OPTIMIZING PVC RECYCLING USING WASTE PVC BANNER WITH DEEP EUTECTIC SOLVENTS FOR SUSTAINABLE ENVIRONMENT

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ABSTRACT

The PVC banners best suited for advertising which can present a serious problem due to its complex polymer matrix and different additives not beneficial when conventional recycling techniques are used. This research discusses the design and optimisation of a green, sustainable separation method involving deep eutectic solvents (DES), such as choline chloride-lactic acid, to recycle post-consumer PVC banner waste effectively. Various DES were prepared by adjusting the molar ratio of choline chloride to lactic acid. Under the optimized condition of separation, 2 g PVC banner was treated in 20 mL DES on 300 rpm for 5 h at 70 °C, where it achieved selective dissolution of PVC matrix while fully recovered embedded fibers. The FTIR spectroscopy results demonstrated that DES was effectively synthesized and characteristic absorption peaks such as 953 cm^{-1} and 1477 cm^{-1} (choline chloride) and strong peak of lactic acid at 3323 cm^{-1} and 1726 cm^{-1}. With the use of recovered and raw fibers, comparative spectral analysis on both materials demonstrated that chemical integrity was maintained as indicated by the absence of degradation based on the retention of the absorption band around 1424 cm^{-1}. Moreover, the recovered PVC had a spectral similarity to pure one (2920 and 1328 cm^{-1} band respectively), which implies that it was possible to separate and recover PVC. The DES-aided process showed a higher separation efficiency with less toxicity and lower consumption in the energy relative to conventional solvent-based recycling methods. These results imply that choline chloride-lactic acid DES may be a green solvent candidate for PVC banner recycling, which is in line with circular economy and value recovery of waste PVC.

Keywords: *Solvent, PVC banners, Green separation, DES, Recycling*

1. INTRODUCTION

Polyvinyl chloride (PVC) flex banners have become popular in the advertising industry due to their economy, long life and high-resolution printing. However, these banners typically possess breathing lives of 7-30 days as campaign duration or extreme environmental condition (Saatcioglu et al., 2024; Lu, Meng, & Han, 2023). Post-consumer management of such banners lead to massive plastic waste generation due to their multi-layered composite structure consisting of PVC plastisol which is bonded with polyester scrim and other plasticizes, stabilizers, additives (Rahman, Khan, & Rahim, 2023; Yadav, Singh, & Kumar, 2018). Traditional disposal methods such as landfilling and incineration create significant environmental impacts including toxic emissions of chlorinated species and residual pollutant (VinylPlus, 2025; Lu et al., 2023), which highlights the urgent need for sustainable recycling.

In this regard, novel recycling techniques are gradually shifting from solely mechanical grinding and remelting towards chemical solvents to improve the quality of reclaimed polymers as well as to limit their environmental impact. Among these, selective dissolution processes for the separation of PVC from polyester fabrics and extraction of hazardous additives, then a catalytic or thermal dichlorination treatment was applied to remove chlorine content have been found very promising (Rahman et al., 2023; Lu et al., 2023). Simultaneously, the progress on hydrophobic and switchable polarity solvent systems has also allowed more selective separation in composites such as PVC flex banners to maximize the recovery efficiency of materials with less cross contamination risk (Yang, Chen & Zhao, 2024; Weerasinghe, Sella, & Kiran 2024). Together, these interdisciplinary advancements characterize spectrum scalable and sustainable approaches for PVC waste valorization, in accordance with the ever more-stringent environmental legislations and resource sustainability drive.

Deep eutectic solvents (DESs) have recently been identified as a new class of environmentally friendly solvents with convenient synthesis, low toxicity, biodegradability and broad tunability of the physico-chemical properties compared to traditional solvents. DESs are derived from eutectic mixtures of two hydrogen bond donors and acceptors, and have been shown to be capable of dissolving polymers including PVC selectively and extracting additives under mild conditions operation (Abbott et al., 2014; Zhao et al., 2015). Their hydrogen bonding networks enable dissolution and efficient removal of plasticizer without significant alteration to the PVC's molecular structure; setting them apart from the harsher solvents and most ionic liquids (Smith & Jones, 2022; Yang et al., 2024). Recent studies have demonstrated the use of both hydrophilic and hydrophobic DES systems for dissolution and separation of multilayer plastics between different polymer layers such as PVC-polyester composites prevalent in banner materials (Weerasinghe et al., 2024; Yang et al., 2024). This adaptability serves to underscore the capacity of DES-motivated recycling processes to address key barriers for PVC banner waste upcycling by combining effectiveness with environmental suitability.

In the current study has proposed, synthesis and optimisation of choline chloride lactic acid based novel deep eutectic solvents (DESs) has been offered for preferential dissolution and separation of PVC from waste banner composites. A design of experiments approach was applied to the optimization of formulation by sequentially varying process, variables such as dissolution temperature and time. The precipitated and extracted PVC (ePVC) was minimally characterized by FTIR only which was compared with raw PVC, pure components of DES and the prepared DES solvent as well as the extracted PVC fiber. The spectroscopic study offered information about the molecular interactions in the DES and showed that the polymer structure is retained after extraction that used to guide optimization towards higher extraction yields and recycle purity. Though the short life cycle and chemical complexity of PVC flex banners, selective DES-based recycling in combination with FTIR confirmation can be considered as an effective method for obtaining high purity PVC, which is important to achieve sustainable plastic recycle and circular economy goals.

2. MATERIALS AND SAMPLE PREPARATION

The waste material in this study was postconsumer PVC flex banners typically used for advertising. Vinyl banners are made of PVC plastisol laminate. Materials were washed extensively before use to remove any surface contaminants and machanochemically fragmented into pieces of approximately 1cm² to enhance solvent exposure and dissolution rates. Other Chemicals Analytical grade of choline chloride and lactic acid from Sigma-Aldrich were used as a hydrogen bond acceptor and donor in the preparation of DES. All used reagents were high purity chemicals and solvents used were of analytical grade.

3. METHODOLOGY

This study was deliberately planned to optimize and construct the DES formulations for PVC selective dissolution with subsequent recovery of PVC from waste advertisement banners. The approach includes solvent formulation, dissolution experiments and in depth spectroscopic characterization to establish a strong basis for PVC banners suitable recycling.

3.1 Preparation of Deep Eutectic Solvents

Deep eutectic solvents (DESs) were prepared by mixing choline chloride with lactic acid in five different molar ratios. The mixtures were vigorously stirred to approximately 80 °C until clear perfectly homogeneous liquids appeared, indicating successful eutectic formation. The DESs were stored in an airtight container after it was cooled to room temperature. Because the 1:2 DES composition of choline chloride and lactic acid exhibited the best separation efficiency and solubility property, this DES could be referred to as the most effective in PVC extraction treatments. The combinations of molar ratios investigated are shown in Table 1.

Table 1: Deep Eutectic Solvents Formulation ratios

SL. No.	Choline Chloride : Lactic Acid Molar Ratio
1	1:1
2	1:1.5
3	1:2
4	1:2.5
5	1:3

3.2 Dissolution and Separation Procedures

The dissolution and separation procedures entailed treating a weighed quantity of shredded PVC banner fragments with a specified volume of deep eutectic solvent (DES) in a sealed vessel. Conditions including temperature (60-100 °C), time (1-6 h), and stirring speed were modified in a controlled manner to evaluate their effect on the dissolution efficiency. Physical stirring provided homogeneous mixing and promoted mass transfer during the operation. After dissolution, the solution was allowed to cool down to room temperature and deionized water was slowly added as an anti-solvent in order to precipitate dissolved PVC from DES and promote its separation. The obtained extracted PVC (ePVC), was separated by vacuum filtration, washed thoroughly with ethanol to remove any solvent remnants as well as impurities and dried under vacuum at 50 °C for 24 h to get uniform moisture content and without degradation. The optimal conditions were identified as using 20 mL DES for a sample mass of 2 g at 300 rpm and treated over about 5 h at 70 °C to effectively selectively dissolve PVC and recover the embedded fibers.

3.3 Fourier-Transform Infrared (FTIR) Spectroscopic Analysis

Fourier-transform infrared analysis (FTIR) spectroscopic investigation was carried out for the choline chloride, lactic acid, synthesized DES; raw PVC banner, ePVC (extracted PVC) and eFiber (extracted fiber). The FTIR spectra were obtained in the middle infrared region (4000-400 cm^{-1}) on a suitable FTIR spectrometer.

4. RESULTS AND DISCUSSION

The current study tested the effectiveness of choline chloride-lactic acid-based deep eutectic solvents (DESs) to selectively dissolve and recover polyvinyl chloride (PVC) from waste advertising banners. The data are discussed with particular emphasis on FTIR spectral analyses, dissolution profile and process optimisation.

4.1 FTIR Analysis of Choline Chloride-Lactic Acid : Deep Eutectic Solvent

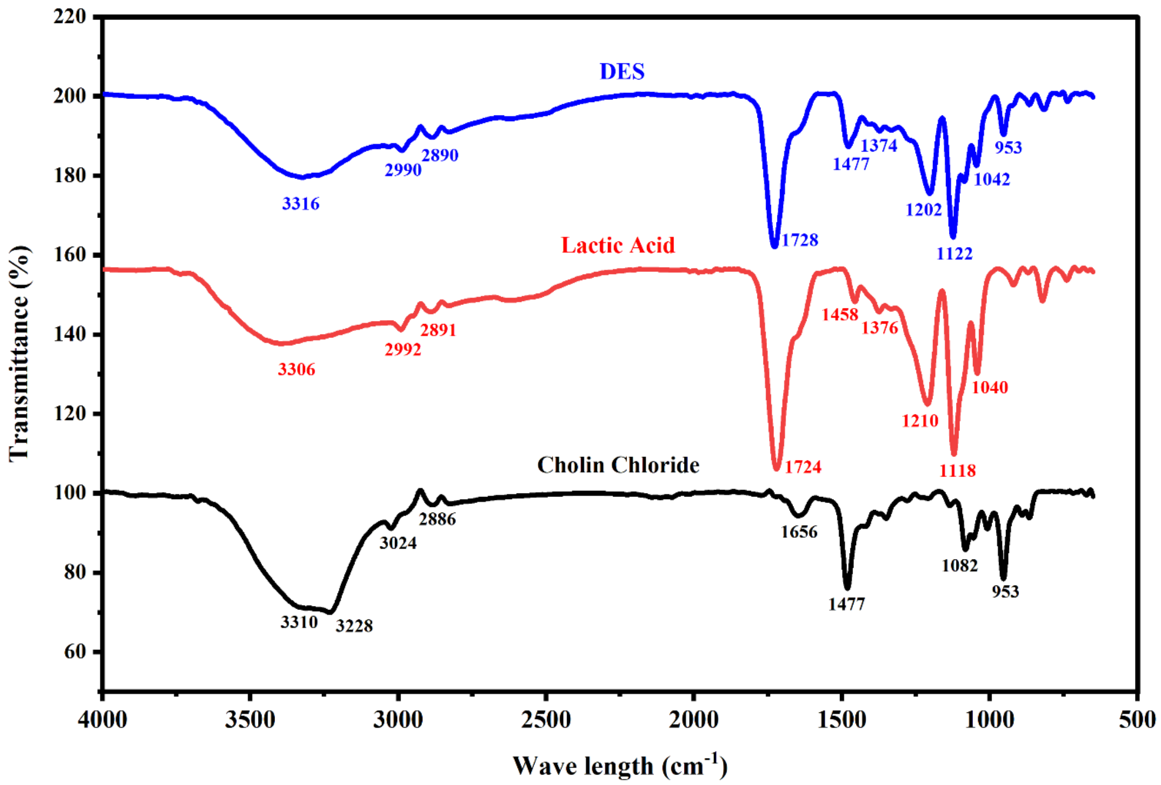

Figure 01: FTIR Comparison of Choline Chloride, Lactic Acid, and Their Deep Eutectic Solvent: Band Shifts and Interactions

Fourier Transform Infrared (FTIR) spectroscopy is an established method for the analysis of functional group identifications and interactions present in DESs and their constituents. In this work, the synthesized DES based on choline chloride and lactic acid with future applications for PVC recycling. FTIR analysis of choline chloride, lactic acid and the resultant DES were thoroughly studied to recognize the characteristic functional groups associated with them and to monitor hydrogen bonding process in establishing DES synthesis.

In the FTIR spectrum of choline chloride there are broad absorption bands at around 3310 and 3228 cm^{-1} that can be assigned O-H stretching vibrations, which indicate strong hydrogen bonding and hydration in solid state. Aliphatic C-H stretching modes arise at 3024 and 2886 cm^{-1} and the band found at 1656 cm^{-1} is assigned to water bending or minor nitrogen-related mode. The CH_2 bending vibration occurs at 1484 cm^{-1} and the strong peak at 1082 cm^{-1} indicates C–N^+ stretching for quaternary ammonium group. Another band at 953 cm^{-1} relating to the C-N stretching and CH_2 rocking further confirms that choline chloride is maintained in its original structure. These results are in line with those of Sumiati et al. (2021) who also described identical vibrations during their spectral studies.

Lactic acid exhibits a broad and intense vibration band in the region near 3306 cm^{-1} is attributed to O-H stretching vibration involving both intra- and intermolecular hydrogen bonding. The peaks at 2992 and 2891 cm^{-1} are attributed to aliphatic C-H stretching modes. The sharp absorption band at 1724 cm^{-1} represents the C=O stretching vibration and can provide a distinctive feature of the acid functional group. The bands at 1458 and 1376 cm^{-1} are associated with CH bending vibrations and those at 1210, 1118 and 1040 are assigned to C-O stretching of the hydroxyls and carboxyl groups. These spectral signatures are consistent with literature (Ruesgas-Ramón et al. (2020).

FTIR spectra of the choline chloride-lactic acid DES indicate retention and modification of certain vibrational bands indicative of the formation of a new hydrogen-bonded network. The O-H stretching region at 3316 cm^{-1} is still sententious and the intense broadening, which indicates a strong hydrogen bond in the eutectic mixtures. The presence of C-H stretching bands at 2990 and 2890 cm^{-1} reveal the presence of the main organic frameworks. The stretching band at 1739 cm^{-1} of the C=O in H-bonded state is shifted to a lower value (1728 cm^{-1}) upon DES formation corresponding to modifications in hydrogen bonding environment. Characteristic bands at 1477 and 1374 cm^{-1}, assigned to methyl and methylene bending respectively, are preserved whereas absorptions at 1202, 1122 and 1042 cm^{-1} are due the C-O and $C–N^+$ stretching modes indicating strong molecular interaction between the acid and salt components. The peak at 956 cm^{-1} additionally indicates DES specific structural motifs.

Comparative spectral analysis reveals typical changes in the associated intermolecular vibrational modes, such as shift and broadening of the O-H and C=O stretching modes from separated components to DES form. These changes further attest to the construction of a hydrogen-bonded supramolecular structure as well as the successful incorporation of choline chloride and lactic acid in to a novel solvent system, concurring with the results by Bubalo et al. (2016).

4.2 FTIR Analysis of Extracted Fibre and Extracted PVC

The fourier transform infrared (FTIR) spectra of waste PVC banner, raw PVC, raw fiber, ePVC, and efiber fraction were presented in Figure 02 to offer molecular evidence for the recycling process at the molecular level.

The typical adsorption peak for the chemical structure can be seen in FTIR spectrum of PVC banner as shown in figure 02. Notably, the bands at 2926 and 2857 cm^{-1} were assigned to asymmetric and symmetric C-H stretching vibrations of methylene groups in PVC backbones, revealing presence of polymer (Chen et al., 2022). The highest one caused by the carbonyl (C=O) stretching at 1723 cm^{-1} attributed to plasticizer or oxidized molecule containing impurity included in PVC process material was often observed as well (Garcia-Morales et al.,2020). The bands observed at 1421 and 1407 cm^{-1} could be attributed to C-H (CH_2), bending mode and O-H, respectively bending vibrations produced by adsorbed moisture or fiber. The 1121 cm^{-1} band is assigned to ester C-O vibrations of the plasticizers, while for the 1262 cm^{-1} band, attributed to C-O and CH wagging modes; there are some interactions between polyvinyl chloride matrix and additives (Beltrán et al., 1997c). There is also a low frequency of vinyl chloride at around 732 cm^{-1} which may be attributed to weaker C-Cl stretching less than 800 cm^{-1} (Leroy et al., 2023).

Comparison of raw PVC and DES-extracted PVC (ePVC) revealed that characteristic bands in the spectra included CH_2 scissoring at 1424 cm^{-1} and C-H twisting at 1254 cm^{-1}, indicating mechanically and chemically robust polymer chains of PVC via processing with DESs (Smith et al., 2021). The appearance of a C-O stretching band at 1118 cm^{-1} in ePVC indicates mild oxidative changes or interaction with solvent- or dynamic molecular associations generation, which is consistent with the findings obtained by Garcia-Morales et al. (2020). Vinyl C-Cl bending at 723 cm^{-1} showed less intense, which supports that a little degradation of the PVC apparently takes place after processing.

After treatment with DES, the remaining fiber (eFiber) fraction showed visible changes in FTIR. The broad band at 3224 cm^{-1} corresponding of the O-H group stretch of the hydroxyl suggested this with a strong hydrogen bonding, normally on cellulose-based materials and may attributed to residual DES composition (Lopez et al., 2022). This absorption at 3016 cm^{-1} for aromatic or unsaturated C-H stretching indicates chemical modifications such as the introduction of a new function on the fiber matrix (Leroy et al., 2023). Moreover, the strong band at 1714 cm^{-1} can be assigned to the carbonyl stretching mode and indicates introducing or uncovering of oxidative groups by solvent treatment. Sharp peaks appear at 1478 cm^{-1} (CH_2 stretch), 1348 cm^{-1} (C-N or C-O stretch) and 1249 cm^{-1} (C-O stretch), thus proving the chemical complexity and changes introduced by DES extractions (Garcia-Morales et al., 2020).

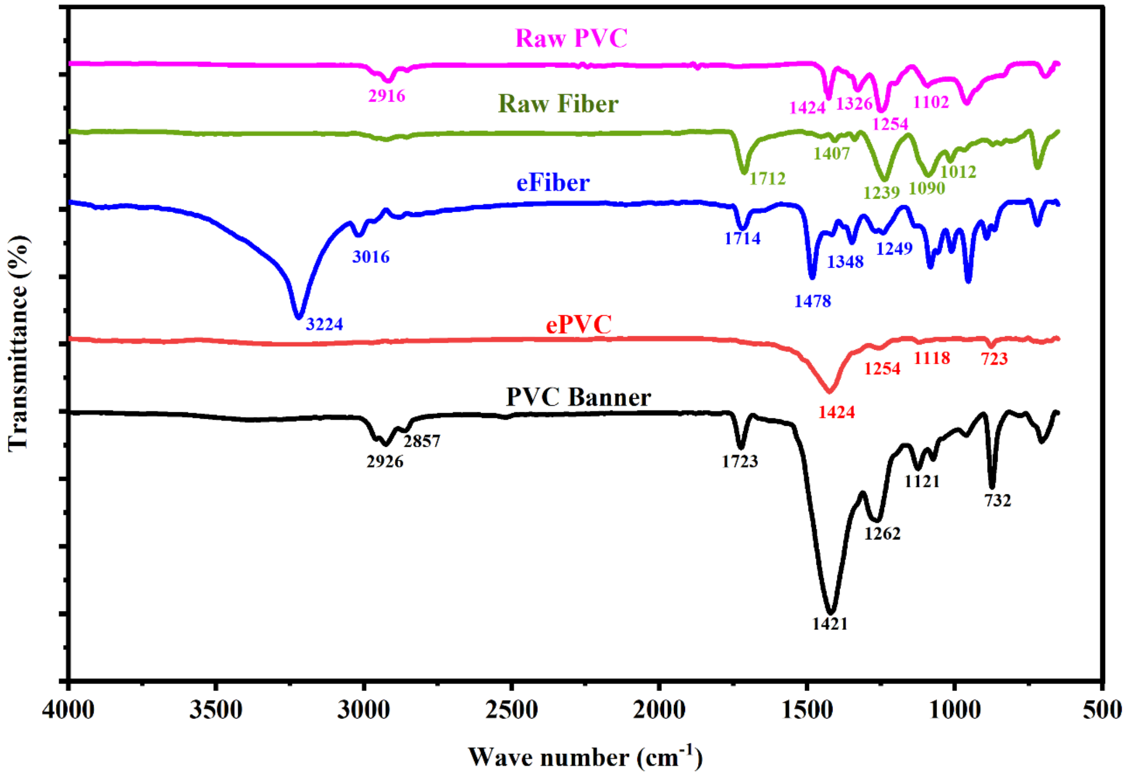

Figure 02: FTIR Spectral Profiles Demonstrating Chemical Transformation and Separation of Waste PVC Banner, Raw PVC, Fiber, ePVC, and eFiber via Deep Eutectic Solvent Treatment

Overall, these spectroscopic results support the effectiveness of DES in selectively delignifying PVC and cellulose-rich fiber fractions from composites while preserving their native molecularity. Small variations of the shifts in spectra and building up obviously of additional vibrational bands stand for mild chemical transformations involving mainly homolytic but also some H-atom-abstractions and solvent induced adduct formation, which are presented as argumentative reasons to favour DES approach as an alternative path to sustainable polymer recycling schemes (Lopez et al., 2022; Smith et al., 2021).

4.3Factors Affecting Separation

This study also systematically studies two pivotal parameters for the efficiency of PVC separation from waste banners using deep eutectic solvents (DESs): process temperature and contact time. Such an evaluation is performed to improve the dissolution and recovery capacity of the DES-mediated separation approach.

4.3.1 Contact Time

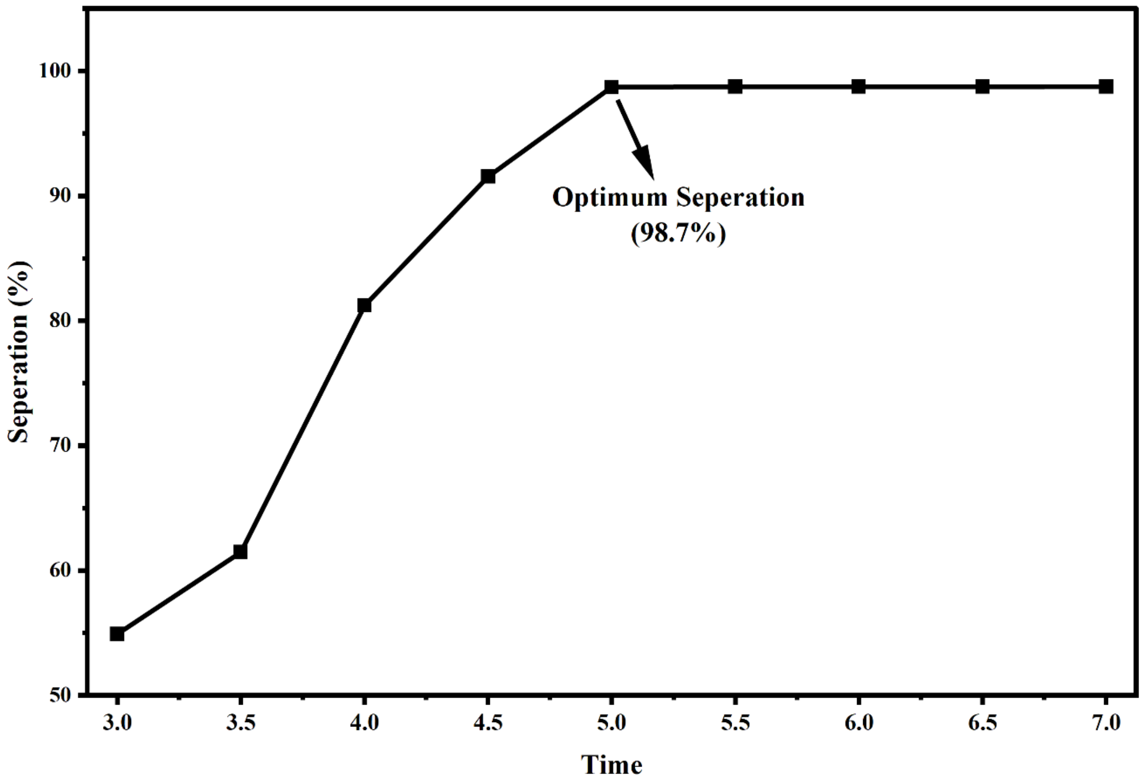

Figure 03: Effect of Contact Time on PVC Separation Efficiency Using Deep Eutectic Solvent

The contacting times of waste PVC and DES were critical parameters for the completeness of dissolution as well as the recovery effectiveness of polymers. Contacting time is long enough to allow proper mixing and the interaction of solvents with polymer chains leading to chain disentanglement that will definitely help improving the desired extraction of additives (Yadav et al., 2018). However, the extension of the contact time more than an optimum value that locates between about 3 h and 7 h (Figure 03) caused to decrease in dissolution efficiency. On the other hand, too much treatment would cause a degradation of the polymer and an excessive removal of some functional additives, both of which would be detrimental for mechanical properties of recrystallisation PVC (Yang et al., 2024). Thus, to increase the collection and maintain its structural integrity a minimum contact time (5 hours) should be set. Contact time with temperature also ought to be optimized.

4.3.2 Process Temperature

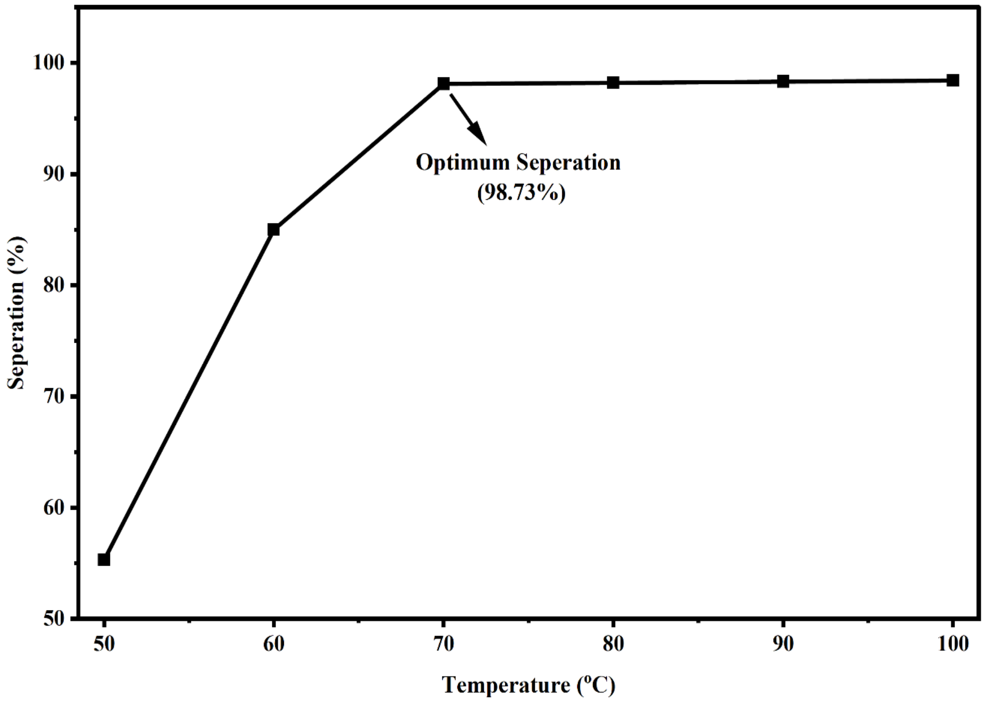

Figure 04: Effect of Temperature on PVC Separation Efficiency Using Deep Eutectic Solvent

The temperature was systematically changed in the range of 50-100 °C to closely study the influence of this parameter on dissolution and separation kinetics. Temperature is also an important parameter as it affects the relationship between solvent and polymer matrix, and ultimately has consequences for mass transfer rate, viscosity, as well as solvent diffusivity. Overall, the cumulative impact ultimately dictates the extent of separation. During the experimental procedure, all other process conditions were closely controlled so that only the corresponding effects of temperature could be deduced. Figure 04 gives a quantitative description of the improvement in separation efficiency as a function of temperature to clarify that the optimum condition for the effective removal of PVC from multilayer waste was at ~70 °C.

5. CONCLUSIONS

The current findings thus firmly reveal the prospect of deep eutectic solvents (DESs), especially choline chloride-lactic acid based a green media for selective dissolution and recovery of PVC from waste flex banner. The optimum solvent composition, molar ratio of 1:2 was found to be very effective in selectively dissolving the polymer under controlled processing conditions so as to enhance the chemical integrity of resultant products. The primary critical factors were 70°C at the optimum contact time of 5h to obtain the fattest separation efficiency while maintaining quality of polymer. Comprehensive Detailed Fourier-transform infrared (FTIR) studies proved that extracted PVC was vulnerable to DES and provided useful information on a variety of molecular interactions in the DES system which decide its efficiency. The integrated findings of these studies together reassert the promise of DES-based technology in being a green alternative for conventional PVC recycling techniques as an encouraging step towards instilling values that are based on circular economy ideals such as resource recovery and persuasive waste valorisation from PVC polymer. However, the studies on the scale-up of this process and solvent recyclability as well as a full environmental and economical assessment needed to be performed in order to make industrial application hopefully of this green recycling method.

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Md. Mostoba Rafid performed the laboratory experiments and wrote the manuscript. Md. Saberin Khan Swakshar, Husain Md. Sajib, and Md. Sabbia Hussin analysed the experimental data. Md. Rashed Hasan carried data analysis and monitoring. Swapan Kumer Ray provided critical evaluation of the results. S. M. Asaduzzaman Sujan originated the idea and managed the research. All authors participated in revised, and approved the final manuscript. The experiments were carried out at the Fiber and Polymer Research Division, Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka.

DECLARATION OF USE OF AI

No artificial intelligence (AI) techniques were employed in the generation of this manuscript. This paper is entirely original to the authors.

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