




Review

Recent Studies and Technologies in the Separation of Polyvinyl Chloride for Resources Recycling: A Systematic Review

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Abstract: Material recycling and thermal treatment are the two most common recycling methods employed for plastic waste management. Thermal treatment for energy recovery is more widely applied compared with material recycling because the latter requires a high efficiency of separation and a high purity of products. Unfortunately, certain plastics like polyvinyl chloride (PVC) are unsuitable for thermal treatment because they contain additives like chloride (Cl^-) that have adverse effects on refractory materials used in boilers. As a result of this, mixed plastic wastes containing PVC generally end up in landfills. PVC-bearing mixed plastics, however, remain valuable resources as championed by the United Nation Sustainable Development Goals (UN-SDGs): Goal 12 “Responsible production and consumption”, and their recycling after the removal of PVC is important. In this paper, recent studies (2012–2021) related to the separation of PVC from other types of plastics were systematically reviewed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A total of 66 articles were selected, reviewed, and summarized. The results showed that various separation technologies conventionally applied to mineral processing—selective comminution, gravity separation, magnetic separation, electrical separation, and flotation—have been studied for PVC separation, and the majority of these works (>60%) focused on flotation. In addition, more advanced technologies including sorting and density-surface-based separation were introduced between 2019 and 2021.

Keywords: plastic; recycling; separation; flotation; polyvinyl chloride

1. Introduction

Plastics offer numerous advantages as flexible materials in various applications and critical industries, such as packaging, electrical/electronic equipment, and automotive components, due to their lightweight nature, chemical and moisture resistance, and excellent insulation properties [1]. According to a report published by Plastics Europe, global plastic production reached 391 million metric tons in 2021 [2,3]. Among the wide array of plastics, PVC stands out as a commonly used material with diverse applications, ranging from

construction and automotive manufacturing to healthcare and consumer products [1,4]. Recent reports indicate that PVC production has reached approximately 32 million metric tons annually, accounting for 9.6% of total plastics production in 2021 [2]. Consequently, the escalating production and consumption of PVC-based products have led to a surge in PVC waste generation, necessitating the development of efficient and sustainable approaches for its removal and recovery. The disposal of PVC waste presents significant environmental challenges due to its non-biodegradable nature and the potential release of hazardous substances during incineration or landfilling [5,6]. Additionally, plastic debris or microplastics (MPs) derived from plastic waste accumulation can interact with organic pollutants or heavy metals, leading to concentrated toxicity in marine and freshwater systems [7].

Despite their many advantages, plastics are environmentally undesirable because they persist for a long time in nature. Plastic degradation and decomposition take hundreds of years under natural conditions, resulting in their accumulation in landfills, oceans, and other ecosystems [8]. The disposal of PVC waste presents significant environmental challenges due to its non-biodegradable nature and the potential release of hazardous substances during incineration or landfilling [5,6]. Incinerating PVC can release toxic pollutants, including dioxins and furans, which have detrimental effects on both human health and the environment [8]. Furthermore, PVC waste deposited in landfills contributes to long-term environmental contamination, as it persists for extended periods without significant degradation [8]. Additionally, plastic debris or microplastics (MPs) derived from plastic waste accumulation can interact with organic pollutants or heavy metals, leading to concentrated toxicity in marine and freshwater systems [7]. Moreover, landfills contribute to the contamination of land and aquifers through the release of leachable components trapped in plastic and washed away by rainwater. One example of such leaching is the release of bisphenol A and lead compounds from PVC waste, posing risks to human health and the environment [9,10]. Improper disposal and the littering of PVC waste pose significant threats to wildlife, marine life, and overall ecosystem health, highlighting the need for effective waste management practices.

In recent years, there has been a growing emphasis on shifting towards sustainable waste-management strategies, particularly within the concept of the circular economy, which prioritizes material recycling and resource recovery in line with the Sustainable Development Goals (SDGs): Goal 12 “Responsible consumption and production” [11]. This focus is crucial in reducing the environmental impact of plastics, including PVC, by decreasing the amount of waste for disposal and minimizing the industrial demand for virgin plastics derived from fossil fuels. As a result, the recycling of PVC and other plastics has become a central area of research and technological advancements. Effective strategies for PVC removal and recovery have garnered considerable attention to mitigate the environmental impacts associated with PVC waste and promote sustainable resource management. PVC recycling not only reduces dependence on virgin materials but also minimizes energy consumption and greenhouse gas emissions linked to the production of new PVC [12]. Furthermore, the recovery of valuable components from PVC waste presents an opportunity for resource conservation and aligns with the principles of the circular economy.

In general, conventional plastic waste management practices can be classified into two categories: (i) incineration and (ii) landfilling. Incineration, particularly the field burning of waste, is widely used but notorious due to its negative impacts on air quality, the release of toxic components, and the wastage of energy content in the waste. It is notoriously widespread in low-to-medium income countries with inadequate waste treatment infrastructure [13]. Despite the various options available, landfilling remains the dominant form of waste disposal for mixed plastic waste, including PVC-containing plastics like electronic wastes [14]. Although landfills occupy a relatively small portion of land, they have other serious environmental consequences. The decomposition of organic matter, such as food waste, in landfills leads to the release of odorous compounds and greenhouse gases, including biogas, which is a mixture of carbon dioxide (CO₂) and methane (CH₄).

Moreover, landfills contribute to the contamination of land and aquifers through the release of leachable components trapped in plastic and washed away by rainwater. One example of a leachable toxic component in PVC is bisphenol A and lead compounds [9,10]. Bisphenol A is an endocrine-disrupting chemical (EDC) because it can mimic the functions of estrogen in the body, while lead is a heavy metal notorious for causing neurological damage especially in the developing brain of babies and children [15–18].

PVC can undergo two main recycling processes: mechanical recycling and feedstock recycling [18]. On the one hand, mechanical recycling is the recommended method for PVC recycling, which involves repurposing and reprocessing the material directly within the production plant where the waste was generated. This type of waste arises during various manufacturing stages, such as the start-up and end of production, mechanical processing of finished products, or waste resulting from production errors. On the other hand, feedstock recycling is another approach for managing PVC waste and should be employed for those that cannot be mechanically recycled due to economic or environmental reasons [19]. Energy recovery, including the gasification of fuels or direct combustion in specialized thermal utilization plants, is one relatively straightforward method of feedstock recycling [13,19,20]. These processes require appropriately designed thermal decomposition facilities and often involve significant investment costs for constructing specialized plants. While this type of recycling may sometimes be considered uneconomical, it may be necessary to facilitate the closed-loop circulation of materials in the global economy. It is important to note that advancements in science and technology continue to offer new possibilities for processing PVC into alternative raw materials, as well as prospects for further enhancing existing recycling technologies to utilize recycled PVC and reduce the consumption of virgin PVC.

In general, plastic recycling encompasses various stages, including classification, separation, and production, which involve both chemical and mechanical recycling methods [21]. Mechanical recycling is suitable for various types of plastic waste but yields low-value materials [20]. Chemical recycling aims to convert plastic waste into plastic monomers, chemicals, fuels, feedstock, and value-added polymers while recovering energy through chemical reactions [22]. Consequently, separation plays a crucial role in plastic recycling, as impurities and non-targeted plastic within waste mixtures can disrupt the recycling process and diminish the expected benefits. Despite the relatively straightforward separation between plastic and other materials like steel, copper, aluminum, and metallic alloys, efficient and clean separation techniques hold significant importance in plastic–plastic separation and recycling. This is because separating homogeneous, high-purity plastics from plastic mixtures with similar densities and surface properties remains extremely challenging. As a result, various separation methods for plastic recycling, including manual separation, gravity separation, tribo-electrostatic separation, magnetic separation, spectroscopy sorting, and plastic flotation have been developed.

The objective of this systematic review is to provide a comprehensive overview of recent technological advancements in PVC removal and recovery, with a specific focus on their potential for resource conservation and recycling. By examining the state-of-the-art approaches and evaluating their advantages and limitations, this study aims to contribute to the development of sustainable practices for PVC waste management. The subsequent sections of this paper are organized as follows: Section 2 explains the review methods, Section 3 presents the comminution techniques for PVC separation from other materials, Section 4 discusses gravity separation techniques for PVC removal, Section 5 explores the application of magnetic separation in PVC recycling, Section 6 examines various approaches for electrical separation, Section 7 introduces sorting technologies for PVC recovery and recycling, Section 8 addresses the challenges and future prospects of flotation technology for PVC removal and recycling, Section 9 explores other relevant PVC recycling technologies, and Section 10 presents the conclusions of this work.

2. Review Methods

A systematic review was conducted to examine the current state of technologies related to the separation of PVC from other materials between 2012 and 2021. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [23], as well as the guidelines recommended by Andrews [24]. Peer-reviewed journal publications were identified using specific keywords, including “PVC”, “polyvinyl chloride”, “separation”, “recycling”, “sorting”, “recovery”, and “removal”. The databases of Web of Science and Scopus were utilized, and the publication dates were restricted to between 2012 and 2021. Initially, a total of 4720 articles were obtained based on these criteria; that is, 2407 papers from Web of Science and 2313 papers from Scopus. After removing duplicates, 3123 articles underwent screening, as shown in Figure 1. The screening involved examining titles, highlights, abstracts, and keywords to eliminate articles that did not focus on “PVC”. Among the screened articles, 2821 papers were excluded, leaving 302 papers for the next step. During the eligibility evaluation, full-text articles were assessed [25]. The results revealed that 26 papers were inaccessible, 30 papers were not peer-reviewed, 13 papers were not written in English, 22 papers were either review papers, technical papers, features, focuses, letters, or case studies, and 137 papers were unrelated to PVC separation. Following the systematic selection process, a total of 66 papers remained and were included in this review. These papers were categorized based on their contents into the following: selective comminution (1 paper), gravity separation (6 papers), magnetic separation (1 paper), electrical separation (13 papers), sorting (2 papers), flotation (40 papers), and others (3 papers).

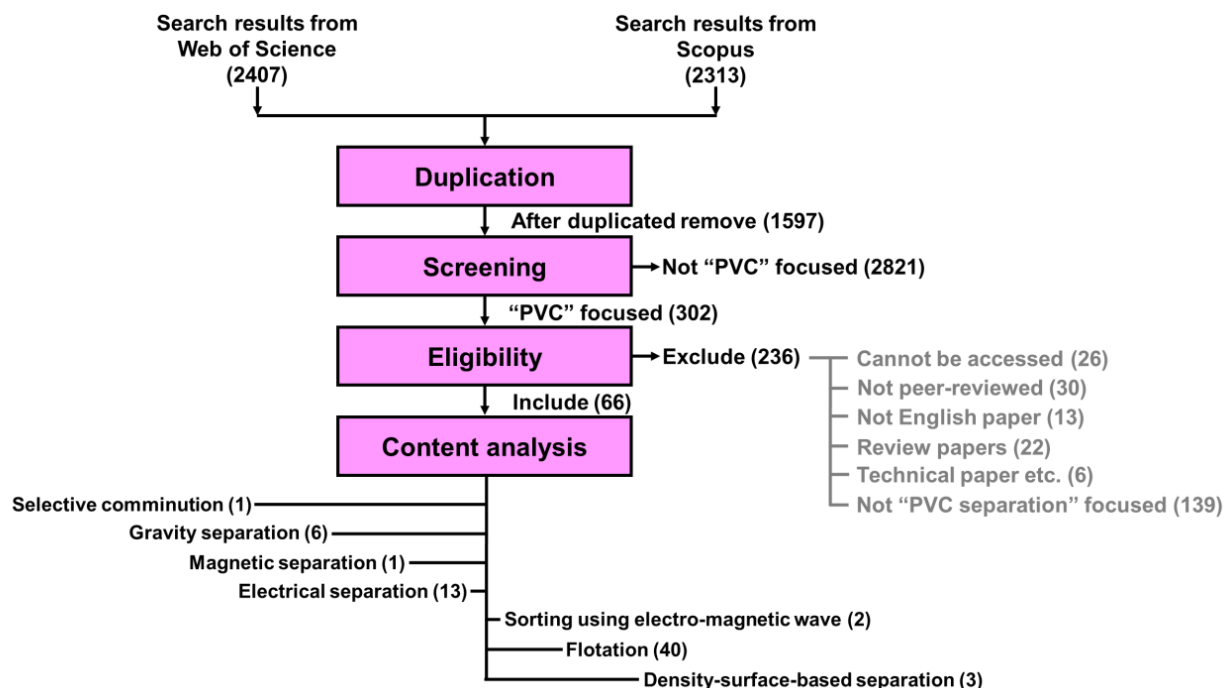


Figure 1. A schematic diagram of the study selection criteria and methodology to identify related research for this systematic review.

3. Selective Comminution

The comminution technique has been applied to isolate plastics from metals, as well as to separate PVC from wire harnesses which usually consist of copper (Cu) strands coated with thin PVC cables. Kumar et al. [26] reported the separation of PVC from Cu-wire harness using n-butyl acetate to swell the PVC coatings and remove them by comminution in a rod mill with an inner diameter of 160 mm and a length of 160 mm including seven stainless steel rods with 125 mm in length and 15 mm in diameter (Figure 2). The results show that PVC and Cu-wires (20 cm long) were completely separated within 60 min at

a rotation speed of 15 rpm. In addition, it was observed that n-butyl acetate extracted approximately 90 wt% of the phthalate plasticizer from the PVC coating during the swelling treatment. This technique is promising because it efficiently reduced the environmental impacts of PVC by chemically separating its phthalate plasticizer component.

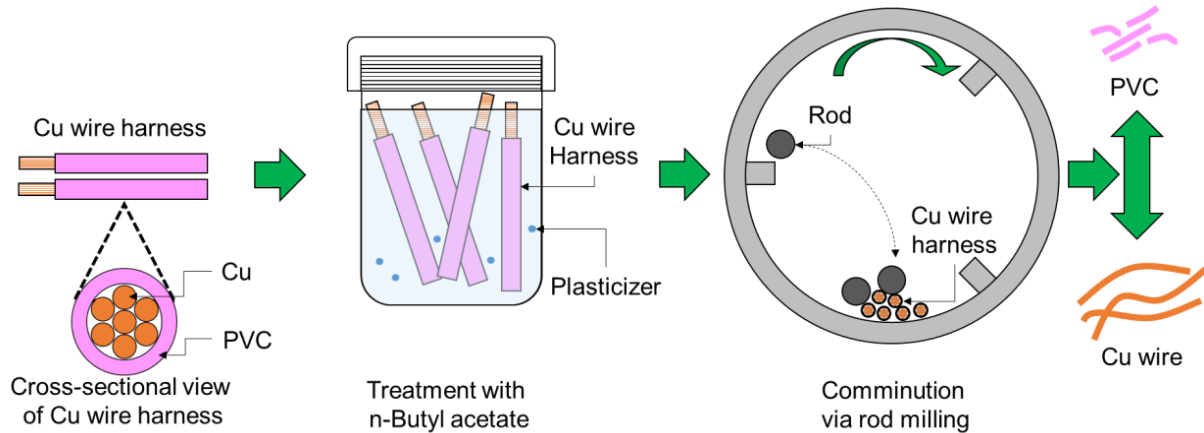


Figure 2. A schematic illustration of PVC separation from Cu wire harnesses via comminution.

4. Gravity Separation

Gravity separation is a well-established technique in various industries like mineral processing and coal cleaning because of its simplicity, low cost, low energy consumption, and high efficiency. This technique relies on the principle that different materials settle at different rates under the influence of gravity in a fluid medium like air, water, and dense media. It involves creating controlled conditions where the heavier plastics (i.e., high density) sink while the lighter plastics (i.e., low density) float. According to relevant research compiled in this systematic review, many gravity separation methods have been extensively investigated and employed for PVC recycling. These techniques include sink–float separation [27], hydrocyclone with suspension media [28,29], hydraulic separator [30], and jig separation [31,32], and they vary in terms of equipment requirements, operational parameters, and applications as summarized in Table 1.

The sink float separation technique was developed and has been employed as a method of separation based on varying the density of the aqueous media utilized during the density-based process. According to Quelal et al. [27], multiple separation steps were needed with different media density (i.e., 1.000, 1.090, 1.100, and 1.175 g/cm³) to separate post-consumer plastics including PVC, polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), and acrylonitrile butadiene styrene (ABS). These authors reported an approximately 84.6% recovery of each plastic using sodium hydroxide (NaOH) and tap water as an aqueous media for separation.

Hydrocyclones are widely utilized in various industries for their exceptional capability to separate solid particles from liquid suspensions based on the principles of centrifugal force and fluid dynamics. As reported by Yuan et al. [28], a hydrocyclone was used to separate binary mixtures of PVC/PET with a 94.6% PVC recovery and a purity of 87.5%. In addition, calcium chloride (CaCl₂) was used by these authors as a medium with a density of 1.3 g/cm³. Moreover, this work noted that to improve the separation performance, a series of cyclone separations known as LARCODEMS is required [29] to recover PVC from residual plastic products containing PVC, PET, PS, polycarbonate (PC), ABS, and polymethyl methacrylate (PMMA). They also highlighted that a 100% PVC recovery and purity was obtained when the media suspension (i.e., suspension of ground calcite) was adjusted to 1.27 g/cm³.

An apparatus called Multidune, proposed by Lupo et al. [30], was developed as a hydraulic separator for the purpose of separating plastics based on variations in water flow rate. This device was demonstrated to be capable of achieving high levels of purity and

recovery when separating PVC from PVC/PC mixtures, with a purity reaching up to 99.9% and recovery rates reaching up to 99.7%.

Table 1. A summary of recent gravity separation techniques for PVC.

Technique	Density [g/cm ³]							Size [mm]	Conditioning Details	Purity [%]	Recovery [%]	Reference
	PVC	PP	PE	PET	PS	PC	ABS					
Sink–float	1.35	0.91	0.95	1.35	1.04	1.20	1.07	3.0	Tap water (Density = 1.00 g/cm ³)	N/A	84.6	[27]
Cyclone with suspension media	1.44	–	–	1.34	–	–	–	0.75	NaOH (Density = 1.09; 1.10; 1.18 g/cm ³)	94.6	87.5	[28]
Cyclone with suspension media (LARCODEMS)	1.44	–	–	1.36	1.05	1.20	1.05	2.0–4.0	Suspension prepared from CaCl ₂ (Density = 1.30 g/cm ³)	100.0	100.0	[29]
Hydraulic separator	1.61	–	–	–	–	1.21	–	2.0–4.8	Suspension prepared from ground calcite (Density = 1.09; 1.18; 1.27 g/cm ³)	99.9	99.7	[30]
Jig	1.28	–	–	–	1.05	–	–	1.0–5.6	Frequency of diaphragm movement 30 cycles/min; water displacement 30 mm	99.3	82.2	[31]
	1.38	–	–	1.31	–	–	–	2.0–8.0	Vary the water flowrate in multitudine (700–1400 cm ³ /s)	94.3	N/A	[32]

Note: “N/A” means “not available”, and “–” means “not included in the experiments”.

Jigging is another gravity concentration technique that operates within a pulsated bed where a combination of solid and water is contained in a perforated vessel. Vertical currents of water are introduced to generate water pulsation and induce the stratification of particles based on density differences among the constituent particles within the mixture. Consequently, particles with a higher density migrate downward and remain confined within the jigging chamber, while particles with lower density ascend and overflow from the system. As highlighted by Pita and Castilho [31] and Phengsaart et al. [32], jig separation has a high performance and it recovered PVC from binary mixtures of PVC/PS and PVC/PET with a purity between 94.3% and 99.3%.

5. Magnetic Separation

Magnetic separation is another physical separation technique that has been applied to recover PVC. Based on the literature, a novel magnetic separator was recently developed to separate PVC from various mixed plastics called magnetic projection [33]. This device consists of a feed unit, magnetic ring unit, and a separation area as illustrated in Figure 3. The feed unit is comprised of an entrance, a feeding channel, and a feeding pendulum driven by an actuator. Meanwhile, the separation area is composed of a paramagnetic solution (MnCl₂) and baffles to separate and collect particles of different densities. The separation process begins when the feeding pendulum pushes samples through the anti-magnetic force, which is generated by a ring magnet placed between the feeding part and

the separation area. The samples are then projected and thrown into the separation area. These authors reported that the method can reach a 96.4% PVC recovery from mixtures of PP, ABS, PC, polylactic acid (PLA), and PET [33].

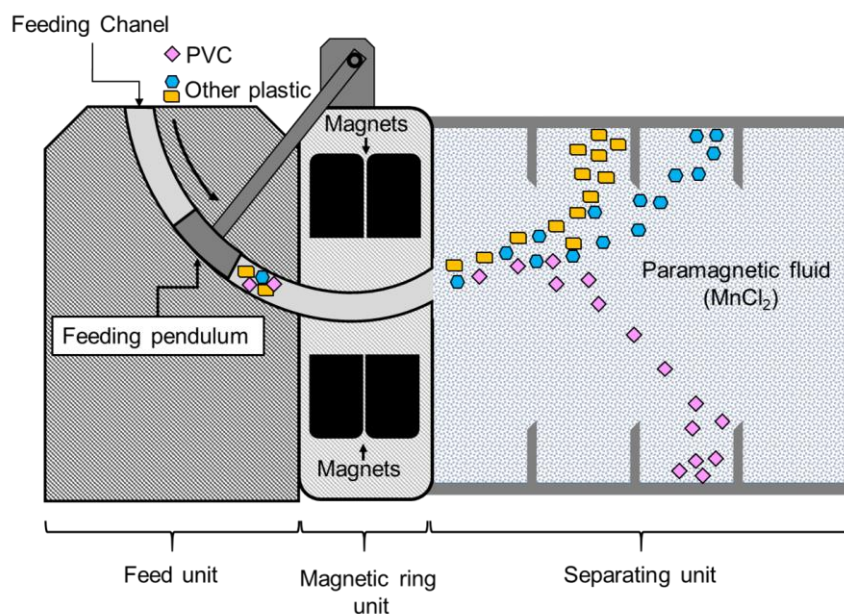


Figure 3. A schematic diagram illustrating the principles of magnetic projection [33].

6. Electrical Separation

Electrical separation is a technique that separates plastics from other materials using differences in electrical conductivity. In addition, this technology is beneficial due to its low cost, low environmental impact, high recovery rate, and high purity of products.

The tribo-electrostatic separator is the most frequently used electrical-based technique to separate PVC from other plastics reported in recent related research (Table 2). This separation method was found to be suitable for separating mm-sized particles as shown in Table 2, and its optimal size range is between 1 and 10 mm. Generally, the separator compartment consists of a feeding device, charging device, high-voltage electrical field, and collection bin. The separation step can be divided into two parts as displayed in Figure 4: (i) electrical charging on particles (i.e., tribo-charger), (ii) deflection process (i.e., electrostatic separator).

In the tribo-charger, particles are charged by an electric source or contact-friction between the particle–particle and particle–wall resulting in the creation of positive and negative electric charges that accumulate on plastic surfaces. In general, it can be classified into two types: solid single-phase and gas–solid two-phase. Solid single-phase includes vibration, corona, and friction rotating drum charging [34–37] while fluidized bed, propeller-type, and cyclone charging are categorized as gas–solid two-phase [34,35,38–44].

In the deflection step, charged particles from the first step are separated and deflected by an electric field depending on their polarity and amount of charge. There are typically three types of deflection process reported in the literature: free fall, drum-type, and belt separator. The free fall type allows particles to fall freely into the electrostatic field generated by applying a high voltage on the positive and negative electrodes of the separation system. Within the electric field, charged particles move towards the oppositely charged electrodes and are collected in the corresponding boxes [34,39,41]. For drum-type and belt separators, charged particles are placed on a drum or belt that is electrically grounded. Highly conducting particles lose their charge, are pulled away from the drum surface, and are placed in collection boxes in the zone farthest from the drum. In contrast, poorly conducting particles retain their charge, are held on the drum surface, and brushed off into the boxes closest to the drum [36,37,40,42–44].

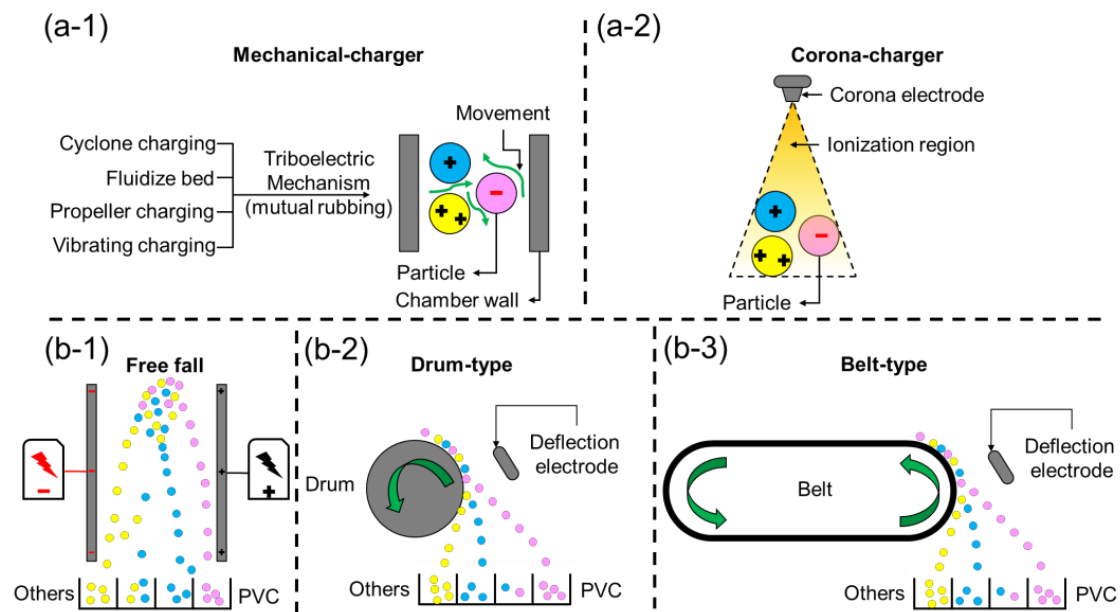


Figure 4. Schematic diagrams illustrating the principles of electrical separation; (a) electrical charging on particles ((a-1) mechanical-charger and (a-2) corona-charger) and (b) deflection process ((b-1) free fall, (b-2) drum-type, and (b-3) belt-type).

Table 2. Relate research on the separation of PVC from other materials using electrical separator.

Separators	Charging Mechanism	Moving Mechanism	Samples								Size [mm]	Purity [%]	Recovery [%]	Reference			
			PVC	PP	PE	PET	PA	PC	ABS	Others					Metals		
Tribo-electric separator	Fluidized bed	Free fall	✓				✓					3.0–5.0	N/A	98	[34]		
			✓				✓					0.01–0.1	N/A	90	[38]		
			✓					✓				2.0–2.5	N/A	90	[39]		
			✓						✓			2.0–2.5	N/A	92	[39]		
			✓			✓						6.5–10	98	66	[41]		
			✓			✓	✓					3.5–6.5	91	77	[41]		
	Tribo-electric separator	Drum-type	Drum-type	✓			✓						2.0–2.8	N/A	96	[42]	
				✓						✓		0.02	N/A	95	[43]		
				✓			✓				✓		2.7–4.0	N/A	<50	[44]	
		Belt-type	Belt-type	✓				✓	✓		✓		1.0–2.0	93	N/A	[40]	
				Propeller charging	Free fall	✓				✓				3.0–5.0	N/A	97	[34]
				Cyclone charging	Free fall	✓	✓	✓			✓	✓	✓		<5.0	N/A	N/A
✓	✓	✓					✓	✓	✓		<5.0	N/A	N/A	[35]			
Vibrating charging	Free fall	✓				✓		✓	✓	✓		3.0–5.0	N/A	85	[34]		
		✓					✓					1.6–3.2	N/A	50–100	[36]		
Corona charging	Belt-type	✓	✓					✓		✓		1.6–3.2	96	99	[36]		
		✓	✓					✓		✓							
Friction rotating drum charging	Drum-type	Drum-type	✓	✓								4.0–8.0	97	41	[37]		
Electrostatic adhesion	No charging	Vibrating inclined plane-type	✓		✓						✓	0.5–5.0	99	95–100	[45]		
Electrostatic separator	No charging	Drum-type	✓								✓	2.0–5.0	N/A	100	[46]		

Note: “✓” means “included in the experiments”, “blank” means “not included in the experiments”, “N/A” means “not available”, “PA” means “polyamide”, “Other” means “other plastics including PS, polyurethane (PU), polylactide (PLA), polycaprolactone (PCL), and poly(3-hydroxybutyrate-co-4-hydroxybutyrate) (P(3,4HB))”, and “Metals” means “aluminum and copper”.

Electrostatic separators like the drum-type electrostatic separator and electrostatic adhesion are suitable for separating electrically conducting from non-conducting mate-

rials and could be applied to separate PVC when some metals are present in the feed sample [45,46]. These separation techniques have been shown to achieve high separation performances with 95–100% PVC recovery.

7. Sorting Using Electromagnet Wave Sorting

In past decades, researchers have diligently strived to advance increasingly accessible and efficient methodologies for the purpose of plastic sorting. These techniques are widely employed in the non-destructive assessment of plastic samples through analysis of the unique molecular and elemental signatures emitted or absorbed by plastics. These techniques include laser-induced breakdown spectroscopy (LIBS), near-infrared spectroscopy (NIR), mid-infrared spectroscopy (MIR), Raman spectroscopy, and X-ray fluorescence spectroscopy (XRF) [47]. The underlying principle of these sorting technologies entails directing a light beam, such as a neodymium-doped yttrium aluminum garnet laser or halogen light, onto the surface of plastics. The atoms, ions, and molecules within the plastic sample become activated and transition to excited states, subsequently emitting photons of specific frequencies upon returning to a steady state. Light collectors are employed to gather the emitted light, which is then processed by computer software to generate a distinct spectrum. Subsequently, an air gun is employed to eject the specifically selected plastic, guided by signals from the operating software. Finally, each plastic is sorted into the appropriate container, as depicted in Figure 5. More recently, machine learning algorithms have emerged as powerful tools in plastic sorting technology. These algorithms leverage vast datasets of plastic samples to learn and recognize patterns, enabling the automated identification and sorting of plastics. Notably, Peng et al. [48] reported achieving 100% accuracy in plastic sorting through LIBS techniques by compressing the training image data of each plastic type, such as PVC, ABS, polyamide (PA), and PMMA, into a singular image for use by the machine-learning algorithms. Additionally, Duan and Li [47] explored the classification of distinct plastic categories using NIR spectroscopy, demonstrating that sorting plastics via NIR techniques could accurately distinguish between PVC, PP, PS, PET, high-density polyethylene (HDPE), low-density polyethylene (LDPE), and PC with 100% accuracy when incorporating multiple regions of the spectrum to enhance the machine-learning model.

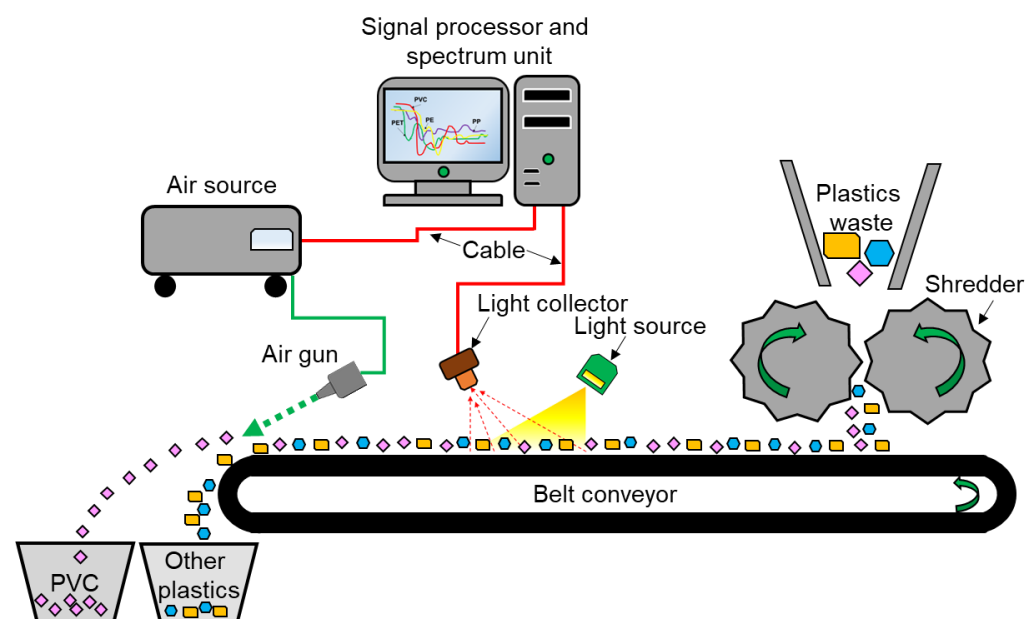


Figure 5. A schematic diagram of sorting technology for the separation of plastic waste.

Overall, the principle of plastic sorting technology lies in the systematic analysis and categorization of plastics using a combination of spectroscopic analysis, automated sorting systems, and machine-learning algorithms. By effectively segregating plastic materials, this

technology facilitates the recycling and reutilization of plastics, contributing to sustainable waste management and resource-conservation efforts.

8. Flotation

Early research has demonstrated that flotation technology can be used as a separation approach for plastic wastes, due to its previous successful industry application in mineral processing. This technique is based on the difference in the surface wettability of materials utilizing bubbles as a particle carrier. Hydrophobic particles (i.e., water-hating) are brought to the water surface via bubble attachment, while hydrophilic particles (i.e., water-loving) remain in the flotation cell and sink to the bottom. In mineral flotation, collectors are commonly employed to enhance the hydrophobicity of mineral particles. However, the approach taken in plastics flotation differs significantly, as it primarily centers on enhancing the hydrophilicity of plastic particles to augment the disparity in their wettability. Nevertheless, the proximity in hydrophobicity among different plastic types presents challenges in segregating individual plastic types through flotation alone. Consequently, the field of plastics flotation heavily relies on modifying the hydrophobicity of plastics to improve flotation efficiency. Extensive investigations have been conducted on various reagents known as wetting agents to address this requirement. Figure 6a illustrates the fundamental concept of mineral flotation in comparison to plastic flotation (Figure 6b). Additionally, prior surface treatments of plastics are necessary before flotation can be carried out. These pretreatment steps are particularly effective for separating high-density plastics, notably PVC, owing to PVC's unique surface properties, characterized by a higher dielectric-loss coefficient compared with other plastics. The application of surfactants facilitates the selective separation of PVC through selective surface reactions on PVC; the abundance of hydrophilic functional groups, such as ether, hydroxyl, and carboxyl moieties, can be increased or decreased relative to other plastics [49]. Based on our assessment of the literature, this technique can be classified into two categories: flotation with surfactants and flotation without surfactants.

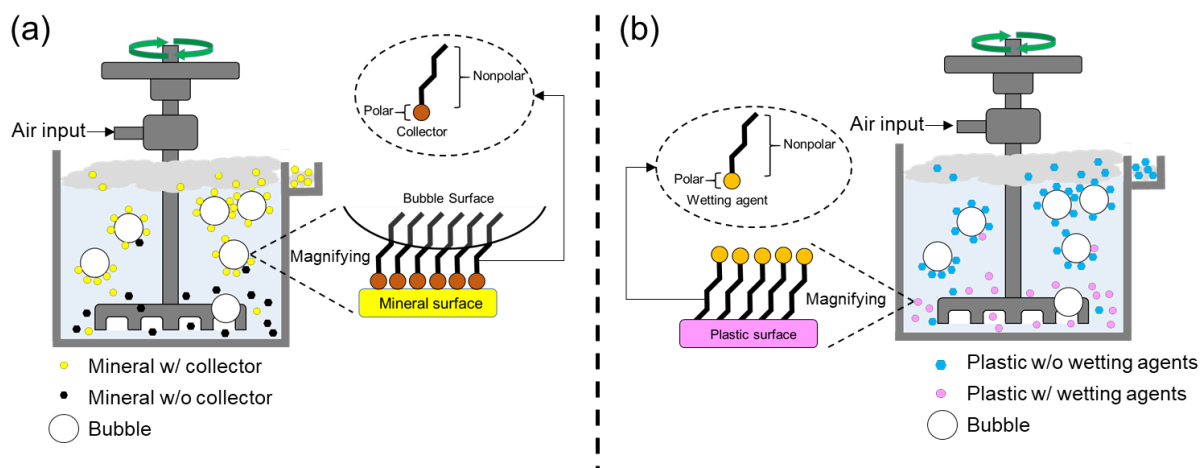


Figure 6. Schematic diagrams illustrating the flotation of (a) minerals and (b) plastics.

8.1. Flotation with Surfactants

The separation of polymeric materials poses challenges, as gravity separation and hand sorting are not effective due to the similar densities of different polymers. Therefore, froth flotation is utilized to separate materials that cannot be separated by gravity. Naturally, all types of plastics exhibit hydrophobic properties. In separation techniques, it is crucial to modify the surface properties of plastics, making one surface more hydrophilic while keeping the other hydrophobic. Plasticizer reagents or wetting agents are employed to alter the behavior of plastic surfaces [50–52] and various reagents have been applied to modify the surface characteristics of plastics (Table 3).

Table 3. A summary of flotation studies on PVC separation using flotation and various surfactants.

Flotation Type	Reagents	Concentration	Condition Time [min]	Samples						Size [mm]	Purity [%]	Recovery [%]	Ref.
				PVC	PET	PS	PC	ABS	Others				
Direct	LA	250 g/t	3	✓	✓					2.0–3.4	98.9	57.0	[52]
	Gelatin	1250 g/t											
	PVA	800 mg/L	N/A	✓	✓	✓				N/A	N/A	N/A	[53]
	PEG	2000 mg/L											
	MC	2000 mg/L											
TA	1200 mg/L												
Reverse	Diisooctyl Azelate	600 g/t	10	✓	✓					2.0–3.4	52.0	99.0	[50]
	LA	0–500 g/t	2	✓	✓					2.0–3.4	–	–	[51]
	DIB	0–1500 g/t											
	LA	25–55 g/t	5	✓	✓					2.0–3.4	99.4	90.1	[54]
	Triton XL-100N	1000 g/t	3	✓	✓					2.0–3.4	86.4	100.0	[55]
	DIB	1000 g/t											
	LS		10							<5	98.7	98.9	[56]
	TA												
	MC	N/A		✓	✓	✓	✓	✓	✓				
	Triton X-100		5	✓	✓	✓			✓	1.0–5.6	95.8	94.4	[57]
	TA	0–10 mg/L											
Saponin	10–30 mg/L	5	✓	✓	✓			✓	N/A	95.7	72.8	[58]	
SL	100–300 mg/L	4	✓						2.0–5.0	N/A	99.8	[59]	
CaCl ₂	30%					✓	✓	✓					

Note: “✓” means “included in the experiments”, “blank” means “not included in the experiments”, “N/A” means “not available”, and “Others” means “Other plastics including PP, PE, PA, PMMA, and PTFE”.

In direct flotation in which PVC is recovered as a froth product, many reagents such as tannic acid (TA), polyethylene glycol (PEG), polyvinyl alcohol (PVA), methyl cellulose (MC), lignin alkali (LA), and gelatin have been used as wetting agents. Without the use of these reagents, PVC, PET, and PS simply sink to the bottom due to their higher density compared with the surrounding liquid media. The concentration of TA up to 1200 mg/L, for example, significantly affected the wettability of PVC, achieving 100% recovery by flotation [53]. Due to the presence of chlorine in the PVC structure, it facilitates the molecular absorption of TA on the PVC surface because chlorine possesses the highest electron affinity and the third-highest electronegativity among chemical elements. Other reagents such as PEG, PVA, and MC are also adsorbed on PVCs, but they exhibit less intensification of hydrophobicity compared to TA. Binary mixtures of chemical agents including PVA-PEG, PVA-MC, TA-MC, TA-PVA, PEG-MC, and TA-PEG have been investigated, resulting in a PVC floatability of 0%, 35%, 40%, 50%, 75%, and 85%, respectively [44]. The highest recovery of PVC from plastic mixtures (PET, PS, and PVC) is achieved using TA-PEG due to the more hydrophobic surface of PVCs after wetting-agent adsorption [53]. Additional research conducted by Yenial et al. [52] examined two other chemical reagents—lignin alkali and gelatin—and reported that both wetting agents affected PVC separation from PET/PVC mixtures. Both of these compounds are anionic substances, causing the surface of PET to become more hydrophilic, depressing PET particles and allowing PVC to float naturally.

In reverse flotation, PVC is recovered in the tail product by depressing PVC plastics using chemical reagents. Altering the wettability and contact angle of the plastic surface influences its floatability behavior. Guney et al. [51] investigated PET/PVC separation using LA and diethylene glycol dibenzoate (DIB) as chemical agents, both of which increased the hydrophobicity of PET and reduced the hydrophobicity of PVC. These findings are consistent with the study of Yuce et al. [55], who also examined PET/PVC separation using LA. The concentration of LA was highlighted by these previous works as a critical factor in depressing PVC particles; that is, increasing the concentration of wetting reagent leads to a higher PVC content in the tail/sink product [55].

Contact angle is another important factor influencing the separation process during flotation. The addition of LA reduces the contact angle of PVC as the concentration

increases. Experimental results have shown a reduction in the contact angle from 79° to 73° , indicating the increased wettability of PVC [51]. A high dosage of TA also resulted in contact angle reduction as depicted in Figure 7. However, it is unnecessary to reduce the contact angle of PVC to zero, as the contact angle of PVC is 49° , which leads to a nearly 100% depression rate [57]. Saponin and sodium lignosulfonate (SL) also influenced PVC flotation by reducing the contact angle [58].

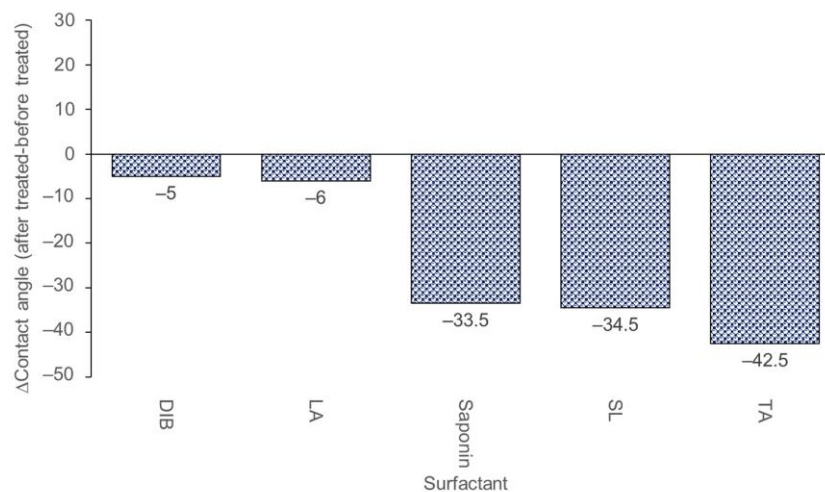


Figure 7. Changes in the PVC contact angle in the presence of various surfactants.

Furthermore, PVC can be depressed due to its higher density compared to other plastics, allowing the other plastics to float. CaCl_2 solution is utilized as a wetting agent for PVC separation from ABS, PC, and PA. Increasing the concentration of CaCl_2 enhanced the purity of separated PVC. However, a 30% CaCl_2 solution reduced the recovery potential of PVC, likely due to the similar densities of the solution and PVC [59].

8.2. Flotation without Surfactants

8.2.1. Pretreatment Using Reagents

The similar surface hydrophobicity of PVC with other plastics makes it impossible to freely isolate from plastics mixtures by flotation without surface modifiers. Hence, surface treatment with chemical reagents is required to increase the difference in surface wettability of PVC with other plastics. According to recent studies, many reagents have been investigated as summarized in Table 4. Direct flotation, whereby PVC is reported as a froth product, has been applied using various reagents for surface oxidation such as chlorine dioxide (ClO_2) [60], potassium ferrate (K_2FeO_4) [61], potassium permanganate (KMnO_4) [62,63], sodium persulfate ($\text{Na}_2\text{S}_2\text{O}_8$) [64,65], ammonium persulfate ($(\text{NH}_4)_2\text{S}_2\text{O}_8$) [66], and combinations of potassium hydroxide and ethylene glycol (KOH and $(\text{CH}_2\text{OH})_2$) [67], as well as sodium hydroxide (NaOH) [68–72] for surface hydrolysis. These reagents enhanced the hydrophilicity of other plastics, while the hydrophobicity of PVC was unaffected. The contact angle of PVC after treatment was stable when these reagents were used, but those of other plastics such as PET, PC, PS, ABS, and PMMA significantly decreased, resulting in the decrease in the floatability of these plastics and their separation from PVC (Figure 8).

Table 4. A summary of flotation studies on PVC separation using flotation without surfactants.

Flotation Type	Mechanism	Reagents	Concentration	Treatment Temperature	Treatment Time	Sample						Size [mm]	Purity [%]	Recovery [%]	Reference	
						PVC	PET	PS	PC	ABS	PMMA					
Direct	Surface oxidation	ClO ₂	0.5 g/L	70.0	70	✓			✓			0.8–5.0	N/A	100.0	[60]	
		K ₂ FeO ₄	0.18 M/L	75.0	11.5	✓				✓		3.0–4.0	98.4	98.4	[61]	
		KMnO ₄	5 mM/L	60.0	10.0	✓			✓		✓	2.0–3.2	98.4	98.7	[62]	
		KMnO ₄	2 mM/L	N/A	1.0	✓			✓		✓	3.2–4.0	95.0	98.6	[63]	
		Na ₂ S ₂ O ₈	0.1 M/L	70.0	30.0	✓		✓	✓			0.9–4.0	99.8	100.0	[64]	
		Na ₂ S ₂ O ₈	0.1 M	20–70	10	✓				✓		2.0–4.0	99.7	100	[65]	
		(NH ₄) ₂ S ₂ O ₈	0.2 M	70.0	30.0	✓		✓	✓	✓		3.0–4.0	100.0	99.7	[66]	
		KOH and (CH ₂ OH) ₂	2 g (KOH) and 10 mL (CH ₂ OH) ₂	25.0	5.0	✓	✓		✓	✓		3.0–4.0	N/A	N/A	[67]	
	Surface hydrolysis	NaOH	10%	70.0	20.0	✓	✓					2.0–4.0	94.6	94.9	[68]	
		NaOH	40 g/l	90	20	✓	✓	✓				2.0–4.0	N/A	95.9	[69]	
		NaOH	1 M	N/A	10	✓	✓					2.0–3.4	N/A	N/A	[70]	
		NaOH	N/A	60	20	✓	✓					5.0	N/A	100	[71]	
		NaOH	10%	70	20	✓	✓					0.9–3.2	98.22	93.98	[72]	
	Reverse	Surface oxidation	KMnO ₄	1.25 mM/L	60.0	50.0	✓	✓					0.9–4.0	99	99.7	[73]
			KMnO ₄	4.6 mM/L	66.5	38.0	✓	✓					2.5–3.2	96.6	97.9	[74]
CaCO ₃			0.11 g	50.6	20.0	✓	✓					2.0–4.0	100.0	99.0	[75]	
Surface coating		H ₂ O ₂	3%	30.0	30.0	✓	✓					5.0	99.8	100.0	[76]	
		H ₂ O ₂	3%	30.0	30.0	✓	✓		✓	✓		5.0	99.5	100.0	[77]	
		AlCl ₃	0.2 M	25.0	1.7	✓			✓			1.0–2.0	100.0	99.7	[78]	
		Ca/CaO	5%	N/A	30	✓	✓		✓	✓	✓	5.0	96.4	100	[79]	
Fe/Ca/CaO	0.5%	25.0	N/A	✓	✓		✓	✓	✓	5.0	99	100	[80]			
Direct and reverse	Surface oxidation	Ca(ClO) ₂	0.2–0.5 g/L	70.0	30–50	✓	✓	✓	✓	✓	✓	2.0–2.5	73.0	99.6	[81]	

Note: “✓” means “included in the experiments”, “blank” means “not included in the experiments”, and “N/A” means “not available”.

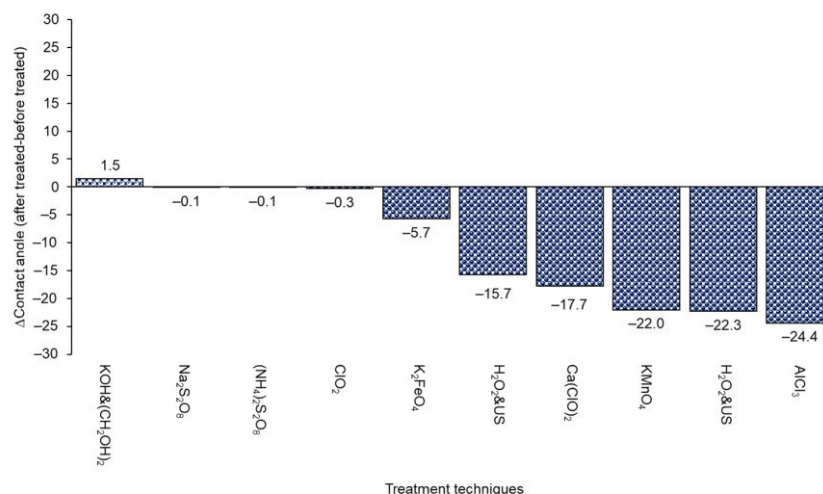


Figure 8. Changes in the PVC contact angle after treatment with various reagents.

Aside from increasing the surface wettability of other plastics, reverse flotation has also been utilized when the PVC surface is more sensitive during surface treatment than other plastics. During flotation, PVC particles remain in the flotation cell and are reported in the sink product. Table 4 summarizes the recent studies on the reverse flotation of PVC and the use of wetting agents and surface modifiers, including KMnO₄ [73,74], CaCO₃ [75], H₂O₂ [76,77], AlCl₃ [78], and Ca(ClO)₂ [79]. These previous works reported that these reagents render the PVC surface more hydrophilic compared with other plastic surfaces. As illustrated in Figure 8, these wetting agents directly decreased the contact angle of PVC by approximately 15.7–24.4°, while those of other plastics like PC, ABS, and PET only had minor changes. It is also interesting to note that the dechlorination of PVC surfaces induced by KMnO₄, CaCO₃, H₂O₂, and AlCl₃ was the primary mechanism responsible for the decrease in the hydrophobicity of PVC.

8.2.2. Pretreatment with Fenton Reaction

According to recent studies on plastics flotation, the utilization of the Fenton reaction is an emerging and promising pretreatment method for enhancing the efficiency of plastics flotation. Through an extensive analysis of the available literature, this section reviews the contributions made by various researchers, with particular emphasis on the works of Wang and Wang [82], Wang et al. [83], and Zhang et al. [84]. The Fenton reaction, which involves the generation of hydroxyl radicals (•OH) through the reaction between hydrogen peroxide (H₂O₂) and ferrous ions (Fe²⁺), has been employed to improve the flotation efficiency of PVC in the presence of other plastics, such as PS, PC, and ABS. Experimental observations indicate that the Fenton treatment significantly reduced the hydrophobicity of PS, PC, and ABS, while no discernible change was observed on the surface of PVC. Wang and Wang [82] conducted experiments wherein PVC, PC, and PS were subjected to the Fenton reaction prior to flotation and found that the optimal treatment conditions consisted of (i) a molar ratio of H₂O₂/Fe²⁺ of 7500:1, (ii) a H₂O₂ concentration of 0.2 M, and (iii) a treatment time and temperature of 2 min and 25 °C, respectively. Moreover, Zhang et al. [84] expanded the scope of the study of Wang and Wang [82] by incorporating the use of green-synthesized nanoscale zero valent iron (GnZVI) for the Fenton reaction. These authors revealed that a lower molar ratio of H₂O₂/Fe⁰, specifically 40:1, could be employed with a high performance and speculated that a reduced reagent dosage may be utilized in the Fenton treatment to render the PS surface hydrophilic. Meanwhile, Wang et al. [83] explored the separation of PVC and ABS through Fenton pretreatment and flotation, and demonstrated that a H₂O₂/Fe²⁺ molar ratio of 10,000:1 improved the selectivity and separation efficiency of PVC and ABS, resulting in a high recovery (100%) and purity (>99%) of PVC.

In terms of understanding the underlying mechanism of this treatment, previous works noted that the application of the Fenton reaction introduced hydrophilic functional groups (such as C–O–H and O=C–O) to the surfaces of PC, PS, and ABS, thereby rendering these plastics more hydrophilic and reducing their ability to float. In contrast, the hydrophobic nature of PVC remained largely unaffected following the Fenton treatment, a selective surface reaction that specifically enhanced the flotation efficiency of PVC.

8.2.3. Pretreatment with Thermal heat Treatment (Mild Heat and Microwave)

Thermal heat treatment has emerged as an environmentally friendly pretreatment technique for PVC recycling by enhancing the surface hydrophilicity of PVC. Previous studies have reported that mild heat or microwave pretreatment can generate reactive species, including free radicals, by disrupting chemical bonds within the polymer structure [49,85]. These reactive species have the potential to modify the surface chemistry of plastics [85]. Several investigations conducted by Truc and Lee [49], as well as Mallampati et al. [86], explored the impacts of microwave treatment on the contact angle of various plastics, such as PVC, PC, PS, ABS, and PMMA. The results of these previous works revealed a significant reduction in the contact angle of these plastics following pretreatment, particularly for PVC. Moreover, a combination of powder-activated carbon (PAC) coating and microwave treatment further decreased the contact angle of PVC [49,86]. Specifically, the contact angle of PVC decreased by approximately 17° , while the contact angle of other plastics remained relatively unchanged. This combined treatment involving PAC coating and microwave treatment holds promise in selectively depressing PVC particles while allowing other plastics to float during froth flotation. The optimal treatment conditions for this technique involved microwave treatment for 0.5–1 min at a power of 1120 Watts and a frequency of 2450 MHz. The optimized froth flotation process, based on these treatment conditions, achieved PVC recovery rates of 90–100% with a purity ranging from 82% to 100% when separating PVC from plastic mixtures. These findings offer valuable insights for the development of efficient strategies in the separation and recycling of PVC from mixed plastics. Furthermore, the proposed approach exhibited a great potential in advancing the sustainable management of plastic waste and fostering a circular economy within the plastics industry. Future research should focus on scaling up the process and optimizing treatment conditions for practical implementation in industrial settings.

8.2.4. Pretreatment with Corona Discharge

Corona discharge is one of the techniques for localized hydrophilization, which utilizes a high-voltage electric field to generate a localized plasma on the plastic surface. The corona discharge treatment leads to the formation of highly reactive species, such as oxygen radicals, which induce chemical reactions on the plastic surface. These reactions modify the plastic surface, leading to increased hydrophilicity and surface energy. The enhanced surface properties enable better wetting and the adhesion of flotation agents, improving the efficiency of plastics flotation. Numerous studies have investigated the application of corona discharge pretreatment in separating PVC from other plastics [87]. For instance, Zhao et al. [87] examined the impact of corona discharge pretreatment on the surface properties of PVC and HDPE. They found that a corona discharge activating energy of 12.0 kJ/m^2 significantly increased the hydrophilicity of HDPE, while causing a slight decrease in the hydrophobicity of PVC. This modification resulted in an improved difference in contact angle between the two plastics, ultimately enhancing the flotation efficiency of PVC. The study achieved an impressive 88.1% recovery with 94.2% purity for PVC, with the contact angle of HDPE decreasing to 63.5° (a decrease of 32° from the untreated surface), while the contact angle of PVC was maintained at 87.5° (a decrease of 2.7° from the untreated surface). Furthermore, when the activating energy was increased to 15.0 kJ/m^2 , the hydrophobicity of PVC was significantly reduced [87]. Similarly, Zhao et al. [88] investigated the use of corona discharge pretreatment for PVC and PET before flotation. The results demonstrated that corona discharge treatment effectively modified the surface

properties of PVC, leading to a substantial decrease in its contact angle from 90.2° to 70.1°. However, the impact on PET was found to be insignificant and only a slight decrease in its contact angle was observed. An additional advantage of corona discharge pretreatment is its dry operation and environmentally friendly nature. Unlike other methods that may involve the use of chemicals or solvents, corona discharge pretreatment relies solely on electricity to induce surface changes. This aspect makes corona discharge an appealing option for large-scale applications in plastic-recycling facilities.

9. Density-Surface-Based Separation

Recently, the techniques of gravity separation and flotation were combined as density-surface-based separation, which was applied for plastic separation including PVC.

One approach for the separation of PVC from other plastics involves the combination of elutriation and flotation, exploiting settling characteristics and differential hydrophobicity, respectively [89]. Researchers have successfully employed the elutriation principle in a teeter bed separator to achieve the density-based concentration of plastics [89]. The method utilizes surface active reagents, such as TA and KMnO_4 , to modify the floatability of plastics and enhance selectivity during separation [89]. By integrating crossflow separation with froth flotation, a novel process flowsheet was developed, demonstrating a high efficiency and selectivity in the recovery of different plastics [89]. Notably, HDPE and PVC were recovered at high rates, showcasing the effectiveness of the approach [89].

Another promising technique in the separation of PVC from other plastics is the hybrid jig, which combines the principles of jig separation and flotation [90,91]. A two-step approach involving a pre-wetting step with a solution containing the wetting agent (AOT) and subsequent hybrid jig separation in water was proposed to separate PVC from PA [90]. To further optimize the hybrid jig separation process, the estimation of critical parameters such as the apparent specific gravity ($\text{SG}_{\text{apparent}}$) and attached-bubble volume on plastic particles during water pulsation have been investigated [91]. By utilizing this measurement method, researchers conducted hybrid jig separation experiments on various plastic mixtures including PET and PVC with similar specific gravities [91]. The results demonstrated that $\text{SG}_{\text{apparent}}$ and a newly proposed index called the apparent concentration criterion ($\text{CC}_{\text{apparent}}$) could be used to estimate the separation efficiency of the hybrid jig [91].

10. Conclusions

In this paper, research works between 2012 and 2021 related to the separation of PVC from other materials were systematically reviewed using the PRISMA guidelines. The findings revealed that most studies employed flotation techniques and the surface modification of plastics to facilitate the separation of PVC from other plastics. These techniques demonstrated impressive results, achieving PVC recovery rates of 82% to 100%, purity levels ranging from 94% to 100%, and efficacy within a specific size range of 1.0–5.6 mm. In comparison, electrical separation presented a broader operational window, catering to a size spectrum of 0.01–5.0 mm. Notably, this method excelled particularly when PVC was intermixed with other waste materials, especially those containing metals. The electrical separation approach has shown remarkable success in achieving high recovery and purity levels in such complex waste streams.

Flotation has emerged as a widely investigated method for PVC separation, driven by the inherently hydrophobic nature of plastics and its compatibility with plastic separation from various materials. Recent studies highlighted that flotation could achieve significant PVC recovery rates ranging from 57% to 100%, achieving purity levels of 52% to 99%, all without necessitating the use of surfactants. Previous works have also explored the modification of plastic surfaces using an array of surfactants, such as ClO_2 , K_2FeO_4 , NaOH , KMnO_4 , $\text{Na}_2\text{S}_2\text{O}_8$, $(\text{NH}_4)_2\text{S}_2\text{O}_8$, KOH , $(\text{CH}_2\text{OH})_2$, CaCO_3 , H_2O_2 , AlCl_3 , and $\text{Ca}(\text{ClO})_2$, and found that this approach was effective in enhancing PVC separation by amplifying the differences in hydrophobicity among plastics during flotation. Notably, both direct and

reverse flotation methodologies have shown promise in recent investigations, achieving impressive PVC recovery rates of 94% to 100% alongside purity levels ranging from 73% to 100%.

A cutting-edge magnetic separation technique known as magnetic projection has emerged as a recent innovation for isolating PVC from a range of mixed plastics. This method achieved an impressive PVC recovery rate of 96% when dealing with a mixture comprising of PP, ABS, PC, PLA, and PET. Furthermore, the refinement of plastic sorting methodologies was evident in the widespread development of electromagnetic wave sorting. This technique significantly enhanced the precision of plastic separation. Within the scope of this systematic review, it is worth noting that both LIBS and NIR techniques have demonstrated remarkable accuracy in plastic sorting. Specifically, these techniques achieved a 100% accuracy rate when applied to mixed plastics containing ABS, PA, PMMA, PP, PS, PET, and PE. In addition, recent advancements in the field with more sophisticated technologies such as density-surface-based separation have been introduced.

The emergence of the UN-SDGs is expected to catalyze further research endeavors aimed at mitigating environmental impacts and promoting resource conservation across the entire life cycle of materials and products. Recycling, recognized as a pivotal approach towards achieving sustainability, offers the dual benefit of reducing environmental burdens and decreasing reliance on finite natural resources. By continually improving the separation processes and exploring innovative recycling techniques, we can make significant strides in addressing the challenges associated with PVC separation and contribute to a more sustainable future.

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