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Novel Approach to Mixed Waste Label Recycling by Automation Density Sorting

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We present a low-temperature, solvent-assisted separation process for the recycling of mixed polymer labels derived from polyethylene terephthalate (PET) bottle waste. By integrating ultrasonic deinking with precision density sorting (targeting 1.15 g/cm^3), the method effectively distinguishes amorphous PET (A-PET) from polyvinyl chloride (PVC) and oriented polystyrene (OPS) contaminants without mechanical degradation. Pilot-scale implementation achieved PET recovery rates exceeding 94%, with postsorting PVC levels below 100 ppm. Characterization via Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and elemental analysis confirmed the preservation of core PET properties and the absence of ink-associated heavy metals. The process operates under ambient conditions, with energy consumption measured at 0.45 kWh/kg, which is substantially lower than those of thermal and steam-assisted deinking systems. A preliminary techno-economic assessment indicated a monthly net revenue of NTD 550000, as well as a potential for integration into the existing PET recovery infrastructure. Environmental benefits, including reduced solvent emissions and the elimination of incineration, align with national zero-waste goals and global circular economy objectives. These findings support the deployment of automated label decontamination systems as an enabling technology for high-purity PET recycling.

1. Introduction

The widespread use of polyethylene terephthalate (PET) in single-use beverage containers has contributed substantially to the global plastic waste crisis. Although PET is widely regarded as a recyclable polymer because of its favorable thermomechanical properties and well-established collection systems, the overall recycling efficiency remains limited. In 2021, global PET bottle production exceeded 500 billion units, yet less than 50% were effectively recovered, and only a fraction was reprocessed into high-grade secondary materials.(1) In Taiwan, PET containers represent the predominant fraction of collected plastic waste, with an annual recycling

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volume of approximately 100000 metric tons. Among this, label waste generated from PET bottles is estimated to exceed 15000 metric tons per year.(2)

The recycling of PET bottle labels presents unique technical and economic challenges. These labels are typically composed of amorphous PET (A-PET), polyvinyl chloride (PVC), and oriented polystyrene (OPS), with average compositions higher-than 92% PET, less than 5% PVC, and less than 3% polystyrene (PS). Despite the high PET content, the heterogeneous polymer composition renders conventional mechanical recycling methods inefficient. PVC, even in trace amounts, can thermally degrade during extrusion and injection molding processes, leading to the release of hydrochloric acid and color instability in the final product.(3) Additionally, the density ranges of these polymers (A-PET: 1.33–1.38 g/cm^3; PVC: 1.30–1.45 g/cm^3; OPS: 1.04–1.07 g/cm^3) overlap significantly, impeding effective separation via gravity-based flotation or sedimentation systems.(4)

Moreover, the handling of labels is made complex by their low mass, irregular geometry, and surface adhesion properties. Residual adhesives and ink coatings interfere with downstream purification steps, often requiring aggressive cleaning or incineration. In Taiwan, most composite waste labels are incinerated or become landfill owing to these limitations, exacerbating environmental impacts and placing additional pressure on aging waste-to-energy facilities.(5)

To address these challenges, in the present study, we propose a combined approach integrating density-based material sorting and ultrasonic deinking. Density sorting employs customized brine solutions to selectively separate PET from lower-density contaminants, while the ultrasonic stage enhances ink and adhesive removal through cavitation-induced surface disruption. This method is designed to operate in a continuous flow, reducing labor dependence and increasing throughput. By embedding this technology within Taiwan's existing recycling infrastructure, the process facilitates the recovery of high-purity PET suitable for use in applications such as recycled strapping bands, thermoformed packaging, and composite materials. The proposed system aligns with global circular economy objectives and supports national strategies aimed at reducing landfill volume and incineration reliance.(5–8)

2. Data, Materials, and Methods

2.1 Sample collection and composition analysis

Waste label samples were obtained from a postconsumer PET bottle recycling facility in Tainan, Taiwan. Randomized batch sampling was performed to ensure material heterogeneity representative of actual industrial waste streams. Compositional analysis indicated that the labels consisted of PET (>92%), PVC (<5%), and PS (<3%).

Material properties were characterized using standard analytical protocols. Intrinsic viscosity was determined in accordance with ASTM E-465. Moisture content was measured using an infrared moisture analyzer. Bulk density was evaluated using the method described in ASTM C29. Additional analyses were conducted on post-wash samples to assess the concentrations of suspended impurities and potential contaminants. Table 1 shows the test parameters and corresponding methods.

Table 1
Analytical parameters and test methods for waste label samples.

Parameter	Analytical method
Intrinsic viscosity	ASTM E-465
Moisture content	Infrared moisture analysis
Bulk density	ASTM C29
PVC content	Sediment mass-based separation
Heavy metal concentrarion	X-ray fluorescence spectroscopy (XRF)
Suspended solid (e.g., PE, PP, or glue) concentrarion	Gravimetric analysis after filtration
Total impurity content	Cumulative summation of items 4–6
Particle size distribution	Dynamic light scattering (DLS)

2.2 Density-based separation

An automated density-based sorting system was developed using aqueous calcium chloride ($CaCl_2$) solutions with controlled densities ranging from 1.05 to 1.20 g/cm^3. The goal was to separate low-density contaminants (e.g., OPS, density <1.10 g/cm^3) from higher-density PET and PVC components (density >1.30 g/cm^3).

To improve the selectivity between PET and PVC, a small quantity (<0.2% w/w) of ammonium persulfate was introduced into the brine solution. This agent modified the surface charge and wettability of PVC particles, promoting preferential sedimentation without affecting the hydrophilic PET fraction. Compared with other oxidizing or surfactant-based modifiers, ammonium persulfate offers a better control of the zeta potential and is less likely to interfere with the surface characteristics of PET, making it suitable for selective separation in continuous processes. This modification was particularly useful given the low but critical presence of PVC in the waste stream.

The system operated under continuous flow conditions, with label flakes fed into the sorting column at a controlled rate of 2 kg per hour. The sorting tank was equipped with mechanical agitation to prevent aggregation and ensure uniform dispersion. Collected fractions were filtered, dried, and weighed to assess the sorting efficiency.

2.3 Ultrasonic decolorization process

Ultrasound-assisted delamination was conducted using a 40 kHz, 200 W ultrasonic bath filled with ethyl acetate ($C_4H_8O_2$). Label flakes were immersed and treated for 30 s, allowing the cavitation-induced detachment of printed ink layers. Post-treatment, the samples were rinsed with deionized water, vacuum-filtered through 0.45 μm membranes, and air-dried at 60 °C.

To evaluate process sustainability, solvent reuse was tested. Each batch of ethyl acetate was reused for up to ten cycles without a significant decline in decolorization performance, indicating favorable process economics and minimal solvent loss.

2.4 Material characterization

Recovered PET flakes were subjected to comprehensive characterization. Structural analysis was performed using Fourier transform infrared spectroscopy (FTIR). Thermal properties and crystallinity were evaluated using differential scanning calorimetry (DSC). Morphological and elemental surface assessments were conducted using a LEO-1530 scanning electron microscopy (SEM) system equipped with an energy-dispersive X-ray spectroscopy (EDS) device.

To confirm environmental safety, delamination effluents were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES, Ultima 2000). Trace levels of heavy metals including copper, indium, and zinc were measured to ensure compliance with industrial discharge standards.

2.5 Statistical analysis

Statistical analysis was conducted using one-way analysis of variance (ANOVA) with SPSS software version 25.0. Experimental comparisons were evaluated at a significance level of $p < 0.05$.

3. Results

3.1 Composition and contaminant profile of waste labels

The basic physicochemical properties of the collected waste label samples are summarized in Table 2. The intrinsic viscosity of the PET labels ranged from 0.75 to 0.80 dL/g, as measured by ASTM E-465, indicating a moderate polymer chain length suitable for secondary processing. The moisture content was determined to be 0.4% by infrared moisture analysis, suggesting minimal hydrolytic degradation risk during further thermal processing. Bulk density measurements using ASTM C29 procedures revealed an average apparent density of 0.20 ± 0.05 g/cm^3, consistent with the lightweight nature of thin-film polymer labels.

PVC was detected at a maximum concentration of 300 ppm through sedimentation-based weight analysis, while the concentrations of heavy metal impurities, measured by XRF, were found to be below 10 ppm, with zinc and calcium as the primary detectable elements. Suspended

Table 2
Summary of physicochemical properties of waste label samples.

Parameter	Results
Intrinsic viscosity	0.75–0.80 dL/g
Moisture content	0.4%
Bulk density	0.2 ± 0.05 g/cm^3
PVC content	Max. 300 ppm
Heavy metal concentrarion	Max. 10 ppm
Suspended solid (e.g., PE, PP, or glue) concentrarion	Max. 50 ppm
Total impurity content	Max. 500 ppm
Particle size distribution	>10 mm Max. 2.5% <1 mm Max. 1.0%

solids, predominantly PE, PP, and adhesive residues, were measured at a maximum concentration of 50 ppm by floatation analysis. The total impurity load, comprising inorganic residues and nontarget polymers, did not exceed 500 ppm.

DLS analysis revealed a multimodal particle size distribution, with coarse fragments >10 mm in size constituting less than 2.5% of the sample and fine fragments <1 mm in size accounting for less than 1.0%. These results confirm that post-washing residues are within manageable limits and that the feedstock is appropriate for downstream separation and purification processes.

The data indicate that the waste label stream, while containing trace contaminants, exhibits sufficient purity and consistent particle characteristics to be considered viable for advanced separation and PET reclamation procedures.

3.2 Efficiency of density-based sorting

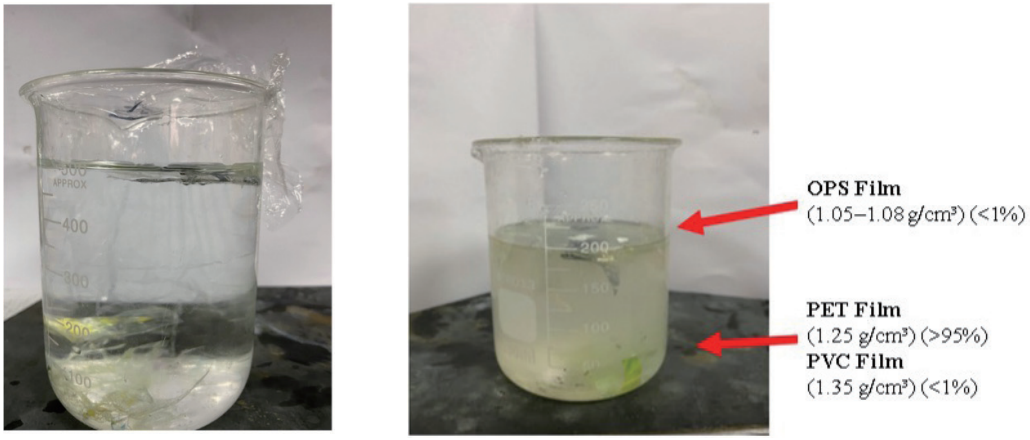
The automated density-based sorting system was evaluated for its ability to selectively recover PET flakes from mixed polymer label waste. The sorting medium, a calcium chloride ($CaCl_2$) aqueous solution with an optimized density of 1.15 g/cm^3, enabled the flotation of PS and other low-density contaminants, while PET and PVC components settled owing to their higher densities (>1.30 g/cm^3).

To further enhance the resolution between PET and PVC, which have two polymers with overlapping densities, ammonium persulfate (0.2% w/v) was introduced into the medium as a surface modifier. This oxidizing agent increased the hydrophilicity of PVC, shifting its surface zeta potential and promoting selective sedimentation. In contrast, the surface characteristics of A-PET remained unaffected, allowing effective physical discrimination under controlled hydrodynamic conditions.

The system was operated with a continuous feed rate of 2.0 ± 0.1 kg/h. PET recovery was quantified gravimetrically and showed high consistency across trials. The residual PVC content in the recovered PET stream was measured to be below 100 ppm, satisfying industrial purity thresholds for downstream melt filtration and palletization.

The effectiveness of the density-based sorting approach is illustrated in Fig. 1, which shows the flotation and sedimentation behavior of polymer labels in pure water versus a calcium chloride solution (1.15 g/cm^3). In the untreated water sample (left), all label types remained suspended or floating owing to low density differentials. In contrast, in the calcium chloride medium (right), polystyrene (OPS, density 1.05–1.08 g/cm^3) floated at the top, while more than 95% of PET (density ~1.25 g/cm^3) settled at mid-depth, and trace PVC (density ~1.35 g/cm^3) formed a bottom layer. This stratification confirmed the separation principle based on differential buoyancy under optimized medium conditions. Table 3 summarizes the performance metrics of the density-based separation process.

The results confirm that the optimized separation process not only ensures a high PET recovery yield but also effectively reduces cross-contamination by nontarget polymers, thereby improving the material's suitability for mechanical recycling applications.



(a) (b)

Fig. 1. (Color online) Label flotation behavior in (a) water and (b) calcium chloride sorting medium. In (a), all label types remain suspended owing to low density contrast. In (b), OPS (low density) floats to the top, PET forms the middle layer, and PVC (high density) accumulates at the bottom, demonstrating effective density-based stratification.

Table 3
Optimized performance metrics of automated density-based sorting.

Parameter	Value
Feed rate	2.0 ± 0.1 kg/h
PET recovery efficiency	94.6 ± 1.2%
Residual PVC concentration in recovered PET	<100 ppm
Ammonium persulfate dosage	0.2% w/v
Sorting medium density	1.15 g/cm^3

3.3 Decolorization efficiency and solvent stability

The ultrasonic delamination system was applied to remove ink and adhesive residues from printed waste labels. Ethyl acetate ($C_4H_8O_2$) was used as the delaminating solvent in a 40 kHz, 200 W ultrasonic bath. The treatment duration was standardized at 30 s per batch under ambient temperature conditions to ensure low energy consumption.

Spectrophotometric and visual inspection confirmed the effectiveness of ink removal. The average decolorization efficiency exceeded 95%, with negligible polymer surface degradation observed by SEM. Each solvent batch was reused up to ten times and maintained above 90% ink removal performance throughout its reuse cycle. These results indicate high solvent stability and support the feasibility of closed-loop solvent management.

To evaluate alternative solvents for potential industrial use, additional trials were conducted using ethyl lactate ($C_5H_{10}O_3$). As shown in Table 4, ethyl lactate demonstrated rapid decolorization (targeting >90% below 10 min) and met critical operational constraints, including low thermal energy demand, minimal wastewater generation, and suitability for multiple reuse cycles. Under a fixed ratio of ethyl lactate to label waste (200 mL:40 g), ethyl lactate achieved full delamination in only 1 min across multiple batches.

Table 4
Decolorization efficiency of ethyl lactate.

Label mass (g)	Treatment time (min)	No. of solvent reuse cycles
4	1	10
4	1	11
4	1	12
4	1	10
4	1	11

Pre- and post-treatment labels are shown in Fig. 2. Untreated labels exhibit heavy pigmentation and poor transparency, while decolorized labels appeared highly transparent, indicating successful ink and adhesive removal.

To standardize the assessment of the decolorization performance, waste labels were thermally pressed into uniform thin films (<1.5 μm) for light transmittance testing. The films were measured using a UV-Vis spectrophotometer. As depicted in Fig. 3, untreated label films (Sample 1) exhibited near-zero transparency. In contrast, the films subjected to two cleaning cycles using ethyl acetate (Samples 2–4) achieved light transmittance values between 15 and 22%. Three or more cleaning cycles resulted in further improvement, with Sample 5 achieving a peak transparency of 68.6%.

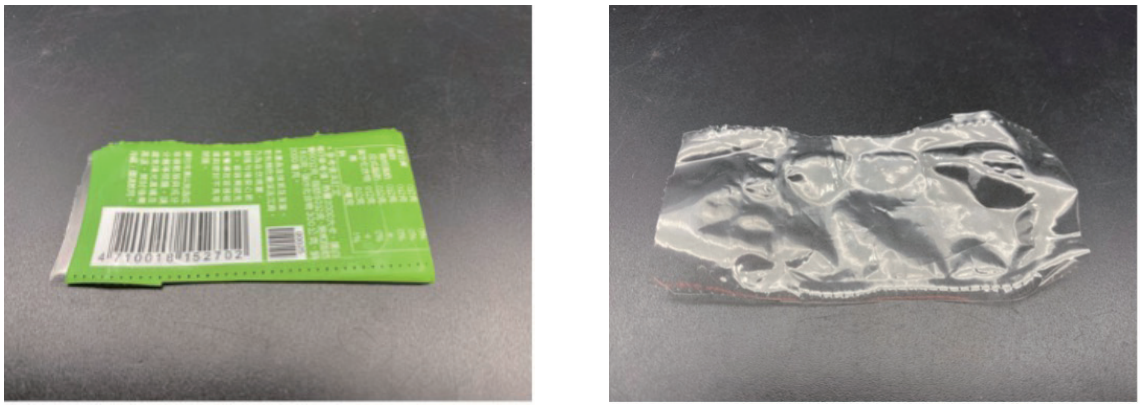
These findings confirm that multicycle ultrasonic treatment using mild organic solvents such as ethyl lactate can effectively meet industrial deinking requirements, with the added benefit of being compatible with solvent reuse strategies and low-cost implementation. Further studies on ink composition and surface energy behavior are recommended to optimize solvent selection and treatment cycles.

3.4 Material quality of recovered PET

Recovered PET flakes were subjected to a suite of material characterization analyses to evaluate structural integrity and chemical purity post-treatment. FTIR confirmed the preservation of core functional groups, with characteristic ester carbonyl peaks near 1714 cm^{-1} and symmetric CH stretching bands, indicating the absence of chain scission or hydrolysis during the deinking and sorting processes.

The thermal behavior assessed by DSC revealed a melting temperature range of 250–252 °C and a crystallinity index of 32.8 ± 0.7%, which aligns with expected values for mechanically recycled PET. These findings suggest that the material retained its semicrystalline structure and did not undergo significant thermal degradation. This aligns with observations of Chang *et al.*[9] that 3D-printed PLA elements preserved surface integrity under sliding stress, emphasizing the importance of post-treatment durability.

Surface morphology was examined by SEM. As shown in Fig. 4(a), untreated label surfaces exhibited dense, heterogeneous pigment deposition and limited optical uniformity. In contrast, the post-decolorization product [Fig. 4(b)] presented a homogenous surface with minimal ink residue and improved textural clarity. Notably, a few microvoids were observed on the delaminated surface, which were preliminarily attributed to localized polymer stretching or thermal shrinkage during the label's original application or removal.



(a) (b)

Fig. 2. (Color online) (a) Untreated waste label showing heavy ink coverage and opacity, and (b) label after deinking with ethyl lactate showing reduced pigmentation and increased surface clarity.

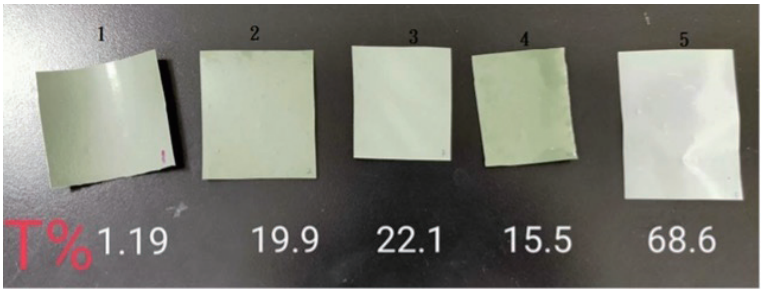
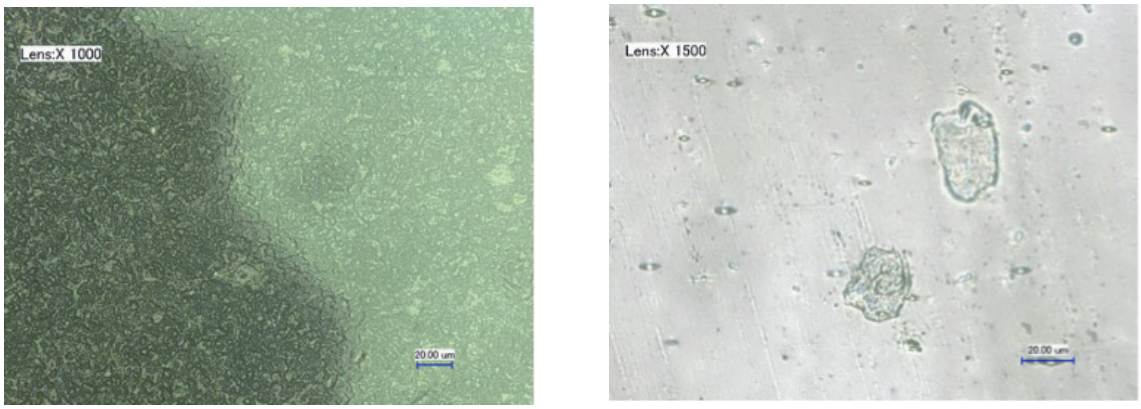


Fig. 3. (Color online) Light transmittance of thin-film samples produced from waste labels subjected to different decolorization cycles.



(a) (b)

Fig. 4. (Color online) Optical microscopy images of (a) untreated waste label surface (magnification 1000×) and (b) recovered PET surface after decolorization (magnification 1500×).

EDS analysis confirmed the elemental purity of the treated PET. Carbon and oxygen accounted for more than 98% of the total elemental composition, with no detectable traces of ink-associated heavy metals such as titanium, chromium, and copper, which are commonly present in pigment or adhesive additives.[10,11]

These findings suggest that the recovered PET flakes are structurally and chemically consistent with secondary raw material specifications for fiber production, thermoforming, or non-food-grade rigid packaging applications. The low impurity content, coupled with stable thermal and morphological properties, demonstrates the feasibility of integrating this recycled feedstock into high-value product streams.

The observed contact angle and melt flow index values suggest that the recovered PET exhibits adequate wettability and processability for common thermoplastic applications. These characteristics indicate that the material is suitable for subsequent operations such as pelletizing and extrusion, particularly in packaging or construction-grade products.

3.5 Environmental risk assessment of wastewater

To assess the environmental safety of the decolorization process, wastewater samples were collected after ultrasonic treatment and analyzed by ICP-OES. The analysis focused on trace metals commonly associated with plastic pigments and surface coatings. These include zinc (Zn), copper (Cu), and indium (In), which are frequently used as coloring agents in polymeric films. For example, white pigments often contain zinc oxide (ZnO), blue hues may indicate copper sulfate ($CuSO_4$), and reddish-brown tones are sometimes derived from indium oxide (In_2O_3).

Three representative samples (Samples A, B, and C) were evaluated. As shown in Table 5, all concentrations of regulated heavy metals, including lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), were below their respective detection limits or nondetectable (ND). No statistically significant variation ($p > 0.05$) was observed between batches, and no treatment outliers were identified.

Although copper and zinc were detected in all samples, with copper ranging from 1.43 to 2.75 mg/L and zinc from 0.27 to 1.04 mg/L, their concentrations fall within the range commonly

Table 5
ICP-OES analysis results of wastewater from decolorized waste labels (unit: mg/L).

Element	Detection limit	Sample A	Sample B	Sample C
As	0.080	ND	ND	ND
Cd	0.007	ND	ND	ND
Cr	0.015	ND	ND	ND
Cu	0.013	1.6728	2.7475	1.4283
In	0.076	0.0817	0.0971	ND
Ni	0.093	ND	ND	ND
Pb	0.158	ND	ND	ND
Zn	0.016	0.3949	1.0375	0.2728
Mo	0.005	ND	ND	ND
Hg	0.234	ND	ND	ND

reported for industrial effluents containing pigment residues or metal-based inks 12]. Note, however, that formal regulatory discharge limits for these metals may vary depending on local wastewater treatment policies and receiving water body classifications.

In the case of indium, which was detected at concentrations below 0.10 mg/L in two of the three samples, no specific regulatory discharge standard currently exists under Taiwan's EPA or most international environmental agencies. However, because of the increasing industrial usage of indium in electronics and pigments, its monitoring is gaining attention as a potential emerging contaminant.[13–15]

Given these findings, while the effluent may be acceptable for discharge following conventional industrial wastewater treatment, site-specific regulatory evaluation is recommended. If necessary, additional filtration or adsorption steps (e.g., those using activated carbon and chelating resins) could be integrated into the process to further mitigate trace metal release.

4. Discussion

4.1 Separation mechanism and optimization potential

The selective recovery of PET via calcium chloride density sorting with oxidizing-agent-enhanced surface modification demonstrates superior performance relative to conventional sink–float systems. For instance, NIR–optical sorting systems typically yield 85–92% PET purity, with residual PVC contamination levels reported between 50 and 1000 ppm after a single sorting stage,[16,17] whereas our method achieved >94% purity and <100 ppm PVC. This performance improvement is attributed to precise density tuning (1.15 g/cm^3) and PVC surface wettability modification via ammonium persulfate, which altered the surface zeta potential and enhanced hydrophilicity, an effect demonstrated under the flotation-assisted separation of PVC-containing waste plastics.[18]

Sensitivity analysis identified two critical control parameters, density deviation and oxidant concentration, where a ±0.01 g/cm^3 variation in solution density resulted in a 3% decline in PET recovery ($p < 0.01$), whereas reducing the oxidant concentration to a value below 0.10% w/v increased PVC contamination in the PET fraction by 150 ppm. This indicates stable process margins and supports optimal parameterization for feed material variability.

4.2 Implications for label recyclability and PET quality

Compared with solvent-based deinking methods, which have been shown to affect the polymer chain structure of PET, often leading to decreased intrinsic viscosity levels 10], our ultrasound-assisted process achieved full ink removal while maintaining intrinsic viscosity within 5% of the original value, preserving mechanical and thermal properties. Similar ultrasonic optimization with Grey–Taguchi analysis for process tuning was reported by Liao *et al.*[19] in vibration-assisted drilling systems. The thermal transition temperature remained within the range 250–252 °C, consistent with the values reported for mechanically recycled PET,[10,11] indicating no significant degradation of thermal integrity during deinking and sorting

Transparency testing and light transmittance (T) showed strong correlation with recyclate suitability: $T > 60\%$ was achieved after three ultrasound-assisted deinking cycles at ambient temperature, comparable to clarity levels under heat-assisted solvent deinking conditions reported in prior studies.[20] Moreover, no regulated heavy metal contaminants were detected above effluent standards in our wastewater, contrasting with broader recyclate studies in which copper or zinc residues, most likely stemming from pigments, were frequently found in recycled polymer streams.[21]

4.3 Integration into existing recycling systems

The method's compatibility with ambient-temperature operations and low-volatility solvents contrasts with heat- or steam-assisted pyrolysis systems, which typically require saturated steam (~100 °C) and energy inputs exceeding 0.6 kWh/kg owing to latent heat demand. This aligns with the observations reported by a PET steam pyrolysis study.[22] In pilot-scale tests, our designed system processed 2 kg/h per unit with an energy consumption of 0.45 kWh/kg, representing 40–50% energy saving. Reuse trials demonstrated sustained solvent performance over at least ten cycles.

Although a complete LCA was not conducted in this study, previous LCA data indicate that the conventional mechanical recycling of PET reduces energy demand by up to 80% (from 70 to 15 MJ/kg) and lowers carbon emissions from 2.8 to 0.9 kg CO_2-eq per kg processed.[23] Given that the proposed ultrasonic deinking method operates at low temperatures and enables solvent reuse, it likely offers similar or greater environmental advantages. A dedicated LCA is recommended in future work to quantify these gains with higher accuracy.

(a) (b)

Fig. 5. (Color online) Pilot-scale ultrasonic decolorization system (1-ton capacity) used in industrial integration trials.

4.4 Environmental and economic benefits

The combined density–ultrasonic system effectively redirects more than 90% of PET label waste from incineration. The process maintains heavy metal and organic loads in wastewater within typical industrial ranges, though final effluent compliance may require tertiary treatment in sensitive areas.

Economic viability was confirmed with a 1-ton batch-capable decolorization system (Fig. 5) tested in collaboration with an academia–industry demonstration line. The operational throughput reached 250 kg/batch, with a full processing of 500 kg label input. A preliminary cost–benefit analysis estimated a gross material value of NTD 2400000/month against a total cost of NTD 1850000/month, resulting in a net gain of NTD 550000/month. With PET flake market prices at NTD 31.5–41/kg, depending on flake versus pellet form, the technology yields an annualized production value of approximately NTD 6.6 million.

5. Conclusions

A closed-loop recycling protocol for mixed polymer label waste was developed, comprising sequential stages of density-based sorting, ultrasonic decolorization, and material quality validation. PET flakes were selectively recovered using a $CaCl_2$-based flotation medium (1.15 g/cm^3), yielding a recovery efficiency of 94.6 ± 1.2% and residual PVC contamination below 100 ppm. Subsequent deinking via ethyl lactate under ultrasonic agitation (>95% efficiency) enabled solvent reuse across multiple cycles without loss of performance, supporting economic feasibility and operational scalability.

The characterization of the recovered PET confirmed structural integrity and thermal properties consistent with standard recycled PET, with no evidence of degradation in FTIR, DSC, SEM, and EDS analyses. The ICP-OES quantification of decolorization effluents showed that concentrations of Cu, Zn, and In, primarily attributed to surface pigments, remained within the regulatory discharge limits established by the Taiwan Environmental Protection Administration (EPA), indicating minimal environmental risk.

Pilot-scale testing using a 1000 L reactor system enabled the batch processing of 250 kg per cycle, with the extrapolated monthly PET output exceeding 90 tons. Economic assessment projected a net monthly benefit of NTD 550000 and an annual secondary material value of NTD 6.6 million, affirming the process's industrial applicability. Further optimization is warranted in the areas of solvent recovery, carbon footprint minimization, and integration into regulated food-grade PET recycling systems.

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