European Journal of Interdisciplinary Research and Development
Volume- 40 June- 2025
Website: www.ejird.journalspark.org ISSN (E): 2720-5746

METHODS FOR RECYCLING POLYVINYL CHLORIDE WASTE

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Аннотация
This article highlights the environmental impact of polyvinyl chloride waste, the necessity of its recycling, and the practical methods used for its processing. Due to the widespread application of polyvinyl chloride in industrial and domestic sectors, a large amount of waste is generated. The article analyzes thermal, mechanical, and chemical methods for recycling this waste. The technological process, advantages, and disadvantages of each method are examined. Additionally, the most suitable approaches are identified from the standpoint of environmental safety and economic efficiency. The results of the study aim to improve the efficiency of polyvinyl chloride waste recycling and expand the possibilities of using it as a secondary raw material.

Keywords: Polyvinyl chloride (PVC), dioxins, furans, bioaccumulation, ecosystem, polypropylene (PP), polyethylene (PE), pyrolysis, pyrogas, alkaline hydrolysis.

Introduction

Polyvinyl chloride (PVC) is a highly efficient, low-cost, and widely used thermoplastic material that finds extensive applications in construction, electrical engineering, medicine, the automotive industry, and packaging. Its physical and mechanical properties, chemical stability, and long service life make it one of the most commonly produced polymers. However, the extensive use of PVC has led to an annual increase in the amount of waste generated.

Due to the presence of chlorine in its structure, the disposal of PVC poses significant environmental risks. Improper or uncontrolled incineration of PVC waste results in the release of dioxins, furans, and other toxic gases into the atmosphere, posing serious threats to human health and ecological balance. Furthermore, PVC waste can persist in soil and aquatic environments for long periods without degrading, leading to bioaccumulation and negative impacts on ecosystems. Therefore, the environmentally safe and economically viable recycling of PVC waste is one of the urgent issues today. This article examines effective recycling methods for PVC waste by analyzing its impact on the environment.

Secondary PVC includes both technological waste and production and household consumption waste. Technological waste (such as scraps, castings, trimmings, ribbons, etc.) is generated during the synthesis and processing of polyethylene terephthalate and is used in secondary recycling. Production and household PVC waste includes packaging for liquids, household chemicals, and powders. PVC is considered one of the more durable polymers, and its depolymerization process under natural conditions occurs very slowly. Therefore, various recycling methods have been developed for PVC waste, including mechanical, thermal, and chemical methods.

Thermal Recycling Method. The main valuable products obtained as a result of polymer pyrolysis include benzene, o-xylene, p-xylene, m-xylene, styrene, isoprene, acetone, naphthalene, coumarone, cresols, phenanthrene, anthracene, pyrroles, nitrogen-containing compounds (such as carbazole, indole, pyridine, and picoline), sulfur-containing compounds (such as thiophene), and others.

To carry out the pyrolysis process, the following laboratory apparatus was assembled (Figure 1).

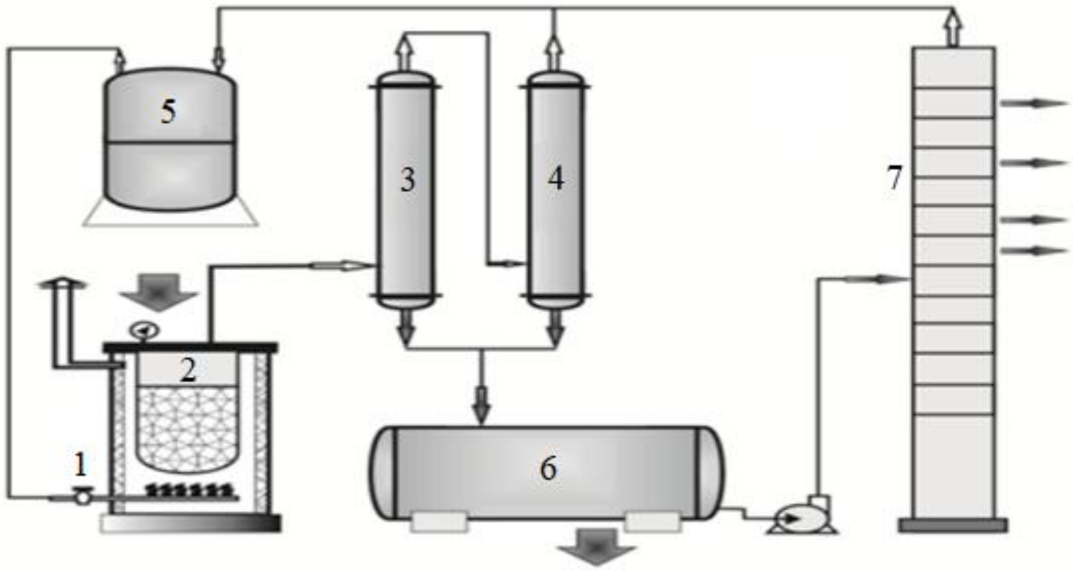

Figure 1. Laboratory apparatus for recycling polymer waste by pyrolysis

A pre-prepared mixture of polymer waste was loaded into the retort (2). A 10-liter metal vessel equipped with a lid and a return pipe was used as the retort. The return pipe was connected to a condenser (3). The retort filled with raw material was placed into the pyrolysis furnace (1).

The temperature in the inner chambers of the furnace gradually increases (by 5–10 °C per minute). In the retort, the decomposition of the material in an oxygen-free environment is observed. Under the influence of heat, molecular bonds break down, leading to the formation of pyrolysis gases. As a result, pressure inside the retort increases, and the system transitions to operational mode.

Initially, the device operates using external heat sources. Once the process stabilizes, the pyrolysis continues due to the heat generated from the combustion of the released pyrolysis gases. The gases pass through the return pipe into the condensers (3, 4), where the temperature drop causes the substances to change their aggregate state into the liquid phase.

As a result of pyrolysis, complex polymer chains are converted into kerosene and olefin compounds. A condensed mixture of cyclic, aromatic, and heterocyclic products accumulates in the storage tank (6). It is then sent to the rectification unit (7) for fractional distillation.

In the rectification unit, non-condensable pyrolysis gases are directed to the gas collection tank (5). These gases are either supplied to consumers or used as fuel in the pyrolysis furnace. This method prevents the release of waste gases into the atmosphere.

The residue obtained from the rectification process is either briquetted or sent to special storage containers.

Despite the prospects and technological advantages of recycling polymer waste—such as polyvinyl chloride, polypropylene, polyethylene, and other synthetic polymers—through pyrolysis, certain issues related to the economic efficiency (profitability) of this process remain relevant. One of the main drawbacks of pyrolysis is the need for preliminary sorting of the waste. When unsorted mixed waste is subjected to pyrolysis, obtaining target products—particularly liquid fuel or other valuable fractions—with high yield becomes significantly more difficult.

In addition, the high operating temperatures required for pyrolysis (ranging from 400 to 800 °C) necessitate the use of heat-resistant and advanced technological equipment. This, in turn, increases both the cost of the equipment and operational expenses. Therefore, pyrolysis technology is currently considered a recycling method that is not yet sufficiently economically viable.

Mechanical Recycling Method. The mechanical method of recycling polyvinyl chloride (PVC) waste involves the use of both clean, single-type PVC waste and polymer mixtures contaminated to various degrees (such as polypropylene (PP), polyethylene (PE), labels, adhesive residues, etc.). This method is considered one of the technologically simpler and less costly approaches.

However, to obtain high-quality products, a multi-stage process must be carried out, which increases the consumption of time and labor resources. Recycled PVC waste is often used in combination with virgin (primary) materials or directly directed into production as a secondary product.

The mechanical recycling process typically includes the following main stages: sorting, washing, drying, shredding, extrusion, and granulation (see Figure 2). Through these stages, waste is converted into polymer raw materials that are stable in quality and suitable for technological use.

PVC containers are initially collected and sorted either manually or using color-detecting equipment. During the machine sorting process, electronics separate PVC, glass, and other materials within seconds and classify them based on size and shape. The sorted containers are then grouped and sent to appropriate facilities for secondary recycling.

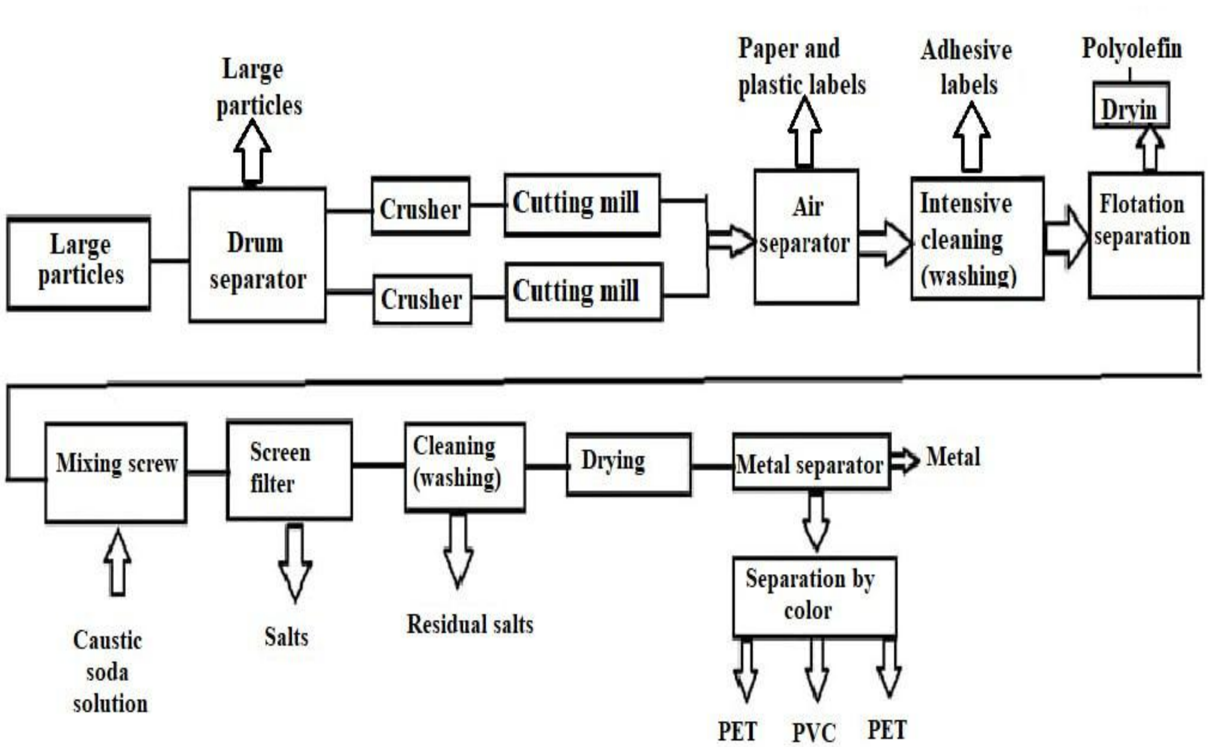

Figure 2. Flowchart of Mechanical Recycling of Polymer Waste

Upon arrival at the recycling plant, the PVC containers are loaded onto a conveyor belt using a loading device. The containers are directed to the fragmentation process via the conveyor: first, the binding (shaft) holding them together is removed, and large contaminants are eliminated on separator drums. Then, the containers are cut into large pieces using cutting blades and further ground into uniform-sized fragments using a mill. As a result, a mixture of PVC fragments, labels, and caps is obtained.

Paper and labels are separated from the mixture using an air separator; the separated label residues are cleaned through intensive washing. In the next stage, the flotation method is applied to separate light PVC fractions from heavier ones. During the flotation process, PVC fragments are also freed from metallic contaminants: fine metal particles are separated from the crushed material by a separator.

In the following stage, the cleaned PVC particles are mixed with a caustic soda (NaOH) solution in a mixing container. This mixing lasts for several hours and is followed by processing through a 26-meter-long rotating drying kiln. As the material passes through the kiln, foreign materials are removed under the influence of heat and air flow, resulting in a filtered pure PVC suspension. After filtration, the material is rinsed again and dried in preparation for the next stage.

The recycled PVC layer is passed through a spectrometric sorting device. The spectrometer compares the spectrum of each particle with a reference signal to determine its color and ensure its purity. Pneumatic grippers remove any incorrect or unwanted material. Finally, the purified PVC material is blended with virgin polyvinyl chloride through a thermal melting method in extruders and prepared for granulation. As a result, high-quality PVC granules are obtained.

Specific Difficulties and Limitations of Mechanical Recycling. These include label and adhesive residues. Adhesive residues remaining on labels and caps (based on rosin acids and complex esters) negatively affect the transparency of PVC and alter its color.

High Moisture Content. PVC fragments that have not been sufficiently dried and contain bulk moisture are easily subject to degradation during the recycling process.

The Need for Color Sorting. PVC pieces must be sorted by color to preserve the material's properties.

Contamination with Foreign Materials. Paper, glue, and other waste materials stuck to PVC pieces must be minimized; otherwise, the quality of recycling decreases.

Molecular Weight (Intrinsic Viscosity). It is necessary to maintain the molecular weight of PVC close to its original values during the recycling process; loss of this parameter affects the quality of the resulting granules.
These challenges negatively impact the final product quality of mechanically recycled PVC. Therefore, maintaining high quality standards for secondary PVC granules is one of the most important tasks of the mechanical recycling process.

Chemical Recycling Method. Efficient recycling of polyvinyl chloride (PVC) waste is one of the current priorities of modern chemical technology. The thermal and chemical stability of this material, as well as the presence of chlorine atoms in its structure, create specific difficulties during disposal.

PVC Pyrolysis. The pyrolysis of PVC waste is a decomposition process carried out at high temperatures (250–500°C) in an oxygen-free environment. Pyrolytic degradation begins with dehydrochlorination in the initial stage, during which hydrogen chloride (HCl) is released from the PVC chain. This process leads to the formation of unsaturated alkene bonds within the polymer chains. In subsequent stages, the resulting unsaturated chains break down at high temperatures into short-chain gaseous hydrocarbons, liquid fuel fractions, and carbonaceous residues.
The main products obtained from pyrolysis include:
Gaseous fractions: ethylene, acetylene, propylene;
Liquid fractions: light fuel mixtures;
Solid residue: carbon-based tars and coke;
Hydrogen chloride (HCl): a major byproduct with aggressive corrosive properties.

Advantages of pyrolysis include the potential for energy recovery from waste and significant volume reduction. However, the formation of chlorinated organic compounds, dioxins, and furans during the process poses serious environmental risks. Pyrolysis equipment must be resistant to high temperatures, which contributes to the economic inefficiency of the process.

Alkaline Hydrolysis of PVC. Hydrolyzing PVC using strong alkalis (typically NaOH or KOH) is considered one of the promising chemical recycling methods. The process is usually carried out at temperatures ranging from 130–180°C, sometimes under pressure, in aqueous or alcoholic solutions. As a result of alkaline hydrolysis, PVC molecules undergo depolymerization, breaking down into unsaturated chain compounds, chloride salts, and other low-molecular-weight products.
This reaction can be summarized as follows:

$$[–CH_2–CHCl–]_n+NaOH \rightarrow –CH=CH–+NaCl+H_2O$$

Main Products Formed from Alkaline Hydrolysis:
Sodium chloride (NaCl) or potassium chloride (KCl);
Unsaturated hydrocarbons (e.g., alkenes);
Dark residual substances formed as a result of partial carbonization.

Key Limitations of the Process Include:
The requirement for high alkali concentrations and elevated temperatures;
Operation in an alcoholic medium complicates the process and increases economic costs
Recycling of PVC waste through pyrolysis and alkaline hydrolysis presents scientifically and technologically intriguing solutions. While pyrolysis enables the recovery of energy and fuel, it involves environmental risks and requires high temperatures. Alkaline hydrolysis allows for the chemical breakdown of PVC into its components but is associated with harsh conditions and high costs. Therefore, future research should focus on improving these methods to make them more economically and environmentally viable.

CONCLUSION
This article provides a comprehensive analysis of the three main approaches to polyvinyl chloride (PVC) waste recycling — mechanical, thermal (pyrolytic), and chemical (alkaline hydrolysis) methods. Each method has been evaluated in terms of its technological features, environmental impact, economic efficiency, and practical applicability.
The mechanical recycling method is relatively simple and cost-effective. In this process, PVC waste is washed, dried, shredded, and granulated for use as secondary raw material in the production of new products. However, contamination from labels, adhesive residues, and color impurities complicates the process and reduces the final product quality. Due to the high sensitivity of PVC, insufficient drying can lead to thermal degradation during processing.
The thermal method, or pyrolysis, enables the recovery of energy and fuel fractions from waste. However, the process demands high temperatures and releases corrosive and toxic substances

like hydrogen chloride (HCl). From an environmental safety perspective, pyrolysis requires specialized equipment and gas purification systems.

The chemical method — alkaline hydrolysis — allows PVC to be broken down into its chemical components. In the presence of strong alkalis (NaOH, KOH), PVC undergoes depolymerization, producing useful chemical compounds such as chloride salts, unsaturated hydrocarbons, and other intermediates. This method stands out for its high selectivity and product quality. However, the need for high temperatures, pressure, and reagent consumption limits its economic feasibility on a large scale.

Based on the analysis, combining mechanical and chemical recycling methods may be considered the most optimal strategy for PVC waste processing. Initially, waste is mechanically sorted, washed, and granulated, while complexly contaminated fractions are processed via chemical hydrolysis. This integrated approach maximizes waste utilization, improves the quality of the final product, and reduces environmental risks.

In the future, it is crucial to advance PVC waste recycling technologies, particularly by developing energy-efficient and environmentally safe chemical methods suitable for industrial implementation.

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