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Recent Advances in Polyvinyl Chloride (PVC) Recycling

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Abstract

Polyvinyl chloride (PVC) recycling is crucial for mitigating the environmental impact of PVC wastes, which take decades to decompose in landfills. This review examines the current state of PVC recycling processes, focusing on challenges and future research opportunities. It explores the types and sources of PVC wastes, including post-consumer, industrial, and construction wastes. Conventional recycling methods such as mechanical, thermal, and chemical recycling are discussed, highlighting their advantages, limitations, and successful applications. Furthermore, recent advances in PVC recycling, including biological, plasma-assisted, and solvent-based recycling, are explored, considering their potential benefits and challenges.

The review emphasizes the European context of PVC recycling, as the region has implemented regulatory initiatives and collaborations. It points out the Circular Economy Action Plan and directives targeting PVC waste management, which have promoted recycling and established a supportive framework.

Challenges of current PVC recycling methods and technologies, such as low yield and high energy consumption, are identified. The review calls for the development of efficient and cost-effective recycling technologies, along with improvements in recycling infrastructure and consumer awareness. Assessing the environmental and economic impacts, PVC recycling significantly reduces greenhouse gas emissions and conserves resources compared to virgin PVC production. The economic benefits include job creation and reduced raw material costs.

KEYWORDS

Polyvinyl Chloride (PVC); Thermoplastics; Recycling; Waste Management; VinylPlus; Innovative recycling.

1. Introduction

Thermoplastics have become an integral part of our daily lives, finding extensive application across industries such as automotive, sports equipment, medicine, and textiles, among others [1,2]. With global production surpassing 350 million tonnes and the world population continues to grow, the significance of thermoplastics [3], including 6.5 million tonnes of polyvinyl chloride (PVC) produced in the EU-27, Norway, UK, and Switzerland [4] (Figure 1), cannot be overstated. However, the environmental repercussions at the end of their life cycle are significant [5], as the majority of thermoplastic waste ends up in landfills due to the lack of efficient and cost-effective recycling methods [5].

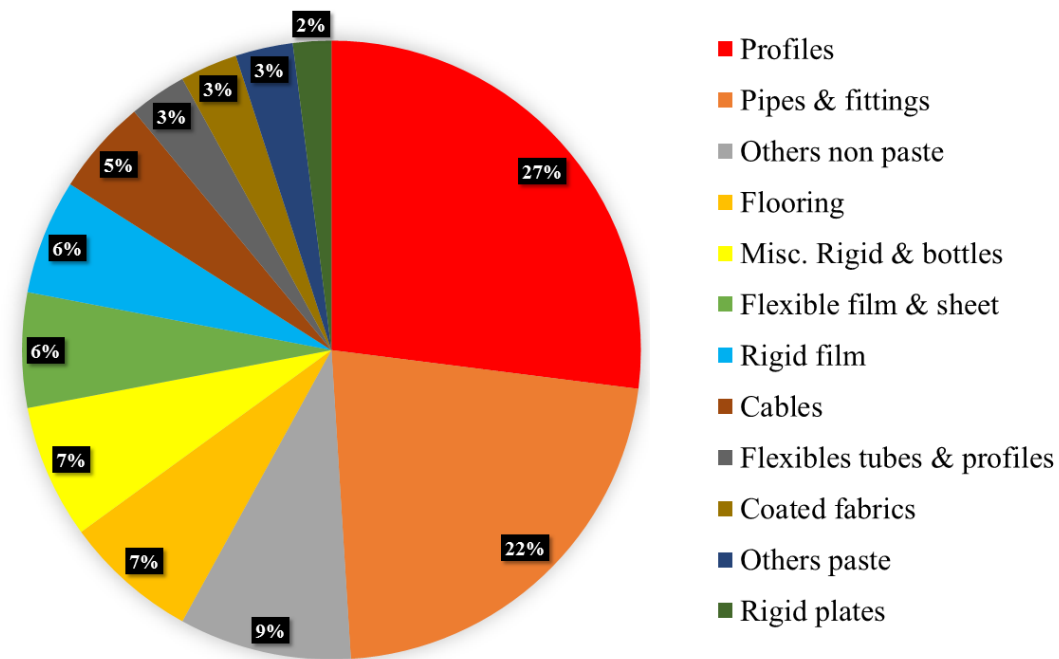


Figure 1. Different applications of the 6.5 million tonnes of PVC produced in the EU-27, Norway, the UK, and Switzerland.

This review focuses specifically on the recycling of PVC, one of the most widely used thermoplastics [6]. Composed of 43% petroleum derivatives and 57% sea salt [7], PVC possesses unique properties that make it highly prevalent in various sectors [8]. Its resistance to water and fire [9,10], along with its easy maintenance and exceptionally long lifespan, contribute to its attractiveness [11]. PVC's flexibility, rigidity, color variations, and other characteristics depend on the specific additives, such as lubricants, plasticizers, or pigments, used to achieve the desired final product [12,13]. Its versatility is evident in its applications in construction, electrical systems, consumer goods, etc. [4,14].

Despite its widespread use and numerous benefits, PVC poses significant environmental challenges [15,16]. Like other plastics, PVC waste generation contributes to environmental risks [5]. The transformation of PVC generates two types of waste: end-of-life waste, encompassing automotive

and construction waste, and process waste [17,18]. To address these challenges and mitigate the environmental impact, effective PVC recycling methods are crucial and pressing.

This review delves into various aspects of PVC recycling, exploring the types of PVC wastes and their sources, conventional recycling methods, innovative technologies, challenges, opportunities, and the environmental and economic impacts of PVC recycling. By examining these facets, we aim to shed light on the potential for sustainable PVC waste management and recycling practices.

Furthermore, the advancements made in PVC recycling technologies will be explored, with a focus on innovative approaches that show promise for enhanced efficiency, reduced environmental impact, and increased economic viability. The challenges encountered in PVC recycling will also be discussed, such as the complexity of PVC waste streams, the necessity for effective collection and sorting systems, and the economic feasibility of large-scale recycling. By conducting a comprehensive assessment of the environmental and economic impacts of PVC recycling, the benefits it offers in terms of waste reduction, resource conservation, energy saving, and greenhouse gas emissions can be evaluated. Moreover, the potential economic opportunities stemming from PVC recycling will be examined, including job creation, the establishment of a circular economy, and the promotion of sustainable practices across industries.

This review aims to provide a comprehensive understanding of PVC recycling, its challenges, opportunities, and the broader implications it has on environmental sustainability and resource management.

2. Types of PVC wastes and their sources

PVC wastes encompass various types that originate from diverse sources across industries and consumption patterns, thus amplifying the overall environmental impact of PVC (Table 1) [17]. Post-consumer PVC waste materializes from the end-of-life stage of consumer products, encompassing bottles, food containers, packaging materials, PVC pipes, window frames, and furniture [17–19]. On the other hand, post-industrial PVC waste emerges during the manufacturing and production processes, encompassing scraps, trimmings, rejected or defective products, and surplus materials from the construction, automotive, electronics, and packaging sectors [17,20]. The construction and demolition sector contributes significantly to PVC waste through the disposal of PVC pipes, fittings, electrical cables, flooring materials, roofing membranes, window profiles, and other construction components [21–23]. Additionally, packaging waste adds to the PVC waste stream, originating from its use in blister packs, clamshell packaging, shrink-wrap, and films, which become waste after their intended purpose. In the healthcare sector, PVC waste arises from the disposal of medical devices like intravenous bags, tubing, catheters, gloves, and packaging materials employed in medical settings [17,22,24]. The realm of electrical and electronic waste (e-

waste) also incorporates PVC in cable insulation, wiring, connectors, and casings, contributing to PVC waste when obsolete or non-functional electronic devices are discarded [25]. Automotive waste comprises PVC components present in end-of-life vehicles, including interior elements like dashboards, door panels, and seats, as well as exterior parts [26,27]. PVC manufacturing processes yield process waste, including off-cuts, trimmings, and rejects stemming from PVC resin production, compounding, extrusion, injection molding, and other manufacturing stages [28,29]. Defective, damaged, or unused PVC products such as toys, office supplies, footwear, textiles, and other consumer goods made from PVC contribute to PVC product waste [28,30,31]. Furthermore, improper disposal and littering of PVC-based items result in marine debris, posing threats to aquatic ecosystems when PVC waste infiltrates coastal areas and rivers [32,33]. It is crucial to acknowledge that sources and types of PVC waste may differ across industries [34,35]. Effective waste management practices, particularly recycling, play a pivotal role in minimizing the environmental repercussions associated with PVC waste and fostering the principles of a circular economy [36,37].

Table 1. Classification of PVC wastes according to the European Commission

Classification of PVC wastes	PVC Applications
	Construction Products (Window profiles, pipes, ...)
	Furniture components (Rigid films, flexible profiles, ...)
	Packaging Products (Bottles, flexible films, ...)
	Electric/Electronics (Cables, adhesive tapes, ...)
	Automotive (Car cables, battery separators, ...)
	Other Consumer and commercial products (Bags, shoes, ...)
	Other Products (Agricultural films, medical products)

3. Why is PVC recycling so important?

PVC recycling holds immense importance for several reasons [8,38]. Firstly, PVC is well-suited for recycling and has the longest history of recycling among all plastics [8]. This means that established and advanced mechanical recycling systems exist for PVC, enabling efficient and effective recycling processes [17,24]. Additionally, there are significant volumes of recyclable PVC waste available, creating ample opportunities for recycling and reducing waste [39].

The benefits of recycling PVC extend beyond waste reduction [40]. Utilizing recycled PVC helps meet resource efficiency objectives and preserves raw materials [41]. By recycling PVC instead of relying solely on virgin materials, valuable resources can be conserved, contributing to a more sustainable approach to resource management [42]. Furthermore, the use of recycled PVC reduces emissions [43] and minimizes the need for landfills [44,45]. This not only mitigates environmental

impacts but also helps address challenges associated with landfill space [46] and the long decomposition period of PVC wastes [47].

The environmental advantages of PVC recycling are further highlighted when considering specific applications [48,49]. For example, manufacturing window profiles using recycled PVC instead of entirely new PVC can reduce the danger to the environment by up to 70% [50]. Moreover, such a shift towards recycled PVC can lead to over 60% reduction in air emissions and more than 60% reduction in water emissions [51,52]. These statistics demonstrate the substantial environmental benefits associated with incorporating recycled PVC materials into production processes [50,51].

Another critical aspect of PVC recycling is its contribution to a circular economy [53,54]. By collecting and recycling PVC wastes, it becomes possible to transform it into new PVC products [18]. This approach reduces waste generation, minimizes reliance on virgin PVC production, and fosters a sustainable and circular approach to resource utilization [42,55]. Embracing PVC recycling not only aligns with sustainability goals but also presents economic opportunities [53]. The recycling industry creates jobs [28] and stimulates economic growth while also offering cost savings for manufacturers, as producing PVC using recycled content often requires less energy and fewer resources [56].

Importantly, PVC possesses a thermoplastic nature that allows it to be recycled multiple times without significant loss of performance [57]. This characteristic enhances the long-term viability of PVC recycling as a sustainable solution.

4. Additives in PVC

4.1. Plasticizers

Plasticizers are integral components in polyvinyl chloride (PVC) formulations, serving to enhance the material's flexibility, workability, distensibility, and durability [54,58–60]. They encompass various chemical families (phthalates, adipates, trimellitates, phosphates, citrates, etc.) [59,61], and are added to PVC at concentrations ranging from 30% to as high as 50% by weight [62]. These compounds play a pivotal role in tailoring PVC to meet specific application requirements, making PVC a versatile and widely used material [59]. However, the presence of plasticizers has significant implications for PVC recyclability [63]. They disrupt intermolecular forces within the PVC matrix, effectively reducing its glass transition temperature (T_g) and rendering the material more pliable [64]. While this flexibility is advantageous in the context of PVC's initial use, it poses challenges during recycling processes [24,63]. Notably, plasticizers lower the melting point of PVC, complicating uniform melting and homogenization [65]. Additionally, plasticizers influence PVC's rheological behavior, affecting its viscosity and flow characteristics [66]. These alterations

necessitate careful consideration when designing recycling methods for PVC materials, including the selection of appropriate recycling techniques and potential strategies to mitigate the challenges posed by plasticizers, ensuring the efficient and sustainable recycling of PVC [67].

4.1.1. Effect of plasticizers during recycling

Plasticizers exert a significant influence on the recyclability of polyvinyl chloride (PVC), presenting a range of challenges that must be carefully considered in recycling processes [24,63,67]. These challenges encompass issues such as plasticizer separation [68]. Hence, the industry pledged to VinylPlus its commitment to elevate the PVC recycling rate and to substitute essential additives in the production of fresh plastics [69].

One primary challenge arises from the need to separate PVC from its plasticizers during recycling. The intermolecular interactions between PVC and plasticizers can be persistent, making it difficult to efficiently isolate these components [64,70]. This challenge is particularly pronounced in mechanical recycling processes, where maintaining the purity of the recycled PVC is essential. Contamination by residual plasticizers can negatively impact the quality and performance of the recycled material [71].

Additionally, plasticizers can migrate out of PVC materials over time, especially when exposed to heat and sunlight. This migration can lead to contamination of the recycled PVC material with plasticizer residues. Contaminated PVC may not meet the desired purity and quality standards for recycled materials [72–74]. Addressing these challenges requires innovative approaches and ongoing research. Potential solutions may involve the development of specialized separation techniques tailored to the specific interactions between PVC and plasticizers, as well as the optimization of recycling processes to minimize contamination [75–77]. Moreover, ongoing research endeavors are aimed at formulating PVC compositions that are recyclable and contain lower levels of plasticizers, or exploring alternative plasticizers that can be separated from PVC more effectively. These efforts have the potential to enhance the sustainability of PVC recycling practices. Concurrently, there is also research dedicated to promoting eco-friendly "green" plasticizers in this context [78–80].

4.2. Recycling challenges of PVC thermal stabilizers

Recycling challenges associated with thermal stabilizers containing compounds such as lead, tin, barium, calcium, or zinc, which have been historically used to enhance the stability of PVC-based materials, primarily revolve around environmental and health concerns [81,82]. While these compounds serve to improve PVC's processing and application stability, their presence in PVC waste streams raises significant issues during recycling. Environmental impacts are a key concern, as the release of heavy metals like lead and barium into the environment can result in soil and water

pollution, necessitating compliance with stringent regulations on heavy metal exposure [83,84]. Additionally, the health risks associated with lead exposure make it a critical consideration, potentially posing dangers to recycling workers and consumers [85–87]. Compliance with regulations governing hazardous compounds in various regions is essential but may limit the practicality and legality of certain recycling processes [88,89]. To address these challenges, strategies such as substituting hazardous stabilizers with safer alternatives, advancing sorting and separation techniques, exploring chemical recycling methods for detoxification, and ensuring rigorous regulatory compliance have emerged as vital components of sustainable PVC recycling efforts [90–93].

4.3. Challenges posed by other additives in PVC recycling

Additives, including lubricants, antioxidants, polymeric modifiers, fillers, and colorants, which are commonly incorporated into PVC formulations to enhance their properties and performance, introduce multifaceted challenges in the recycling of PVC [70,94]. These additives can become intimately integrated into the PVC matrix, complicating the separation of pure PVC during recycling processes and leading to contamination of recycled materials. Moreover, the presence of additives can alter the physical and chemical properties of recycled PVC, potentially affecting its suitability for specific applications [70]. The chemical compatibility of additives with recycling methods is a critical consideration, as some additives may react with recycling agents or impede the efficiency of the recycling process. Sorting and separation, essential steps in recycling, are further complicated by the diverse range of additives present in PVC formulations, each with unique characteristics that may require specialized separation techniques [24].

In response to the previously mentioned difficulties concerning PVC additives, a comprehensive study conducted by Sibel Ügdüler et al. (year?) explores the research and development initiatives related to additives in plastics. Additionally, the study examines various techniques for extracting solvent-based additives in the context of plastic recycling [70]. The findings indicate that, over an extended period, material recycling yields favorable outcomes, even in light of potential risks associated with additives present in plastics [40].

5. Other challenges related to the PVC recycling process

5.1. PVC-PET separation

Polyvinyl chloride (PVC) and polyethylene terephthalate (PET) are two commonly used plastics in various industrial and daily life applications [14,95]. The challenge of effectively separating PVC from PET during recycling processes is a significant concern in the plastics recycling sector [96]. PVC and PET have been chosen over other plastic polymers due to their similar, relatively high

densities, both exceeding 1 g/cm^3 within a narrow range. This shared density range presents a challenge when attempting separation using conventional methods. Moreover, PET has a higher melting point (250–260 °C) compared to PVC (140–160 °C). Consequently, during PET processing, PVC can deteriorate, leaving behind residue that adversely impacts product quality. Conversely, PET does not become pliable at PVC processing temperatures and necessitates removal through filtration [77,97–99]. Additionally, the presence of PVC in plastic waste can result in the production of environmentally harmful chlorinated compounds, such as gaseous hydrogen chloride and chlorine-containing dioxins, during melting processes for both material recycling and thermal energy recovery [100,101].

Various methods and technologies have been developed and proposed to address this separation challenge [96,102,103]. One common approach relies on material identification and sorting using near-infrared (NIR) spectroscopy or advanced sensors. These systems can distinguish between PVC and PET based on their unique spectral signatures and can be integrated into automated sorting processes in recycling facilities [104,105]. The hyperspectral approach presents a valuable alternative methodology for separating various plastic polymers and contaminants from plastic wastes, distinct from traditional techniques. This technology combines spectral reflectance measurements with advanced signal processing methods, offering effectiveness, affordability, reliability, and efficiency. It addresses common challenges encountered in widely used separation methods [96].

Chemical treatment and selective dissolution provide another avenue for separation. This method employs solvents or chemical processes that selectively dissolve PVC while leaving PET unaffected. Researchers are actively working on developing eco-friendly solvents and processes to minimize environmental impacts [106,107]. In addition to these methods, ongoing innovations in recycling technology are continually emerging. Advanced sorting and separation equipment, coupled with artificial intelligence and machine learning algorithms, enhances accuracy and efficiency in PVC-PET separation [108,109]. These technologies offer real-time monitoring and adjustment, improving the purity of separated materials [109,110].

5.2. PVC and PVDC barrier layers in film packaging

5.2.1. Role of PVC and PVDC barrier layers in film packaging: implications for recyclability

Polyvinylidene chloride (PVDC) remains a prevalent choice for enclosing bulk meat portions, serving as a shrink film within a blend of PVDC/Ethylene vinyl acetate (EVA) copolymer. It is also employed in single-layer configurations for long-lasting retorted products in a compact form factor and as a protective barrier layer in fibrous casings. PVC, the predominant film material for retail

packaging of fresh meat, is commonly utilized as a pliable cling film and occasionally as a tray. There have been trials involving environmentally friendly films and containers in the context of meat and cheese product packaging [111–114]. These barrier layers are instrumental in impeding the ingress of moisture vapor and gases, thereby preserving the integrity, shelf life, and quality of packaged products [115]. However, while PVC and PVDC are highly effective in their designated roles as barrier layers, their presence can introduce complexities to the recycling of film structures [116,117].

PVDC serves as the crucial barrier component in multi-layer shrink films utilized for packaging meat and cheese. These co-extruded films, comprising a combination of polyethylene (PE) and PVDC, typically encompass 10–25% w/w PVDC content, occasionally incorporating ethylene vinyl acetate (EVA) at levels of up to 50% w/w. Solvay is the manufacturer behind PVDC grades belonging to the IXAN® family, produced through suspension polymerization and specially designed for co-extrusion applications [114,118].

In contemporary waste disposal and recycling practices, there is a growing emphasis on minimizing the presence of halogenated polymers like PVC and PVDC when mixed with other olefins in solid plastic waste (SPW). The integration of chlorine-containing polymers in PVC and PVDC waste streams presents a significant challenge in both mechanical and chemical recycling processes. Nonetheless, certain technologies and methodologies have been developed to handle limited proportions of chlorine-containing polymers [114,119,120]. It is worth noticing that the inclusion of higher chlorine loadings, if not specifically accommodated by the recycling technologies, can lead to reduced yield, compromised quality of the recycled output, and the potential for corrosion risks due to hydrochloric acid (HCl) production. In light of these challenges, it becomes essential to carefully assess the role of PVC and PVDC in film structures and consider alternative materials or recycling strategies when sustainability and recyclability are primary concerns [119,121].

Zhuo Xu et al. proposed a solution to mitigate the issue of chlorine presence in PVC and PVDC. Their research primarily addresses the obstacle posed by the high chlorine content, primarily from polyvinyl chloride (PVC), in solid waste, which hampers its potential use as a raw material for power generation. The scientists applied torrefaction, a thermal treatment process, to mitigate the chlorine content in blends of fiber-plastic waste and PVC. The torrefaction process was carried out at 400°C, resulting in a reduction of organically bonded chlorine due to the mass loss incurred during the process. Notably, the removal of chlorine was predominantly influenced by factors such as temperature and residence time, rather than the initial chlorine concentration in the waste material. Furthermore, as mass loss occurred, the heat content of the sample increased, reaching a peak at approximately 34 MJ/kg with a 45% mass loss. The study also observed a significant

decrease in organic chlorine content per unit heat content at around 30% mass loss, while approximately 90% of the energy was retained. The core concept of this investigation demonstrates the efficacy of torrefaction in reducing chlorine levels in waste feedstocks, rendering them more suitable for applications in power generation [122–124].

Shreyas S. Kolapkar et al. have introduced a pilot-scale system that combines torrefaction and extrusion to transform a mixture of fiber and plastic waste into fuel pellets. These resultant pellets exhibit a range of desirable characteristics, including affordability, a high heating value, improved consistency, and minimal environmental impact. They serve multiple purposes, functioning as solid fuels or serving as input material for pyrolysis and gasification processes. Through their Techno-Economic Study (TEA) and Life Cycle Analysis (LCA), it is revealed that the fundamental cost of manufacturing consistent pellets stands at approximately \$55 per dry ton (adjusted for the year 2020). The LCA findings also highlight that the torrefied product demonstrates negative net greenhouse gas emissions from cradle to gate, although these emissions are marginally higher compared to a similar wood chip product derived from forests [125].

5.2.2. Selection of recycling processes for packaging films with PVC and PVDC barrier layers

There is a growing need to revamp food packaging films to make them more recyclable. Currently, the existing infrastructure for recycling packaging films in most countries primarily depends on mechanical recycling, and as a result, most of these films are not effectively sorted and recycled [126].

In the realm of plastic recycling, PVDC has often been linked to PVC, causing the coexistence of PVDC and PVC in multilayer films to be commonly regarded as making the packaging ineligible for recycling, as defined by the Association of Plastic Recyclers (APR), particularly in the context of Mechanical Recycling [127]. In recent years, numerous chemical recycling technologies have emerged. When combined with solvent-based layer separation methods, these innovations are poised to significantly expand the scope of multilayer film recycling, including films containing PVC and PVDC, shortly [128,129]. Domenico Ferrari and his research team have demonstrated the production of aromatic compounds known as benzene, toluene, and xylenes (collectively referred to as bio-BTX) through *ex-situ* catalytic pyrolysis of commercial 5-layer polyolefin-based films utilized in food packaging that contain PVDC. In their study, they successfully extracted 23% by weight of BTX from the multilayer polymer sample containing PVDC [114]. Solvay is actively exploring alternative methods for recycling PVDC from multilayer films. They are investigating techniques such as solvent-based layer separation and chemical recycling through processes like pyrolysis and gasification. These efforts hold promise for significantly expanding PVDC recycling

in the future [128,130]. Various approaches exist for recycling plastics, including packaging films. These methods typically fall into two categories: mechanical recycling and chemical treatments utilizing solvents [24,131–134]. A research endeavor led by Ioannis Antonopoulos and his team, drawing upon data collected from facilities engaged in the sorting and recycling of plastic packaging waste, sheds light on the subject. Notwithstanding certain challenges, such as the impact of these plastics on factory equipment and notable material losses during the sorting phase, the recycled products consistently adhere to quality specifications and enjoy widespread acceptance within the market. Despite these hurdles, an envisaged scenario for the year 2030 presents a promising outlook: the attainment of an end-of-life recycling rate of 49% becomes plausible when implementing state-of-the-art practices and cutting-edge technologies [135].

A recent European study conducted by Irdanto Saputra Lase et al. using data from 2018, reveals that the current recycling rate for end-of-life plastics, specifically through mechanical recycling methods, stands at approximately 18%. This calculation is based on the amount of recycled plastic generated in comparison to the reported production of plastic waste. The study also envisions several potential strategies to enhance recycling rates in the coming years. One promising approach involves the expansion of existing mechanical recycling technologies currently in commercial use. This expansion could potentially elevate the overall end-of-life recycling rate to as high as 49% by the year 2030. Furthermore, the research highlights the positive impact of implementing recycling technologies reliant on chemical and solvent processes. The recycling of plastics to plastics and the transformation from plastic to chemical products (achieved through chemical recycling) could significantly boost the recycling rate to 80%. In this optimistic and potentially realistic scenario, chemical recycling complements, rather than competes with, improved mechanical recycling. In this context, a plastic-to-plastic ratio of 61% could be attained, with 46% attributed to mechanical recycling and 15% to chemical recycling. Additionally, there would be a plastic-to-chemical ratio of 19%. It is worth noting that the conversion rate of plastic to fuel presently ranges from 3% to 6%. However, it is expected to decrease in the future as the emphasis shifts towards polymer and chemical production [136].

6. Conventional PVC recycling methods

This section examines the conventional methods already employed for PVC waste recycling, including mechanical recycling [137], feedstock recycling, and hydrothermal treatment [138] (Figure 2). These methods have been widely used in the industry to address the challenge of PVC waste management [139]. However, it is essential to acknowledge the limitations associated with these conventional approaches [67]. By understanding the constraints involved, opportunities for improvement and the necessity for innovative solutions in PVC recycling can be explored.

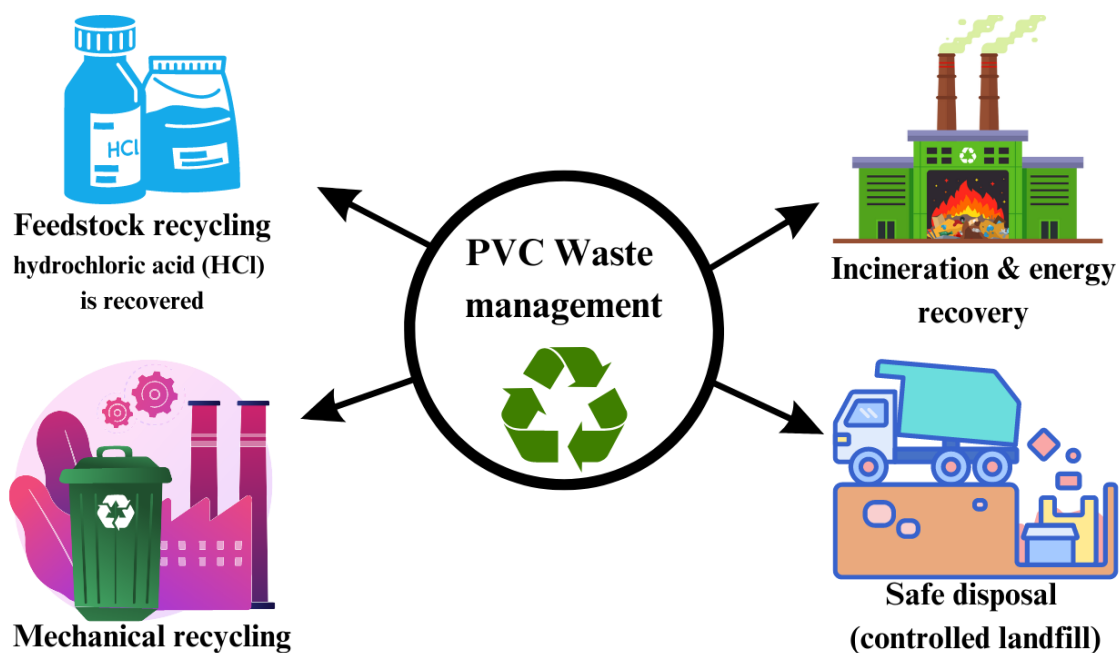


Figure 2. Hierarchy of PVC end-of-life waste management in the industry.

6.1. Mechanical recycling

Mechanical recycling stands as a well-established and commonly employed method for PVC recycling, encompassing a range of processes that include sorting, shredding, and grinding [24,137] (Figure 3). Its purpose is to convert PVC waste into smaller particles, known as recycled PVC (r-PVC) flakes, which hold considerable potential as valuable raw materials in various applications [140,141]. To optimize the effectiveness of mechanical recycling, advanced sorting techniques such as automated optical sorting and near-infrared (NIR) technology have been integrated [142].

However, it is important to recognize the limitations associated with mechanical recycling [24]. One of the primary challenges lies in the presence of contaminants and impurities within the PVC waste stream [143]. These contaminants, including other plastics, additives, and mixed materials, can affect the quality and performance of the recycled PVC [143]. Contamination can arise from inadequate separation during the sorting process, leading to a decrease in the overall quality of the recycled material [24,143]. Additionally, the mechanical recycling process can cause degradation of the PVC polymer chain, resulting in a loss of certain physical and mechanical properties and limiting the range of applications of the r-PVC flakes [24,143,144].

Another limitation of mechanical recycling is the dependency on a consistent supply of PVC waste with uniform composition and characteristics [24]. Variations in PVC formulations, such as the presence of different additives and stabilizers, can complicate the recycling process and affect the quality of the resulting recycled material [24,145]. Furthermore, the collection and sorting of PVC waste pose logistical and infrastructural challenges, particularly in regions with inadequate recycling systems or low participation rates [146,147]. Despite these limitations, ongoing research

and development efforts are dedicated to addressing these challenges and improving the efficiency of mechanical recycling. Strategies such as improved sorting technologies, optimized processing parameters, and enhanced quality control measures are being explored to overcome the limitations and maximize the potential of mechanical recycling for PVC wastes. These advancements aim to enhance the quality, purity, and market acceptance of r-PVC flakes, ensuring a more sustainable and effective PVC recycling process.

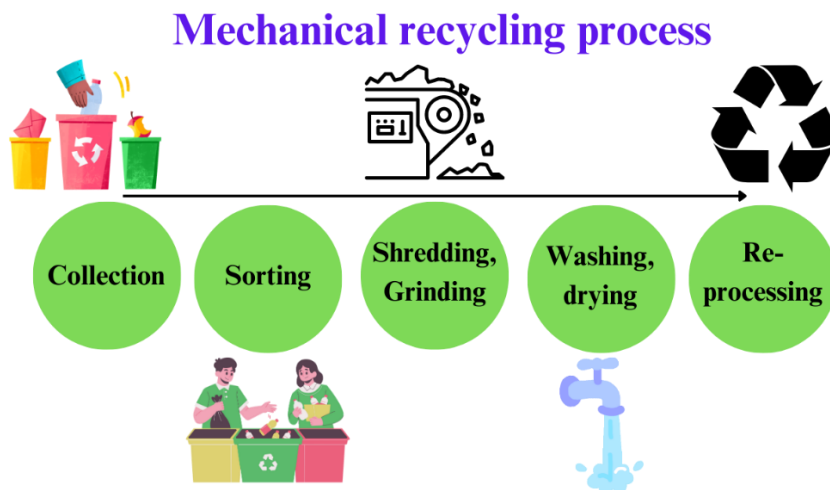


Figure 3. The general procedure for mechanically recycling waste plastics.

6.2. Feedstock recycling

Feedstock recycling, known as chemical recycling, refers to the process of breaking down plastic waste into its basic constituents, such as monomers or oligomers, to be used as a feedstock for the production of new plastic or chemical products [148,149]. This process encompasses a range of techniques (see Figure 4), including hydrothermal treatment, gasification, catalytic cracking and reforming, hydrogenation, and chemical depolymerization [150–152].

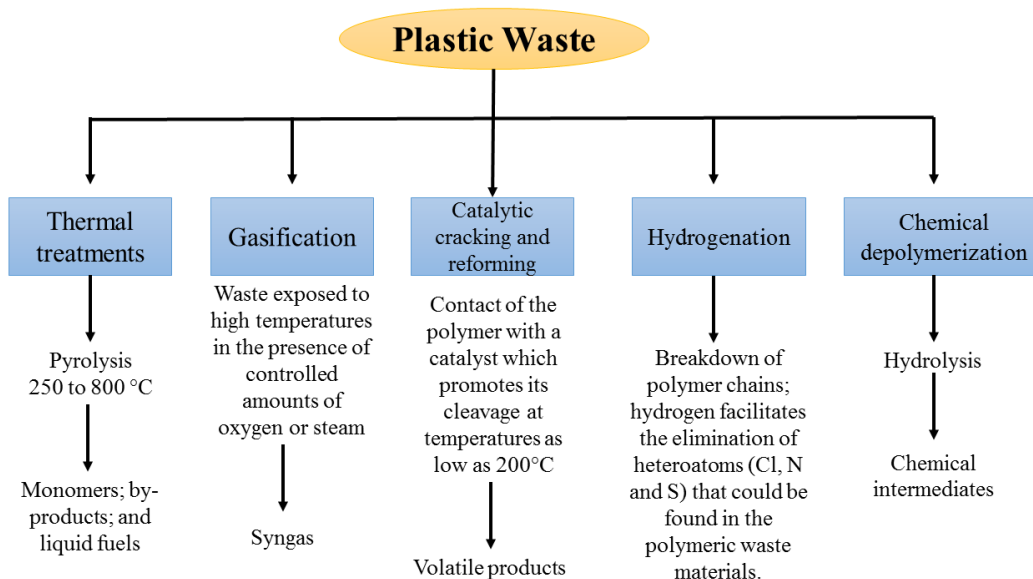


Figure 4. Different feedstock recycling methods are used for plastic waste recycling. Adapted from [151].

Pyrolysis involves the thermal decomposition of PVC waste in the absence of oxygen, resulting in the formation of different products. In a concise explanation, the breakdown of PVC initiates with dehydrochlorination and the elimination of HCl. Subsequently, benzene formation occurs through the cyclization of $(\text{CH}=\text{CH})_n$. Figure 5 provides a visual representation of this process [153].

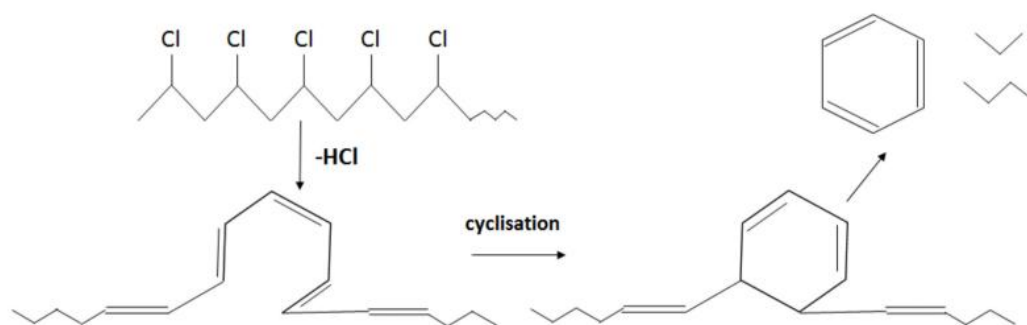


Figure 5. Illustrates the schematic process of cyclization occurring in PVC pyrolysis. Reproduced with permission [153]. Copyright 2018, Multidisciplinary Digital Publishing Institute (<https://creativecommons.org/licenses/by/4.0/>).

Operating at elevated temperatures ranging from 250 to 800 °C, pyrolysis promotes the breakdown of PVC into its constitutive components [154,155]. A significant outcome of pyrolysis is the generation of vinyl chloride monomer (VCM), a crucial building block for PVC. VCM produced through pyrolysis can be used as a precursor for the synthesis of new PVC, thereby closing the loop in the PVC life cycle and reducing the dependence on virgin materials [154]. Moreover, pyrolysis can yield valuable by-products such as syngas (a mixture of hydrogen and carbon monoxide) and liquid fuels, which have applications in energy generation or as raw materials in other industries [156–158].

Gasification is another feedstock recycling technique that converts PVC waste into a gas-like product called syngas [156,159]. The process involves subjecting the waste to high temperatures in the presence of controlled amounts of oxygen or steam. Gasification enables the transformation of PVC into syngas, which consists of hydrogen, carbon monoxide, and small amounts of methane [159]. Syngas can serve as a versatile feedstock for producing various chemicals, including methanol and ammonia, or as a source of energy through combustion or in gas turbines [148].

Solvolytic (see Figure 6), the third method of feedstock recycling, utilizes solvents to dissolve PVC waste and facilitate the recovery of valuable chemical components [150]. Solvolytic processes can be categorized as hydrolysis, aminolysis, ammonolysis, methanolysis, or glycolysis, depending on the type of solvent employed [160]. Hydrolysis involves the use of water to break down PVC into its basic constituents, while methanolysis uses methanol as a solvent, and glycolysis utilizes glycols [161,162]. These solvolytic techniques convert PVC into chemical intermediates, including VCM,

which can be integrated into new PVC production or as starting materials for synthesizing other chemicals [150,161].

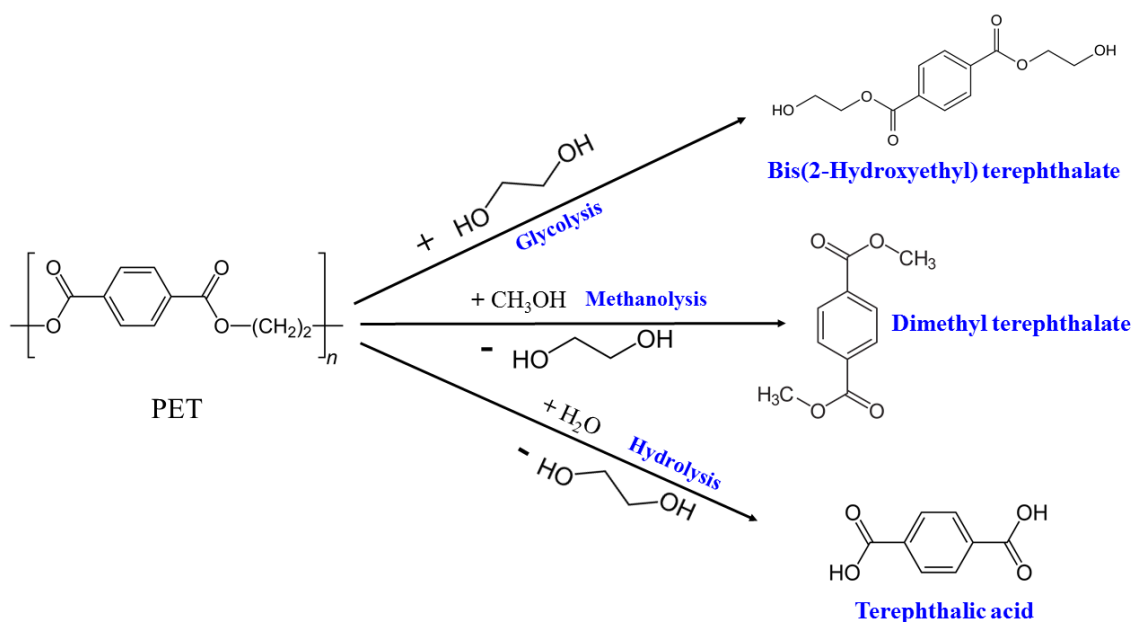


Figure 6. Methods for the solvolysis of plastic waste, with PET depolymerization as an example. Adapted from [163].

Feedstock recycling methods offer distinct advantages for PVC waste management [150]. They involve converting PVC waste into valuable chemical raw materials, promoting a circular economy, and reducing reliance on virgin resources [164,165]. Feedstock recycling aligns with sustainability principles by reducing the environmental burden and pollution risks associated with traditional disposal methods [150]. Additionally, the chemical intermediates derived from PVC waste are highly processable, allowing for their integration into various manufacturing processes and supporting resource efficiency [164,165].

It is important to acknowledge that feedstock recycling techniques are still under development and optimization and they have many limitations such as energy consumption, development of cost-effective catalysts, and constraints in industrial applications [150]. With further advancements, feedstock recycling holds the potential to play a significant role in the sustainable management of PVC wastes and contribute to a more circular PVC industry.

6.3. Hydrothermal Treatment

Hydrothermal treatment is another conventional method used for the recycling of PVC wastes (see Figure 7) [161,166]. This process consists of subjecting PVC materials to high-pressure and high-temperature conditions in the presence of water or steam [167]. The objective is to break down the PVC polymer chains and separate them into their constitutive components for further use or conversion [161,167].

One of the main advantages of hydrothermal treatment is its ability to handle a wide range of PVC wastes, including complex and mixed materials [168]. It can effectively process PVC products that contain additives, such as plasticizers, pigments, and stabilizers, which are commonly found in various PVC applications [168]. This versatility makes hydrothermal treatment a promising option for PVC recycling.

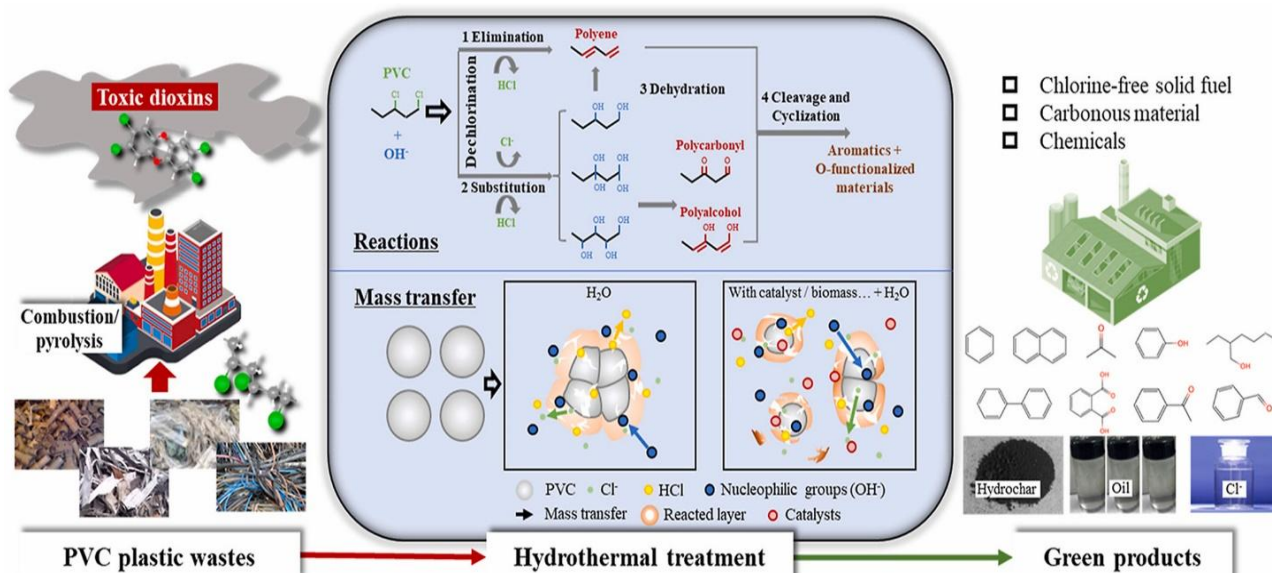


Figure 7. Hydrothermal treatment process and mechanism for recycling PVC [166]. Copyright 2023, reproduced with permission from Elsevier.

However, hydrothermal treatment also has its limitations [169]. One significant challenge is the high energy consumption associated with the process [167]. The elevated temperature and pressure required for efficient PVC breakdown require a considerable amount of energy input [167]. This energy demand can impact the overall environmental footprint of the recycling process and limit its cost-effectiveness [170]. Furthermore, hydrothermal treatment may generate by-products or residues that require further treatment or disposal. Depending on the specific conditions and additives present in the PVC waste, these by-products can vary in composition and may need to be managed appropriately to avoid environmental contamination [171]. Another limitation of hydrothermal treatment is its scalability and applicability at the industrial level. While the process has been successfully demonstrated in laboratory settings, implementing it at a larger scale can present technical and logistical challenges [172]. To overcome this, ongoing research focuses on optimizing hydrothermal treatment parameters, exploring advanced reactor designs, and developing more efficient energy recovery systems. Addressing these challenges will contribute to the advancement of hydrothermal treatment as a viable and sustainable process for PVC recycling [172].

7. Innovative PVC recycling technologies

The utilization of innovative recycling methods for PVC waste holds immense importance in addressing the environmental challenges posed by PVC disposal and promoting a sustainable circular economy [39]. The three innovative processes that have gained attention in recent years are dissolution and extraction [70], electrochemical recycling [173], and 3D printing (additive manufacturing) [174]. These processes offer unique advantages and opportunities for enhancing the efficiency and sustainability of PVC recycling techniques. To achieve this objective, the scientific community remains dedicated to seeking an efficient and effective solution for recycling plastic waste. However, there is a notable scarcity of studies focused specifically on PVC recycling, as indicated by the limited research documented in Table 2.

Table 2. Some examples of studies on the recycling of PVC waste: Methods and applications.

Author	Year	Method	Products	Application	Ref
Marco Tomatis et al.	2023	Ionic-liquid process for material separation and dehydrochlorination of PVC	HCl, aluminum, oriented polyamide and other wastes	Possibility of being used on an industrial scale	[175]
Lan Hong et al.	2023	PVC dechlorination using iron oxide (Fe_3O_4 et Fe_2O_3)	HCl, H_2 , Polyene and FeCl_2	N/A	[176]
Yingying Qi et al.	2023	Hydrothermal reaction for PVC dechlorination using waste iron scraps	A mixture of solid, liquid, and gas products	Colorimetric detection of H_2O_2 and glucose using PVC residues as a peroxidase mimic	[177]
Zhuang Liu et al.	2022	Co-hydrothermal dechlorination of PVC	HCl, hydrochar	Remove chlorine (Cl) to produce low Cl hydrochar for solid fuel	[178]
Simon Windels et al.	2022	Catalytic upcycling of PVC (coupled (trans)esterification–hydrogenation process)	Phthalates extracted from post-consumer PVC waste	Conversion of phthalates to cyclohexanedicarboxylates, which are suitable to be re-used as safer plasticizers.	[63]
Adewale George Adeniyi et al.	2022	Thermal recycling of Coca-Cola PVC label by co-carbonization with <i>Terminalia ivorensis</i> leaves	<i>Terminalia ivorensis</i> leaves (TIL)-biochar and TIL-PVC-biochar	Preparation of TIL-PVC-biochar for the production of conductive composites and an adsorbent for the sequestration of pollutants from the environment.	[179]
Seth Kane et al.	2021	Biom mineralization of PVC waste using <i>Sporosarcina pasteurii</i> soil bacterium	CaCO_3 deposit on plastic	Enhancing the strength of cement mortar reinforced with plastic	[180]
Linhai Ye et al.	2021	Co-pyrolysis of Fe_3O_4 -PVC	FeCl_2 , polyene, HCl, and volatiles	Development of a PVC recycling technology with reduced chlorine emissions	[181]
Apinya Duangchan	2008	Copyrolysis	HCl	N/A	[182]

and Chanatip Samart					
Nazdaneh Yarahmadi et al.	2003	Mechanical recycling of old PVC flooring materials	1-butanol and 2-ethyl-1-hexanol	Energy recovery	[183]

7.1. Biological Recycling

Biological recycling, also referred to as biodegradation or enzymatic degradation processes, presents a highly promising and innovative approach to tackle the recycling challenges associated with plastic waste (see Figure 8) [150,184]. In the example of PVC recycling, this method leverages the capabilities of microorganisms or enzymes to effectively break down PVC waste into simpler compounds, enabling efficient and sustainable PVC recycling. Ongoing research in this field is primarily focused on identifying and optimizing specific microorganisms or enzymes with the ability to efficiently degrade PVC and its additives. The use of microorganisms or enzymes in PVC recycling offers several significant advantages [184]. Firstly, it is an environmentally friendly approach that aligns perfectly with the principles of a circular economy [185]. By the use of natural processes, biological recycling minimizes the environmental impact typically associated with conventional PVC waste disposal methods and other challenges mentioned previously in the section on conventional methods. It facilitates the breakdown of PVC into biodegradable components, thereby reducing the accumulation of PVC waste in landfills and other disposal sites [184].

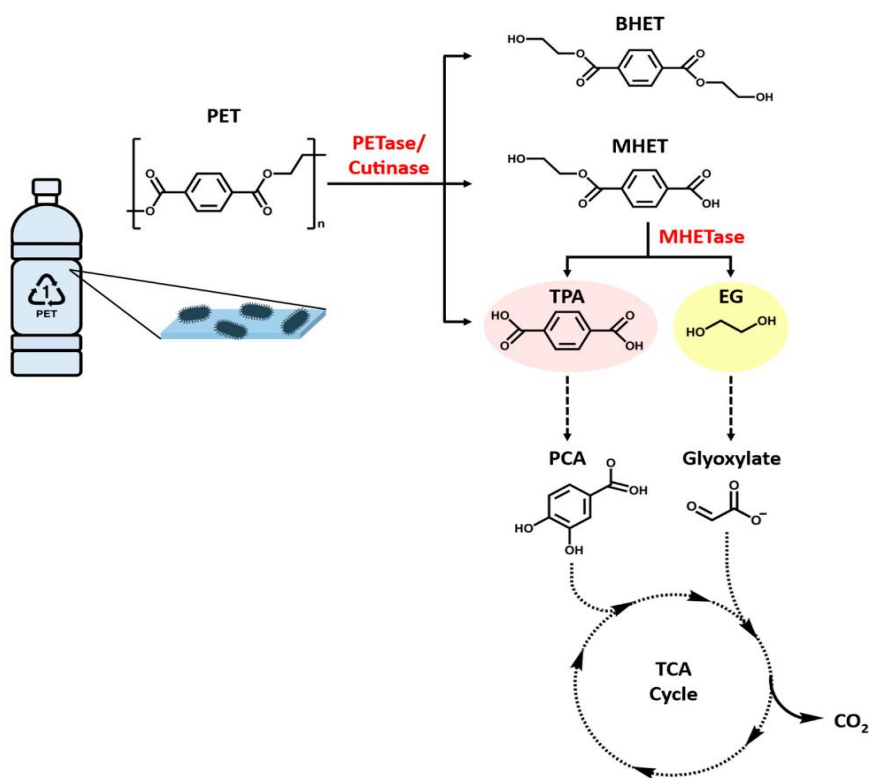


Figure 8. Biological degradation of plastic waste (PET as an example). Reproduced with permission [184]. Copyright 2022, Multidisciplinary Digital Publishing Institute (<https://creativecommons.org/licenses/by/4.0/>).

Furthermore, the biological recycling of PVC is characterized by its energy efficiency [186]. The degradation process is facilitated by the metabolic activities of microorganisms or the catalytic properties of enzymes [184]. Consequently, the recycling process can be conducted at ambient temperature and pressure, resulting in lower energy consumption compared to conventional recycling methods that rely on high temperature or mechanical processes [185].

Scientists are exploring diverse sources, including natural environments and specialized microbial communities, in order to discover microorganisms that possess the desired PVC/plastics-degrading capabilities [187]. In addition to identifying suitable microorganisms, research efforts are also focused on optimizing the conditions for PVC degradation. Factors such as temperature, pH, oxygen availability, and nutrient composition play crucial roles in facilitating the activity of microorganisms or enzymes [184]. By fine-tuning these conditions, researchers aim to enhance the efficiency and effectiveness of PVC degradation, ensuring maximum PVC waste recovery while minimizing any potential negative impacts [184,186].

Moreover, research in this field extends beyond PVC degradation alone. The potential of utilizing the by-products generated during PVC biodegradation was investigated [188].

In conclusion, biological recycling, employing microorganisms or enzymes, represents a highly promising and environmentally friendly solution for the efficient and sustainable recycling of PVC wastes. Ongoing research endeavors aim to identify and optimize microorganisms or enzymes capable of degrading PVC and its additives. By harnessing the power of nature, biological recycling provides an energy-efficient and eco-friendly alternative to traditional PVC disposal methods. Continued advancements in this field will contribute to the development of a more sustainable and circular PVC industry.

7.2. Electrochemical Recycling

Electrochemical recycling has emerged as an energy-efficient and promising innovative method for recycling PVC wastes, enabling the recovery of high-purity materials [173,189,190]. This approach capitalizes on electrochemical reactions to break down PVC wastes into its elemental components, such as chlorine and carbon [173]. By subjecting the PVC waste to an electric current in the presence of an electrolyte, the PVC molecules dissociate, facilitating the separation of its constituents [191]. The recovered materials can then undergo purification processes and find application in the production of new PVC or other valuable products [192].

One of the significant advantages of electrochemical recycling lies in its environmentally friendly nature, as it eliminates the need for high temperature and chemical additives commonly used in traditional recycling methods. By operating at ambient or moderate temperature, it minimizes

energy consumption and reduces associated carbon emissions [192]. Furthermore, electrochemical recycling demonstrates versatility in handling various types of thermoplastic wastes [173,191,192]. Despite its significant potential, the large-scale implementation of electrochemical recycling requires further research and development. Ongoing studies aim to optimize process parameters, electrode materials, and electrolytes to enhance efficiency, yield, and cost-effectiveness. Exploring advanced electrode designs and innovative cell configurations can further enhance the performance and scalability of electrochemical recycling systems [192].

The study conducted by Danielle E. Fagnani et al. explores novel techniques to tackle the reduction and recycling of plastic waste, specifically focusing on PVC (see Figure 9). They employ a paired-electrolysis process in which intentionally produced HCl from PVC is harnessed to chlorinate arenes. This process demonstrates remarkable tolerance to both air and moisture, mainly due to the involvement of plasticizers. What's noteworthy is that this reaction maintains its efficiency even in the presence of other plastic waste, and it can be applied to commercial plasticized PVC products, such as laboratory tubing. Furthermore, the study encompasses a simplified life-cycle assessment, revealing that employing waste PVC as the source of chlorine in the paired-electrolysis reaction results in a lower global warming potential compared to using HCl. In summary, this method presents an innovative approach for repurposing discarded PVC and similar polymers through electrosynthetic reactions, making use of existing polymer additives. It has the potential to serve as a source of inspiration for the development of other strategies aimed at addressing the challenges associated with plastic waste [189].

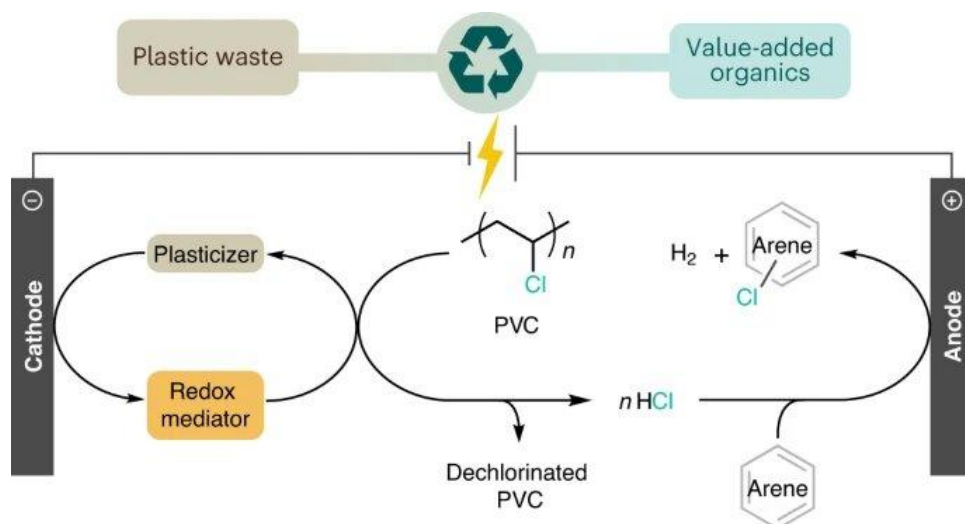


Figure 9. Initiating PVC recycling through reductive dechlorination: chlorine removal process. Reproduced with permission [189]. Copyright 2022, Springer Nature.

7.3. Dissolution and Extraction

Dissolution and extraction methods are essential for the efficient recovery of PVC from complex waste streams (i.e. composite materials), enabling its reuse or conversion into new products [70].

These techniques involve selectively dissolving PVC in solvents, facilitating the separation of PVC from other waste materials. By targeting PVC dissolution, these methods offer a highly effective approach to extracting PVC from diverse waste sources [193]. The choice of solvent used for PVC dissolution can vary depending on the specific recycling process [48]. Organic solvents such as ketones, esters, and aromatic hydrocarbons have demonstrated effective PVC dissolution capabilities. However, their potential environmental impact and associated costs have prompted the exploration of more sustainable alternatives [194].

Researchers are actively working to develop environmentally friendly and economically viable solvents for PVC dissolution. These alternative solvents aim to minimize ecological harm while maintaining high dissolution efficiency [195,196]. For instance, bio-based solvents derived from renewable resources like natural oils or ionic liquids are being investigated as greener substitutes with effective PVC dissolution properties [193,196].

Furthermore, the selection of a solvent depends on the composition of the PVC waste stream [193]. Complex waste streams containing PVC, along with other polymers and additives, require tailored solvent systems that selectively dissolve PVC while leaving other materials untouched [133].

Dissolution and extraction methods not only enable PVC recovery but also contribute to the overall sustainability of PVC recycling. By effectively separating PVC from other materials, these techniques enhance the quality and value of the recycled PVC, making it more desirable for various industries and applications. The recovered PVC can be used in the production of new PVC products, reducing the dependence on virgin PVC and conserving valuable resources [70].

This versatility and flexibility in reusing and converting dissolved PVC expand the possibilities for its application and create a more sustainable PVC recycling loop [197].

As research and development progress, dissolution and extraction techniques for PVC recycling are expected to become more efficient, cost-effective, and environmentally friendly [36]. The optimization of solvent systems, exploration of innovative solvents, and the development of integrated processes will further enhance the viability and scalability of these technologies. Embracing and implementing these innovative approaches will help unlock the full potential of dissolution and extraction methods in PVC recycling, contributing to a more sustainable and circular PVC industry.

7.4. Additive Manufacturing (3D Printing)

Additive manufacturing (also known as 3D printing) has emerged as an innovative and transformative method to revolutionize the recycling of PVC wastes (see Figure 10) [198–200]. The approach provides direct and efficient utilization of PVC wastes as a valuable feedstock for the creation of new products, thereby reducing the dependence on virgin PVC materials [201]. The

process begins with the shredding and processing of PVC wastes into filament or powder form, which can then be used as raw material in 3D printing [199]. This not only helps in reducing the volume of PVC waste but also offers a sustainable and cost-effective solution for manufacturing diverse items [201].

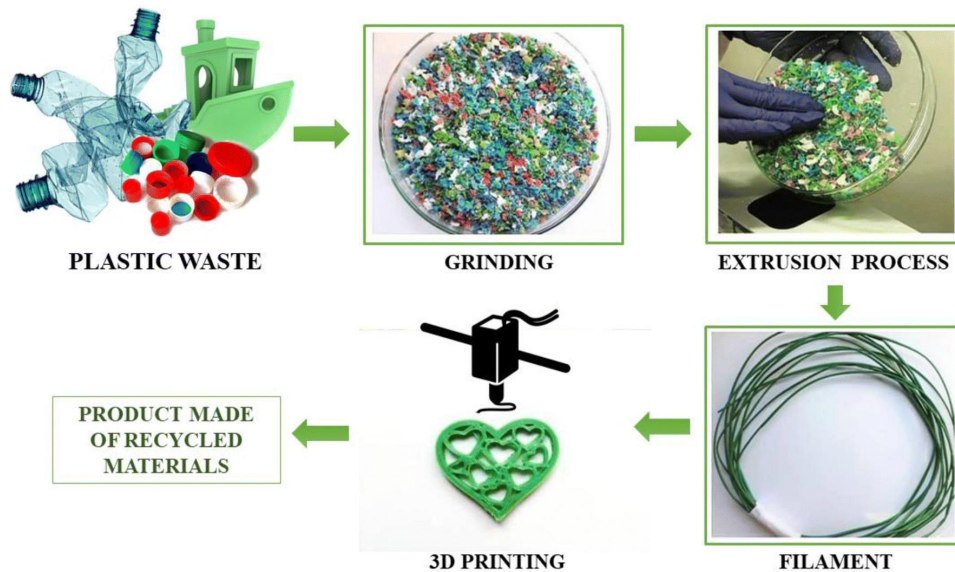


Figure 10. Process of recycling plastic waste for the production of 3D Printing filament. Reproduced with permission [200]. Copyright 2021, Springer (<http://creativecommons.org/licenses/by/4.0/>).

Incorporating additive manufacturing into PVC recycling enables the establishment of a closed-loop system, where PVC waste can be repeatedly reused in the production process [201]. This significantly reduces the environmental impact associated with PVC disposal and promotes resource efficiency [199,201]. Additionally, the flexibility and versatility of 3D printing allow for the creation of customized products with intricate designs and complex geometries that are often challenging to achieve using traditional manufacturing methods. This presents new prospects for innovation in product design and offers greater creative flexibility across diverse industries [202].

The integration of additive manufacturing in PVC recycling aligns perfectly with the principles of the circular economy, as it facilitates the transformation of waste into valuable resources [201]. By harnessing this technology, manufacturers can reduce their reliance on virgin PVC and contribute to a more sustainable production cycle [199,201]. Moreover, the ability to directly utilize PVC waste in the manufacturing process reduces energy consumption and lowers greenhouse gas emissions associated with the production of new PVC materials [201].

However, further research and development efforts are necessary to optimize additive manufacturing techniques specifically for PVC recycling [199,201]. Advancements in materials science are also essential to enhance the mechanical properties and durability of recycled PVC products [201]. Standardization and certification processes will play a crucial role in establishing the credibility and market acceptance of 3D-printed PVC products [203].

In conclusion, the utilization of 3D printing/additive manufacturing in PVC recycling presents a promising pathway towards a more sustainable and circular PVC industry. It offers the potential to reduce PVC wastes, create customized products, and minimize the environmental impact associated with traditional manufacturing processes. By investing in research and development and fostering collaborations between industry, academia, and policymakers, the full potential of 3D printing technologies could be unlocked, transforming PVC recycling and contributing to a more sustainable future.

7.5. Chemical Upcycling of PVC

Chemical upcycling has emerged as a transformative approach in the field of PVC recycling, offering an innovative solution to the challenges associated with traditional recycling methods. By employing chemical reactions, PVC waste can be broken down into valuable chemical feedstocks or monomers, enabling the production of high-quality materials for various applications (see Figure 11) [112,204]. Chemical upcycling involves the controlled degradation of PVC polymers through chemical processes, such as hydrolysis, glycolysis, or methanolysis [112,205,206]. These reactions break down the polymer chains into smaller units, typically monomers like vinyl chloride, which can then be used as building blocks for the synthesis of new polymers or other chemical products [112,204,206]. The aim is to convert PVC waste into materials with properties comparable to virgin PVC, ensuring their usability in diverse industries. Unlike mechanical recycling, which often leads to a downgraded material quality due to contamination and degradation, chemical upcycling allows for the production of recycled PVC with properties equivalent to or even better than virgin PVC. This opens up opportunities for its use in demanding applications. By carefully selecting the chemical reactions and conditions, a wide range of monomers and chemical intermediates can be obtained, facilitating the production of different polymers or chemical products suited for specific applications [112].

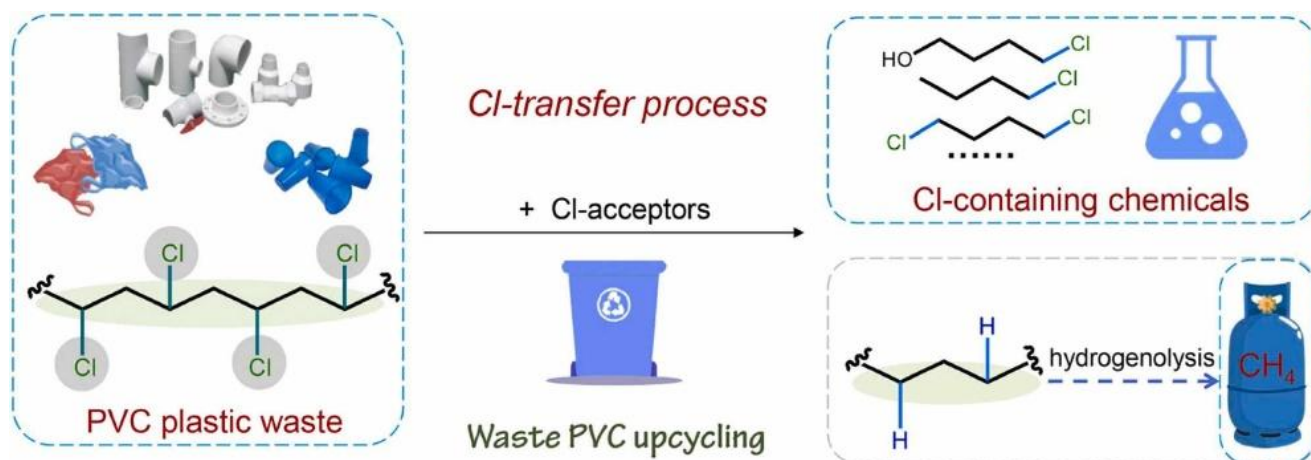


Figure 11. The conversion of PVC waste into an organic chloride stream through a chlorine transfer mechanism. Reproduced with permission from [204]. Copyright 2023, Elsevier.

Chemical upcycling offers a promising solution as it can process PVC in the presence of other plastics, enabling the recovery of PVC even from complex waste streams [207]. Chemical upcycling supports the principles of the circular economy by closing the loop on PVC waste. By converting PVC into valuable chemical feedstocks, it reduces the dependency on fossil resources and promotes the efficient use of materials [208]. While the chemical upcycling of PVC holds great promise, several challenges need to be addressed for its widespread implementation [197]. These include optimizing reaction conditions, ensuring energy efficiency, scaling up the process, and developing cost-effective catalysts [112,197]. Continued research and development in chemical upcycling techniques will pave the way for a more efficient and sustainable future of PVC recycling.

7.6. Microwave-assisted PVC recycling

Microwave-assisted PVC recycling is an innovative method using microwave irradiation to facilitate the rapid and energy-efficient degradation of PVC waste (see Figure 12) [209]. By subjecting PVC to microwave energy, the polymer undergoes selective heating, leading to the breakdown of the material into smaller chains [209,210]. This approach offers several advantages and unique features. Firstly, microwave-assisted PVC recycling enables a rapid and energy-efficient process compared to conventional thermal methods. The selective heating properties of microwaves allow for precise targeting of PVC, minimizing the degradation of other materials present in the waste stream [210]. Another significant advantage is the enhanced safety and reduced environmental impact associated with this method [211]. Furthermore, microwave-assisted PVC recycling exhibits scalability and flexibility, allowing it to be adapted to various waste streams and quantities of PVC waste [212].

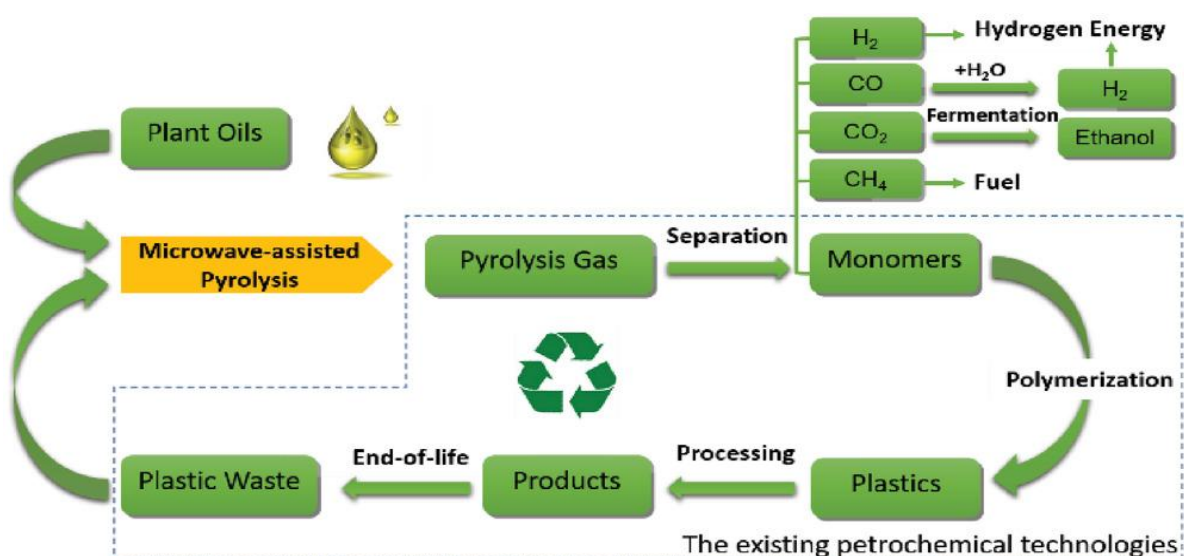


Figure 12. Demonstrating a plastic waste recycling cycle utilizing microwave irradiation to accelerate the efficient breakdown of plastic waste. Reproduced with permission from [209]. Copyright 2020, Wiley (<https://creativecommons.org/licenses/by/4.0/>).

While microwave heating offers numerous benefits, it also presents several limitations [213]. For instance, one issue is the emission of volatile degradation compounds, which can be problematic [214]. Additionally, accurately measuring the temperature within the reaction mixture is challenging, as indicated by a previous study [215]. Furthermore, a simulation study on microwave design suggests that non-uniform heating can occur due to the uneven distribution of scattered hotspots within the sample [216]. Another significant challenge is quantifying the dielectric properties of the material to be treated. The efficiency of heating is heavily reliant on the dielectric response of materials, but there is currently insufficient data available on dielectric materials [213]. In conclusion, microwave-assisted PVC recycling is an innovative approach that utilizes microwave irradiation to enable rapid and energy-efficient degradation of PVC wastes. Its advantages include fast processing, selective degradation, improved material properties, and enhanced safety. Nonetheless, challenges related to equipment requirements, process optimization, and cost considerations need to be overcome for broader implementation. Continued research, development, and advancements in microwave-assisted PVC recycling will contribute to its potential as a sustainable solution for PVC waste management.

7.7. Supercritical fluid extraction of PVC

Supercritical fluid extraction (SFE) of PVC is an innovative method for PVC recycling that utilizes a supercritical fluid, typically carbon dioxide (CO₂), as a solvent to selectively extract PVC from waste materials [217]. SFE takes advantage of the unique properties of supercritical fluids, which exhibit gas-like diffusion and liquid-like density when exposed to specific temperature and pressure conditions [218]. The process offers several advantages and innovative features. Firstly, SFE enables the selective extraction of PVC from mixed plastic waste streams, avoiding the need for extensive separation processes and reducing contamination of the extracted PVC [144]. This process can be used for rapid reaction rates, minimal liquid residue, effortless solute separation, and a reduced number of separation steps [219]. It is also an environmentally friendly method, as supercritical CO₂ is non-toxic, non-flammable, and readily available [220]. The process also allows for the recovery of other valuable additives or materials present in the PVC waste, enhancing its overall sustainability [221]. Furthermore, supercritical fluid extraction supports the principles of the circular economy by enabling closed-loop recycling, and reducing the dependence on virgin PVC production [219]. However, there are limitations and challenges to consider. The maintenance of equipment can pose a potential drawback due to the high-pressure technology utilized in SFE [222]. In conclusion, supercritical fluid extraction of PVC is an innovative process offering selective extraction, mild operating conditions, environmental friendliness, versatile applications, and the potential for closed-loop recycling. Overcoming challenges through further research and

technological advancements will contribute to the wider adoption and commercialization of this sustainable PVC recycling method.

7.8. Transforming PVC Waste into Nanostructured Catalyst Supports

The transformation of PVC waste into nanostructured catalyst supports presents a promising solution for both addressing the environmental concerns associated with PVC waste and advancing catalyst development (see Figure 13) [191,223–227]. By utilizing PVC waste as a precursor, innovative conversion processes can be employed to create nanostructured materials with increased surface area and improved catalytic properties [228–230]. These catalyst supports can serve as platforms for active metals or metal oxide catalysts, enabling efficient chemical reactions in various applications. This approach not only reduces waste generation but also contributes to the development of sustainable and eco-friendly technologies [223].

The scientific community is actively pursuing the selective and efficient recovery of plastic waste for environmental depollution applications, including the production of composites [223]. One particular challenge is the development of polymer supports that are cost-effective, durable, and efficient for use as heterogeneous catalysts in treating organic and inorganic contaminants. In this regard, researchers have focused on recovering various types of plastic waste, such as polystyrene, polypropylene, polyethylene terephthalate, polyethylene, and polyvinyl chloride (as shown in Figure 13), with the aim of addressing this challenge [223,228].

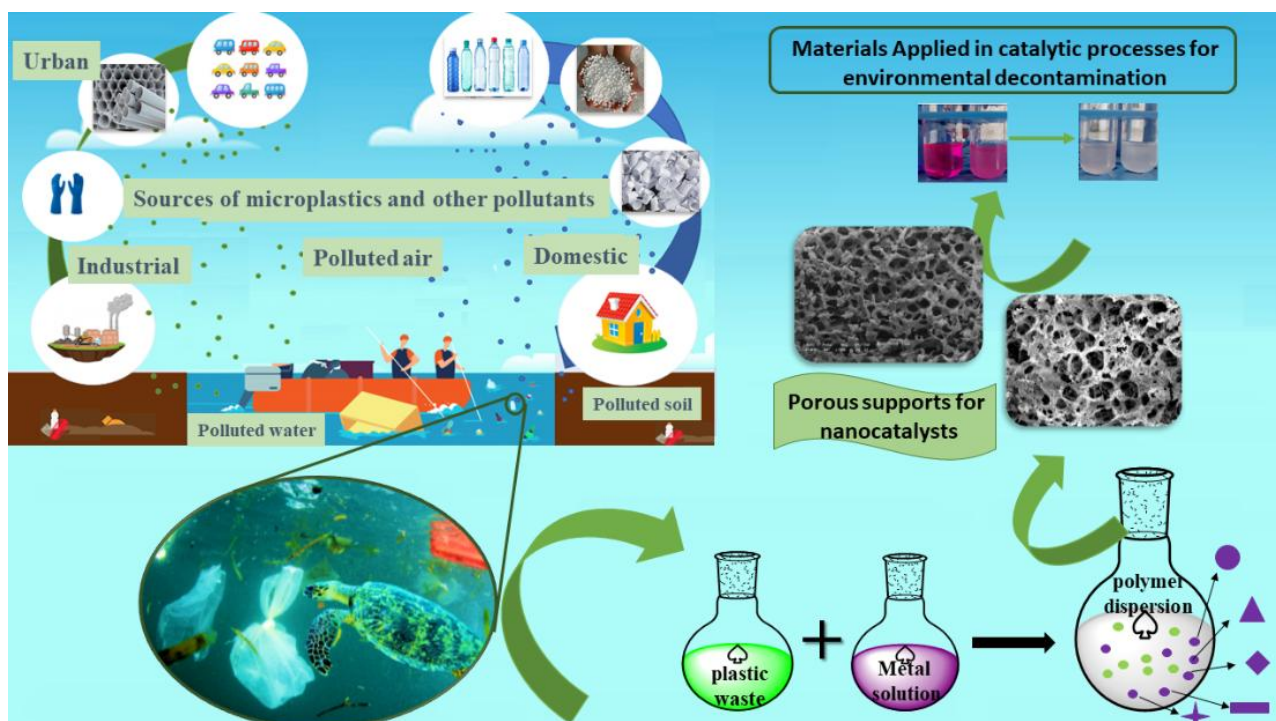


Figure 13. Schematic illustration of the conversion cycle of PVC waste into supports for nanostructured heterogeneous catalysts. Reproduced with permission [223]. Copyright 2021, Multidisciplinary Digital Publishing Institute (<https://creativecommons.org/licenses/by/4.0/>).

Extensive research has been conducted on the utilization of PVC waste in composite fabrication applications, specifically for filtration and ultrafiltration membranes [231–233]. In a study by Aji et al. (2020) [234], PVC waste was explored as a component for producing ultrafiltration membranes. To overcome the hydrophobic properties of PVC during membrane manufacturing, it was blended with cellulose acetate. The findings indicated a significant increase in the hydrophilicity of the prepared membranes, reaching approximately 25%. Furthermore, the thermal stability of the membranes improved when PVC was incorporated. These results highlight the potential of PVC waste as a viable resource for manufacturing ultrafiltration membranes [234].

Among the various techniques discussed in this review, we have compiled Table 3 to categorize the methods that are deemed scalable for practical application. It is important to note that while significant progress has been made in exploring innovative approaches to PVC recycling, the majority of these processes remain confined to the laboratory setting. The transition from laboratory-scale experiments to full-scale industrial implementation presents various challenges and necessitates further time, research, and investment for rigorous testing and optimization.

Table 3. The most commonly employed methods for recycling PVC waste on an industrial scale.

Type	Technology	Method	Ref
Mechanical recycling technologies	Neidhardt Rohstoff GmbH	Neidhardt Rohstoff has successfully developed a method for recycling composite materials containing aluminum and PVC. The composite material arrives in a pristine state and undergoes a shredding process, reducing it into approximately 20 mm-sized fragments. These fragments are subsequently conveyed to a cyclonic separator, which utilizes high-speed rotation to effectively segregate the two materials. Ultimately, following the classification of the material particles by size, the separation of aluminum and PVC is achieved through the application of an electrostatic device.	[235]
	R-Inversatech	This innovative Japanese technology effectively disentangles fibers from PVC within waste materials, such as tarpaulins, employing a rapid mechanical beating process. The separated fibers may have promising utility in thermal and/or acoustic insulation. Furthermore, this method yields granulated PVC recyclate suitable for a diverse array of applications involving flexible PVC.	[236]
	FG Kunststoffmatten GmbH (Former Jutta Hoser)	FG Kunststoffmatten manufactures plastic mats for greenhouse flooring using recycled PVC composite films, plasticized films, and coated fabrics. These mats feature drainage holes for watering plants from below and efficient water drainage. The added heat insulation protects plants from freezing, and the surface is durable for small machine use, offering easy cleaning.	[237]
	Caretta	This method is used to separate fabrics from flexible PVC cords. It's worth noting that the majority of the PVC strips recovered through this process are crushed, resulting in fragments measuring approximately 4-6 cm. Subsequently,	[235]

		the material is sifted to separate the fibers from the PVC. The resulting PVC is used in the production of various items, including sharpeners and more.	
	Texyloop®	This approach, developed by the Serge Ferrari Group, primarily targets the recycling of technical fabrics composed of flexible PVC matrices reinforced with polyester fibers. It allows for the recovery of plasticized PVC, which can be repurposed in various applications.	[238]
	AgPR - PVC flooring	Located in Troisdorf, Germany, the AgPR facility cryogenically treats PVC to ease its mechanical recycling. This plant boasts a theoretical production capacity of around 4,000 tons annually.	[237]
	Rubber Research Elastomerics	In the United States, this company employs proprietary technology to blend PVC waste (such as tarpaulins and cable scrap) with shredded tire scrap, incorporating a rubber compatibilizer. Equal parts of this mixture yield sturdier products, potentially serving as a substitute for wood in specific construction uses.	[235]
	Solvay's VinyLoop	This facility operates based on a Solvay patent crafted in 1998 and follows a physical-mechanical batch process consisting of three primary phases: dissolution of PVC in a solvent; filtration of the resulting solution and precipitation of the recuperated PVC.	[239]
Feedstock recycling technologies	Sumitomo Metals	Sumitomo Metals in Japan has pioneered a waste gasification and smelting system that relies on high-temperature metallurgy and oxygen injection. This innovative system excels in the reliable gasification and fusion of not just municipal waste but also plastic waste and polyvinyl chloride (PVC) waste. It achieves this by employing a combination of a top-blow oxygen lance and sideways-blow oxygen lances.	[240]
	Ebara process	The Ebara method relies on high-temperature gasification, where limited quantities of air, oxygen, or steam trigger a chemical reaction to transform PVC into a mixture of syngas and carbon dioxide.	[241]
	Redop process	The Reduction of Iron Ore by Plastics (REDOP) method is designed to address the mixed plastic component found in municipal waste, typically containing approximately 1% chlorine, with levels ranging from 0.5 to 5.0 wt.%. The process involves the following stages: (After segregating plastic and paper from municipal solid waste; isolating the mixed plastics from the paper portion; removing chlorine from the mixed plastics and co-injecting them (alongside coal) into a blast furnace to produce pig iron.	[242]
	AlzChem	The dehydrochlorination process involves the utilization of a high-temperature upstream extruder to break down PVC. This method effectively eliminates chlorine from the plastic waste stream while simultaneously recovering hydrochloric acid (HCl).	[243]
	KU Leuven	A research team based at KU Leuven in Belgium is investigating the dehydrochlorination of PVC within ionic liquid environments. These liquids exhibit minimal volatility, even under high temperatures, such as 250°C and beyond. This property facilitates the removal of HCl through vacuum extraction or gas streaming, effectively	[235]

		preventing the formation of salt resulting from the reaction between HCl and caustic soda. Consequently, the dehydrochlorinated PVC would undergo precipitation.	
Incineration with energy recovery and material recycling	SUEZ	Recovery of hydrochloric acid (HCl) and salt during incineration procedures offers the potential for recycling a portion of the waste output. SUEZ has been utilizing a rotary kiln for this purpose since 1999, facilitating the recovery of HCl and energy from various sources, including PVC waste, polluted oils, bio-sludge, and hazardous solids containing chlorinated compounds. Recently, SUEZ assumed control of this facility.	[121]
	Melt volume-flow rate (MVR)	A facility in Germany was established with the aim of reclaiming hydrochloric acid (HCl) from 320,000 tonnes of waste annually, in the form of a 30% aqueous solution. This high-purity HCl is well-suited for use in the chemical industry. The acid byproducts resulting from the incineration of PVC are neutralized using sodium bicarbonate. The resulting sodium chloride is purified and utilized as a replacement for naturally mined sodium chloride in the production of sodium carbonate.	[244]
	HALOSEP® and the SOLVAir®	Alternatively, this approach enables salt reclamation. The initial step yields a calcium chloride brine, thereby decreasing the volume of waste necessitating landfill disposal. Simultaneously, the second step facilitates the recycling of sodium bicarbonate, employed for gas neutralization, while minimizing the residue generation associated with the procedure.	[235]

8. PVC Recycling in Europe

In Europe, there have been efforts to promote PVC recycling and establish recycling circuits. The European PVC industry has implemented voluntary commitments to increase the recycling and reuse of PVC products, aiming to reach specific targets by certain deadlines [29,245]. These initiatives focus on improving collection and sorting techniques, developing innovative recycling technologies, and increasing awareness about PVC recycling among stakeholders [245].

Vinyl2010 and VinylPlus are two significant initiatives within the PVC industry that focus on promoting sustainability, responsible production, and recycling of PVC materials [29,245].

Vinyl2010 was an industry-wide voluntary commitment established in 2000 with the goal of advancing sustainable development in the European PVC industry. Its primary objectives were to enhance the sustainability of PVC production, promote the use of best practices, and increase PVC recycling rates. Under Vinyl2010, significant progress was made in improving the environmental performance of PVC through the implementation of innovative technologies and the development of sustainable PVC applications. The initiative played a crucial role in shaping the foundation for subsequent sustainability initiatives in the PVC sector [246].

Building on the success of Vinyl2010, VinylPlus was launched in 2011 as a 10-year voluntary commitment by the European PVC industry. The initiative expanded upon the objectives of its

predecessor and aimed to further drive the sustainability agenda within the PVC industry. VinylPlus set ambitious targets to achieve by 2020, including the recycling of 800,000 tons of PVC annually, the sustainable use of additives, and the reduction of greenhouse gas emissions throughout the PVC life cycle [245].

Under the VinylPlus initiative, significant progress has been made in advancing sustainable PVC production and recycling. The PVC industry has made substantial investments in improving recycling infrastructure, developing innovative recycling technologies, and expanding the collection and recycling of PVC wastes. These efforts have resulted in increased recycling rates and the establishment of a circular PVC economy in Europe [247].

VinylPlus operates based on the principles of sustainable development, encompassing economic, environmental, and social aspects [247]. It promotes transparency, stakeholder engagement, and collaboration among industry players, regulators, Non-governmental organizations (NGOs), and other stakeholders to achieve its objectives [39,248]. The initiative has been widely recognized for its contributions to the circular economy and the sustainable management of PVC throughout its life cycle [247,248].

VinylPlus continues to work towards its long-term sustainability goals, focusing on areas such as resource efficiency, waste management, sustainable additives, and innovation [39]. The initiative plays a vital role in driving the PVC industry towards a more sustainable and responsible future, fostering continuous improvement and ensuring the industry's contribution to a circular and low-carbon economy [39,249].

9. Challenges and opportunities for PVC recycling

Despite the advancements in PVC recycling methods and technologies, there are several challenges and limitations that need to be addressed to maximize the efficiency and sustainability of the process. Some of the key challenges are: Please highlight this short part

9.1. Low Yield

One of the primary challenges in current PVC recycling methods is achieving high yield rates. The complex nature of PVC, including its various additives and blending with other materials, can make complete separation and recovery difficult. As a result, the yield of recycled PVC is often lower than desired, reducing the overall effectiveness of the recycling process [250,251].

9.2. Energy Consumption

Many PVC recycling methods require significant energy inputs, particularly those involving mechanical processes, thermal treatment, or chemical reactions. High energy consumption not only adds to the operational costs but also increases the environmental impact of the recycling process.

Finding energy-efficient alternatives is crucial for improving the sustainability of PVC recycling [252,253].

9.3. Contamination

Contamination from other materials, such as different types of plastics or non-recyclable waste, poses a challenge in PVC recycling. Contamination can affect the quality and properties of the recycled PVC, limiting its potential applications and market value. Developing effective sorting and separation technologies is essential to minimize contamination and enhance the quality of recycled PVC [254,255].

9.4. Technical Complexity

PVC is a complex polymer, often blended with various additives and fillers to achieve desired characteristics. These additives can complicate the recycling process by interfering with the separation and degradation of PVC. Addressing the technical complexity associated with the diverse formulations of PVC is crucial for developing efficient recycling methods [256,257].

9.5. Infrastructure and Collection

Establishing a robust infrastructure for PVC waste collection and recycling is a significant challenge. PVC waste is generated from various sources, including construction, packaging, and consumer products, making its collection and sorting a complex task. Building efficient collection systems and promoting proper disposal practices are necessary to ensure a consistent supply of PVC waste for recycling [257–259]. Despite these challenges, there are opportunities for improvement and advancement in PVC recycling:

9.6. Technological Innovation

Continued research and development efforts can lead to the discovery of innovative technologies and methods that overcome the limitations of current PVC recycling. This includes exploring new processes, such as chemical or biological recycling, to enhance yield rates, reduce energy consumption, and improve the overall efficiency of PVC recycling [260–262].

9.7. Collaboration and Stakeholder Engagement

Collaboration among stakeholders, including manufacturers, recyclers, policymakers, and consumers, is crucial for driving progress in PVC recycling. By working together, stakeholders can share knowledge, resources, and best practices, fostering a more sustainable and circular approach to PVC waste management [263–265].

9.8. Education and Awareness

Increasing public awareness about the importance of PVC recycling and promoting responsible consumption and disposal practices can significantly contribute to improving recycling rates.

Educating consumers and industries about the environmental impact of PVC waste and the benefits of recycling can drive behavioral changes and support the growth of PVC recycling initiatives [266–268].

9.9. Policy and Regulation

Implementing supportive policies and regulations can incentivize PVC recycling and create a favorable environment for investment in recycling infrastructures. Policy measures, such as extended producer responsibility and product labeling, can encourage manufacturers to use recyclable materials and support the development of effective recycling circuits [22,269,270].

While PVC recycling methods and technologies have made significant progress, challenges and limitations persist. Low yield, high energy consumption, contamination, technical complexity, and inadequate infrastructure and collection systems are some of the key challenges to be addressed. However, through technological innovation, collaboration, education, and supportive policies, there are opportunities to overcome these challenges and improve the efficiency and sustainability of PVC recycling. By doing so, the environmental impact of PVC waste will be minimized contributing by the way to the transition towards a circular economy.

Conclusion

This review has provided an overview of the current status of PVC recycling and its challenges and opportunities. The conventional PVC recycling methods, including mechanical, thermal, and chemical recycling, have limitations in terms of quality, cost, and environmental impact. Innovative PVC recycling technologies, such as biological, plasma-assisted, and solvent-based recycling, offer promising alternatives for PVC waste management.

However, these emerging technologies still require further research and development to improve their efficiency, scalability, and economic viability. Additionally, the lack of infrastructure and regulations for PVC recycling poses significant challenges for the effective implementation of these technologies.

Despite these challenges, PVC recycling has significant environmental and economic benefits compared to conventional disposal methods. Recycling reduces greenhouse gas emissions, conserves resources, and reduces the landfill and incineration of PVC wastes. Additionally, recycling promotes the circular economy and sustainable development, creating opportunities for job creation and local economic growth.

To improve PVC recycling infrastructure and technology, further research and development are needed in areas such as materials synthesis and characterization, process optimization, cost analysis, and life cycle assessment. Additionally, governments and industries should support the

development of regulations and policies that promote PVC recycling and incentivize investment in recycling infrastructure.

PVC recycling is an essential strategy for reducing the environmental impact of PVC wastes and promoting sustainable development. The challenges and opportunities of PVC recycling require multidisciplinary research and collaboration between academia, industry, and governments.

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Conflicts of Interest

The authors declare no conflict of interest.

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