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Recovery of polyvinyl chloride from single-use waste banner: a cleaner recycling strategy

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Abstract

Usage of polyvinyl chloride (PVC)-coated and PVC-based materials has been increased worldwide. Particularly, short-term, usable PVC-based flexible banners present significant environmental concerns when freshly disposed of due to their inherent toxicity and limited recyclability. This study presents a solvent desorption and extraction method for extracting and characterizing PVC from waste banners (WB), aiming to advance material recovery within a circular plastic economy framework. This extraction process successfully yielded four distinct components: reinforced fibers (RFs), solvent-soluble parts (SSPs), centrifuged liquid parts (CLP), and extracted polyvinyl chloride (ePVC). Successfully, 34.3% of ePVC from the total mass of WB, where only 0.08% mass loss was calculated. The structural analysis, conducted via FTIR, revealed that the ePVC closely resembled virgin PVC. Additionally, a minor carbonyl (C=O) stretching peak at 1727 cm^{-1} was observed, indicating the presence of residual plasticizers or phthalate derivatives. The ePVC demonstrated 81.44 mL/g intrinsic viscosity, where the K-value was 60.9, the melting point was 200°C, and the electrical conductivity was 50.29 μS. The qualitative values suggest viability for fundamental physicochemical properties and industrial reuse. Overall, the findings validate the potential of this approach as an environmentally responsible recycling strategy and a promising alternative to incineration or landfilling of PVC-based waste.

Keywords: PVC recycling; Chemical recovery; Waste banners; Sustainable materials; Polymer characterization

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Introduction

Plastics are the most widely used expansion polymers in global manufacturing due to their exceptional functional properties and relatively low production costs. Among these, polyvinyl chloride (PVC) ranks as the third most widely utilized thermoplastic in terms of global market share (Saatcioglu and Venkatraman, 2024). It is considered as a universal polymer due to its affordability, versatility, and favorable physical and chemical characteristics. It is also heavily used in manufacturing disposable consumer products, such as packaging for food and beverages, as well as packaging for cleaning products, medical devices, toys, and containers. Furthermore, it is used as a resistant coating for products such as advertising banners, tarpaulins, and grain covers (Cholake *et al.* 2018a). In the building industry, PVC is primarily used for the construction of pipes, window frame profiles, roofing membranes, floor coverings, and cable insulation in long-term applications. Different additives added to PVC enable the production of two distinct forms of PVC: flexible and rigid. These forms can be processed through various means, including injection molding, calendaring, roto molding, thermoplastic extrusion, hot pressing, and plastisol casting (Ciacci *et al.* 2017). Namely, by coating PVC in either thin or thick layers on a flexible polyester backing, it is possible to create advertising banners that boast high tensile strength, waterproofness, and durability for long-term outdoor use. With 87% of polymer-coated fabrics in total sales, the market size of PVC, including other polymer-coated textiles, was $17.3 billion in 2014

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and it is forecasted to be around $21 billion in 2020 (Cholake *et al.* 2018b). Although PVC-coated banners laminated on a polymer base, such as polyester, have durability, they also become a significant source of post-consumer plastic waste. In Bangladesh, 27,000 tons of banners were used in the 12th national elections, with 17,000 tons concentrated in Dhaka city alone (Miliute-Plepiene *et al.* 2021).

Furthermore, additional sources of PVC waste include an estimated 4,000 to 9.5 million square meters of discarded grain covers and 410 tonnes of obsolete truck tarpaulins, much of which ends up in landfills (Figure 1). These materials pose serious environmental risks through the release of toxic leachate and greenhouse gases. The escalating cost of landfill use, coupled with the lack of economically viable recycling technologies for end-of-life banners, exacerbates the waste management crisis (Cholake *et al.* 2018c). Additives such as stabilizers, plasticizers, and colorants present additional health and environmental hazards, especially legacy additives regulated under the EU REACH directive, which restricts substances including DEHP, DBP, DIBP, and aBBP (Ciacci *et al.* 2017; Miliute-Plepiene *et al.* 2021). Incineration generates harmful by-products such as dioxins, hydrochloric acid, and heavy metal residues, while landfilling remains the least desirable disposal option. Therefore, the development of sustainable and effective recovery solutions is urgently required (Sahen *et al.* 2025).

The production, use, and disposal of polyvinyl chloride (PVC) contribute to the release of various environmental pollutants, with incineration being a particularly problematic phase. As Table II, commonly employed in the treatment of municipal, hazardous, and medical waste, incineration of PVC-containing materials, especially those used in medical applications, results in substantial emissions of dioxins due to the polymer's high chlorine content, positioning incinerators as significant sources of air and soil contamination (Wang *et al.* 2020). In light of increasing global concerns over plastic waste, addressing the environmental impacts associated with PVC disposal is of critical importance (Ahmed *et al.* 2025). Recycling offers a viable mitigation strategy; substituting virgin PVC with recycled PVC in window profile production, for example, has been shown to reduce environmental risk by up to 70% and lower air and water emissions by more than 60% (Biçergil and Atılgan Türkmen, 2023; Getor *et al.* 2020). These findings emphasize the necessity of integrating recycled PVC into manufacturing processes to achieve meaningful reductions in environmental harm.

Bangladesh holds significant potential to emerge as a global leader in the PVC plastics sector (Hossain and Shams, 2020). Despite this promise, less than 5% of waste PVC banners are currently recycled within the country. According to Rahul et al. (Tiwari *et al.* 2023), strategic contribution between public and private functions could render the recycling industry highly profitable, even in the absence of institutional or governmental support. Bangladesh has long employed circular economy principles, often integrated with traditional resource management practices (Mourshed *et al.* 2017). However, the development of robust waste management systems, supporting infrastructure, technological frameworks, and a comprehensive value chain for plastic waste collection is essential to unlock the sector's full potential (Rahman *et al.* 2017). Mechanical recycling is based on sorting, shredding, and grinding PVC into reusable flakes, which is commonly practiced, yet suffers from limitations such as contamination, polymer degradation, and inconsistent waste supply, all of which compromise material quality (Schyns and Shaver, 2021). Feedstock recycling, involving pyrolysis, gasification, or solvolysis to decompose PVC into chemical building blocks, is energy-intensive, costly, and associated with the release of hazardous materials as by-products such as hydrochloric acid (HCl) and dioxins (Vasudeo *et al.* 2016). Hydrothermal treatment, which utilizes high-pressure steam, offers flexibility in managing additives but requires considerable energy input and produces secondary waste requiring additional treatment (Mumtaz *et al.* 2023). Although promising at the laboratory scale, industrial application remains hindered by reactor inefficiencies and energy demands (Laredo *et al.* 2023). Therefore, the advancement of sustainable practices and modern recycling technologies is imperative for realizing efficient, scalable PVC recycling in Bangladesh.

Despite ongoing progress, polyvinyl chloride (PVC) recycling continues to face significant obstacles due to the presence of persistent plasticizers, hazardous stabilizers such as lead and barium, and various additives, including fillers and colorants (Table I). These components hinder separation processes and diminish the quality of recycled materials. Moreover, the similar densities of PVC and polyethylene terephthalate (PET) complicate mechanical separation, while misprocessing can result in the formation of toxic by-products such as dioxins (Ait-Touchente *et al.* 2024; Jiang *et al.* 2023). To address these challenges, several advanced recycling technologies have been explored. Biological recycling utilizes microorganisms or enzymes to depolymerize PVC into simpler, potentially biodegradable compounds; however, issues of scalability and process optimization remain significant barriers to its prevalent industrial applications (Soong *et al.* 2022; Zheng *et al.* 2022). Electrochemical recycling enables decomposition into high-purity products but demands improvements in electrode materials and operational efficiency (Petersen *et al.* 2021). Dissolution and extraction methods selectively isolate PVC using solvents and allow additive recovery, though traditional solvents and high processing costs limit widespread adoption (Xie *et al.* 2019). Additive manufacturing offers a means to repurpose PVC waste for 3D printing, thereby reducing reliance on virgin inputs, though scalability requires further research (Bourell *et al.* 2017a; Wu *et al.* 2022a). Chemical upcycling converts PVC into high-value feedstocks, aligning with circular economy objectives, but it remains energy-intensive and expensive (Feng *et al.* 2023a). Microwave-assisted recycling enables rapid and selective polymer degradation but involves costly equipment and challenges in managing by-products (Hu *et al.* 2023). Supercritical fluid extraction, particularly with supercritical CO_2, facilitates eco-friendly PVC separation and additive recovery; however, scalability is constrained by the demands for high-pressure equipment (Yao *et al.* 2019). Additionally, nanostructured catalyst supports offer pathways to transform PVC waste into functional catalytic materials, presenting a promising frontier for waste valorization, albeit with scalability and cost barriers (Valadez-Renteria *et al.* 2021). Together, these emerging technologies have the potential to overcome PVC recycling constraints to make significant strides in sustainability.

The objective of this work is to recover and characterize PVC from waste banner (WB) through the systematic fractionation of its constituents, thereby obtaining extracted PVC (ePVC). In the extraction, ePVC is separated using both the solvent dissolving method and the mechanical separation technique with minimal degradation. The reconstituted ePVC is characterized by FTIR spectroscopy, intrinsic viscosity measurement, and thermal stability determination, and the relevant structural and physicochemical properties are compared with those of pure PVC. Furthermore, the efficiency of the extraction, the existence of residual additives, and the thermal stability of ePVC are examined. Risk analysis is performed to evaluate the applicability of ePVC for recycling in relation to the chemical purity, processing properties, and potential industrial uses. The results provide support for the sustainable management of plastic waste, and offer a solution for PVC-disposal problems and circular-economy strategies

Materials and methods

Material collection and preparation

The banner was collected from a seminar at the Bangladesh Council of Scientific and Industrial Research (BCSIR), Dr. Qudrat-i-Khuda Road, Dhaka 1205. Analytical grade (99.9%) of Tetrahydrofuran (solvent) was purchased from Fisher Scientific, UK, 99.9% of Ethanol from Sigma Aldrich, Germany, and pure PVC (PCode: 4102071807) purchased from Sigma Aldrich, USA. After collecting WB, it was washed out to remove all outer pollutants with a commercial detergent. Then, dried it adequately under the sun for 48 hours, cut it into small pieces, and stored.

PVC extraction process

Initially, 8 g of the prepared WB sample was dissolved in tetrahydrofuran (THF) and subjected to continuous stirring for 1 hour to ensure complete dissolution. The reinforced fibers (RFs) embedded in the WB matrix were subsequently separated through filtration and washed thoroughly with THF to eliminate any residual matrix components. After 30 minutes of washing, the RFs were dried in a hot air oven at 80°C for 2 hours and then weighed. The resulting THF solution, containing the dissolved components, was centrifuged at 8,000 rpm for 20 minutes using a Centrifuge Machine (Model 2-16P, Sigma, Germany) to separate the solvent-soluble parts (SSPs). This process yielded two distinct phases: a centrifuged solid part (CSP) and a centrifuged liquid part (CLP). The THF from the CLP was evaporated and condensed for potential reuse. Upon complete solvent removal, the CLP solidified and was subsequently weighed and stored for further purification.

PVC recovery process

The processed dry CLP was cut into small pieces for better interaction. Then the Soxhlet extraction was performed on these small parts of CLP. Here, ethanol was used to wash out CLP parts, and this Soxhlet extraction was carried out over eight cycles to remove residual additives, plasticizers, and stabilizers from processed CLP. The resulting purified solid, designated as extracted PVC (ePVC), was collected and dried before further physicochemical characterization. The Figure 2 was depicted this whole extraction process.

Characterization

Physicochemical properties

A comprehensive characterization of the WB and extracted PVC (ePVC) samples was performed by evaluating key physicochemical parameters, including ash content, sample thickness, melting point, burning point, electrical conductivity, and intrinsic viscosity. Ash content was determined by ISO 4047 using a muffle furnace (CWF 1200, CARBOLITE, UK). For this analysis, 10 g of each sample was treated with carbonation and sulfuric acid and subsequently incinerated at 550°C for 24 hours in a sealed chamber to obtain the residual inorganic content. The melting point was assessed following ISO 11357-3 using Differential Scanning Calorimetry (DSC), where 5 mg of sample was heated and allowed to increase temperature to 650°C at the rate of 10°C/min. The melting point was identified on the DSC thermogram as the temperature corresponding to the transition from solid to viscoelastic state. Burn point was evaluated using the ISO 4589-2 standard, which measures the minimum oxygen concentration required to support combustion under a vertical testing configuration. Electrical conductivity was measured by ASTM D1755-21. In this procedure, 2 g of the sample was dissolved in 5 mL of isopropanol, followed by the addition of 100 mL of hot water. After heating for 5 minutes and cooling to 20°C, conductivity was measured using a Conductivity Meter (Model 3540, Jenway, UK). Moreover, intrinsic viscosity, an indicator of molecular weight, was determined using ISO 1628-2. Samples were dissolved in cyclohexanone at 30°C, and the flow time was recorded using a Micro Viscometer (LOVIS 2000M, Anton Paar, Austria). Molecular weight was calculated using the standard viscosity equation 1. These analyses were conducted on four representative samples to ensure the reliability and accuracy of the study's results

$$M_v = \left(\frac{\eta}{K}\right)^{\frac{1}{a}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where η = Intrinsic viscosity (dL/g), M_v = Viscosity-average molecular weight, K = degree of polymerization (dL/g), and a = 0.77 (typical for PVC).

Mechanical properties test

The tensile strength and elongation at break of the samples were evaluated using a Universal Testing Machine (UTM) (Model: Titan 5, Brand: James Heal, UK), operated at a crosshead speed of 300 mm/min, by ASTM D5035-06. Test specimens were prepared with standardized dimensions of 50 mm in length and 10 mm in width. Each sample was mounted between the machine grips and subjected to uniaxial tensile loading under controlled environmental conditions of 23 ± 2°C temperature and 50 ± 5% relative humidity. Tensile strength was calculated as the ratio of the maximum applied force (N) to the original cross-sectional area of the specimen (mm²), as described by equation 2. Simultaneously, elongation at break was assessed during the same tensile procedure, as specified in ISO 527-1. This parameter reflects the ductility of the material and is expressed as the percentage increase in gauge length at the point of rupture. Elongation at break was determined using displacement data obtained during testing and calculated using equation 3. The UTM generated load-extension curves for each sample, capturing the mechanical response of the material from initial loading to failure. These curves were used to analyze both the strength and deformation characteristics under tensile stress.

$$Tensile\ strength\ (MPa) = \frac{Maximum\ load\ (N)}{Cross\ sectional\ area\ (mm^2)} \ldots (2)$$

$$Elongation\ (\%) = \frac{l_f - l_o}{l_o} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, lo = Initial gauge length (mm) and lf = Final gauge length (mm).

Fourier-Transform Infrared spectroscopy test

An FTIR analyzer (Frontier, PerkinElmer, USA) was used to investigate the chemical bonding in the composite sheet by performing FTIR spectroscopy; 2 μm Definition DFT80 film was analyzed in transmission. This high-resolution spectrometer (resolution of 4 cm^{-1}) enabled to record high-resolution spectroscopy. FTIR spectra were recorded in the range of 400 cm^{-1} to 4000 cm^{-1} to investigate detailed molecular vibrational and interaction properties in the composite. The FTIR spectra provided valuable information on the functional groups, chemical bonding configuration, and vibration behavior of the materials.

Thermogravimetric analysis

Thermogravimetric Analysis (TGA) and Differential Thermogravimetric Analysis (DTG) of the material was studied using a thermogravimetric analyzer (Model: TGA/S-DTA 851e, Mettler Toledo, Columbus, Ohio). Loss at temperatures, under controlled heating in an inert atmosphere, following ASTM E1131. TGA analysis was used to identify thermal degradation zones, estimate the temperatures of the onset and end of decomposition, and assess the complex thermal stability of the investigated sample over the entire temperature range, which was slightly above room temperature.

Energy Dispersive X-ray analysis (EDX)

The surface morphology and elemental composition of the dehydrated samples were observed using an energy-dispersive X-ray spectrometer (EDS) mounted on a scanning electron microscope (EV018, Carl Zeiss AG, Germany). The samples were also sputter-coated with platinum before testing, after being fixed using carbon tape with adhesive. A charge compensator was used for observation, and an electron voltage of 15 kV was applied.

Results and discussion

Waste banner characterization

The WB provides physico-chemical properties that indicate the composition and strength of the WB before it enters the

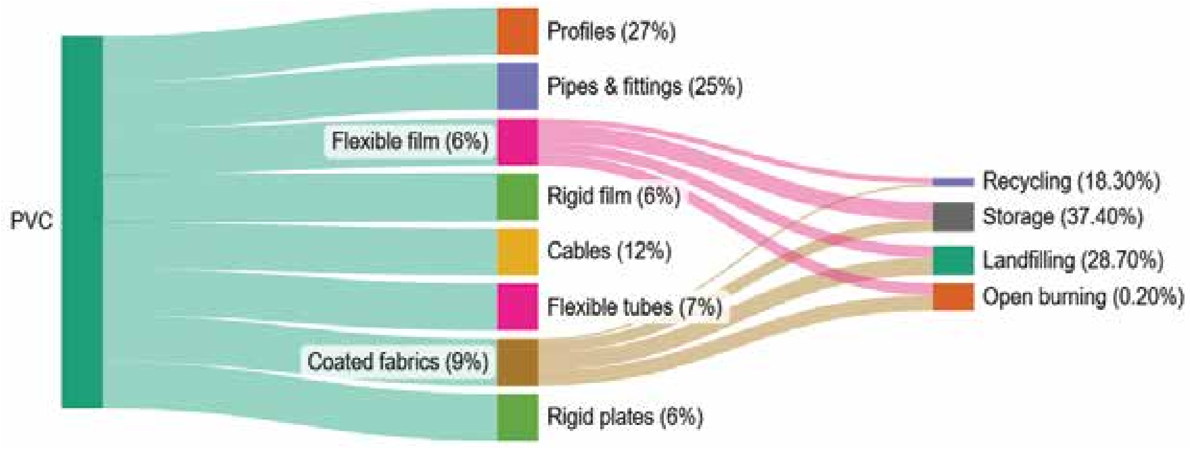

Fig. 1. Material flow of PVC and end-of-life pathways

Table I. Major additives and their functions in PVC polymer-based products.

SI no.	Additives	Major function	Example	Ref
1	Plasticizer	Enhances the flexibility of PVC and lowers its glass transition temperature (T_g).	Phthalate esters; Aliphatic diesters; Epoxidized oils; Phosphate esters; Polyesters.	(Yu *et al.* 2016a)
2	Stabilizer	Reduces or eliminates the harmful effects of heat, light, or oxygen on PVC.	Barium-cadmium; Tin mercaptides; Fatty acid salts; Alkyl benzenes; Lead salts; Epoxidized soya; Bean oil.	
3	Lubricant	Prevents the compound from adhering to processing equipment.	Lead stearate, Calcium stearate; Normal and dibasic.	
4	Filler	Increases opacity, improves hardness, and costs minimize.	Magnesium carbonate; Calcium carbonate; Barium sulfate.	

process. As Table III, waterborne polyurethanes (WBPs) have melting points (150°C) that are significantly lower than those of pure PVC, indicating the presence of plasticizers or additives that lower their thermal stability. Its low thermal resistance is confirmed with the burn point (230-235°C), which needs to be considered when selecting proper technologies for recycling. The ash content (26.40%) is high, suggesting that fillers or inorganic additives may have an impact on mechanical properties and should be considered for recycling purposes. The tensile strength (13.13 MPa) and elongation at break (33.22%) indicate that the mechanical properties of the PVC-coated fabric are moderate, consistent with typical PVC-coated fabric materials. These key WB property data points establish an initial benchmark for determining the performance efficiency of the extraction operation in separating fiber, plastic, and additives, as well as the compatibility of recovered materials.

PVC recovery efficiency

As Figure 3, the separation of WB components yielded ePVC (34.3%), CSPs (29.6%), CLP impurities (19.4%), and RFs

Table II. Recycling history of PVC from different types of PVC waste

SI no.	Method	Types of PVC	Advantage	Limitations	Ref
1	Solvent-based Dissolution Recycling	PVC-coated banner waste	Effective in separating PVC from mixed materials, producing high-purity recycled PVC.	Potential environmental risks from solvent use.	(Feng *et al.* 2023*a*)
2	Solvent-based extraction of PVC additives	Mixed plastic waste	Effectively remove hazardous plasticizers and stabilizers, improving the quality of recycled PVC.	Potential environmental risks from solvent use.	(Ügdüler *et al.* 2020)
3	Mechanical recycling	General PVC waste	Most economical and energy-efficient recycling method.	Contamination and degradation of polymer chains limit usability.	(Kroell *et al.* 2023)
4	Feedstock recycling (Chemical Recycling)	PVC waste	Converts PVC into valuable raw materials and fuels.	High energy consumption, need for cost-effective catalysts.	(Jiang *et al.* 2022)
5	Thermal degradation of PVC	General PVC waste	It can recover energy and useful chemicals.	Emission of toxic pollutants such as dioxins and heavy metals.	(Yu *et al.* 2016b)
6	Non-conventional mechanical recycling	PVC cable waste	Reduces landfill waste, potential material recovery.	Difficulties in removing plasticizers, low copper recovery rate.	(Kumar *et al.* 2024)
7	Mechanical sorting and recycling of PVC packaging	PVC packaging	Enables reprocessing into new PVC products.	High material loss and factory equipment damage.	(Murugesan and Scheibel, 2021)
8	Biomineralization of PVC waste using Sporosarcina pasteurii	PVC waste	Biodegradable and environmentally friendly approach	Limited scalability and high process time.	(Bourell *et al.* 2017b)

Continued

9	Paired-electrolysis process for PVC recycling	Laboratory tubing and flexible PVC	Enables dichlorination without high heat or emissions.	Requires specific electrode materials and process optimization	(Fagnani *et al.* 2023)
10	Co-hydrothermal dichlorination of PVC	HCl, hydrochar	Produces low-chlorine solid fuel.	Transfer chlorine to produce low Cl hydro-char for solid fuel	(Liu *et al.* 2022)
11	Catalytic upcycling of PVC (coupled (trans)esterification–hydrogenation process)	Phthalates extracted from post-consumer PVC waste	Converts hazardous phthalates into safer plasticizers.	Conversion of phthalates to cyclohexane-di-carboxylates, which are suitable for reuse as safer plasticizers.	(Windels *et al.* 2022)

(16.0%), with minimal material loss (0.8%). Because of several solvent eliminations, a small portion (0.8%) of WB was broken down and washed out, resulting in material loss. The high ePVC recovery confirms the efficiency of the extraction process in reclaiming reusable polymer, while the CSPs fraction indicates significant soluble additives or plasticizers. The CLP and RFs fractions highlight the residual polymeric and fiber content, reinforcing the composite nature of WB. The negligible loss suggests an optimized separation method with minimal waste, demonstrating its potential for sustainable PVC recovery.

Physicochemical properties of ePVC

The characterization of ePVC reveals notable differences compared to Pure PVC, highlighting the impact of the extraction process that depicted in Table IV. The intrinsic viscosity of ePVC (81.44 mL/g, k = 60.9) falls within the standard range of 60–100 mL/g, indicating a moderate molecular weight (6.84 × 105 g/mol), which is suitable for reuse in polymer applications. The melting point of ePVC (200–215°C) is slightly higher than that of pure PVC (160–210°C), suggesting thermal stability improvements due to residual additives or polymer crosslinking. Additionally, the conductivity of ePVC (50.29 µS) suggests the presence of minor ionic impurities, possibly from residual stabilizers or plasticizers. These findings confirm that ePVC retains the core properties of PVC, with slight variations due to processing effects, making it a viable candidate for potential reuse in sustainable material recovery applications.

Fourier-Transform Infrared spectroscopy analysis

Fourier Transform Infrared (FTIR) spectroscopy was used to characterize the chemical functional groups of raw waste banner (WB) and its derivatives, including reinforced fibers (RFs), centrifuged solid parts (CSPs), and centrifuged liquid parts (CLPs). The FTIR spectrum of WB (Figure 4b) exhibited a broad absorption band at 3200-3600 cm^{-1}, indicative of O–H stretching vibrations associated with moisture. Peaks at 2800-3000 cm^{-1} (C–H stretching), 1716 cm^{-1} (C=O stretching), and 877 cm^{-1} (C–Cl stretching) confirmed the presence of PVC and associated plasticizers. Following fiber extraction, the RFs spectrum (Figure 4a, black) showed a reduction in C–Cl and plasticizer-associated peaks, signifying partial removal of PVC and additives. Retention of C–H bending signals at 1250–1350 cm^{-1} suggested the presence of residual polymeric material (Suresh *et al.* 2017). The CSPs spectrum (Figure 4a) exhibited a distinct C=O stretching peak at 1596 cm^{-1}, likely attributable to carbonyl-containing plasti-

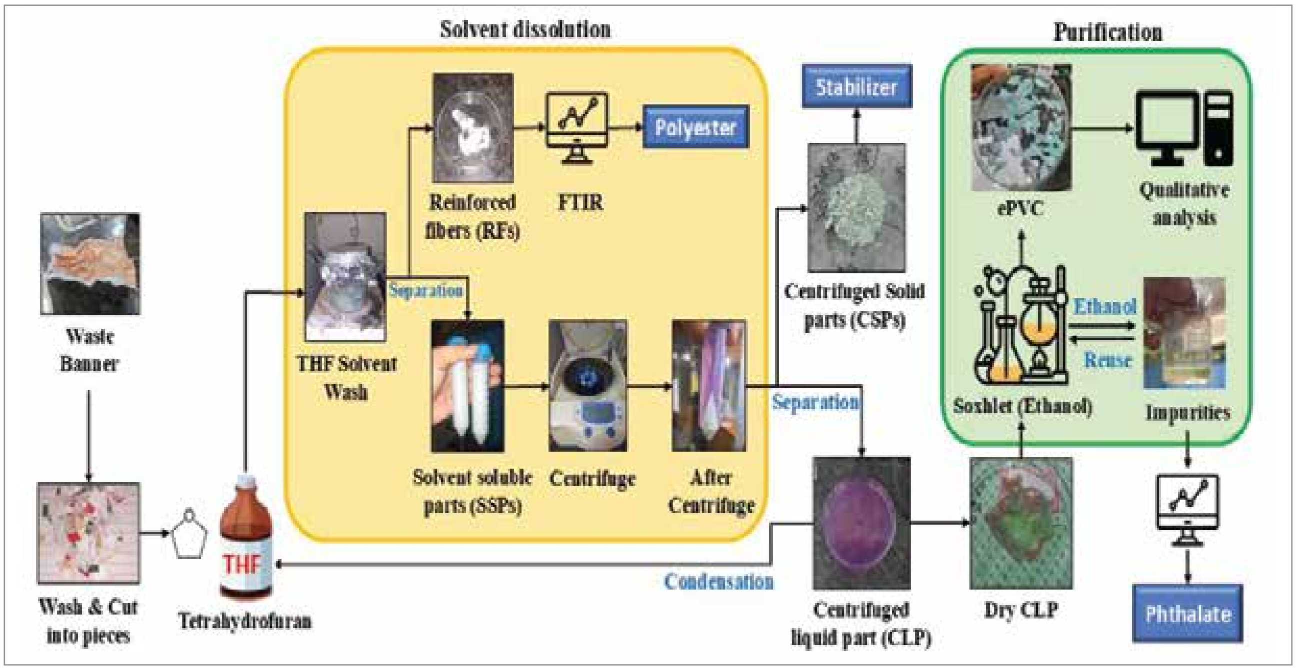

Fig. 2. Flow diagram PVC extraction process

Table III. Physicochemical properties of raw WB

Properties	Unit	Value
Thickness	mm	0.255
Melting point	ºC	150
Burn point	ºC	230-235
Ash content	%	26.40
Tensile strength	MPa	13.13
Elongation break	%	33.22

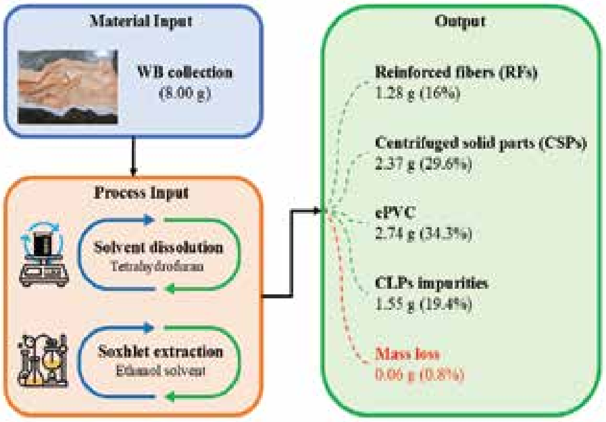

Fig. 3. Mass balance of the PVC extraction process

cizers or thermal degradation by-products (Klempová *et al.* 2023). The CLP spectrum (Figure 4a) retained prominent C–H, C–O, C=O, and C–Cl absorption bands, indicating a complex mixture of polymeric residues. These spectral features validated the presence of PVC and other additives, informing the refinement of the extraction protocol. Post-extraction analysis included comparison of extracted PVC (ePVC) with pure PVC (Figure 4b). The ePVC spectrum showed strong alignment with that of pure PVC, confirming the successful isolation of PVC from CLP. A minor additional peak at 1727 cm^{-1}, absent in pure PVC, was observed in the ePVC spectrum and attributed to residual carbonyl-containing plasticizers such as phthalates (Apchain *et al.* 2022; Greco *et al.* 2017). Conversely, the CLP spectrum displayed multiple additional peaks, indicative of non-PVC constituents, including additives and degradation products. These findings demonstrate the efficacy of the extraction method in isolating PVC with minimal chemical alteration.

Table IV. Characterization of ePVC

Properties	Unit	Our study	Pure PVC
Intensive viscosity	mL/g	81.4396 (k=60.9)	60-100
Melting point	°C	200	160-210
Conductivity	µS	51.89	50.29
Glass Transition Temperature	°C	89	83

Fig. 4. Functional analysis of (a) intermediate components of WB, (b) comparison of WB, ePVC, and pure PVC

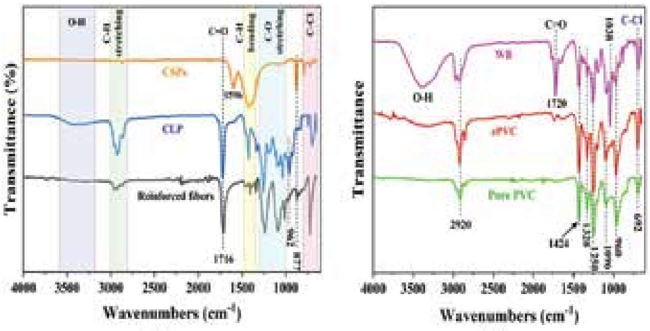

Table V. Energy dispersive X-ray analysis value of Pure PVC and ePVC

Elements	Pure PVC	ePVC
Name	Atomic %	Atomic %
C	40.70	36.23
Ca	15.62	18.10
N	0.49	0.83
O	6.07	12.66
Zn	0.12	0.15
S	9.01	9.14
Cl	27.98	22.90

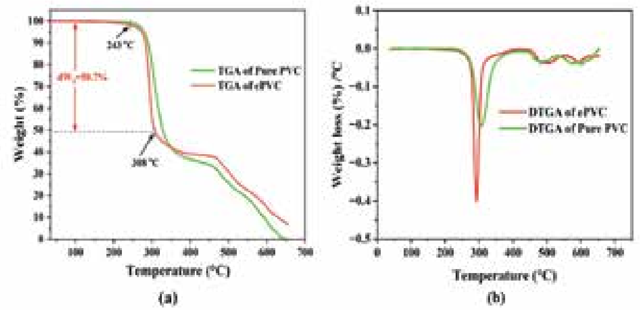

Fig. 5. (a) TGA and (b) DTGA plots for ePVC and pure PVC

Thermogravimetric assessment (TGA)

TGA was conducted to evaluate the thermal stability and decomposition behavior of pure PVC and ePVC that was graphically illustrated at Figure 5. The degradation of both samples follows a two-step process. The first stage, corresponding to dehydrochlorination, begins at 243°C for pure PVC, while ePVC shows a slightly lower onset degradation temperature, likely due to impurities, plasticizer residues, or processing-induced modifications. The second major decomposition step occurs at 308°C, where approximately 50.7% weight loss is observed, indicating the breakdown of the polyene backbone into volatile hydrocarbons (Rijavec, 2020; Ye *et al.* 2021). Compared to pure PVC, ePVC exhibits a broader decomposition range, suggesting minor structural variations due to the recycling process. The slightly lower thermal stability of ePVC indicates potential chain scission or residual additives, but the overall decomposition pattern remains consistent with that of pure PVC (Ji *et al.* 2020). This confirms that ePVC retains sufficient thermal properties for potential reuse, making it a viable alternative for recycled applications.

Energy dispersive X-ray (EDX) analysis

Figure 6 and Table V represent a quantitative breakdown of the elements found by EDX and their respective elemental compositions. According to Table V, ePVC showed almost same amount of element content as pure PVC. During the extraction process, THF (containing Jaiman oxygen) and incorporated phthalate (C=O) increased the oxygen content of ePVC (Tüzüm Demir and Ulutan, 2013). Similarly, WB contained a stabilizer that was incorporated with Ca. Thus, ePVC is also slightly enriched with Ca than pure PVC. In contrast, C and Cl content were detected in lower amounts in our ePVC than in pure PVC. Usage of THF degrades the C chain and Cl,

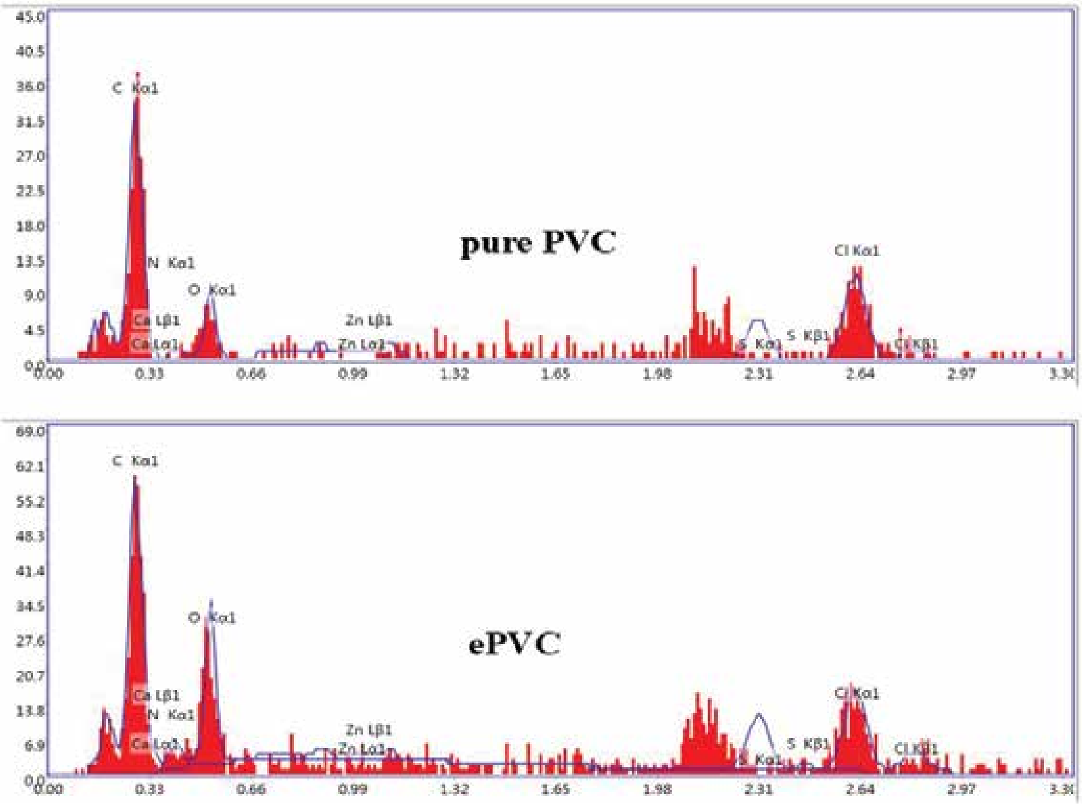

Fig. 6. EDX analysis plots of pure PVC & ePVC

which were the backbone of PVC, and showed a slightly lesser value of C and Cl content compared to pure PVC (Feng *et al.* 2023).

Conclusion

This study shows that PVC can be successfully extracted and characterized from WB, demonstrating the feasibility of recovering usable polymer from waste materials. The extracted ePVC retained key structural and thermal properties of pure PVC, with only minor plasticizer residues detected. The high extraction yield (34.3%) and minimal material loss (0.8%) validate the efficiency of the separation process. However, further refinement is required to eliminate residual additives and assess the mechanical performance of ePVC for industrial reuse. Despite these limitations, this research offers a promising approach to PVC waste recycling, thereby reducing plastic pollution and promoting sustainable material recovery. Future work should focus on scaling up the process, conducting life cycle assessments, and exploring applications for recovered PVC in industry.

Data availability

All data presented or analyzed during this study are included in this article.

Ethical clearance

Not applicable in this study.

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