogenic pressure and the level of contamination of aquatic environments. Plastic microparticles are characterised by high chemical and physical stability, allowing them to persist in aquatic environments for hundreds or even thousands of years. Properties once regarded as a structural advantage now constitute one of the main factors of ecological risk. Microplastics exhibit the ability to adsorb heavy metals, organic pollutants, and pathogenic bacteria, thereby increasing threats to both ecosystems and human health. J. Antunes et al. demonstrated the presence of highly toxic substances such as engine oils, PCBs, and DDT in environmental samples, highlighting the role of microplastics as carriers and concentrators of these contaminants [5,6]. As microparticles enter food chains, these pollutants may undergo biomagnification, leading to delayed and difficult-to-attribute ecological effects. An important aspect of the problem also concerns the consequences for technical systems, particularly hydraulic pipeline installations, in which microparticles may act as abrasive material. This accelerates the wear of operational components, generates leaks, and reduces the energy efficiency of systems. Many mechanisms operate in marine environments where, despite high salinity and favourable sedimentation processes, the problem persists. P. Bhatt et al. reported that the amount of floating plastic waste remains at approximately 250,000 tons, indicating the insufficiency of natural ocean self-cleaning mechanisms [5]. In response to the growing threat, intensive research is being conducted on methods for separating solid particles from aqueous media. These efforts include both laboratory experiments and field tests in real pipeline installations and port environments. The need for standardisation and validation of separation methods is becoming increasingly urgent, particularly in the context of European regulations concerning marine environmental protection. As noted by J. Gago et al., environmental assessment systems should encompass all fractions of plastic pollution, not only the microscale, and should consider the full spectrum of available separation methods [7,8]. Microplastic separation methods are typically classified into three groups: physical, chemical, and biological. L. Dayal et al., analysing over 250 publications

on liquid–solid separation, demonstrated that the effectiveness of available methods exceeds 85% in most cases, although none guarantees complete removal of microparticles [8]. Physical methods, including filtration, adsorption, magnetic and acoustic separation, and foam flotation, preserve the properties of both the medium and the microparticles. Their advantages include simplicity and low cost; however, susceptibility to human error and limitations resulting from the presence of organic contaminants significantly reduce their effectiveness [9–11]. Chemical methods, such as coagulation, flocculation, electrochemical oxidation processes, and photodegradation, enable the transformation of microplastics into less toxic forms. S. Ahmed et al. identify electrocoagulation as one of the most promising methods, although its drawbacks include limited electrode lifespan and the need for precise control of process parameters [12,13]. Biological methods, in turn, exploit the sorption or degradation capabilities of living organisms. As noted by W. Gao, fungi exhibit particularly high degradation potential due to their ability to colonise surfaces, high resistance, and production of a wide spectrum of degradative enzymes. For safety reasons, however, they are mainly considered as components of closed or semi-closed systems [14]. The comprehensive analysis of separation methods presented by L. Dayal includes their classification, evaluation of operational efficiency, and investment potential. The authors emphasise that physical methods exhibit the highest practical potential, provided they are integrated with modern measurement systems, adaptive control, and data analysis tools, thereby enabling the use of numerical methods, statistical analyses, and artificial intelligence [8,15]. This clearly indicates that the future of separation systems—including those applied in pipeline installations—lies in the direction of automation and intelligent process supervision.

Problem Definition and Characterisation of Microplastics

In order to enable a consistent and comparable evaluation of microplastic separation methods, this study defines a specific set of particle characteristics, process variables, and performance metrics relevant to aqueous pipeline systems. The analysis focuses on microplastics occurring in water, wastewater, and drinking water infrastructure, where continuous operation, limited installation space, and stable hydraulic conditions impose strict engineering constraints. In this study, microplastics are defined as plastic particles with characteristic dimensions of less than 5 mm. In this size class, plastics occur mainly as irregular fragments, fibres, and less frequently as spherical or nearly spherical particles. Fibrous and fragmentary shapes are particularly relevant for separation analysis because they dominate reported occurrences in sewage systems and drinking water and exhibit more complex hydrodynamic and interfacial behaviour than idealised spherical particles [5,9,10]. Particle size and morphology are therefore considered key factors influencing separation efficiency, especially for physical methods based on size exclusion, buoyancy, or interactions between waves and particles. The chemical composition of the analysed microplastics includes polymers most commonly found in aquatic environments: polyethylene and polypropylene, composed of non-polar hydrocarbon chains; polystyrene, containing aromatic functional groups; and polyethylene terephthalate, characterised by ester bonds in the polymer backbone. These material differences determine the density of the polymer, surface polarity, and susceptibility to chemical and biological processes. Low-density polyolefins, such as polyethylene and polypropylene, favour buoyancy- and acoustic-based separation, while higher-density polymers, such as polystyrene and polyethylene terephthalate, show increased affinity for coagulation- and oxidation-based methods. Reported microplastic concentrations vary significantly depending on the water matrix and treatment stage. In this study, concentration is treated as a variable reflected in reported separation efficiencies rather than a constant value. The separation methods considered are classified as physical, chemical, or biological and are evaluated under operating conditions relevant

to pipeline systems. Performance is assessed using removal efficiency, final concentration where available, process cost and energy demand. For chemical and biological methods, reported degradation or transformation efficiencies are interpreted in accordance with the definitions used in the source studies. This problem definition provides the basis for the comparative and multi-criteria analyses presented in the subsequent sections.

2. Materials and Methods

To develop a reliable and comparable analysis of technologies used for separating microplastic particles from aquatic media, a three-stage research methodology was adopted, combining elements of classification, a literature review, and parameter-based evaluation grounded in experimental studies. The fundamental assumption was to ensure the possibility of an objective comparison of methods with different operating mechanisms, as well as to adapt the assessment criteria to the specific characteristics of pipeline systems, which are marked by limited installation space, variable flow conditions, and the requirement for high operational continuity. The applied three-stage methodology consisted of: (I) classification of microplastic separation methods based on their physical, chemical, or biological principles, (II) a semi-quantitative, criteria-based evaluation adapted to the constraints of a continuous pipeline system, and (III) selection of representative methods from each group based on frequency of occurrence and technological maturity analyzed on the basis of data available in the literature [8,11,14].

2.1. Methodology for Selecting Effective Separation Methods

The methodology for comparing plastic microparticle separation technologies was developed to enable the selection of a method that can be implemented in the most effective, stable and automatable way in pipe systems operating in real-world conditions. The key element was not only to describe the available technologies and categorise them in the traditional way but above all to develop a consistent assessment logic that would make it possible to identify a solution combining high separation efficiency with minimal medium losses, low operating requirements and resistance to environmental parameter variability. Particular emphasis was placed on the possibility of automating the process, as this is now a critical factor for reducing costs, ensuring the continuity of production facilities, and resisting changing operating conditions. The scientific literature clearly indicates that separation methods can be divided into three main groups: physical, chemical, and biological. Three representative methods were selected from each category to ensure methodological balance while avoiding overrepresentation of any single technological group, as recommended in comparative reviews of separation technologies. The selected physical methods include membrane filtration, acoustic separation and foam flotation, while the chemical methods representing this group are coagulation and flocculation, electrocoagulation and advanced oxidation processes. In biological methods, biosorption, enzymatic biodegradation and microbial degradation involving fungi show the greatest potential in the literature. Each of these methods represents a different approach to separation, so in order to make the most reliable comparison possible, it is necessary to develop a consistent set of criteria that relate to the actual operational challenges of piping systems. The following criteria were adopted as the main criteria:

- K1—Minimum implementation cost
- K2—High efficiency
- K3—High potential for automation
- K4—Small loss of medium
- K5—High resistance to environmental conditions

To determine the relative importance of the adopted criteria (K1–K5), a structured pairwise comparison approach was applied. Each criterion was directly compared with every other criterion using a three-level preference scale, where 0 denotes lower importance, 0.5 denotes equal importance, and 1 denotes higher importance with respect to applicability in continuous pipeline systems. The comparison results were organised in the form of a pairwise comparison matrix (Table 1). For each criterion, the individual comparison scores were aggregated by summing the values in the corresponding matrix row. In order to enable further multicriteria evaluation and ensure numerical consistency, the obtained row sums were normalised by dividing each value by the total sum of scores across all criteria. This procedure yielded a normalised weight vector with a total sum equal to 1.0, which was subsequently used in the criteria-based assessment of the analysed separation methods.

Table 1. List of criteria weights for assessment. The obtained weights were normalised so that their sum equalled 1.0 before being used in the multi-criteria scoring.

	K1	K2	K3	K4	K5	$\Sigma = 8.0$
K1	x	0	0	0.5	0.5	0.5
K2	1	x	0.5	1	1	3.5
K3	1	0.5	x	0.5	1	2
K4	0.5	0	0.5	x	0.5	1
K5	0.5	0	0	0.5	x	1

Based on the column sum values, normalised criteria weights were calculated by dividing each row sum by the total sum of all criteria scores ($\Sigma = 8.0$). The resulting weights were: K1 = 0.0625, K2 = 0.4375, K3 = 0.25, K4 = 0.125, and K5 = 0.125. First, separation efficiency (K2) was analysed, as it represents the dominant criterion; any method that does not remove microplastics in a stable and repeatable manner cannot be considered practically useful. At the same time, medium losses (K4) were taken into account, since processes that result in significant water loss or require water regeneration become economically unviable in high-flow systems. The next aspect considered was low implementation cost (K1), understood as the ease of integrating a given method into existing pipeline installations. This criterion includes both the geometric requirements of separation devices and the possibility of inline installation, which directly affects investment costs and the extent of necessary infrastructure modifications. Resistance to environmental conditions (K5) was also considered; however, under closed-loop operating conditions, its influence becomes secondary once minimum stability requirements are met. Automation capability (K3) emerged as the second most influential criterion and a key enabling factor for practical implementation. Modern industrial systems increasingly operate within intelligent installations equipped with flow, pressure, and turbidity sensors, as well as PLC-based control architectures. Consequently, the separation method must allow full real-time control of process parameters. This applies both to monitoring separation efficiency and to the ability to dynamically adjust operating parameters such as ultrasound intensity, electrode voltage, coagulant dosing, or flow rate. Methods that require intensive manual operation, frequent visual inspection, or operator intervention are significantly more prone to measurement errors and difficulties in maintaining consistent performance. As a result, methods that combine high efficiency with strong automation potential can be clearly identified as the most effective and promising options for separation in the context of intelligent and fully automated pipeline systems.

2.2. Physical Methods

Physical methods for microplastic separation are based on exploiting differences in particle size, density, surface properties, or their response to mechanical and wave-based interactions, without the need to modify their chemical structure. Their main advantages include the ability to operate in continuous mode, relatively straightforward integration, and a high potential for automation, which makes them particularly attractive for industrial applications. Depending on the separation mechanism employed, microplastic particles may be retained on a physical barrier, transported within a wave field, or lifted at a phase boundary [8,9].

Membrane filtration is currently one of the most thoroughly researched methods for removing microplastics. Membranes used in water treatment systems have varying porosity, which allows for the precise retention of particles across a wide range of sizes. Studies have shown that microfiltration with pores ranging from 0.1 to 10 μm removes 78 to 92% of microplastics, while ultrafiltration achieves 91 to 99% efficiency and nanofiltration up to 97 to 100%. This means that membranes are capable of almost completely removing polymer particles, even if they occur in the form of fine fibres or flakes of secondary microplastics. Studies of composite membranes show that the energy required for filtration ranges from 0.25 to 0.45 kWh per cubic metre of flowing medium, which is relatively low for industrial applications. The operating cost of membrane filtration, including energy and periodic regeneration, averages 0.12–0.25 euros per cubic metre of water, while the cost of replacing membranes occurs every 18–36 months. Medium losses are low, typically ranging from 3 to 10% of volume, most of which is due to periodic backwashing, which is fully automated. Membrane filtration is also resistant to changing environmental conditions. The membranes remain stable at temperatures between 5 and 60 $^{\circ}\text{C}$, can operate in environments with a pH between 3 and 10, and are relatively resistant to the presence of mineral suspensions. The most important operational problem remains fouling, i.e., the accumulation of contaminants on the membrane surface. Studies show that membrane permeability can decrease by 20–35% within eight hours of operation without flushing, and in the case of biofouling, by as much as 50%. Nevertheless, this process can be effectively controlled by automatic regeneration systems, making it susceptible to automation-based modifications [8,12,13,16].

Acoustic separation, also known as ultrasonic separation, is a technology used mainly in microfluidics, but research results indicate its very high potential in tubular applications, especially where contact-free operation and minimal losses are desired. The process involves generating ultrasonic waves in the range of 0.5–5 MHz, which creates pressure gradients that move microplastics towards the nodes or antinodes of the standing wave. The separation efficiency is estimated at 85 to 95%, depending on the frequency, system geometry and polymer properties. Importantly, for low-density particles, efficiency can exceed 90% even at high flow rates. Acoustic separation is characterised by very low medium losses, as the process does not require any filtration or water retention—the particles are not retained on the membrane but are moved to a separate zone from which they can be removed. The energy consumed by the ultrasonic generator is typically 0.05–0.15 kWh per cubic metre. Due to the absence of moving parts and the lack of need for chemicals, the process is characterised by very high stability and low operating costs. The biggest advantage of acoustic separation is its unique automation potential. The entire process can be controlled electronically, and parameters such as frequency, amplitude and ultrasonic power can be dynamically adjusted based on signals from flow and turbidity sensors. Studies have shown that such systems remain stable even at variable medium velocities. However, a limitation remains in the form of reduced effectiveness in the

presence of large amounts of organic suspensions, which dampen ultrasonic waves, and at flow rates significantly exceeding 2–3 m/s [15,17–19].

Foam flotation is one of the oldest methods of separating hydrophobic particles. Studies confirm that flotation achieves an efficiency of 80 to 92%, depending on the type of polymer, its degree of oxidation, particle size and the presence of surfactants. Due to its hydrophobicity, microplastic easily attaches to air bubbles, which allows it to be carried to the surface. The cost of implementing flotation is significantly lower than membrane filtration or acoustic separation—flotation installations are among the cheapest solutions, with operating costs of only €0.02–0.05 per cubic metre. Energy consumption is minimal, usually less than 0.03 kWh/m³, especially when mechanical aeration is used. Medium losses are also very low, as only a thin layer of foam is removed. However, foam flotation has a lower automation potential than membrane filtration or ultrasonic separation. Foam parameters such as height, stability and particle content require constant monitoring, and the presence of oils or organic substances can interfere with the process. Furthermore, this method is sensitive to changes in temperature and viscosity of the medium [8,20–22].

2.3. Chemical Methods

Chemical methods for microplastic separation are based on chemical interactions with polymer particles or the carrier medium, aiming to modify their physicochemical properties, such as surface charge, tendency to agglomerate, or susceptibility to degradation. Unlike physical methods, chemical processes do not always result in the direct mechanical separation of microplastics; instead, they often serve as an intermediate stage that facilitates subsequent removal through sedimentation, flotation, or filtration processes.

Coagulation and flocculation are among the most common chemical processes used in water and wastewater treatment. Their mechanism of action involves destabilising particles suspended in a liquid by neutralising their surface charge and forming larger agglomerates, which can then be removed by sedimentation, flotation or filtration. Coagulation and flocculation allow for the removal of approximately 60 to 75% of microplastics present in liquids, while with the use of additional separation stages, such as sedimentation or filtration, this efficiency increases to 70–83%. However, it is worth noting that the effectiveness of coagulation is strongly dependent on the morphology of microplastics—larger fragments and granules are removed more effectively than thin synthetic fibres, for which the effectiveness often does not exceed 60–65%. From an economic point of view, coagulation is one of the cheapest chemical methods; the cost of coagulants, such as ferric chloride or aluminium sulphate, together with the energy required for mixing, is usually between 0.04 and 0.10 euro per cubic metre of treated water. Energy consumption is low, ranging from 0.005 to 0.015 kWh/m³, while medium losses associated with the discharge of microplastic-containing sludge are typically between 1 and 3% of the volume. This method has moderate automation potential, as it requires constant monitoring of parameters such as quantitative acidity and alkalinity (pH scale), coagulant dosage and mixing speed, but it is relatively resistant to changing environmental conditions and easy to implement in existing installations [8,23,24].

Electrocoagulation is an advancement of classic coagulation, in which galvanic anodes, most often made of iron or aluminium, act as a source of coagulating ions. Under the influence of electric current, they dissolve and form metal hydroxo complexes, which effectively bind microplastic particles. Studies conducted on sewage and post-treatment water indicate that electrocoagulation achieves significantly higher efficiency than conventional chemical coagulation, reaching 85–96%, and in the case of synthetic fibres, even 90–98% after a process time of 20–30 min. This efficiency is also maintained with smaller microplastic fragments, which makes electrocoagulation particularly attractive for piping

systems where it is difficult to use very fine mechanical filters. However, the cost of electrocoagulation is significantly higher than that of conventional coagulation. Electricity consumption is typically between 0.15 and 0.45 kWh/m³, and the total cost of the process, including energy and electrode consumption, is between 0.20 and 0.55 euros per cubic metre. Media losses are relatively low, ranging from 0.5 to 2%, but the need for periodic electrode replacement remains a significant operating factor. From an automation point of view, electrocoagulation is very advantageous because parameters such as current, voltage and process time can be fully controlled electronically, allowing for easy integration with industrial automation systems and continuous operation [8,25–27].

Advanced oxidation processes (AOPs) comprise a group of technologies that use highly reactive radicals, mainly hydroxyl radicals, for the chemical degradation of microplastics. Unlike coagulation and electrocoagulation, AOPs do not focus on the physical removal of particles, but on their structural damage, reduction in molecular weight and gradual fragmentation. Studies indicate that, depending on the technology used (UV/H₂O₂, ozonation, TiO₂ photocatalysis), it is possible to reduce the mass of microplastics by 20–55% in a few to several hours, as well as to reduce the average particle size by up to 30–70%. These processes significantly increase the hydrophilicity and susceptibility of microplastics to further separation or biodegradation but rarely lead to their complete mineralisation. From an economic point of view, AOPs are the most expensive of the chemical methods analysed. Energy consumption ranges from 0.30 to as much as 1.50 kWh/m³, and the total cost of the process, including energy and reagents (e.g., hydrogen peroxide, ozone), is between 0.25 and 0.90 euros per cubic metre. Medium losses are minimal, usually less than 0.2%, as the process does not generate sludge. AOPs have a high potential for automation, but their use in piping systems requires adequate contact time and stable process conditions, which limit their use as a stand-alone separation method [8,28–31].

2.4. Biological Methods

Biological methods for the separation and reduction of microplastics rely on biological or biochemical interactions between polymer particles and naturally derived materials, enzymes, or living microorganisms. In contrast to physical and chemical methods, biological processes are generally characterised by longer reaction times, greater sensitivity to environmental conditions, and limited applicability in systems with high flow rates. Their potential advantages include relatively low material costs and the possibility of partial degradation or immobilisation of microplastics without the use of intensive mechanical processes.

Biosorption involves the capture of microplastics by biological or biogenic materials such as biochar, biomass or algae. The literature data indicate that the effectiveness of microplastic biosorption under laboratory conditions is typically between 60 and 95%, with the highest values achieved for biochar with a high specific surface area (>300 m²/g) and materials chemically modified to increase hydrophobicity. The material cost of biosorbents is relatively low, ranging from approximately €0.05 to €0.20 per m³ of treated water, depending on the source, but this cost does not take into account the need to regenerate or dispose of spent sorbent. In practical operation, biosorption is associated with a medium loss of 1–5%, mainly due to the rinsing of sorption columns and the need to remove secondary suspensions. From an automation perspective, biosorption performs moderately. Although it is possible to use flow and pressure sensors in adsorption columns, the process requires periodic replacement or regeneration of the sorption material, which significantly limits its usefulness in continuously operating piping systems. The MDPI literature clearly indicates that biosorption works best in semi-continuous or periodic installations, while its inline implementation in piping systems is associated with a high risk of clogging and hydraulic instability [8,32–34].

The second group of biological methods is enzymatic biodegradation. In recent years, numerous studies have been published on enzymes such as PETase, MHETase, laccases and peroxidases, which are capable of initiating the breakdown of polymer chains. The effectiveness of enzymatic biodegradation, understood as the reduction in microplastic mass, ranges from 10 to 50% over periods of several to several weeks, mainly for ester polymers (e.g., PET). For polyolefins (PE, PP), this efficiency often falls below 10%, even after several dozen days of incubation. The costs of enzymatic biodegradation are currently very high. According to analyses by MDPI and Elsevier, the cost of using enzymes per volume of treated water ranges from €0.20 to as much as €0.80 per m³, mainly due to the price of enzymes, the need to maintain stable pH and temperature conditions, and the limited shelf life of biological catalysts. Medium losses are low (<1%), but the process requires a very long contact time, which in practice excludes its use in high-flow piping systems. From an automation point of view, enzymatic biodegradation is only possible in biological reactors with controlled conditions, which limits it to side or end systems, rather than directly to transmission systems [35,36].

The third category analysed is the biodegradation of microplastics with the participation of microorganisms, in particular bacteria and filamentous fungi. The scientific literature documents the ability of selected strains to degrade various types of plastics, but the effectiveness of these processes on a technical scale remains limited. In most studies, the reduction in microplastic mass ranges from 5 to 40% over periods of one to three months, with values above 30% reported mainly for fungi that degrade polyurethanes or modified polyesters. The operating cost of such processes is estimated at €0.10–0.40 per m³, but it requires the maintenance of active biomass, oxygen, nutrient and temperature control [37,38].

3. Results and Discussion

The chapter compares the information obtained on each separation method studied, taking into account the criteria set. The aim was to obtain the most optimal solution, whose characteristics allow for complete or partial automation. In addition, the way in which it could be implemented is described.

3.1. Comparison of All Analysed Separation Methods

The representative cost and efficiency values presented in Table 2 were derived from data reported in experimental studies and pilot-scale investigations available in the scientific literature, describing microplastic separation under hydraulic conditions comparable to those occurring in in-line pipeline systems. These values should therefore be interpreted as indicative performance levels characteristic of typical operating conditions, rather than as results of statistical averaging. To maintain engineering relevance and ensure comparability between methods originating from different technological categories, the analysis focuses on the mid-range operating parameters reported across multiple studies, while excluding extreme configurations that were laboratory-optimised or strongly dependent on specific local conditions. In cases where comparable performance ranges were reported consistently, values corresponding to stable continuous operation and technologically mature implementations were considered representative. This approach enables a coherent comparison of separation methods while accounting for the inherent variability of reported results arising from differences in experimental configurations, polymer types, and operating conditions.

Table 2. Comparison of separation methods. ^a—The representative cost refers to ranges reported in the literature for flow systems with comparable hydraulic conditions. Values include energy consumption and consumables, where reported. ^b—The representative of effectiveness shows the minimum and maximum removal efficiency values reported in the analysed publications. ^c—In the case of AOP, effectiveness refers to the reduction in mass or particle size, rather than their direct removal from the medium.

Number	Kind of Method	Name	Short Description	Indicative Unit Cost [€/m ³] ^a	Indicative Removal Efficiency [%] ^{b,c}	Automation Capability
R1	Mechanical	Membrane filtration	Separation of particles on a porous barrier; requires membrane regeneration	0.185	88	Very high, fully automated backwash, ΔP sensors
R2		Acoustic separation	Ultrasound directs particles toward pressure nodes	0.100	90	Very high, sensor-controlled frequency adjustment
R3		Foam flotation	Particles captured by air bubbles	0.035	86	Medium, requires foam control
R4	Chemical	Coagulation and flocculation	Aggregation of microparticles into larger flocs	0.065	76	High, automated chemical dosing
R5		Electrocoagulation	In situ generation of coagulant from electrodes under electric current	0.140	90	Very high, automatic current regulation
R6		Advanced oxidation processes (AOP)	Chemical degradation via OH radicals	0.400	73	High, requires control of external conditions
R7	Biological	Biosorption	Capture of microplastics on biological materials	0.125	75	Medium, sorbent regeneration required
R8		Enzymatic biodegradation	Hydrolysis of polymer bonds by enzymes	0.500	30	Medium, high enzyme sensitivity
R9		Microbial biodegradation	Degradation by bacteria and fungi	0.250	25	Low, high environmental requirements

Physical methods exploit differences in the material properties of microparticles and are characterised by high operational predictability, which makes them particularly attractive for applications requiring automation and minimal medium losses. Chemical methods, based on charge modification, coagulation, or chemical degradation of particles, provide very high effectiveness; however, they may generate medium losses or by-products requiring disposal. Biological methods, despite their low environmental impact, are characterised by high variability and slower process kinetics, which significantly hamper their full automation.

3.2. Criteria-Based Assessment

In case of systematise the comparison of the analysed separation methods and to limit the influence of individual technical parameters on the final outcome, a criteria-based assessment was conducted using a set of previously defined preliminary criteria (K1–K5), described in Section 2.1. The applied approach was semi-quantitative and enabled the comparison of methods in a manner that was as objective as possible, while maintaining the flexibility necessary for analysing technologies originating from different methodological groups. In the criteria table, a subjective assessment of the relationships between individual criteria was first performed and subsequently translated into the evaluation of nine technological solutions (R1–R9), corresponding to the separation methods presented in Table 3. A scoring scale from 0 to 3 was adopted, where 0 denotes non-fulfilment of a given criterion, and 3 indicates fulfilment at a very high level, comparable to an ideal solution. The applied scale is ordinal in nature and is intended to express relative performance levels of

individual methods rather than absolute quantitative differences. Quantitative engineering parameters, including unit cost, separation efficiency ranges, energy demand, and medium losses, were initially analysed independently based on the literature data (Table 2) and subsequently transformed into relative values, enabling a consistent comparison of methods without directly combining heterogeneous physical units. To verify the logical consistency of the weighting scheme and the robustness of the resulting ranking, a sensitivity analysis was conducted by varying the weights of individual criteria by $\pm 10\%$. The ranking of the two highest-scoring methods (R2 and R5) remained unchanged, confirming the stability of the obtained evaluation results.

Table 3. Criteria-based assessment.

	K1	K2	K3	K4	K5	SUM	R1	R2	R3	R4	R5	R6	R7	R8	R9	Rideal
K1	x	0	0	0.5	0.5	0.0625	2	2	3	3	2	1	2	1	2	3
K2	1	x	0.5	1	1	0.3125	2	3	2	1	3	1	1	0	0	3
K3	1	0.5	x	0.5	1	0.2500	3	3	1	2	3	2	1	1	0	3
K4	0.5	0	0.5	x	0.5	0.1250	2	3	2	1	2	1	1	0	0	3
K5	0.5	0	0	0.5	x	0.1250	1	2	1	2	2	1	2	1	0	3
SUM							10	13	9	9	12	6	7	3	2	15
PERCENT							66.667	86.667	60	60	80	40	46.667	20	13.333	100

The analysis of the results clearly shows that the highest percentages were achieved by solutions marked as R2 and R5, which achieved approximately 86.7% and 80% compliance with the ideal solution, respectively. These methods are characterised by high separation efficiency, low medium losses and very high automation potential, which confirms their usefulness in continuous operation piping systems. The high results of these solutions are consistent with the qualitative analysis carried out in Section 3.1, where they were identified as the most promising technologies from the point of view of integration with PLC control and process monitoring systems. Solutions R1, R3 and R4 achieved scores of 60–66.7%, suggesting their moderate practical usefulness. These methods can be used under certain conditions, but often require additional process steps or do not ensure full operational stability under variable flow conditions. In contrast, solutions R6–R9 achieved the lowest scores, not exceeding 46.7% compliance with the ideal solution. This group mainly included biological methods and processes with high operational complexity, whose limited automatability and slow process kinetics significantly reduce their usefulness in piping systems.

3.3. Description of the Selected Separation Method

Acoustic separation is a modern physical method based on the phenomenon of acoustophoresis, which involves the interaction of acoustic waves with particles suspended in a liquid medium. In the acoustic field, microparticles experience acoustic radiation forces, the value and direction of which depend on the physical properties of the particles and the medium, such as density, compressibility and size. This phenomenon enables the controlled movement of microplastics towards areas of minimum or maximum acoustic pressure, which in turn leads to their separation from the main flow. In practical engineering solutions, both surface acoustic waves (SAW) and bulk acoustic waves (BAW) are used. In the case of SAW, a distinction is made between standing waves (SSAW) and travelling waves (TSAW). Standing waves are formed as a result of the interference of two counter-propagating acoustic waves generated by interdigital transducers and lead to the formation of a stable system of nodes and pressure arrows. Plastic microparticles then migrate towards these areas depending on the sign and value of the acoustic contrast between the particle and the medium. Acoustic contrast is a function of the difference in density and compressibility between the particles and the carrier liquid, which means

that different types of microplastics—such as polystyrene, polyethylene, polypropylene or PET—behave differently in the same acoustic field. This feature not only allows microplastics to be compacted but also enables their selective separation based on material type or particle size. In the case of TSAWs, the particles are displaced transversely to the direction of flow, which allows them to be discharged into dedicated channels (bypasses) or collection zones.

From a hydraulic point of view, linear piping systems impose severe restrictions in terms of pressure drops, permissible flow rates and operating cycles. Acoustic separation does not introduce physical barriers to flow, resulting in a slight pressure drop compared to membrane systems. The literature data indicate stable operation at flow velocities of up to approximately 2–3 m/s. At higher velocities, a measurable reduction in separation efficiency is observed, typically in the range of 10–25%, caused by increased flow-induced turbulence, reduced particle residence time within the acoustic field, and partial distortion of standing wave patterns.

One of the key advantages of acoustic separation is its non-contact nature. The absence of filtration or reaction elements that remove microplastics directly from the medium significantly reduces the risk of system clogging, component wear and pressure loss. This method does not require the use of chemical reagents or consumables, which translates into low operating costs and high long-term stability. In addition, acoustic separation is characterised by very low medium losses, which in most applications are limited to fractions of a percent of the total flow. From an automation perspective, acoustic separation offers exceptional potential. Process parameters such as frequency, vibration amplitude and acoustic power can be dynamically adjusted in real time based on signals from flow, pressure and turbidity sensors. This allows for adaptive adjustment of operating conditions to changing medium composition and microplastic concentration, which is particularly important in continuously operating piping systems. The integration of acoustic generators with PLC control systems allows for full automation of the process and its inclusion in intelligent process monitoring systems. Research by P. Mesquita et al., conducted both in microfluidic systems and in larger diameter piping systems, confirms the high effectiveness of acoustic separation. Depending on the system configuration, the type of microplastic and the acoustic excitation parameters, separation efficiencies ranging from 70% to over 90% were achieved, with the highest values obtained for particles with diameters ranging from several to several hundred micrometres. A limitation of the method remains the decrease in efficiency for very small particles in the nanometre range, but this problem can be partially compensated for by appropriate frequency selection or by combining acoustic separation with other physical methods [15,17–19].

In summary, acoustic separation meets the key criteria adopted in this work: it is highly effective, has minimal medium losses, is highly resistant to changing flow conditions and is very amenable to automation. Combined with the possibility of integration with inline piping systems, this makes it one of the most promising methods for separating plastic microparticles in modern industrial installations.

3.4. Concept of Automation Control for Inline Acoustic Separation

A conceptual automation architecture for linear acoustic separation systems may be based on a PLC-controlled ultrasonic transducer directly integrated with the process pipeline. The control system can utilise real-time input data acquired from standard industrial sensors, such as flow rate, pressure, and turbidity sensors, enabling continuous monitoring of both hydraulic conditions and medium quality. Based on sensor feedback, key operating parameters—including acoustic excitation frequency and ultrasonic signal

power—can be dynamically adjusted to maintain stable and repeatable separation efficiency under varying environmental and operational conditions.

In more advanced configurations, process monitoring and supervision may be extended by a higher-level systems layer (SCADA/MES), implemented using Java-based development platforms. Owing to its portability, mature tooling ecosystem, and broad support for industrial communication standards (e.g., OPC UA, MQTT, REST), Java provides a suitable environment for implementing supervisory, analytical, and integration applications within Industry 4.0 architectures. This layer can serve as an intermediary between conventional PLC-based control and advanced data analysis and process optimisation algorithms.

Furthermore, process supervision can be enhanced by data-driven control and diagnostic models that integrate multimodal information derived from both sensor signals and vision-based inspection systems. Recent research in the field of Industry 4.0 indicates that computational frameworks combining image processing with language models improve the interpretability and robustness of industrial monitoring systems through the synergistic use of numerical data, visual diagnostics, and contextual descriptions. Such approaches define a viable development pathway for intelligent supervisory systems in automated microplastic separation, while preserving classical, deterministic PLC-based control architectures as the execution layer (e.g., the CNC-VLM framework, doi: 10.1016/j.ymssp.2025.113838).

4. Conclusions

The article provides a detailed analysis of methods for separating plastic microparticles from aqueous media, with particular emphasis on their suitability for use in continuously operating piping systems. Based on a review of the scientific literature and a multi-criteria comparative analysis, nine representative methods belonging to three main groups were evaluated: physical, chemical and biological. The analysis took into account key decision-making criteria, including separation efficiency, implementation and operating costs, medium losses, resistance to environmental conditions, and the potential for automation and integration with industrial control systems. The comparison of the literature data showed that physical methods are characterised by the highest operational stability and the greatest implementation potential in piping systems. Membrane filtration enables very high microplastic removal efficiency (78–99%), but its use is associated with the risk of fouling and the need for periodic regeneration. Despite its low operating costs, foam flotation is highly sensitive to changes in the properties of the medium, which limits its use in installations with variable operating conditions. Among them, acoustic separation achieved the highest degree of compliance with the adopted ideal solution, combining high microplastic removal efficiency of 70–90% with minimal liquid losses due to its closed-flow environment operating characteristics. The non-contact nature of the process, the possibility of dynamic adjustment of operating parameters and the lack of need for chemical reagents confirm the flexible and modular nature of this method. Chemical methods, in particular electrocoagulation, are characterised by high separation efficiency (85–98%), but their use involves greater process complexity, the need to control chemical parameters and the generation of sediments requiring further treatment. Advanced oxidation processes are not a stand-alone separation method but can serve as a supporting stage by degrading and modifying the properties of microplastics. Biological methods, despite their potential environmental benefits, achieve the lowest scores in the criteria analysis. The long process time, high sensitivity to environmental conditions and limited susceptibility to automation mean that their use in continuous piping systems is currently limited mainly to closed or semi-technical systems. Based on the results obtained, it can be

concluded that the complete removal of microplastics from the aqueous medium remains technologically difficult to achieve, especially under real environmental conditions. The effectiveness of most methods depends on particle size, polymer type and the presence of organic matter, which should be taken into account when designing separation systems. In order to obtain a practical industrial solution, the most promising direction of development seems to be optimised hybrid systems, in which acoustic separation plays the role of the basic inline stage, supported, if necessary, by membrane filtration or chemical processes in side systems. This approach allows for an increase in overall separation efficiency while maintaining hydraulic stability and low operating costs. The results obtained indicate that further development of microplastic separation systems should focus on the integration of acoustic methods with advanced measurement systems, adaptive control and data analysis algorithms, including artificial intelligence methods. This approach allows for dynamic optimisation of operating parameters and increased separation efficiency under variable pollutant parameters. The analysis provides a theoretical basis for further experimental research on the design of automated, scalable separation systems for the protection of aquatic environments, in particular technical infrastructure.

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