Review

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Advancements in Plastic Waste Sorting: A Review of Techniques and Applications

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Abstract

The widespread utilization of plastic materials across various sectors has led to significant increase of plastics demand over the decades. This growth has been accompanied by a mounting challenge related to managing of generated plastic waste, as substantial portions of the plastic residual end up in landfills due to limited recycling efforts. Addressing this global concern demands the development of innovative strategies to better assess and recover polymer waste, which should be treated as a different feedstock. In order to do that, efficient sorting techniques are crucial to integrate valuable materials like plastics into municipal solid waste management and improve recycling outcomes. As a matter of fact, technological innovations in this area have given rise to more sophisticated sorting methods, exploring automated sorting techniques to enhance recycling efficiency. Nevertheless, among traditional and modern sorting approaches, manual strategies are still used to perform plastic waste segregation. In this context, the present study aims to comprehensively review and assess pre-treatment classification techniques employed to transform waste streams into valuable compounds, specifically focusing on polyolefin materials present in large quantities in urban solid waste treatment environments.

Keywords: sorting technologies; plastic waste; landfill; municipal solid waste

1. Introduction

Polymers (or simply plastics, in less rigorous denomination) are versatile materials employed in a wide range of fields for their durability, resistance to water, and versatility, including packaging, construction, and agriculture. Because of that, these materials have witnessed a staggering 200-fold increase in demand over the last seven decades [1–3]. For instance, in 2022, the worldwide production of polymers reached 400.3 million tons [4]. Moreover, the plastics industry remains a vital economic sector; in Europe alone, it generated a turnover of approximately 405 billion EUR and provided employment to over 1.5 million people in 2021 [5]. Despite that, plastic waste has evolved into a pressing global concern. Shockingly, it is estimated that merely 9 % of all plastics ever produced have undergone recycling, leaving the vast majority to be disposed of in landfills or just discarded summarily in the open environment [6].

Annually, the world generates more than 2.01 billion tons of municipal solid waste, with production rates varying from less than 1 kg per capita per day in low-income countries to over 2 kg per capita per day in high-income nations [6]. Municipal solid waste (MSW) typically comprises a mixture of materials characterized by its varied and poorly defined composition, including plastics, glass, food scraps, yard trimmings, textiles, paper, and other inorganic waste, which pose challenges for recycling efforts [2,7–9]. Approximately 10% (numbers vary from 5 % to 20 %, depending on the investigated region and economic development) of this waste consists of plastics, with the majority (about 60%) comprising polyolefins such as PE (polyethylene), HDPE (high-density polyethylene), LDPE (low-density polyethylene), LLDPE (linear low-density polyethylene), and PP (polypropylene). The remaining fraction includes PET (poly(ethylene terephthalate)), PVC (poly(vinyl chloride)), PS (polystyrene), and other minor polymers [10–12]. A smaller portion of plastic waste originates from post-industrial sources or car scrap, which is generally cleaner and can be easily sorted [13].

More specifically, plastic waste streams contain a wide array of plastic products crafted from different polymers, such as PE, PP and PET. Often, these plastic components contain small quantities of foreign materials, including different polymers, additives, and various contaminants. The foreign materials and residues are primarily concentrated in components like caps, lids, and labels. The degree of material heterogeneity is even more pronounced in the case of multilayered films, where the principal polymer makes up only 55 wt% of the overall film composition [7,14]. On a global scale, only about 9 % of the discarded plastic is currently recycled [6,8]. A larger proportion is subjected to incineration (25 %), while the majority (around 60 %) ultimately finds its way into the environment, including landfills, unmanaged dumpsites, or litter on land, rivers and oceans [7].

While recent literature provides comprehensive overviews of recycling methodologies, such as the extensive work by Sambyal et al. covering mechanical, chemical, and energy recovery routes, a specific gap remains regarding the technological prerequisites for such processes [15]. The efficiency of the recycling strategies depends on the purity of the feedstock. Consequently, the present study differentiates itself by shifting the focus from the transformation process to the separation engineering. Furthermore, unlike generalist reviews that prioritize academic sources, the current analysis incorporates a patent landscape to capture industrial innovations in sensor-based sorting and artificial intelligence often absent from standard bibliometric surveys.

In this context, many efforts have been made to develop strategies and technologies for sorting of plastic waste, in order to enhance the feasibility of recycling techniques [16]. As a matter of fact, an essential step to promote the recycling of plastics and other materials is to separate valuable materials from municipal solid waste. Consequently, researchers have been actively investigating automated sorting methods to enhance the efficiency of the recycling process [17]. For this reason, the present study is focused on gathering, describing, and critically assessing the classification techniques employed as pre-treatment steps to enhance the quality of waste streams, with the goal of enriching them with the targeted polymers of interest. As shown in the following sections, combination of scientific knowledge and innovative technologies has allowed the development of efficient sorting techniques that can ultimately provide plastic streams with appropriate homogeneous compositions for implementation of distinct recycling techniques, which can be used to manufacture different product streams and provide support for development of a more sustainable and circular chemical chain.

In this context, many efforts have been made to develop strategies and technologies for sorting plastic waste in order to enhance the feasibility of subsequent recycling techniques [16]. As a matter of fact, an essential step to promote the circularity of plastics is to separate valuable polymers from complex municipal solid waste. Consequently, researchers have actively investigated automated sorting methods to enhance recycling efficiency, with notable studies outlining fundamental principles such as manual sorting, magnetic density separation, and triboelectrostatic techniques [17]. However, while these previous works provide a solid foundation regarding conventional physical and electrostatic segregation, they often present these operations in isolation and predominantly from an academic perspective. To bridge this gap, the present study goes significantly beyond existing literature extending the analysis to the forefront of industrial innovation. Specifically, this work uniquely explores the necessary hybridization of mechanical methods with state-of-the-art sensor-based architectures, active identification technologies, and artificial intelligence algorithms. By combining fundamental scientific knowledge with industrial realities, this review demonstrates how to design sorting ecosystems capable of providing the strictly homogeneous plastic streams required to support a sustainable circular chemical chain.

Addressing the complexity of the recycling landscape, this work provides a comprehensive overview of the material separation technologies within the sorting ecosystem, encompassing mechanical, electromagnetic, gravitational, density-based, and wet techniques. Furthermore, it consolidates sensor-based sorting strategies, integrating spectroscopic identification (FTIR, NIR) with advanced data processing and intelligent systems (AI, chemometrics) to optimize the sorting process. This review highlights the operational synergies required to meet the increasing purity demands of the circular economy. Finally, it incorporates an updated analysis of the industrial landscape, identifying key market players and the operational trade-offs of commercial solutions.

2. Materials and Methods

The bibliometric review was systematically executed leveraging the Web of Science and Scopus databases, employing the specific keywords "plastic waste" AND "sorting" to establish the primary dataset. The preliminary search generated a corpus comprising approximately 3,450 papers. However, a subsequent multi-stage screening process demonstrated that a predominant portion of the publications focused on macroscopic waste management policies, life cycle assessments, or general circular economy frameworks, rather than on the technical engineering and physical principles of separation processes.

A detailed examination identified 385 papers addressing the development, optimization, or technical analysis of sorting technologies. A further analysis restricted the selection to approximately 60 core studies that investigated the mechanisms and physical phenomena governing the sorting techniques. However, there is a structural divergence in the dissemination of knowledge: while the environmental implications of sorting receive widespread academic attention, the technological innovation is detailed less frequently in scientific journals and appears more intensively within industrial intellectual property. To address the identified gap, additional specific keywords were introduced to broaden the scope, covering the period from 1997 to January 2026.

Table 1 categorizes the identified technologies, classifying the methods into three distinct domains: (i) material separation technologies based on intrinsic physical properties; (ii) sensor-based sorting employing advanced spectroscopy; and (iii) data processing and intelligent systems.

To bridge the academic lacuna and capture the industrial state-of-the-art, a complementary patent landscape analysis was performed using the WIPO and Google Patents databases. Search terms including "plastic sorting", "artificial intelligence", "tracers", and "chemical recycling feedstock" yielded an initial set of 2,840 patent applications. Following a filtration process for relevance, technical claims, and redundancy reduction, 310 key patents published between 1992 and January 2026 were selected for in-depth evaluation. Table S1 (Supplementary Information) summarizes the recent patents applications related to plastic waste sorting.

The comparative analysis of the bibliometric data and the patent landscape reveal a fundamental distinction in the evolution of sorting technologies. While the academic literature predominantly focuses on the characterization of unit operations in isolation, investigating density separation or spectral signatures independently, the intellectual property data demonstrates a clear industrial trajectory toward process hybridization and digitalization [18]. The patent landscape (2020 – 2026) indicates a paradigm shift from passive separation to active systems capable of distinguishing food-grade materials and black plastics. Such technical capabilities address specific challenges that remain partially unresolved in standard academic studies.

Traditional NIR spectroscopy, while effective for polymer type classification, encounters limitations regarding black plastics due to carbon black absorption and the distinction between food-grade and non-food-grade packaging [19]. Recent patent applications by entities such as Magnomer and Digimarc address the limitations through the introduction of chemical tracers, fluorescent markers, and digital watermarking [20,21]. The approach represents a significant innovation: rather than solely improving the sensitivity of the sensor, the industry is modifying the packaging to communicate the composition to the sorting line, thereby enabling the recovery of high-value food-grade polypropylene and polyethylene [22].

Table 1. Categorization of plastic waste sorting technologies into physical material separation, sensor-based identification, and intelligent data processing systems.

Materials Separation Technologies	Sensor-Based Sorting	Data Processing and Intelligent Systems
Air separator	X-Ray Fluorescence (XRF)	Blockchain
Sink-float separation	Near-infrared spectroscopy (NIR)	Artificial intelligence
Hydrocyclone	Raman Spectroscopy (Raman)	Chemometric
Jigging	Laser-Induced Breakdown Spectroscopy (LIBS)	-
Selective dissolution	Hyperspectral imaging (HSI)	-
Tribo-electrostatic	-	-
Magnetic Density Separation	-	-

The integration of artificial intelligence constitutes another pillar of industrial innovation largely absent from earlier academic reviews. While prior studies explored basic chemometrics, recent industrial developments utilize deep learning and computer vision to classify waste based on object morphology and texture, not merely spectral data [23]. The patent data from companies like Sortera Technologies and Recycleye indicates that combining Medium Wave Infrared cameras with neural networks allows for the efficient sorting of dark materials and complex composites, achieving purity levels previously unattainable with conventional optical sorters.

The analysis further highlights a growing synergy between mechanical sorting and chemical recycling. A subset of the identified patents, such as those from BASF and Versalis, focuses specifically on the purification of feedstock for pyrolysis and gasification. Unlike the production of mechanical recycles, which requires color sorting, the preparation for chemical recycling prioritizes the removal of catalytic poisons such as halogens, metals, and moisture. The intellectual property landscape suggests that future sorting facilities will likely operate as hybrid systems, producing distinct streams for mechanical reprocessing and chemical depolymerization, depending on the purity and polymer degradation level.

The divergence underscores that industrial R&D is currently driven by the necessity to meet regulatory circularity targets, such as the minimum content of post-consumer recycle in packaging. The focus on "high-throughput" and "automated quality control" observed in the patent documents reflects the economic pressure to reduce operational costs and reliance on manual sorting. Consequently, the academic sector may benefit from aligning future research with the industrial challenges, particularly in developing robust sensors for tracer detection and optimizing AI algorithms for real-time waste characterization.

3. Materials Separation Technologies

Solid waste treatment plants commonly receive a mix of domestic and industrial wastes, which are collected without prior sorting. This waste mixture normally contains cardboard, Styrofoam, metallic and non-metallic materials, organic waste, among other components. To enhance sorting and recycling efficiency, pre-sorting techniques are employed as auxiliary technologies to purify the input stream and make it more homogeneous. For example, these techniques aim to separate organic waste from recyclable materials. Various methods can be employed to sort different materials, such as magnetic separators for magnetic metals and eddy current separators for non-magnetic metals [17,24]. For this reason, plastic sorting technologies encompass a wide range of processes and equipment that are designed to achieve maximum recovery yields of each of the desired materials. These technologies may involve gravity separation, air separation, electrostatic separation, magnetic density separation, sensor-based sorting methods, among others [7,24]. These diverse techniques are utilized to effectively separate and recover plastics from the waste stream, contributing to improved recycling outcomes, as described below and summarized in Table S2.

3.1. Pre-Sorting Techniques

Plastic pre-sorting techniques are methods used to separate plastic materials into different categories before further processing or recycling. Separating plastics into different categories can streamline the recycling process, so that more suitable plastic streams can be recycled more properly. These techniques help to improve the efficiency of plastic recycling by reducing contamination and improving the quality of the plastic waste streams making the recycling process more efficient and effective. Plastic pre-sorting techniques include sorting by color, shape, size, and material [7,25]. Some standard plastic pre-sorting techniques include:

- Source separation, which involves separating plastic waste at the generation point, such as homes, business offices or industrial facilities; this technique can be performed with help of simple equipment, including separate bins or containers for different plastic materials;
- Manual sorting, which involves visually inspecting and sorting plastic materials by hand based on their physical characteristics and markings; manual sorting can be performed either at the recycling facility or preferentially at the generation point;
- Size reduction, which involves shredding or granulating the waste plastic materials to reduce their size and make posterior handling and sorting easier;
- Magnetic separation, which involves the use of magnets to separate plastic materials from magnetic metal compounds;
- Air classification, which involves the use of pressurized air streams to separate plastic materials based on their size and weight, as the air stream can carry lighter fractions, while heavier fractions fall into the accumulation vessel.

Pre-treatment techniques can also be used for the preliminary sorting of urban solid waste when undesired or revalued materials must be separated from a particular production line, such as ferrous and non-ferrous materials from plastic recycling lines. At this stage, the organic residues can also be separated from dry residues through trommels, which are tubular sieves that are used to classify by size. After the removal of organic matter, recyclable plastic materials can be treated through comminution and crushing processes to form flakes, which can be handled and recycled easier in the following process stages [17]. Some commonly used tools for comminution of municipal solid waste (MSW) are swing hammer shredders, rotating drums, alligator shears, hammer mills, ring mills, shear shredders and impact crushers [17]. Figure 1 illustrates the commonly employed pretreatment sorting techniques, which are described in greater detail in the subsequent sections.

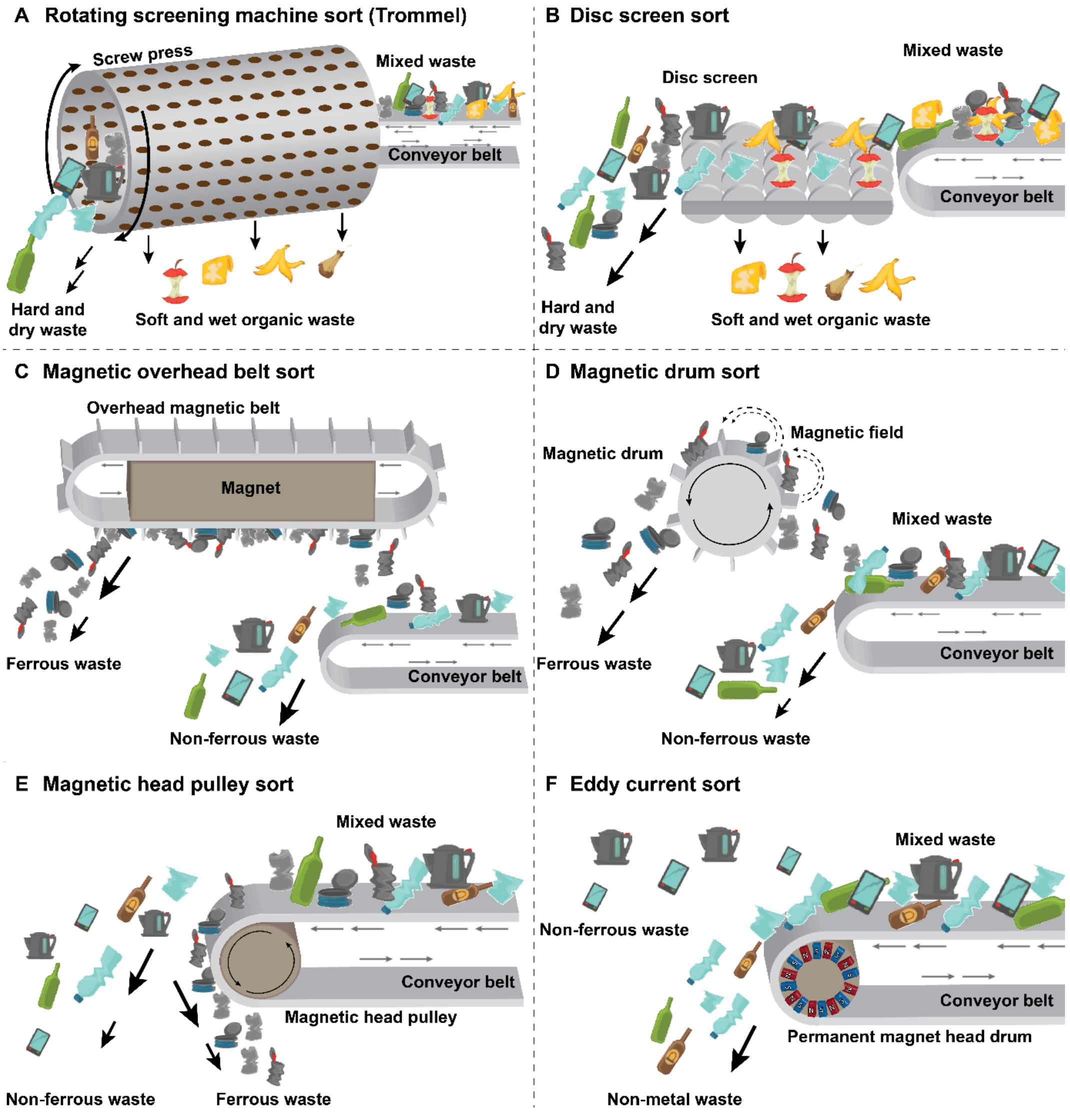

Figure 1. Schematic representation of conventional mechanical pretreatment and material recovery technologies. The panels illustrate size classification units: (A) rotating screening (trommel) and (B) disc screening; followed by ferrous metal recovery systems: (C) magnetic overhead belt, (D) magnetic drum, and (E) magnetic head pulley; and non-ferrous metal removal via (F) eddy current separation.

3.1.1. Rotating Screening Machine or Screw Press (Trommel)

In the waste treatment process, the screw press or rotating screening machine (trommel) compresses the organic fractions through narrow slits, achieving precise and efficient separation of soft, moisture-laden components, commonly referred to as biomass. Furthermore, the screening operation separates waste materials, consisting of a mixture of biomass, plastics, paper, wood, animal bones, and metal, into several size fractions, as the cylindrical screening surface can be composed of successive sections with different aperture sizes [26]. Figure 1A shows a schematic illustration of the rotating screening. First, the mixed waste is fed into the trommel through a conveyor belt. Then, the mixed waste is separated by size, generating the permeate stream (formed by smaller particles, as soft and wet organic mass) and the retentate stream (formed by the bigger particles, which follow to the next separation unit). The trommel efficiency is affected both by geometrical and operational factors, such as length, diameter, angle of slope, rotational speed, and feed rate of the rotating cylinder, and characteristics of the treated materials, such as wet content and shape [27].

3.1.2. Disc Screen

In the waste treatment process, the disc screen constitutes another critical technique for removing organic waste fractions from recyclable materials. Figure 1B presents a schematic representation of the disc screening operation. Inside the chamber, an array of uniformly spaced rotating discs facilitates the precise separation of biomass. The smaller and denser biomass components fall through the gaps between the rotating discs, whereas larger and lighter fractions are directed toward the periphery of the assembly. Such a mechanism ensures efficient and accurate material sorting, thereby enhancing the purity of both the biomass and the recovered recyclable materials [28].

3.1.3. Magnetic Techniques

Appreciable amounts of metal objects are present in solid waste, with concentrations generally varying between 5 % and 15% [28]. Nevertheless, ferrous waste fractions can be segregated from mixed waste streams with help of magnetic techniques. It is worth noting that magnetic-based techniques cannot differentiate the various non-ferrous metal fractions.

For instance, the magnetic overhead belt imposes a magnetic field either along or across the direction of the mixed waste flow. Through the application of such a magnetic force, ferrous metal pieces are attracted and extracted from the mixed waste. A separation drum temporarily retains the recovered metals before discharging the material into a secondary stream with the assistance of a moving belt (Figure 1C) [24]. On the contrary, the remaining wastes (including plastics) continue to flow forward with the waste stream.

The separation of ferrous fractions from non-ferrous and mixed waste streams may be performed using a magnetic drum separator. The device incorporates a stationary permanent magnetic assembly covering approximately half of the drum's circumference. Upon introduction of the waste, the resulting magnetic field attracts and retains ferromagnetic materials against the rotating shell. The shell subsequently transports the ferrous components to the discharge zone, where the materials are collected into specific bins (Figure 1D) [29].

Additionally, the mixed waste can also be conveyed through a magnetic material handling system, a conveyor belt operated with a magnetic head pulley. Consequently, the magnetic belt efficiently seizes and retains the ferromagnetic waste components, enabling the non-ferromagnetic fractions to be separated and discharged effectively (Figure 1E) [24]. The pieces of equipment are positioned before an eddy-current separator to separate ferrous metals and steel cans, for example.

The segregation process can also employ eddy current separators, which make use of a rotary drum equipped with neodymium magnets (NdFeB) arranged with alternating north and south poles. According to this setup, a thin layer of a mixture containing non-ferrous metal fractions (with ferrous fractions already separated through prior techniques) and non-metallic waste is conveyed towards the rotary drum using a conveyor system. The external magnetic field generated by the magnets repels non-magnetic electrically conductive metal fractions from mixed metal waste. This method is notable for its low operating costs and its ability to achieve a high degree of purity in the recovered metal. However, it is important to note that this technique is not intended for sorting metals that can become hot in an eddy current field, as such conditions could potentially damage the separator (Figure 1F) [7,17].

3.2. Mechanical Techniques

Mechanical sorting separation techniques are usually classified as wet and dry techniques, as described in the following sections.

3.2.1. Dry Techniques

3.2.1.1. Air-Based Separation

Air-based classifiers use air as the medium to separate lighter materials from heavier ones. A compressed air nozzle is used to release a high-pressure air jet to impart a force of separation on the mixed waste sample. The air classifier technique can be divided into three categories, (i) gravity air separator, (ii) ballistic separator, and (iii) air table separator, as shown in Figure 2 [30].

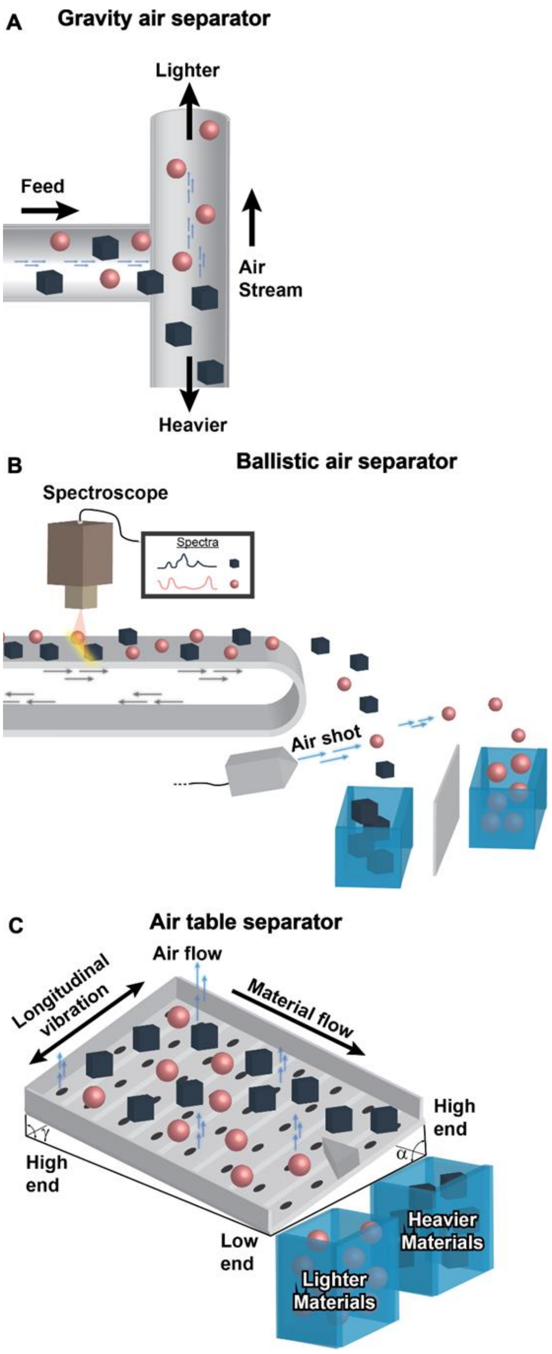

Figure 2. Schematic illustration of dry density separation technologies relying on density and shape differences: gravity air separator (A), ballistic separator (B), and air table separator (C).

Gravity air separation (Figure 2A) is based on the density of materials and relative gravity to separate them: the plastic stream flows into the column, while lighter objects are blown upwards and heavier objects are dropped down. In addition, the air separator can be further improved with the assistance of an electrostatic magnetic field to remove eventual contaminants and promote a fine adjustment in the composition stream [7,30].

Alternatively, the ballistic separator (Figure 2B) is the commonest plastic sorting technique, particularly when combined with spectroscopic techniques. According to this procedure, the waste material is initially identified by a spectrometer, such as a near-infrared spectrometer, and a signal is then sent to an air compressor to release a high-pressure air jet to direct the analyzed material to the appropriate container [17,31].

The air table separator or air tabling (Figure 2C) is based on a porous desk powered by a longitudinal vibration and an electric fan below the porous deck to generate an upward airflow. The longitudinal vibration and upward airflow movement fluidize the mixed plastic flakes to settle the high-density flakes on the deck and then move along the end slope towards the collecting bin, while the low-density flakes remain fluidized to float on top of the deck to the collecting bin [24,30].

It must be noted that the cited air separation techniques are simple, robust, relatively inexpensive, environmentally friendly and able to sort different polymers, films, paper, cardboards, textiles, plastic containers, bottle, stones, and 2D and 3D materials. In addition, the sorting efficiency correlates well with the density differences among the sorted materials [32]. Furthermore, parameters such as particle size, shape and structure (2D or 3D) can also affect the performances of air separation techniques [24,30]. To minimize these effects, milling can be important to standardize the size, shape and structure of the segregated materials, so that the separation efficiency can be controlled by the specific mass. Experimental investigations conducted by Dodbiba et al. demonstrated that optimizing operational parameters such as air velocity and vibration frequency led to the recovery of PP and PVC fractions with high purity grades of 92.5 % and 93.7 %, respectively, due to the distinct specific density of the polymers [33].

Beyond these academic investigations, the industrial relevance of ballistic separation is corroborated by recent 2025 patent filings. These disclosures propose highly integrated systems that sequentially process 2D flexible polyolefin fragments and 3D rolling materials prior to specific optical sorting steps, thereby maximizing the purity of the final fractions [34,35].

Finally, air separation techniques are the most used sorting techniques in sorting plants due to the low number of inputs (spectral signal), the uses of air for separation (safe, well-known and inexpensive), the simple specifications of the process and the high number of materials that can be sorted. In comparison with the three variants of air separation techniques described above, ballistic air separation is the most efficient one, providing selectivity above 90 % and demanding relatively low power consumption [30]. This explains the many suppliers of ballistic separators in the market, including Stadler, Tomra, Amut/Amut-Wortex, Marcovil, Bub-anlagenbau, Bianna, and ASG.

3.2.1.2. Triboelectric Separation

Triboelectric separation is a technique used in plastic sorting to separate different types of plastic based on their electrostatic properties. The triboelectric separation process, illustrated in Figure 3, involves rubbing plastic particles milled through a rotating drum to generate an electrostatic charge on the surface of the plastic pieces [36]. The charged particles are then separated, passing them through an electrostatic field, constituted of two electrodes: a positive one to attract the negatively charged polymer pieces and a negative one to attract the positively charged polymer pieces. Depending on the charge and other physical properties, such as size and density, the charged plastic pieces falling freely in the area between two electrodes change their trajectory due to the mobilized attractive and repulsive electrostatic forces, also allowing the separation by size (although this normally does not constitute the main objective of the operation) [24,30,37–40]. The triboelectric charging sequence of the polymers generally follows the order: (+) PMMA > ABS > PC > PS > PET > HDPE > LDPE > PP > PVC > PTFE (–). However, it is important to note that the exact position in the series may shift depending on surface conditions, humidity, and the reference material used for friction [24,30,37–40].

Based on the previous sequence, when two kinds of distinct plastic materials contact each other, the one placed on the left-most side of the triboelectric series will become positively charged, and the one placed on the right-most side of the triboelectric series will become negatively charged. However, the magnitude and polarity of the resulting charges will also depend on the particle size and shape, surface roughness, presence of dirtiness, additives, and fillers, and the conditions of the rubbing process, such as humidity, temperature, applied voltage, and other environmental conditions. Thus, the process demands some additional specifications, as the polymer waste must be cleaned and milled to produce particle sizes around 1 to 13 mm, with optimum sizes between 2 and 4 mm [30,40]. However, it must be noted that small particle sizes do not favor the process operation, due to the additional cost of energy associated with milling and the reduction of separation efficiency, associated with the relative increase of shocks between particles of similar materials and higher adhesion of particles onto the charger walls [17].

Regarding the charging mechanism, the process can be classified as: (i) solid single phase, which considers only the interaction among solid pieces during the charging process; and (ii) gas-solid two-phase, which considers the interaction between gas and solid pieces to charge the mixed solid particles. The solid single-phase equipment comprises a rotating tube, rotatory blades and vibrating devices, while the gas-solid two-phase equipment comprises a cyclone, a fluidized bed and propeller-type tribochager [17].

Triboelectric separation is an interesting technique to sort plastics due to the high efficiency of plastics separation, normally ranging between 80 and 90 %, and for not demanding additional supplies. For instance, triboelectric separation can be effectively used to separate PE from PP, PVC, PET, ABS, and biodegradable plastics, such as PLA, PCL, and PHBV [41]. For this reason, many commercial suppliers can be found in this field, including Stadler, Alicontrols, and Prodecologia. However, the energy required for triboelectric separation can be high when compared to competitors, reaching 31 kWh ton^{-1} [39,42].

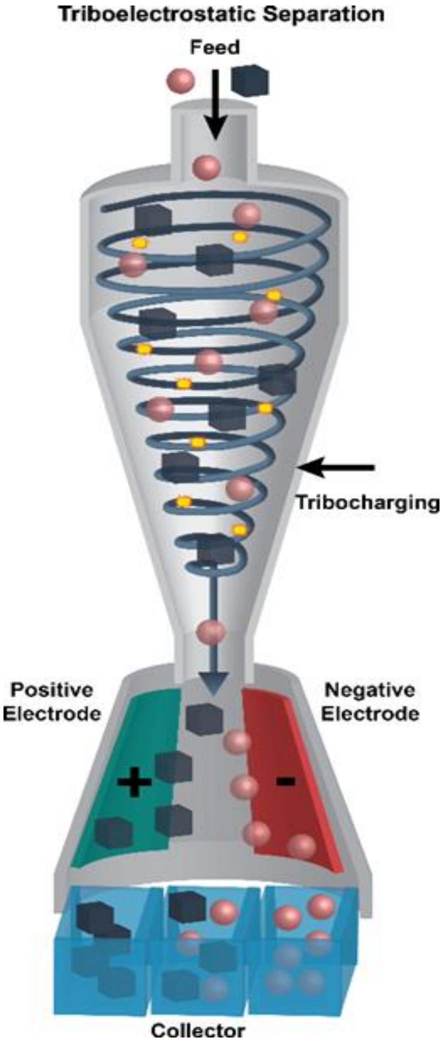

Figure 3. Schematic representation of the triboelectric separation process, illustrating the frictional charging of milled plastic particles and their subsequent trajectory-based segregation within an electrostatic field.

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3.2.2. Wet Techniques

3.2.2.1. Sink–Float Separation

Density separation constitutes a common technique used in recycling facilities to segregate different types of plastics based on their densities. The process, illustrated in Figure 4, initially involves immersing a mixture of plastics into a liquid, typically water and aqueous solutions of inorganic salt or alcohol, and homogenizing the medium to form a suspension. Then, the lower-density plastic pieces will float to the surface, while the higher-density pieces will sink to the bottom, providing the desired separation [17,30,36]. In this case, the solutions prepared with salts and alcohol can provide the desired ranges of densities for finer separation of the waste plastic streams. Density separation is commonly used to separate PET (1.38 g cm^{-3}) or PLA (1.24 g cm^{-3}) from HDPE (0.93 – 0.97 g cm^{-3}), LDPE (0.91 – 0.94 g cm^{-3}), and PP (0.89 – 0.92 g cm^{-3}). Furthermore, density separation can also be used in the initial stages of the process to wash and separate the plastics from other materials, such as paper. In addition, it must be noted that surface properties, such as wettability, and fluid dynamics parameters, such as particle size and shape, residence time and turbulence intensity, can also affect the process [7,42–44].

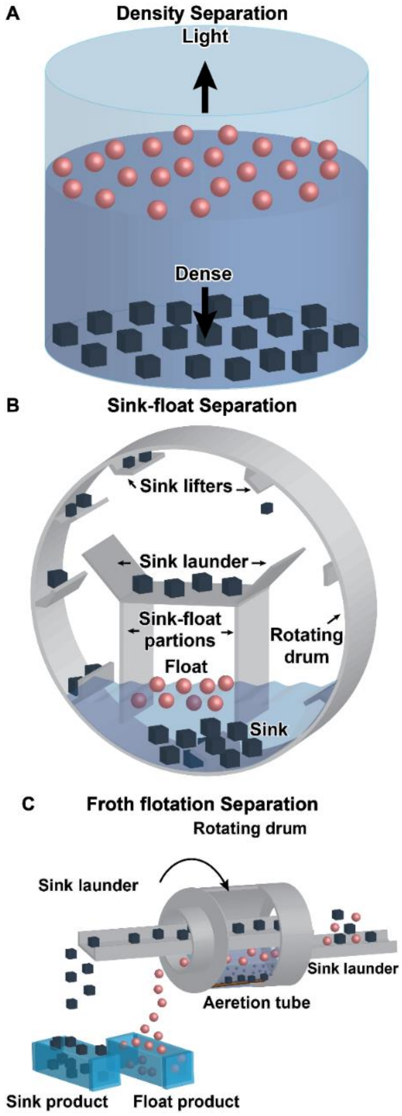

Figure 4. Schematic illustration of density separation principles (A), sink-float (B) and froth floatation (C) separation processes. Schematic representation of wet density separation techniques, illustrating the sink and float method in longitudinal (A), and rotatory (B) tanks, and the froth flotation (C).

Density separation can make use of two distinct strategies to separate the plastic stream: (i) sink-float separation and (ii) froth floatation separation. The sink-float equipment is usually designed as a longitudinal tank (Figure 4A) or rotatory tank (Figure 4B), in which the mixed stream is fed into a tank and the lower-density pieces float to the surface and are collected by the rotary drum, while the higher-density pieces sink to the bottom and flow to the collector placed downstream. On the other hand, the froth floatation separation also depends on the hydrophobicity and surface tension of the plastic particles, as the gaseous bubbles come into contact with the hydrophobic particles and are carried to the top of the floatation apparatus (Figure 4C) [39–41,45].

The sink-float separation is an interesting technique for sorting plastics due to the high efficiency of separating a variety of plastics, usually above 90 %. Besides, commercial equipment can be provided by Amut/Amut-Wortex, ASG, Bub-anlagenbau, Eastman Chem Co, Nippon Kokkan and United Resourses Recovery Corp. It must be observed that the energy required for the sink-float separation can be regarded as moderate, equivalent to 24 kWh ton^{-1}. However, the technique requires the use of high volumes of solvent that can lead to additional financial and environmental costs for water purification and treatment, which have not been evaluated thoroughly yet in open literature. Moreover, after density separation the plastic stream should be dried, imposing additional energy and environmental costs [24,33,37,46,47].

Despite being an established technology with known operational challenges, density-based liquid separation continues to evolve. For instance, recent intellectual property disclosures from 2025 emphasize the development of advanced stratification apparatuses equipped with real-time specific gravity control and automated feedback loops. These industrial innovations aim to optimize the recovery of target polymers, such as polypropylene, from complex waste mixtures [48].

3.2.2.2. Hydrocyclone

Hydrocyclone separation can also be used to separate plastic particles based on their specific gravity under a centrifugal force field. The process, illustrated in Figure 5, initially involves suspending the mixture of shredded plastic particles in an aqueous slurry and feeding the suspension into a hydrocyclone tangentially, generating a centrifugal force field that causes the particles to spin around inside the separation chamber and form a vortex. This spinning flow separates the plastic particles based on their specific gravity and size, separating heavier from lighter particles. The speed of the slurry increases as it follows the centrifugal path downwards from the feed point to the narrow product removal point placed at the bottom of the chamber. The larger and denser particles tend to flow in the vicinities of the cone wall, while the finer/lighter particles migrate towards the center axis of the cone and are removed at the product removal point placed at the top of the equipment [24,33,36,37,49].

The hydrocyclone separation is affected by a large number of fluid-dynamic parameters, such as the water/solids feed ratio, size and shape of the plastic particles, surface properties of the plastic flakes, wettability of suspended materials, the viscosity of the liquid, the flow rate, and the geometrical design of the hydrocyclone. It is important to note that productivity can be limited by the feed composition, as a high concentration of particles can cause clogging or hinder the separation process. Besides, the separation of large particles tends to be more challenging because of the fast movement towards the equipment walls, while the separation of small particles can be inefficient, meaning that the particle size range must be carefully designed for each type of equipment (or vice-versa). Therefore, it must be emphasized that the design and geometry of the hydrocyclone, including the diameter, length, and shape of the cone, can significantly affect the operational ranges of flow rates, pressure drops and separation efficiencies, demanding careful attention of the engineer [17,30,49].

Hydrocyclone separation is an interesting technique to sort plastics due to the highly accurate efficiency of separation, which can reach values that are close to 100 % for most plastics, unless densities are too similar, as in the case of mixtures of PBST (1.35 g cm^{-3}) and PET (1.35 – 1.40 g cm^{-3}).

Providers of commercial equipment include Pla.to and Eastman Chem Co. However, the energy required for hydrocyclone separation can reach 74 kWh ton^{-1} and high volumes of water may be needed, imposing additional energy and environmental costs, as described in the previous section [41,44,50].

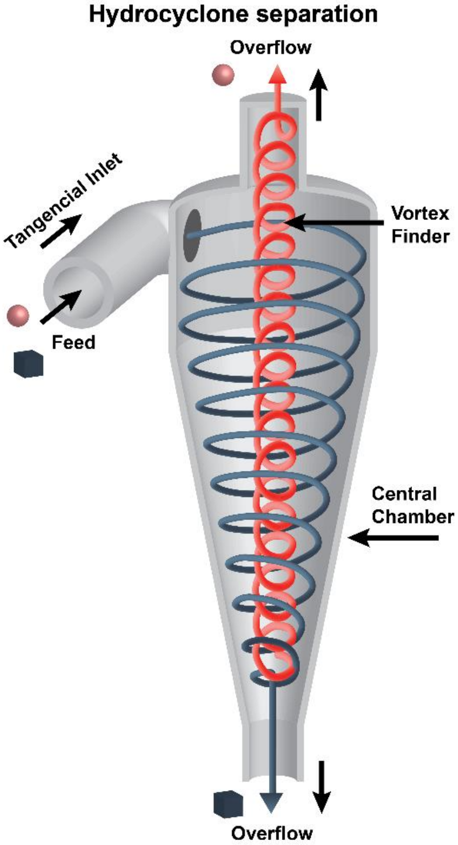

Figure 5. The hydrocyclone separation mechanism applied to plastic waste sorting, demonstrating the centrifugal trajectory of particles according to their density.

3.2.2.3. Jigging

Jigging is a separation technique that is typically used for mineral processing, ore beneficiation and plastic sorting to separate distinct materials based on the different densities of the pieces present in the mixture. The jigging separation process, illustrated in Figure 6A, involves the processing of plastic waste through a series of water tanks that are equipped with vibrating plates that cause the water medium to pulsate, leading to fluidization of the plastic slurry to separate the pieces based on the velocity of particles and density difference [47]. As the feed flows across the jig bed, the denser particles settle down quickly as a concentrate and are collected at the bottom of the jig, while the lighter particles float to the top through the solvent, usually water, and are collected separately. Thus, the phenomena that govern the jig process are buoyancy, drag, gravity and the oscillatory movement of the bed [49,51].

The efficiency of the jigging process depends on several factors, including the size, shape, surface characteristics, density distribution of the particles, amplitude and frequency of the pulsation, water flow rate, stroke frequency, jig stroke length, bed depth, and feed rate. In addition, the traditional jigging separation process can be modified to consider the feeding of air bubbles into the separation chamber to facilitate the plastic separation, as designed by R&E Co. and Ito et al [51,52]. The bubbles fed into the chamber can attach to the hydrophobic particles to induce an apparent lower specific gravity, facilitating the floating of lighter particles, while the hydrophilic particles tend to sink to the bottom [49,51].

Jigging separation is an interesting technique for sorting plastics due to the high efficiency of separation, usually higher than 90 % for segregation of PVC, PET, PS, and ABS. In addition, modified bubble jigging can also separate PP and HDPE from waste with similar efficiencies. Providers of commercial equipment include the University of Beijing, CVP Clean Value Plastics GmbH, and R&E Co. However, jigging requires the use of high volumes of solvent to separate plastics, imposing additional energy and environmental costs, as described in the previous sections [17].

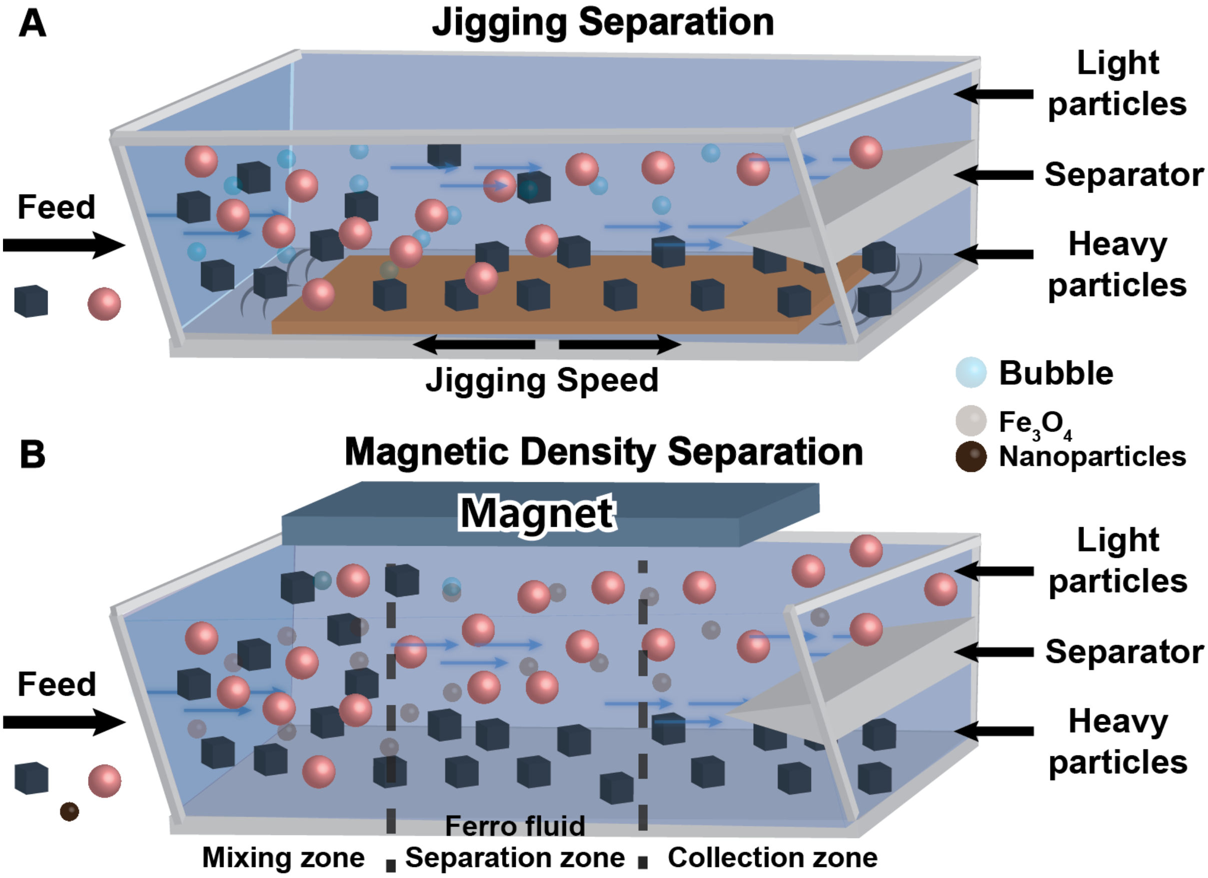

Figure 6. Schematic illustration of the jigging separation process driven by oscillatory fluidization and gravity settling (A) and the magnetic density separation apparatus employing nanoparticles to manipulate the apparent specific gravity of the plastic fractions (B).

3.2.2.4. Magnetic Density Separation

The magnetic density separation technique is based on the relative density of the plastics induced by magnetic nanoparticles. The process involves feeding a tank with the mixture of plastics materials and magnetic nanoparticles, usually Fe_3O_4. The magnetic density separation process is divided into three sections (Figure 6B): (i) mixing zone, (ii) separation zone, and (iii) collection zone. First, in the mixing zone the mixture is homogenized and dispersed with help of a turbulence field. In the separation zone a magnetic field is applied above the tank, causing the magnetic nanoparticles to move upwards and inducing the apparent reduction of density of suspended particles, facilitating plastic separation. The efficiency of the magnetic density separation process depends on several factors, including the size, shape, surface characteristics, density, water flow rate, feed rate, magnetic field intensity and magnetic properties of the magnetic nanoparticles, related to the size and shape of the nanoparticles [24,36,42,53].

Magnetic density separation is an interesting technique for plastics sorting due to its high separation efficiency, normally higher than 95 %, although it can be inefficient to separate plastics with similar densities, such as PP (0.90 – 0.92 g cm^{-3}) and PE (0.88 – 0.96 g cm^{-3}), and PET (1.35 – 1.40 g cm^{-3}), PVC (1.38 g cm^{-3}) and rubber (1.34 g cm^{-3}). Apparently, the only commercial supplier of this equipment is Liquisort Co. due to the recent developments in the field. However, magnetic density separation can exhibit some critical points, such as demanding the use of magnetic nanoparticles and high volume of solvent, which can impose additional energy and environmental costs, as described in the previous sections. Besides, after plastic separation, the magnetic nanoparticles should be ideally recovered, which can be difficult and impose additional economic costs to process operation [24,36,42,53].

3.2.2.5. Selective Dissolution

The selective dissolution technique separates polymer materials through differences of solubilities in solvents, by carefully controlling the operation temperature and selecting the appropriate solvent. Additives and other contaminants can also be removed with this technique through selective extraction, dissolution or reprecipitation [7]. The solvent affinity for the desired components certainly is the most relevant parameter for the selective dissolution process and the solvent must also exhibit high diffusivity through the polymer material to allow the faster dissolution and the design of compact equipment. However, it can be difficult to remove large number of additives with varying solvency properties or dissolve materials with high molar masses with common solvents. Besides, solution viscosities can pose serious operational issues and successful separations can possibly demand product reprecipitation [33,36,37,54,55]. For all these reason, selective dissolution can constitute a niche separation technique for relatively simple plastic separation problems.

In dissolution-precipitation, the remaining polymer (or desired component) must be reprecipitated upon adding an antisolvent (or manipulating the operation temperature). The solvent and antisolvent must then be separated for reuse, leading to additional economic and environmental costs, as already discussed in previous sections. Therefore, the main disadvantage of this technique is the use of high volumes of potentially many organic (and toxic) solvents [7]. However, the selective dissolution technique can be very efficient for separation of plastics with similar densities, when other techniques fail [7,33,36,37,54–56].

3.3. Additional Remarks

From a practical standpoint, most commercial sorting lines make use of pre-sorting and dry-sorting techniques, as described in the previous sections. The use of wet-sorting procedures is normally undesired, as they lead to issues related to handling and treating high volumes of solvents (most times water), which must be recovered and reused, increasing the financial and environmental costs of the operation. Therefore, it is not surprising to observe that commercial suppliers can provide standard equipment to perform pre-sorting and dry-sorting operations, with very high separation efficiencies, normally above 95 %. The scenario is somewhat different in respect to wet-sorting techniques, as some of them are still in the development phase, although more standard procedures, such as density and jigging separations, can also be performed with well-developed commercial technologies. In summary, many standard separation procedures can be used nowadays in the commercial scale to produce relatively pure plastic streams from waste, including the most important plastic commodities such as PE, PP, PET, PS, and PVC. This should be seen as a strong incentive for development and implementation of chemical recycling strategies, using relatively pure plastic waste streams segregated through the previously described sorting procedures as feed.

4. Sensor-Based Sorting

Sensor-based techniques are being used for waste management as methods to separate valuable materials or contaminants from a waste stream after proper identification. Depending on the separation properties, different types of sensors can be used. Particularly, spectroscopic sensors can provide compositions of components of complex mixtures with help of different techniques, including infrared, visible and ultraviolet spectroscopy; however, other types of sensors can also

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provide information about the nature and composition of the distinct components, such as color line scan cameras, electrical conductivity meters and electromagnetic sensors [34]. This section is intended to highlight the sensor-based techniques that are being investigates, developed and implemented for applications in plastic sorting.

More specifically, spectroscopic methods are normally used to characterize the chemical composition of different materials based on their characteristic spectral data, enabling the identification of the presence of different polymer types in mixed polymer waste. Mathematical and statistical procedures can then be used to support the decision-making step regarding the actions that should be taken to enhance the separation performance of polymer waste. Figure 7 presents a schematic overview of the working principles of the main spectroscopic techniques reviewed in this work. Specifically, Figure 7A highlights the electromagnetic wavelength ranges associated with each spectrometric techniques used [57]. Table S3 (Supplementary Information) summarizes the sensor-based techniques characteristics.

Furthermore, to address the intrinsic limitations of conventional passive sensors, recent patented innovations propose active identification strategies. For instance, processes utilizing fluorescent tagging or visible light absorbing molecules applied to automate the sorting operations have been recently patented. These technologies enable precise sorting based on customized chemical signatures, opening new pathways for advanced polymer recovery [58–61].

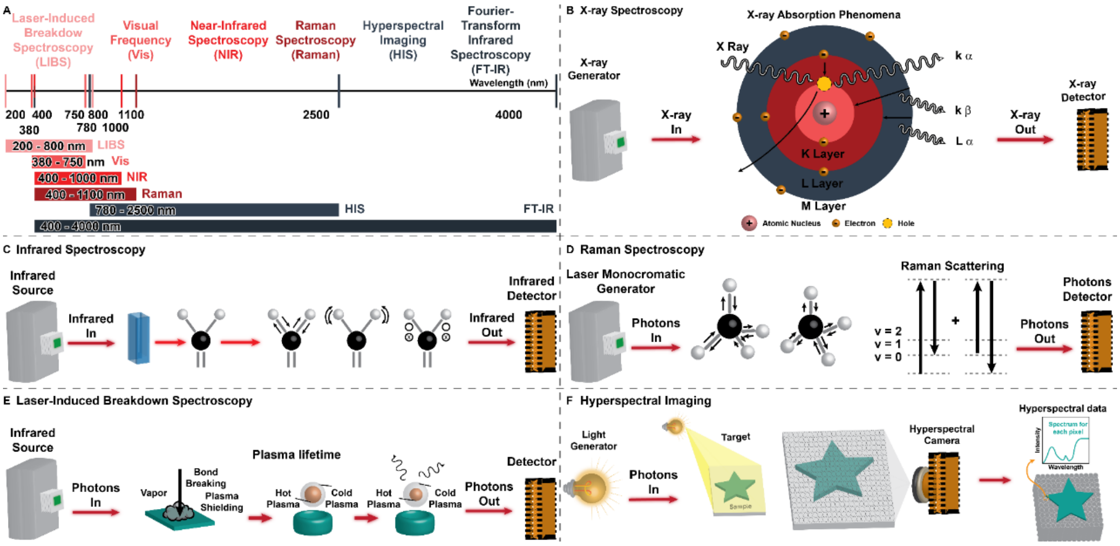

Figure 7. Wavelength range of the main spectrometric techniques. Schematic illustration of the operation of X-Ray Fluorescence Spectroscopy (B), Infrared Spectroscopy (C), Raman Scattering Spectroscopy (D), Laser-Induced Breakdown Spectroscopy (E), and Hyperspectral Imaging (F).

4.1. X-Ray Fluorescence (XRF)

X-Ray Fluorescence (XRF) relies on interactions with X-rays, encompassing the electromagnetic wavelength range between 0.001 and 10 nm. When a sample is irradiated, the X-rays excite inner-shell electrons of the constituent atoms, ejecting them from their original orbitals (Figure 7B). Consequently, the atoms become ionized, and vacancies in the inner shells are filled by electrons from higher energy levels. As outer-shell electrons fill these vacancies, energy is released in the form of characteristic X-ray bands unique to each element. XRF is widely utilized for identifying and quantifying elemental compositions, which can be correlated to specific polymer materials, additives, and mineral fillers (such as flame retardants). The technique is frequently integrated with mechanical sorting systems to enhance the precision of ballistic separators. Prominent suppliers commercializing XRF sorting solutions include Redwave, Tomra, Pellenc ST, and Steinert, among others [17,24,36,40–42,44,57].

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4.2. Near Infrared Spectroscopy (NIR)

Near Infrared Spectroscopy (NIR) is based on the interaction of matter with the near infrared radiation (in the wavelength range between 750 and 2500 nm), which induces the modification of rotational and vibrational modes of atoms in a chemical bond (Figure 7C). Such a technique enables fast, qualitative, and semi-quantitative analyses [4]. Currently, NIR represents the most common spectroscopic technique adopted in industrial recycling plants for quality control and sorting of polymer residues. Frequently, the technology is integrated with the previously described mechanical and air-based sorting systems to achieve precise separation of target materials. Prominent manufacturers providing such integrated sensor-based sorting solutions include Tomra, Steinert, Pellenc ST, Sesotec, Redwave, Stadler, Amut, and Trinamix (BASF), among others [24,30,31,36,39,62–65]. Furthermore, recent industrial developments, highlighted by 2024 patent applications from major players, demonstrate a strong focus on combining NIR and visible spectroscopy to overcome complex challenges, such as isolating food-grade plastics from mixed post-consumer waste streams[60,61,66].

4.3. Raman Scattering Spectroscopy (RSS)

Raman scattering spectroscopy (RSS) is an analytical technique that provides information about the molecular vibrations of a substance. RSS is based on the principle of inelastic scattering of light by molecules (Figure 7D). When a sample is illuminated with a monochromatic laser beam, most scattered light displays the same wavelength of the incident light (Rayleigh scattering). However, a small fraction of the scattered light displays a slightly different wavelength due to interactions with the molecular vibrations within the sample (Raman scattering) [36,42]. RSS can provide information about various molecules, including organic and inorganic compounds, polymers, and biological samples. Each molecule produces a unique Raman spectrum that can be used to identify the molecules present in the sample. Therefore, RSS can provide information about functional groups and molecular orientation of polymer chains in the polymer waste. Some characteristics of RSS include the fact that water is not identifiable by Raman and sample preparation is not necessary, which is very advantageous. As in the XRF and NIR cases, RSS can be combined with mechanical air-based sorting techniques to allow the more precise separation of the desired materials, enhancing the performances of mechanical dry-sorting separators [36,42].

4.4. Laser-Induced Breakdown Spectroscopy (LIBS)

Laser-induced breakdown spectroscopy (LIBS) is based on the interaction of a material with a high-energy laser pulse, which vaporizes and ionizes a small amount of material, creating a plasma that contains excited atoms and ions that emit photons at specific wavelengths to return to their stable state (Figure 7E). The photons emitted are unique to each element and are collected and analyzed using a spectrometer. The resulting spectra can provide information on the elemental composition of the sample and the concentration of the element in the sample, which can then be related to the waste composition. LIBS can be performed very quickly, can detect traces of a water and can be applied to polymer materials and heavy metals, demanding no sample preparation [17,24,36,40,41,57,67]. Therefore, the use of LIBS is expected to grow in the field, combined with mechanical air-based sorting techniques to allow the more precise separation of the desired materials, enhancing the performances of mechanical separators.

4.5. Hyperspectral Imaging (HSI)

Hyperspectral imaging (HSI) is based on the acquisition of spectral images, where each pixel is replaced by some sort of spectrum, leading to a hyperspectral image. Hyperspectral imaging is used to capture information from a scene or sample at a range of contiguous spectral bands, typically covering a broad range of the electromagnetic spectrum (Figure 7F). The spectral information at each pixel in the image is then analyzed to extract valuable information about the composition and properties of the objects or materials being imaged. Hyperspectral imaging has been used as a quality control technique that continuously monitors polyolefin sorting during mechanical recycling. Technological sensors are allocated for the production line, matching solid spatial and spectral analysis of materials [24,30,36,40,57,63,64]. As in the previous cases, HSI can also be combined with different sorting techniques to allow the more precise separation of the desired materials, enhancing the performances of separators.

4.6. Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR is largely used to identify different types of polymers and plastic materials by comparing the infrared spectra (characteristic wavelength in the range between 750 nm and 1 mm, but usually in the range between 2 and 50 mm) of waste samples with those of different model polymers. FTIR is used to obtain an infrared spectrum of emission or absorption from solid, liquid or gas samples. The FTIR spectrometer simultaneously collects high-spectral-resolution data over a wide spectral range and confers significant advantage over dispersive spectrometers, as FTIR uses an interferometer to analyze all IR wavelengths at once, providing a fast and high-resolution spectrum. In contrast, dispersive infrared uses a monochromator (grating or prism) to analyze each wavelength sequentially, making it a slower process with lower resolution. This technology has been combined with sorting procedures to separate PET, PVC and PS successfully [40,68].

4.7. Chemometric Techniques for Data Analysis

Chemometrics constitutes a scientific discipline that employs mathematical and statistical tools to examine chemical data. Within the realm of chemometrics, techniques can be categorized broadly into two groups: (i) exploratory and (ii) confirmatory techniques. Exploratory techniques facilitate the visualization and analysis of data, helping to uncover patterns and relationships, while confirmatory techniques are employed to assess hypotheses and validate models. Chemometrics has found widespread applications in various domains, including quality control in the food and pharmaceutical industries, environmental modeling, and forensics. More recently, chemometric techniques have started to gain traction in addressing the challenges posed by plastic waste [30,31,36,62,68–70].

Chemometric tools encompass a broad range of methodologies, including Principal Component Analysis (PCA), Linear Discriminant Analysis (LDA), Partial Least Squares (PLS), k-Nearest Neighbors (kNN), Support Vector Machines (SVM), Random Forests (RF), Artificial Neural Networks (ANN), Convolutional Neural Networks (CNN), and K-Means Clustering [71]. It is not intended to review the field of Chemometrics in the present manuscript, so that the interested reader is encouraged to refer to one of the many published reviews available in the literature in this field. However, some chemometric techniques are briefed described in the following paragraphs because they have been used in the context of sorting, for analyses of spectroscopic data for purposes of plastic identification.

4.7.1. Principal Component Analysis (PCA)

PCA stands as a cornerstone multivariate statistical analysis whose primary objective is to mitigate the complexity of large datasets, especially those involving numerous variables, without compromising the inherent data patterns. PCA achieves this objective by executing mathematical transformations on the dataset that effectively converts the original variables into a novel set of orthogonal and uncorrelated variables termed “principal components” (related to the eigenvectors and eigenvalues of the covariance matrix of the available dataset), which capture the inherent variance of the original dataset. The main idea behind PCA is that variables in large datasets do not fluctuate independently but are related to each other, varying along well-defined directions that concentrate the most important pieces of information of the problem (the model) and most of the variability of the dataset. The first component (eigenvector related to the largest eigenvalue) represents the largest proportion of the total variance and the subsequent components capture decreasing amounts of variability (the details). Each principal component retains essential information from the original variables, but in a more efficient and compact form, enabling to focus on the most influential features within the data [62]. PCA can be very useful for purposes of sorting because it allows the transformation of spectral data (complex set of wavelengths and spectral signal) into a set of compositions, providing support for the definition of separation decisions.

4.7.2. Cluster Analysis

Cluster analysis is a fundamental technique in the field of data analysis and pattern recognition. It is utilized to categorize measurements as similar within a dataset, thereby enabling the identification of hidden structures and patterns to offer valuable insights into the underlying organization of data, unveiling relationships and subgroups. This method can be used to identify incoming polymer materials based on characteristics that can include color, density, chemical composition and more likely spectral data [72,73]. The technique uses a measure of distance to identify the datasets in a library that are the closest to the set of measurements made available by an instrument, providing valuable information for the sorting procedure.

4.7.3. Factor Analysis

Factor analysis constitutes a set of statistical techniques that is used widely to unravel the intricate relationships within multidimensional datasets. Factor analysis is closely related to PCA (which can be regarded as a type of factor analysis), as its primary objective is to uncover the latent factors that underlie the observed variability in a dataset, shedding light on the hidden patterns governing complex phenomena. However, these procedures can be based on more general representations of the datasets, including the use of nonlinear transformations and the selection of linear combinations that maximize the correlation among subsets of variables instead of the dataset variability. This method excels in dimensionality reduction, a process by which the number of variables is decreased while preserving the essential components that drive the observed variations [74]. As in the case of PCA, factor analysis can be very useful for purposes of sorting because it allows the transformation of spectral data into a set of compositions with help of more involving mathematical transformations, providing support for the definition of separation decisions.

4.7.4. Discriminant Analysis

Discriminant analysis is a statistical technique used to categorize observations into distinct groups based on a set of predictor variables (for example, spectral data of certain polymer samples). This technique can provide valuable insights into the pivotal variables that contribute significantly to group separation and identify the most important variables in distinguishing between groups (for example, combinations of spectral signals at specified wavelengths), enhancing the understanding of complex datasets. This method can be very useful to allow the identification of polymers in a sorting plant line [63].

4.7.5. Regression Analysis

Regression analysis is a statistical technique used to quantitatively model and analyze the relationships between two or more variables, facilitating the data-driven phenomena to identify the critical variables that significantly influence and to predict the value of one variable based on the values of the other variables. This method can help to assess the relationship between the quality of incoming polymer materials and the possibly many distinct sorting equipment parameters in a sorting plant [62]. Regression procedures are closely related to the previous techniques, but is based on the minimization of the distance between a certain predictive equation (which can be defined arbitrarily) and the available data used for modeling purposes. For instance, the regression model can correlate the available spectral data with the plastic stream composition, providing important piece of information for decisions related to the plastic stream separation.

4.7.6. Partial Least Squares (PLS) Regression

PLS regression is a multivariate statistical tool that is used to model the relationship between two or more variables. PLS regression is supported beyond traditional linear regression by tackling complex relationships between two or more sets of variables. This technique is closely related to PCA and is used to identify the most important variables in one set (for example, spectral data) that can be employed to predict the values of variables in a second set (for example, plastic stream compositions). PLS regression can be used to optimize the recovery of specific polymers from the input materials. By modeling the relationship between material characteristics and the yield of each polymer, the plant can make informed decisions about how to sort and recover valuable polymers effectively [75].

4.7.7. ANOVA (Analysis of Variance)

ANOVA is a statistical technique used to investigate and test the hypothesis whether the means and variances of two or more groups are statistically similar or significantly different from each other. By examining variations within and between groups, ANOVA unveils critical insights into the sources of variation, allowing one to conclude about the relationships and similarities in the dataset. ANOVA can be applied to compare the performances of different sorting equipment and operation conditions and to group sets of data that can be regarded as similar. By assessing whether statistically significant differences can be detected in sorting outcomes from different equipment and batches, the plant personnel can determine which machines and operations are the most efficient and accurate, thereby optimizing equipment usage [76]. On the other hand, by assessing whether statistically significant similarities can be detected in a set of measurements, the analytical scheme can identify the sort of plastic material and provide useful information for the sorting operation.

4.8. Additional Remarks

Chemometric techniques can be combined with distinct analytical techniques to provide in-line and real-time identification of polymer compositions in complex waste streams. This type of combination can be based on different mathematical and statistical tools and distinct analytical technologies to allow the implementation of advanced sensor-based sorting procedures, which are indeed being supplied by different providers to assure the high efficiency of plastic separations. As described in the previous chapter, this should be seen as a strong incentive for development and implementation of chemical recycling strategies, allowing the segregation of very pure plastic waste streams and making feasible the processing of well-defined and controlled plastic feeds.

5. Layouts of Sorting Plants and Interactions Among Sorting Techniques

The operation of urban solid waste separation plants constitutes a fundamental waste management tool to lead and treat the post-consumption plastic residuals, preventing that recyclable waste materials end up being sent to the landfill or deposited in the environment, leading to pollution of the land and of the groundwater. In these sorting plants, the definitions of the correct sequence of separation equipment can be essential to assure the efficient recovery of recyclable and organic materials. Thus, by identifying the composition of the solid waste received in the sorting plant and defining the different fractions that should be separated and obtained, it becomes possible to select the most appropriate sorting techniques and equipment that should be used. As widely described in the last sections, the techniques and equipment available are very diverse, making this task more difficult [71].

As described previously, it has been observed that no ideal single method can be regarded as the most appropriate for all possible plastic waste fractions and recycling problems, as each possible

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technological solution presents pros and cons. Therefore, one might expect the combination of different plastic waste sorting methods in different problems, although this issue has not been investigated thoroughly [62]. Jolivet et al. studied the combined application of LIBS and RSS and described the existence of important synergies in terms of instrumentation since both methods make use of laser beams, although with different energy requirements [77]. Shameem et al. studied a hybrid LIBS-RSS system for sorting of PE, PP, PET and PS and found that both methods offer complementary useful information. RSS resulted in more precise separation of different types of transparent polymer, although the performances for separation of colored plastics were not so clear [78]. On the other hand, LIBS performed well for the analyzed plastic streams regardless of the color when cluster analyses were used, but the performances were not good when PCA was applied [79]. The model built with NIR data was found to perform poorly, while the performance of the model built with MIR data was similar to the one built with combined NIR and MIR data, which might suggest the redundancy of NIR data in a hybrid system [80].

According to experts in the area [81], sorting plants can be classified into four groups: (i) basic, (ii) medium, (iii) medium plus and (iv) advanced plant. The basic plant has a relatively low capacity, usually comprising only essential material conditioning steps (sieving and air classification, for example) and relies on manual sorting. The basic plant is becoming increasingly obsolete, as it does not provide an efficient classification and the production volume is low. Medium plants have an intermediate capacity, normally comprising comprehensive conditioning (several sieving steps, air classification and ballistic separation, for example), automatic and manual sorting, although counting primarily on manual product quality control. Medium-plus plants have capacities that are similar to the capacities of medium plants, but can promote more diverse plastic sorting. Besides, additional capacity can be added by running the plant in 3 shifts. Finally, the advanced plant has high capacity, the state-of-the-art process design, and the separation technology is almost entirely based on automatic sorting, also counting on manual and automatic product quality control protocols. The advanced plant is certainly the most effective for processing of municipal solid waste.

The types of input streams and waste quality are essential parameters that must be considered when implementing the sorting plant and the types of equipment that will be installed. Moreover, sorting plants should be adapted to receive different input streams according to need. The input stream can be classified into 4 types of streams: (i) single stream, when all recyclables are mixed together (paper, fibers, plastics, metals, glass, and other containers); (ii) mixed municipal waste stream, consisting of a mixture of non-hazardous waste collected from distinct places and facilities, including households, stores, business offices, among others; (iii) dual stream, when the input is sourced into separate bins (such as mixed paper and cardboard in one bin and commingled materials, such as glass, plastics and cans, in other); and (iv) pre-sorted stream, when recyclables are sorted by materials recovery facilities (MRF) before being sent to the recycling plant [82,83]. It is important to note that in these facilities wet processing is being increasingly replaced by dry processing because of the energy, environmental and financial costs associated with use of solvents (mainly water). For this reason, the use of rotating screens, ballistic separators and optical sensors is becoming more popular in these plants.

5.1. Players of Sorting Plants

The global market for sorting technologies consists of a diverse ecosystem of waste management operators and specialized equipment manufacturers. While major environmental service providers, such as Republic Services (USA) and Suez/Veolia (Europe), manage the logistics and operation of recycling facilities, the technological infrastructure is supplied by engineering firms that customize solutions based on regional waste composition.

In terms of equipment and plant design, the market is served by several key players. Stadler (Germany) is widely recognized for the engineering of complete turnkey plants and the manufacture of mechanical separators, particularly ballistic separators and trommels. Steinert (Germany) holds a

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strong position in magnetic and eddy current separation, having expanded significantly into sensor-based sorting (UniSort technology) for metal and plastic recovery. Similarly, Pellenc ST (France) and Redwave (Austria) provide robust optical sorting solutions adapted for high-throughput industrial environments.

The Tomra Group (Norway) remains a major technology provider, focusing heavily on sensor-based classification (NIR, VIS, Laser). Other relevant manufacturers contributing to the ecosystem include Amut (Italy), focused on washing and recycling lines, Bianna (UK/Spain), and Bub-Anlagenbau (Germany). State-of-the-art material recovery facilities (MRFs) equipped by these manufacturers have demonstrated the capacity to process complex inputs efficiently. Collectively, these modern automated plants are capable of segregating over 16 distinct material fractions, which includes specific polymer grades (PET transparent, blue, green; HDPE, PP, PS, and flexible films), paper, glass, and metals, thereby enabling the high-purity recovery streams required for a circular economy [84,85].

5.2. Examples of Sorting Plants

Depending on the desired final product, the sorting plants may present different layouts and equipment. It is also important to consider whether the input stream and incoming materials have already been pre-sorted elsewhere. Nevertheless, sorting plants associated with urban solid waste treatment usually rely on large and complete sorting systems that can be deployed for polymer recovery (for subsequent recycling) and production of materials for refuse-derived fuels (RDF production) [84].

Figure 8 illustrates a schematic representation of a generic model sorting plant, although the actual series of equipment and the layout can be different at each site. The reception area is the first place which receives the garbage trucks and the waste bags. In this sector, the municipal solid waste bags are fed into the first equipment, where they are torn up to release the waste, which is then conducted by a separation conveyor. In sequence, the waste passes through a manual quality control section for removal of inappropriate materials and large objects, such as rope, wood, and big objects that can disturb the process, break the equipment, and reduce equipment downtime for maintenance [86]. Then, the ferrous magnetic materials are magnetically separated with some of the techniques discussed previously, such as magnetic overhead belt, magnetic drum and magnetic head pulley sorting. In the next process step a trommel is used to remove the glass and organic residues from the flowing waste stream. Typically, the trommel separates the materials into two main streams: the materials with dimensions larger than the hole diameters continue in the main sorting process line, while the pieces with dimensions smaller than the hole diameters (sieved materials) are retained. The sieved materials can be sieved once more to separate the glass pieces from organic residues, as glass pieces can be recycled [87–89] and organics can be sent to composting [90,91]. After the rotating screen, the vibrating conveyors help to separate the material into streams of 2D materials (such as bags, films and papers) and 3D materials (plastic packaging). The material stream goes through the eddy current separation to sort the non-ferrous metals. Finally, the residual waste stream is composed of plastic materials which can be separated according to the desired material.

According to Tomra, depending on the type of the desired material, the support of one to four quality inspectors may be required. For example, Tomra recommends that one to two inspectors should monitor the 2D fraction for separation of 3D materials after the ballistic separator and before the optical separation. Additionally, two to four quality inspectors may be needed to perform the manual quality control and sort mixtures of transparent/white PE films and paper. After sorting, the residual amount of 60 – 80 mm black plastic pieces that remain in the waste stream represent less than 10 – 15 % of the overall input. Tomra also states that this sorting process can produce high-quality raw materials for waste-derived fuel with low PVC content [92].

In order to increase the efficiency of real modern sorting plants, ballistic separators and spectroscopy sensors are combined, to provide accurate and quick detection of the plastic materials, leading to better sorting [17,93]. These techniques can also be used to separate plastics of different colors [72,94]. In this ideal sorting plant, after separation of each process fraction, it is desirable to carry out the quality control, which can be supported by inspectors or performed automatically [95,96].

The Stadler Company is another important global player in the recycling design industry, production, and assembly of automated sorting systems and machines. According to the company, more than 500 sorting plants for municipal solid waste treatment have been implemented with processing capacities ranging from 40,000 ton year^{-1} up to 1,000,000 ton year^{-1} (a particular plant in Spain) [97]. The leading pieces of equipment used in these plants are similar to the ones presented previously for the TOMRA technology. The material streams are initially separated into different sizes according to the shape (flat [2D], rolling [3D], screening) by screening processes that include trommel screening and ballistic separator machinery. In order to achieve the maximum possible sorting efficiency, large-area films are separated from the material streams with the aid of wind shifters. This significantly improves subsequent sorting based on near-infrared technology (NIR). Then the desired high output qualities are attained with the subsequent magnetic and eddy current processes. Finally, the material is separated into fractions with the support of manual quality controlling, collected in hopper belts, and pressed to reduce volume for storage and transport [97]. As an example of a large STADLER plant, the Ecopark 4 in Barcelona, Spain, occupies 52,000 m^2 and treats 365.000 ton year^{-1} municipal solid waste through mechanical and biological treatment, resulting in 75.000 ton year^{-1} of organic fraction from separated collection (OFSC). The reported initial investment was equal to 52 million EUR and the facility operations started in November 2010. In this sorting plant, the primary technology providers are Stadler (mechanical treatment), Sorain Cecchini (biological treatment) and AirClean (air treatment).

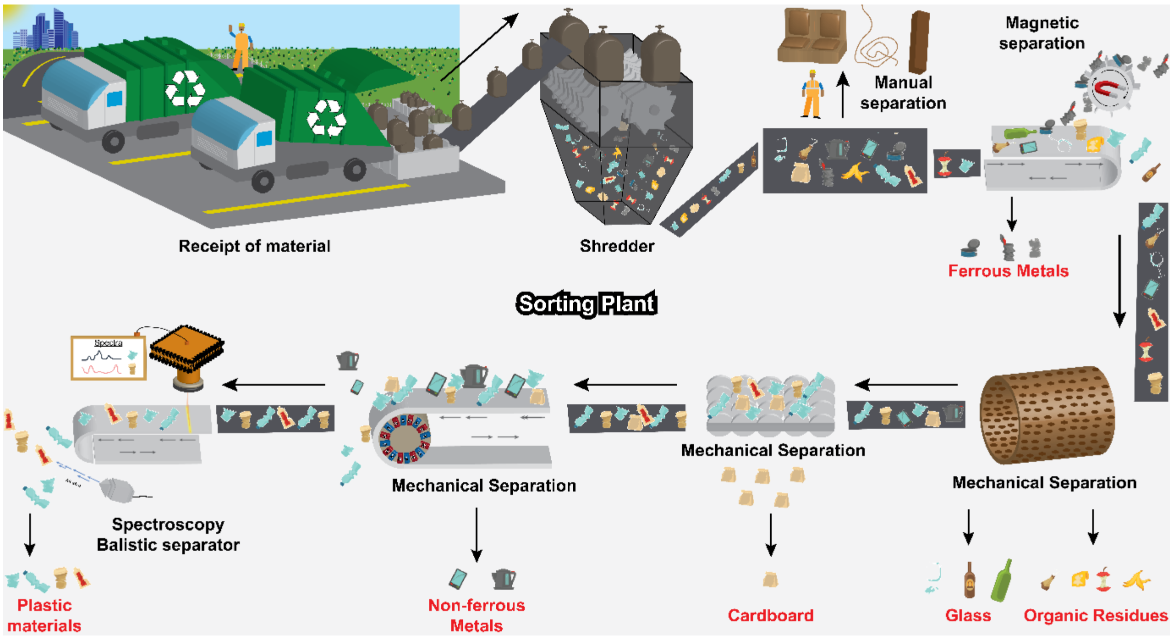

Figure 8. Schematic illustration of a generic hybrid sorting plant featuring the sequential integration of mechanical separation, sensor-based sorting, and intelligent systems to achieve high-purity streams.

In Brazil, the Ecopark Pernambuco uses similar advanced sorting technologies for municipal solid waste sorting in its industrial plant. The sorting plant located in Pernambuco receives about 250,000 tons of municipal solid waste per year, recovers more than 12,500 tons of recyclable materials, and produces about 50,000 tons of waste-derived fuel. This facility operates with TOMRA based technologies and counts on a dedicated line for plastic recovery, including HDPE, PP, PET and polyethylene films (LDPE), ensuring high-speed, high-volume processing, and high levels of purity in the desired final fractions [98].

The Ecopark Pernambuco processes 35 tons per hour of raw urban waste as the main feed stream. The sorting process starts with bag opening, followed by sieving and manual sorting to remove undesirable materials such as ropes, cardboard and glass, which can cause problems to the process operation [98]. The material stream follows the conveyor and is directed to the ballistic separator, which separates the material into three different streams with help of a near-infrared sensor. Figure 9 highlights the three material streams separated in the ballistic air separator, which is considered the heart of this plant. The main pieces of equipment of Ecopark Pernambuco include a trommel, a rotary sorting machine, a shredder (to unpack the bags and grind the polymers), a ballistic air separator (to separate distinct types of polymers, flexible materials (2D), rolling materials (3D) and plastic residues with help of a near-infrared spectrometer and an optical detector) [99].

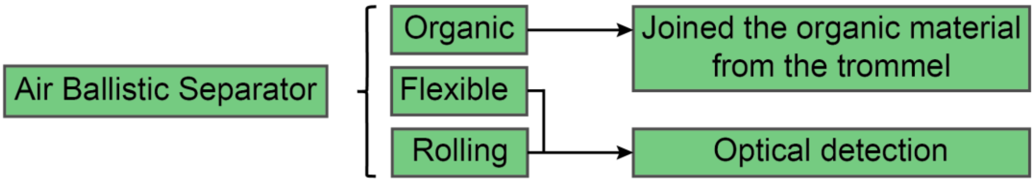

Figure 9. Illustration of the three primary material streams separated by the ballistic air separator at the Ecopark Pernambuco facility.

5.3. A Possible Sorting Plant

By analyzing the reported techniques and cases, it becomes possible to suggest a suitable design for a municipal solid waste sorting plant to sort the organic matter and recyclable materials, as illustrated in Figure 10. The code (Li, I = 1 to 18) above the arrows refers to the number of basic process streams. In the beginning, the garbage trucks dump garbage bags from the municipal collection into a dump (L1), and the bags are torn into a shredder equipped with a magnet to sort the ferromagnetic metals (L2) and expose the garbage in a belt (L3). In sequence, the solid waste is taken to an eddy current to sort the non-ferrous magnetic metals (L4), and the solid waste is directed to a belt (L5). Then, the residues are taken to a trommel with a pore diameter of 90 mm to separate glass and organic matter (L6) from other recyclables (L7). Next, cardboards are separated by a rolling vibratory table (L8) and paper is removed by an upper flow air table (L9). Then, stream L10 is composed mainly of plastics that must be sorted with help of a near-infrared spectroscopy detector (NIR) and a ballistic separator to separate PP (L11) from HDPE and PET (L12). In sequence, a second NIR-based ballistic air separator is required to separate HDPE (L13) from PET (L14). However, as PET can display various colors, a visible spectroscopy detector (Vis) can be combined with a ballistic air separator to sort the colored PET materials automatically, leading to transparent (L15), colored (L16), blue (L17) and green (L18) PET streams. Thus, the main product streams include (i) ferromagnetic metals, (ii) non-ferrous magnetic metals, (iii) a mixture of glass with organic matter (which can be separated with humid techniques), (iv) cardboards, (v) papers, (vi) PP, (vii) HDPE, (viii) transparent PET, (ix) blue PET and (x) green PET.

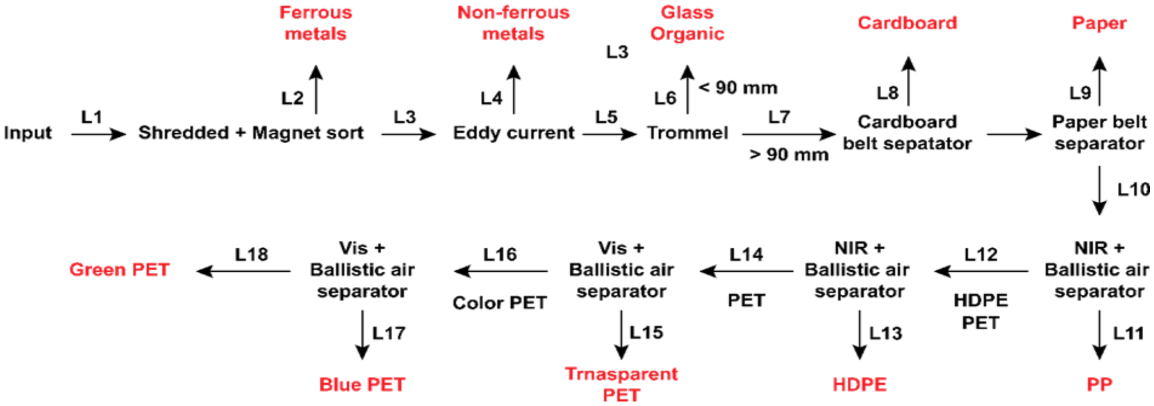

Figure 10. Proposed flowsheet for a municipal solid waste sorting plant, illustrating the sequential unit operations required to recover metals, organics, paper, and high-purity polymer fractions, including color-sorted PET.5.4. Economic and Environmental Aspects**.**

A multifaceted exploration of plastic sorting operations encompasses not only the technical aspects but also the economic and environmental dimensions. Recent studies shed light on economic considerations that can assure the sustainability of sorting plants. The unavoidable and significant costs of municipal solid waste treatment and disposal constitute a fundamental driving force to economic sustainability of sorting operations, as they reduce the amounts of municipal solid waste and consequently the costs of treatment and disposal, while simultaneously generating more valuable process streams and stimulating the development of a circular economy. The world generates around 2.0 billion tons of municipal solid waste annually, although 33 % of this amount is not managed appropriately [100,101]. According to The World Bank, the waste generated per person per day averages 0.74 kg but ranges from 0.11 to 4.54 kg [102]. The waste that is not managed appropriately contaminates the soil, groundwater and air, posing a threat to humans, animals and plants, also reducing the recycling rates. On the other hand, proper management of the municipal solid waste leads to higher recycling rates of recyclables and conversion of organic materials into biogas, biofuel, biomass and fertilizers in composters and bioreactors, allowing the reduction of waste disposal in landfills [103]. Nevertheless, it is always important to reinforce the importance of individual homework to separate the organic and recyclable waste in different bags at our homes to minimize the contamination of the recyclable waste [104].

According to The World Bank, high-income, upper middle-income, lower middle-income and low-income countries can be defined in terms of the per capita gross national income higher than 12,376 USD, between 12,375 – 3,996 USD, between 3,995 – 1,026 USD, and lower than 1,025 USD, respectively [102]. As shown by The World Bank, the municipal solid waste collection rate and composition are different for the different income levels. As it might be expected, the waste collection rate increases with the income levels: while high income countries provide nearly universal waste collection that is close to 96 %, the waste collection rates decrease to 82, 51 and 39 % for the other income levels, respectively [102]. Unfortunately, the non-collected waste can end up in open dumps, contaminating the environment. One must observe that, according to the global waste composition shown in Table 2, organic materials constitute 44 % of urban municipal solid waste, indicating how important it is to separate the organic materials from other recyclable materials at the origin. Table 2 also shows the composition of the municipal solid waste according to income levels. As one might expect, fractions of organic materials are lower and of recyclable materials are higher in high-income countries than in other sectors due to the more efficient waste separation at the origin, higher rates waste collection and incentives for recycling and circular practices from public policies [105].

Al-Athamin et al. delved into the technical and economic performance of the Al-Karak solid waste sorting plant in Jordan, focusing on attaining financial sustainability and enhancing profitability to offset operational expenses [106]. Thus, quantification and characterization of the input and recyclable materials were performed to determine the sorting products, while different pieces of equipment and material streams were considered. An economic model was used to determine the feasibility of the proposed plant options according to three financial factors: present net worth (present net worth), return on investment (ROI) and payback period values [107]. As indicated in the paper, in Al-Karak the municipal solid waste composition contained three main fractions: paper and cardboard (41 %), organic material (28 %) and plastics (15 %), which could generate 12,000 tons/year of recyclable materials, accounting for 63 % of the feed. It was shown that the sorting operation was profitable and that the payback period was smaller than 5 years, when the sorting plant comprised a bale presser, one conveyor belt, a plastics shredder, a forklift, and two waste collection trucks [106].

Table 2. Percentage composition of municipal solid waste categorized by global averages, national income classifications, and a specific regional case study (Al-Karak, Jordan [106]).

Local / Composition	Global waste composition	High-income countries	Upper-middle-Income countries	Lower-middle-income countries	Lower-income countries	Al-Karak – Jordan
Reference	[102]	[108] ([109])	[108]	[108]	[108] ([109])	[106]
Organic material	44	32 (27)	54	53	56 (64)	28
Paper and Cardboard	17	25 (30)	12	12.5	7 (6)	44
Metals	4	6 (7)	2	2	2 (3)	4
Plastics	12	13 (11)	11	11	6.4 (9)	15
Glass	5	5 (7)	4	3	1 (3)	-
Other waste	18	19 (18)	17	18.5	27.6 (15)	9

Gadaleta et al. reported a techno-economic approach to evaluate the performance of a material recovery facilities for plastic waste recovery [107]. The Molfetta material recovery facilities case study in southern Italy considered the inlet plastic feed of about 19,000 tons year^{-1}. The methodological proposal was based on the analysis of the quantity and composition of the different incoming waste streams, calculation of the purity index and recovery index of recyclables, quantification of the individual mass balances and accurate economic assessment of the operations. In the end, the authors compared their results with similar data obtained for a second material recovery facility based on Bedonia, in northern Italy. It is discussed that the analysis of the recovery index for limited number of products can lead to misjudgment of the amounts of contaminants present in other streams. In particular, through polymer and color recognition and sorting, the input plastic waste stream could be divided into product flows and by-product flows: while product flows could be recycled into secondary raw materials, by-product flows were used mainly for energy production [107]. In a technological scenario where fossil fuels are used for energy production, the use of by-product flows as fuels can be supported by environmental arguments; however, it seems appropriate to say that by-product flows should be preferentially recycled and used circularly for manufacture of other useful products.

As the product amounts present as contaminants in other streams are not recovered, they can be defined as "lost" fractions, with average loss values equal to 18.0 % for PET, 3.2 % for PE, 2.6 % for PP and 69.6% for packaging films with sizes smaller than an A3 sheet, the main component of by-product flows and helps to explain the annual production flows of product flows and by-product flows, respectively equal to 8,686 and 9,708 tons. It was shown that the main expenses at the Molfetta plant were annual investment installments, plant maintenance costs, salaries of workers and some variable expenses (electricity and fuel), which comprised 90 % of the annual plant expenses. In spite of that, the Molfetta operation provided annual gains of 234,636 EUR year^{-1} and specific gains of 12.58 EUR per ton of sorted waste [107].

Medina-Mijangos et. al. conducted the technical–economic analysis of a sorting and treatment facility of light packaging and bulky waste in Gavà-Viladecans, Barcelona, Spain [110]. The researchers employed a methodology based on a social cost–benefit analysis, determining the direct impacts and externalities (impacts related to environmental and social aspects) to characterize the total benefit (the difference between revenues and costs) generated by the facility in order to decide whether it was operationally and economically profitable. The facility comprised two plants, one for light packaging waste treatment and the other for bulky waste treatment. In 2017, a total of 22,806 tons of light packaging waste and 63,275 tons of bulky waste were treated in the plant. The annual private costs were obtained directly from the 2017 annual accounts, which was divided by the total amount of waste treated (86,081 tons) to obtain the cost per ton of 96.2 EUR ton^{-1} [110].

The impact of reuse, recycling and waste recovery included the private revenues of the plant. Referring to the 2017 revenues, this included the sale of treated light packaging waste, which recovered 15,868 tons of materials sent to recycling plants and 6,938 tons of materials forwarded to energy recovery facilities. The most representative revenues were related to the waste management service provided for both light packaging (49.89 %) and bulky (38.83 %) waste. Additional studies were carried out to estimate the net CO_2 emissions associated with the operation, being concluded that emissions of 69,655 tons of CO_2 per year were avoided, as calculated with the Simapro and GaBi–LCA tools [110].

Cimpan et al. presented a comprehensive overview of the technological state-of-the-art of sorting and recovery of recyclable materials, describing case studies, reports, and research literature from North America, the United Kingdom, Germany, the Netherlands, and other European countries. Some of the main results collected by the authors are shown in the following lines [111]. First, some studies reported elevated levels of undesired materials and contaminants in collected single streams, a scenario that apparently has changed significantly since then in modern plants. The authors also emphasized that most modern high-tech plants employ additional recirculation of residue streams, which, when combined with mechanical and manual sorting, can significantly contribute to increase of waste recovery and reduction of sorting residues [111]. In these cases, the product streams become richer in the specifically desired products and poorer in undesired contaminant products, allowing the reduction of product loses and increase of revenues because of the higher volume and better quality of product streams [111]. Nevertheless, sorting residues in such highly efficient sorting plants can still account for about 20 % of the input stream [111].

Based on the investigated Dutch reference systems, including three plastic packaging waste recovery plants, Cimpan et al. also developed an empirical model that considered several operation scenarios and was used to evaluate the most impacting strategies that should be implemented in sorting facilities. Among them, source separation was shown to be fundamental to prevent the contamination of plastic waste, increase the amounts and enhance the quality of recycling streams [111].

Cimpan et al. reported that the amounts of potentially recyclable materials recovered in mechanical-biological treatment plants depend on the composition of the residual municipal solid waste feed and, consequently, on seasonal conditions that affect the feed stream composition. Besides, the rates of product recovery depend significantly on the composition of the waste input, the process technology and the purposes of the plants. Moreover, according to Cimpan et al., the total costs per ton of recycled plastic packaging waste ranged from 660 EUR to 870 EUR for the source separation system and from 870 EUR to 920 EUR for the post-separation system, indicating slightly higher costs associated with the post-separation system [111].

6. Conclusions

In the present review, various techniques and strategies to sort recyclables and compost materials from municipal solid waste were described. Besides, typical layouts of sorting plants, the principal players in this field and economic and environmental aspects related to sorting and recycling of municipal solid waste were discussed. Moreover, bibliometric analyses were performed to describe the most relevant papers and patents in the area and to summarize the state-of-the-art sorting technologies. It must be observed that the most relevant techniques employed to separate useful materials from municipal solid waste include mechanical, magnetic, electrostatic, wet and dry technologies. However, technologies that combine spectroscopic methods (used to identify distinct polymer materials in line and in real time) and mechanical separators (such as the air-based ballistic separator) are becoming very popular, as these pieces of equipment open the possibility to develop and implement fully automated systems for sorting of mixed waste. By selecting some representative examples, sorting plant layouts from active site plants and sellers were analyzed to propose a potentially effective sorting plant. Finally, some important economic and environmental aspects were described as reported in the literature, indicating that sorting and recycling of municipal solid waste can constitute a very beneficial and profitable operation. Particularly, current technologies can provide a large number of product streams with high purity and quality, including (i) ferromagnetic metals, (ii) non-ferrous magnetic metals, (iii) glass, (iv) organic matter, (v) cardboards, (vi) papers, (vii) PP, (viii) HDPE, (ix) transparent PET, (x) blue PET and (xi) green PET. In this context, further developments in sorting systems can help the global economy and climate and improve the recovery of materials through recycling and composting.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1. Overview of recent patent applications related to plastic waste sorting. Table S2. Technical overview of mechanical and physical sorting technologies, detailing separation principles, operational and performance metrics. Table S3. Technical specifications of sensor-based and spectroscopic sorting methods.

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Abbreviations

The following abbreviations are used in this manuscript:

ABS	Pol(acrylonitrile-co-butadiene-co-styrene)
AI	Artificial Intelligence

ANNs	Artificial Neural Networks
CNNs	Convolutional Neural Networks
CO_2	Carbon dioxide
EUR	Euro currency
Fe_3O_4	Iron (II, III) oxide
FTIR	Fourier-transform infrared spectroscopy
HDPE	High-density polyethylene
HSI	Hyperspectral Imaging
kNN	k-Nearest Neighbors
LDA	Linear Discriminant Analysis
LDPE	Low-Density polyethylene
LIBS	Laser-Induced Breakdown Spectroscopy
LLDPE	Linear Low-Density polyethylene
MIR	Medium Wave Infrared
MRF	Materials recovery facilities
MSW	Municipal solid waste
NdFeB	Neodymium Iron Boron
NIR	Near-Infrared Spectroscopy
PBST	Poly(butylene succinate-co-terephthalate)
PC	Polycarbonate
PCA	Principal Component Analysis
PCL	Polycaprolactone
PE	Polyethylene
PET	Poly(ethylene terephthalate)
PHBV	Poly(hydroxybutyrate-co-valerate)
PLA	Poly(lactic acid)
PLS	Partial least squares
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PVC	Poly(vinyl chloride)
R&D	Research and Development
RDF	Waste-derived fuel
RF	Random Forests
ROI	Return On Investment
RSS	Raman Scattering Spectroscopy
SVM	Support Vector Machines
USA	United States
USD	Dollar currency
Vis	Visual Spectroscopy/Frequency
WIPO	World Intellectual Property Organization
XRF	X-Ray Fluorescence

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