Optimization of Paint Removal Process for Recycling Post-Consumer Polycarbonate (PC) Plastics: A Cost-Efficiency Integrated Approach

Yuhan Wei*
International Division, The Second High School Attached to Beijing Normal University, Beijing 100088, China
*Corresponding email: weiyuhan081020zoe@163.com

Abstract

The efficient removal of surface coatings from post-consumer polycarbonate (PC) plastics is a critical step in producing high-quality post-consumer recycled (PCR) materials, yet current industrial paint removal processes lack systematic optimization that balances both technical performance and economic viability. This study presents a cost-efficiency integrated approach to optimizing the chemical paint removal process for recycling baked-enamel-coated PC waste. Two novel quantitative evaluation metrics were developed: De-painting efficiency (δ), defined as the product yield per unit processing time, and cost-efficiency index (Δ), which integrates comprehensive production costs into the efficiency assessment. Through preliminary screening of solvents, co-solvents, and process parameters, a systematic L16(45) orthogonal experimental design was implemented to investigate five factors (NaOH concentration, reaction temperature, primary solvent dosage, surfactant dosage, and co-solvent addition) at four levels. Range analysis identified NaOH concentration and reaction temperature as the dominant factors influencing both de-painting efficiency and cost-effectiveness. The optimal cost-efficient process was determined as: NaOH 14.00% (w/w), reaction temperature 80 °C, Solvent A 3.50% (w/w), surfactant 3.50% (w/w), and no co-solvent addition. Triplicate validation experiments demonstrated that the optimized process achieved a 74.20% improvement in de-painting efficiency (δ: 14.089 vs. 8.087), a 43.8% reduction in the cost-efficiency index (Δ: 9.982 vs. 17.774), a 40.00% reduction in batch processing time, and a 4.49% increase in product yield compared to the current industrial process. The proposed dual-metric methodology provides a practical framework for bridging laboratory optimization with industrial-scale implementation in polymer recycling.

Keywords

Polycarbonate, Paint removal, Orthogonal experiment, Cost-efficiency, De-painting

Introduction

Background

The rapid expansion of plastic production and consumption has brought profound environmental challenges. It has been reported that as of 2015, approximately 8.3 billion metric tons of virgin plastics had been manufactured worldwide, of which roughly 6.3 billion metric tons had entered the waste stream, with only 9.0% recycled [1]. According to the OECD Global Plastics Outlook, global plastics production doubled from 234 million tonnes in 2,000 to 460 million tonnes in 2019, while plastic waste generation more than doubled from 156 Mt to 353 Mt over the same period [2]. The vast quantities of mismanaged waste represent an enormous loss of material value. It has been estimated that up to USD 80-120 billion worth of packaging material value is lost annually, with society bearing an additional USD 40 billion in externality costs. Wang et al. reported that waste plastic pollution has become one of the most pressing environmental issues in China, requiring strategic responses integrating policy, technology, and industrial restructuring [3].

In response, a series of landmark policy measures have been adopted globally. The Basel Convention brought plastic waste under its regulatory framework in 2019. The European Union enacted the Single-Use Plastics Directive (EU 2019/904) and the Packaging and Packaging Waste Regulation (PPWR), mandating minimum recycled content thresholds for plastic

packaging. Japan's Plastic Resource Circulation Strategy aims for 100% effective utilization of used plastics by 2035, and the U.S. Resource Conservation and Recovery Act (RCRA) continues to expand regulatory coverage [4]. China reported an actual plastic consumption of approximately 133.3 million tonnes in 2024, generating an estimated 65.0 million tonnes of waste plastic, of which only 19.5 million tonnes were effectively recycled [5]. In early 2025, China advanced the Ecological Environment Code (Draft), which proposes a mandatory system for the inclusion of recycled materials in designated product categories [6]. This global trend toward Post-Consumer Recycled (PCR) material mandates places new demands on the quality and efficiency of recycling technologies.

Properties and recycling value of Polycarbonate

Polycarbonate (PC) is a high-performance amorphous thermoplastic characterized by outstanding impact resistance, optical transparency, dimensional stability, and broad thermal tolerance (as shown in Figure 1).

Global PC consumption reached approximately 5.8 million tonnes in 2023, with China alone accounting for about 3.6 million tonnes in apparent consumption during 2024. A key advantage of PC in the context of circular economy is its resilience under mechanical recycling: Multiple melt-reprocessing cycles cause only modest degradation in molecular weight and mechanical properties, making it an attractive candidate for high-value material recovery.

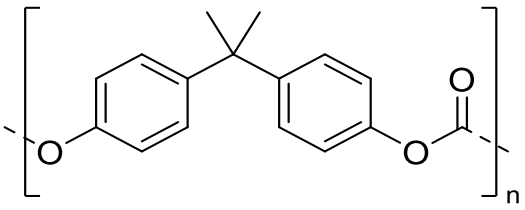

Figure 1. Chemical structure of polycarbonate (PC).

However, a large fraction of post-consumer PC waste carries surface coatings, including baked enamel, UV-cured lacquers, and printed inks. These coatings, if not adequately removed prior to re-extrusion, significantly impair the transparency, impact strength, thermal stability, and overall commercial value of the recycled product [7]. Transparent PCR-PC pellets command a substantial price premium over pigmented (black) grades. Therefore, efficient paint removal is essential for both product quality and economic viability of PC recycling operations. Figure 2 illustrates the typical production flow from post-consumer PC waste to PCR pellets.

Figure 2. Schematic overview of the PC recycling process: (a) shredded post-consumer PC waste; (b) flakes after paint removal; (c) PCR-PC transparent pellets.

Current status of paint removal technologies

Paint and ink removal from plastic substrates is widely recognized as a critical bottleneck in achieving high-quality mechanical recycling [8]. Chemical recycling approaches - including pyrolytic, hydrolytic, alcoholytic, and aminolytic pathways - have been explored to recover bisphenol A and other valuable chemical feedstocks from PC [9,10]. However, as Vollmer et al. emphasized, commercialization of these technologies remains at an early stage, and they are not yet capable of handling the scale of post-consumer PC waste generated globally [11,12].

In industrial practice, therefore, solvent- and surfactant-based chemical wash processes remain the predominant method for de-painting plastic waste during mechanical recycling [13]. These methods exploit the principles of "like dissolves like" and "swelling-penetration" to weaken adhesion between the coating layer and the

polymer substrate, causing the softened paint film to detach [14,15]. Chemical cleaning offers high de-painting efficiency and can be tailored to different substrate-coating combinations through formulation adjustments but faces challenges of high operational costs and potential environmental risks [16].

Despite the practical importance of chemical wash de-painting, the existing literature remains limited. Wang et al. examined surfactant-based removal of solvent-based and water-based inks from plastic films, establishing fundamental structure-performance relationships [17]. Guo et al. screened the effects of surfactant type, concentration, temperature, and agitation on de-inkability across multiple ink systems [18]. Ali et al. applied response surface methodology to optimize catanionic surfactant formulations and identified NaOH concentration as the dominant factor governing de-inking performance [19]. Ügdüler et al. systematically assessed deinking treatments for removing ink resins from printed plastic films [20]. Critically, nearly all published studies have been conducted under idealized laboratory conditions with limited consideration for real-world production constraints such as cost, throughput, and raw material variability [21]. Li et al. noted, the effective commercial application of recycling technologies will be key to enabling broader circular utilization of plastic waste [22]. There remains a clear gap between laboratory research and industrial implementation, particularly for coated PC waste.

Objectives and innovations

This study addresses the identified research gap by developing an optimized, cost-effective paint removal process for post-consumer PC waste, specifically targeting baked-enamel-coated helmet scrap. The key innovations include: (1) establishing a laboratory-scale methodology that simulates industrial production conditions; (2) designing two quantitative evaluation metrics - de-painting efficiency (δ) and a novel cost-efficiency index (Δ) - that simultaneously capture technical performance and economic viability; (3) systematically investigating five process variables via an $L_{16}(4^5)$ orthogonal array; (4) validating the optimized formulation against the current industrial process with techno-economic analysis. The introduction of the cost-weighted Δ metric is, to the best of our knowledge, the first attempt to embed real industrial cost data directly into the performance evaluation of a de-painting process, bridging the longstanding disconnect between laboratory optimization and industrial decision-making.

Materials and methods

Materials and instruments

The raw material consisted of post-consumer polycarbonate (PC) waste, specifically painted helmet trim scraps with baked enamel coatings, representing a typical feedstock in industrial PC recycling operations. The chemical reagents employed included Solvent A (primary solvent, proprietary, commercial designation withheld), Solvent B (proprietary), benzyl alcohol, dimethyl sulfoxide (DMSO), ethyl acetate, sodium hydroxide (NaOH), N, N-dimethyl formamide (DMF), N-methyl-2-pyrrolidone (NMP), isopropanol (IPA), calcium chloride, n-butanol, and cyclohexanone. A non-ionic surfactant was used as the surface-active agent (as shown in Figure 3).

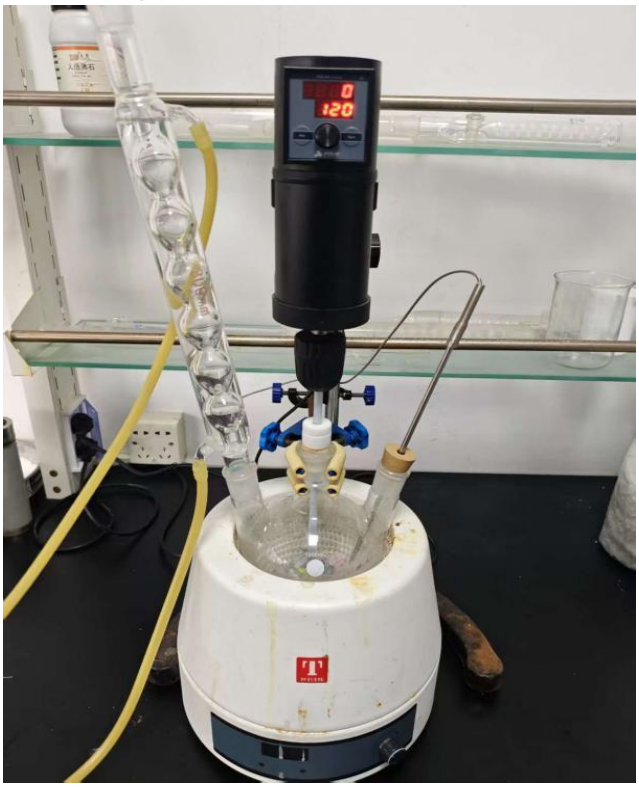

Figure 3. Experimental apparatus for paint removal.

The experimental apparatus comprised an electronic analytical balance (±0.01 g), a magnetic stirrer with temperature control, a mechanical overhead stirrer, a forced-air drying oven, and an electric heating mantle. Reactions were conducted in glass beakers equipped with thermometers for continuous temperature monitoring.

Preliminary experiments

A series of preliminary experiments were conducted to identify key process parameters and establish reasonable

ranges for the subsequent orthogonal design. Considering compatibility with existing industrial equipment, operational safety, and downstream wastewater treatment requirements, an alkaline aqueous solution (NaOH-based) system was selected as the base medium.

(1) Main solvent screening

Based on literature screening, nine candidate solvents were evaluated for paint removal effectiveness. Small PC fragments with intact paint coatings were immersed in each pure solvent for 10 min at ambient temperature, then wiped with a cloth to assess paint dissolution and removal. The solvents were evaluated across multiple criteria: alkaline stability, toxicity, volatility, flammability, solubility parameter, experimental effectiveness, market price, and substrate damage. The comprehensive screening results are presented in Table 1.

Table 1. Screening results of main solvents (ranked on a scale of 1-10).

Solvent	Alkaline stability	Toxicity	Volatility	Flamma-bility	Solubility param	Expt. effect	Price	Substrate damage	Remarks
IPA	7	3	2	2	23.5	7	Med.	None	Highly flammable
n-Butanol	7	4	4	4	23.1	3	Med.	None	Poor effect
Solvent B	8	5	6	5	~19.6	6	High	None	Moderate effect
DMF	2	9	7	5	24.8	9	Med.	Yes	Reacts with alkali
Ethyl Acetate	5	4	3	1	18.6	9	Low	Slight	Extremely flammable
DMSO	6	6	10	10	26.4	9	High	Slight	Decomposes in hot alkali
Solvent A	9	5	9	7	~20.3	8	Med.	None	Selected as main solvent
Cyclohexanone	8	7	8	6	20.3	8	Med.	Notable	Strong odor
NMP	4	8	9	8	22.9	10	Med.	None	Hydrolyzes in alkali

Note: Solubility parameters referenced from Hansen. 33 Rankings are relative within this study.

(2) Co-solvent selection

Given that the paint removal performance of Solvent A alone was not optimal (Table 1), the incorporation of a small amount of co-solvent as a penetration enhancer was investigated. Three candidate co-solvents - DMF, DMSO, and n-butanol - were individually added to Solvent A at a mass ratio of 10:1 (Solvent A: co-solvent, w/w). Immersion tests were performed at ambient temperature under identical conditions (Figure 4). After comprehensive evaluation of stability, safety, substrate compatibility, and paint removal effectiveness - combined with solubility parameter analysis - DMSO was selected as the co-solvent additive. At low concentrations (4‰, i.e., 0.4%, w/w), DMSO enhanced the penetration and swelling of the paint film without causing significant substrate degradation.

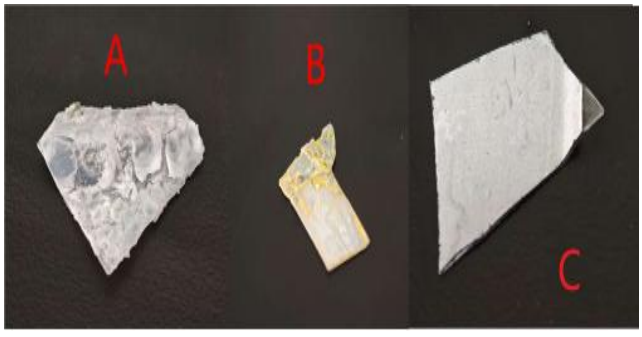

Figure 4. Preliminary immersion tests with different co-solvents: (a) DMF; (b) DMSO; (c) n-butanol.

(3) Parameter range determination

The reaction temperature and NaOH concentration ranges were established based on the existing industrial process parameters and published literature. Alkaline aqueous paint removal systems have been reported to exhibit high efficiency at temperatures between 60 and 75 °C, while NaOH concentrations in the range of 8-15% (w/w) provide effective paint dissolution. Based on these findings, the experimental parameter ranges were determined as shown in Table 2.

Table 2. Experimental parameter ranges determined from preliminary experiments.

NaOH Conc. (%, w/w)	Temp. (°C)	Co-solvent (%, w/w)	Main Solvent (%, w/w)	Surfactant (%, w/w)
8-14	65-80	0.00-0.60	3.50-5.00	3.50-5.00

Orthogonal experimental design

An L16(45) orthogonal array was employed to systematically investigate the effects of five factors, each at four levels, on the paint removal process. The five factors and their respective levels are listed in Table 3: (A) co-solvent concentration (DMSO, 0.00-0.60%, w/w), (B) NaOH concentration (8-14%, w/w), (C) reaction temperature (65-80 °C), (D) surfactant concentration (3.50-5.00%, w/w), and (E) main solvent concentration (3.50-5.00%, w/w). This design required only 16 experimental runs compared to 1024 for a full factorial design (45) (as shown in Figure 5).

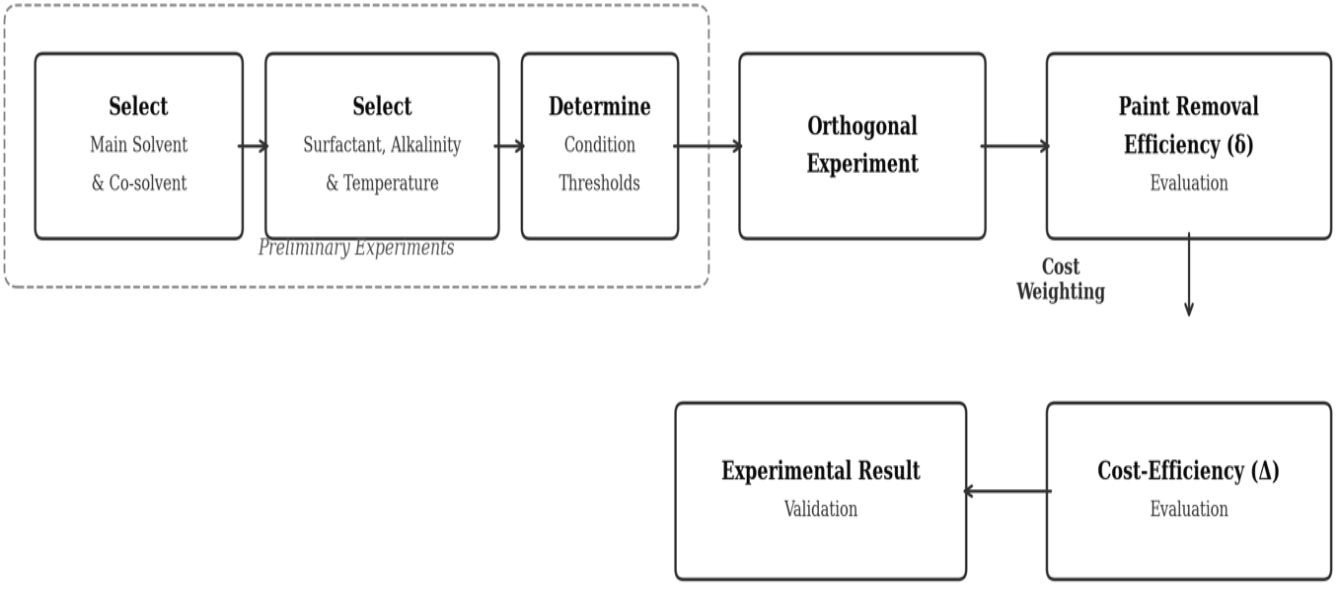

Figure 5. Schematic diagram of experimental design.

Each experiment was performed using 100 g of crushed PC waste fragments in 1000 g of paint removal solution. The reaction mixture was maintained at the designated temperature under mechanical stirring. Upon completion, the treated PC fragments were rinsed with water, dried in a forced-air oven, and weighed. The reaction time was recorded as the point at which visual inspection confirmed adequate paint removal.

Table 3. Factors and levels of orthogonal experiment.

	(A) Co-solvent (%, w/w)	(B) NaOH (%, w/w)	(C) Temp. (°C)	(D) Surfactant (%, w/w)	(E) Main solvent (%, w/w)
Level 1	0.00	8.00	65	3.50	3.50
Level 2	0.20	10.00	70	4.00	4.00
Level 3	0.40	12.00	75	4.50	4.50
Level 4	0.60	14.00	80	5.00	5.00

Evaluation metrics

Two quantitative evaluation metrics were developed to balance removal efficiency with production cost. The product yield (Y) is defined as the mass ratio of the successfully cleaned PC product to the initial raw material:

$$Y = (m_p/m_0) \times 100\% \quad (1)$$

where m_p is the mass of the cleaned product (g) and m_0 is the initial mass of raw material (g). Under idealized conditions, the product yield increases approximately linearly with reaction time within a certain operating window, and the slope of this relationship reflects the process efficiency. Accordingly, the de-painting efficiency (δ) is defined as:

$$\delta = (Y \times 100)/t \quad (2)$$

where t is the reaction time (min). A higher δ value indicates a faster paint removal rate per unit time (as shown in Figure 6).

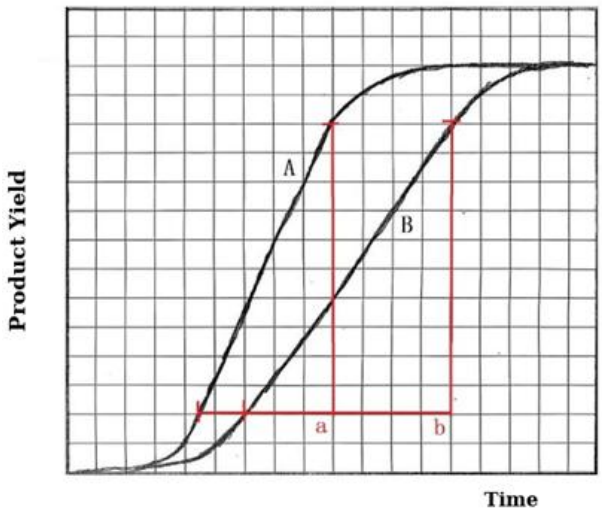

Figure 6. Schematic diagram of the relationship between product yield and reaction time during paint removal.

While maximizing δ identifies the most time-efficient process, it does not account for the cost of reagents and energy. To guide practical industrial implementation, a cost-efficiency index (Δ) was introduced:

$$\Delta = C/\delta \quad (3)$$

where C is the total production cost (dimensionless, calculated from cost-weighted factors for chemicals, surfactants, and energy consumption). A lower Δ value represents a more favorable balance between paint removal efficiency and production cost. This novel metric enables direct comparison of process alternatives on an equal economic footing, bridging the gap between laboratory optimization and industrial feasibility.

The cost weighting factors were derived from current industrial unit prices (NaOH at 3,500 CNY/t, main solvent at 12,500 CNY/t, surfactant at 12,500 CNY/t, co-solvent at 30,000 CNY/t) and steam energy costs (320 CNY/t at 0.50 MPa, adjusted for operating temperature). The detailed cost weighting calculations are presented in Section 3.2.

Results and discussion

Orthogonal experiment results

The complete results of the 16 experimental runs are summarized in Table 4. The mean paint removal efficiency across all runs was δ = 10.191, with an average product mass of 79.74 g (from 100 g raw material) and an average processing time of 8.6 min. Range analysis was performed on the mean δ values at each factor level (as shown in Table 5).

Table 4. Results of orthogonal experiments ($L_{16}(4^5)$).

No.	(A) Additiv.	(B) NaOH	(C) Temp.	(D) Surfact.	(E) Solvent A	Prod. (g)	δ	Time (min)
1	0.00	8.00	65	3.50	3.50	81.70	6.808	12.0
2	0.00	10.00	70	4.00	4.00	79.30	9.913	8.0
3	0.00	12.00	75	4.50	4.50	86.70	7.882	11.0
4	0.00	14.00	80	5.00	5.00	69.70	17.425	4.0
5	0.20	8.00	70	4.50	5.00	83.70	4.924	17.0
6	0.20	10.00	65	5.00	4.50	86.60	8.660	10.0
7	0.20	12.00	80	3.50	4.00	78.60	13.100	6.0
8	0.20	14.00	75	4.00	3.50	76.20	12.700	6.0
9	0.40	8.00	75	5.00	4.00	81.20	8.120	10.0
10	0.40	10.00	80	4.50	3.50	79.00	11.286	7.0
11	0.40	12.00	65	4.00	5.00	73.80	9.225	8.0

No.	(A) Additiv.	(B) NaOH	(C) Temp.	(D) Surfact.	(E) Solvent A	Prod. (g)	δ	Time (min)
12	0.40	14.00	70	3.50	4.50	67.90	9.700	7.0
13	0.60	8.00	80	4.00	4.50	78.70	8.744	9.0
14	0.60	10.00	75	3.50	5.00	83.40	11.914	7.0
15	0.60	12.00	70	5.00	3.50	86.00	10.750	8.0
16	0.60	14.00	65	4.50	4.00	83.30	11.900	7.0
/	/	/	/	/	Mean	79.74	10.191	8.6

Table 5. Range analysis of influencing factors.

Additive	δ	NaOH	δ	Temp.	δ	Surfactant	δ	Solvent A	δ
A1=0.0%	10.507	B1=8%	7.149	C1=65°C	9.148	D1=3.5%	10.381	E1=3.5%	10.386
A2=0.2%	9.846	B2=10%	10.443	C2=70°C	8.822	D2=4.0%	10.145	E2=4.0%	10.758
A3=0.4%	9.583	B3=12%	10.239	C3=75°C	10.154	D3=4.5%	8.998	E3=4.5%	8.747
A4=0.6%	10.827	B4=14%	12.931	C4=80°C	12.639	D4=5.0%	11.239	E4=5.0%	10.872
Range	1.245	Range	5.782	Range	3.817	Range	2.241	Range	2.125

NaOH concentration exerts the strongest influence on paint removal efficiency (R=5.782), consistent with recent literature reporting alkali concentration as the dominant factor in aqueous paint stripping systems. Reaction temperature ranks second among the factors (R=3.817), with both NaOH concentration and temperature exhibiting monotonically increasing trends. Surfactant dosage (R=2.241) and Solvent A dosage (R=2.125) showed moderate influence, while the additive (DMSO) exhibited the smallest range (R=1.245). The range analysis results are shown graphically in Figure 7.

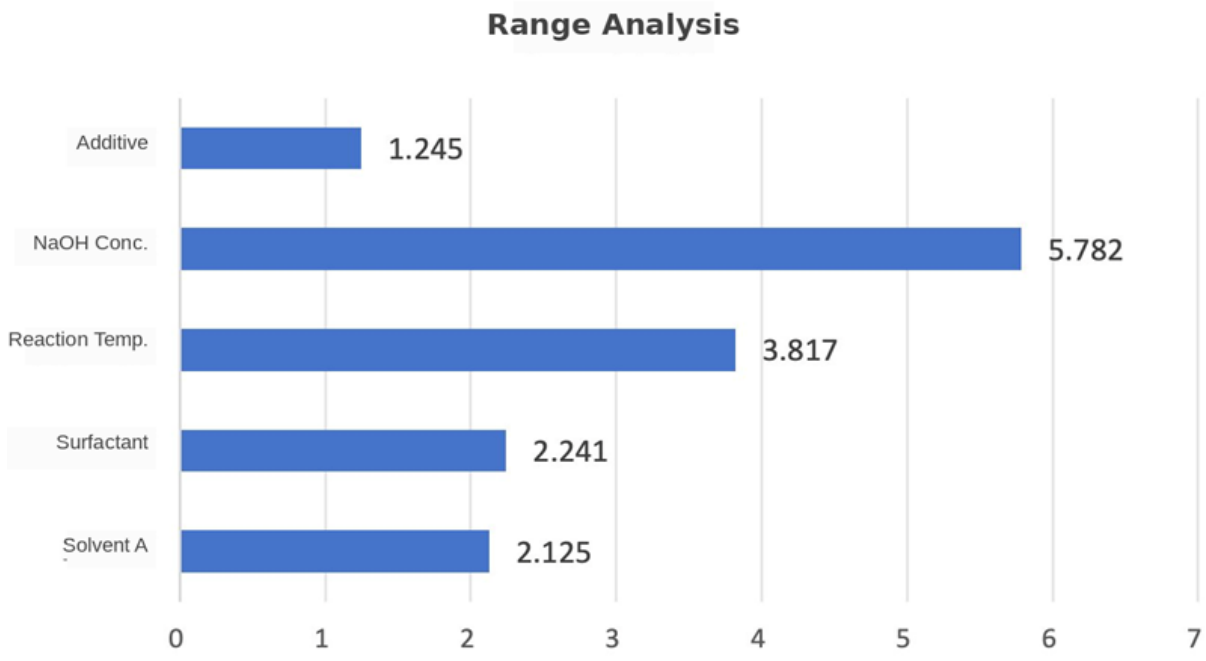

Figure 7. Range analysis of orthogonal experiments.

Based solely on δ values, the optimal combination would be A4+B4+C4+D4+E4 (highest levels of all factors), but this configuration would incur the highest material and energy costs. It is also noteworthy that several runs (No.

5, 9, and 11) produced samples exhibiting visible yellowing and softening, primarily at higher additive concentrations (0.4-0.6%, w/w) combined with prolonged reaction times, suggesting that excessive additive dosage may compromise product quality.

Cost-weighted analysis

To integrate economic considerations, the cost-efficiency metric (Δ) was applied for this purpose. The corresponding industrial cost weighting factors are presented in Table 6. Applying these cost weightings to the orthogonal experiment data yielded the cost-efficiency metric Δ for each run (As shown in Table 7). Range analysis of Δ reveals a markedly different factor hierarchy.

Table 6. Cost weighting factors for industrial production.

Item	NaOH	Solvent A	Surfactant	Additive	Steam*	
Spec.	> 96%	> 98%	> 98%	> 98%	0.50 MPa	
Unit cost (CNY/t)	3,500	12,500	12,500	30,000	320	
Weight factor	3.65	12.76	12.76	30.6	0.200 0.192 0.181 0.162	80°C 75°C 70°C 65°C

Note: *Steam cost weighting factors estimated based on batch production loading.

Table 7. Cost-weighted orthogonal results.

Exp.	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
Total cost	118.68	138.76	158.83	178.90	156.72	164.00	145.82	153.11
δ	6.808	9.913	7.882	17.425	4.924	8.660	13.100	12.700
Δ	17.432	13.999	20.152	10.267	31.831	18.938	11.131	12.056
Exp.	No.9	No.10	No.11	No.12	No.13	No.14	No.15	No.16
Total cost	156.47	151.02	171.04	165.60	156.22	163.51	170.80	178.08
δ	8.120	11.286	9.225	9.700	8.744	11.914	10.750	11.900
Δ	19.270	13.382	18.541	17.072	17.865	13.724	15.888	14.965
/	/	/	/	/	Mean	157.97	10.19	16.657

While NaOH concentration remains the most influential factor (R=8.009), the ordering of the remaining factors shifts: reaction temperature rises to second (R=6.536), followed by surfactant dosage (R=5.242), Solvent A dosage (R=3.901), and additive concentration (R=3.027) (As shown in Table 8).

Table 8. Range analysis after cost weighting.

Additive	$\bar{\Delta}$	NaOH	$\bar{\Delta}$	Temp.	$\bar{\Delta}$	Surfactant	$\bar{\Delta}$	Solvent A	$\bar{\Delta}$
A1=0.0%	15.462	B1=8%	21.599	C1=65°C	17.469	D1=3.5%	14.840	E1=3.5%	14.689
A2=0.2%	18.489	B2=10%	15.011	C2=70°C	19.698	D2=4.0%	15.615	E2=4.0%	14.841
A3=0.4%	17.066	B3=12%	16.428	C3=75°C	16.300	D3=4.5%	20.082	E3=4.5%	18.507
A4=0.6%	15.611	B4=14%	13.590	C4=80°C	13.161	D4=5.0%	16.091	E4=5.0%	18.591
Range	3.027	Range	8.009	Range	6.536	Range	5.242	Range	3.901

The cost-efficiency-optimized process corresponds to A1+B4+C4+D1+E1, i.e., no additive (0.0%), 14% NaOH, 80 °C, 3.5% surfactant, and 3.5% Solvent A. Compared with the efficiency-only optimum, this

formulation reduces surfactant and Solvent A to their minimum tested levels and eliminates the additive entirely, while retaining the higher NaOH concentration and reaction temperature, both relatively inexpensive parameters, to maintain high paint removal performance.

Validation experiments

Triplicate validation experiments were conducted under the cost-efficiency-optimized conditions (A1+B4+C4+D1+E1) and the current production process. The results are presented in Table 9.

Table 9. Validation experiments: current vs. optimized process.

Run	Addit. (%, w/w)	NaOH (%, w/w)	Temp. (°C)	Surfact. (%, w/w)	Solv. A (%, w/w)	Total cost	Prod. (g)	Time (min)	δ	Δ
1	12.24	29.20	0.181	51.04	51.04	143.70	81.20	10	8.120	17.700
2	12.24	29.20	0.181	51.04	51.04	143.70	82.10	10	8.210	17.500
3	12.24	29.20	0.181	51.04	51.04	143.70	79.30	10	7.930	18.120
Current process						Mean	80.90	10	8.087	17.774
1	0.00	51.10	0.200	44.66	44.66	140.62	83.80	6	13.970	10.070
2	0.00	51.10	0.200	44.66	44.66	140.62	85.70	6	14.280	9.850
3	0.00	51.10	0.200	44.66	44.66	140.62	84.10	6	14.020	10.030
Optimized (A1+B4+C4+D1+E1)						Mean	84.53	6	14.089	9.982

Note: Values in the factor columns (Addit. through Solv. A) represent dimensionless cost-weighted factors (see Table 6 for weighting methodology), not actual process concentrations. Actual process conditions - Current: NaOH 10%, 70 °C, surfactant 4.0%, Solvent A 4.0%, additive 0.4%; Optimized: NaOH 14%, 80 °C, surfactant 3.5%, Solvent A 3.5%, no additive.

The optimized process yielded a mean paint removal efficiency of δ=14.089 with a cost-efficiency metric of Δ=9.982, demonstrating excellent reproducibility across three parallel runs (RSD<2% for both metrics).

Techno-economic evaluation

A comprehensive comparison of the optimized and current processes is summarized in Table 10 and Figure 8.

Table 10. Summary of optimization results: current vs. optimized process.

/	δ	Direct cost	Batch time	Yield	Δ
Current	8.087	143.70	10 min	80.90%	17.774
Optimized	14.089	140.62	6 min	84.53%	9.982
Improvement	+74.21%	-2.19%	-40%	+4.49%	-43.8%

The optimized process achieved a 74.2% improvement in de-painting efficiency (δ: 14.089 vs. 8.087), attributable primarily to the elevated NaOH concentration and reaction temperature. The cost-efficiency metric Δ decreased from 17.774 to 9.982 (-43.8%), representing the lowest Δ across all 16 orthogonal runs and their mean (16.657). Reaction time was reduced from 10 min to 6 min (40%), which is expected to translate into significant throughput improvements in full-scale production. Product yield improved from 80.90% to 84.53% (+4.49%), reducing downstream processing burden and preserving product value. Even without accounting for the economic benefits of reduced cycle time, the optimized formulation achieves a 2.19% reduction in direct material and energy costs per batch.

Several limitations should be acknowledged. First, certain factors yielded optimal values at the boundary of the investigated ranges (e.g., NaOH at 14% and temperature at 80 °C), suggesting that extended parameter ranges may reveal further optimization potential. Second, the raw material consisted of industrially crushed helmet scrap, and the inherent heterogeneity may introduce variability. Third, the present findings remain at the laboratory scale and require pilot-scale validation. Fourth, higher co-solvent concentrations (≥0.4%) were observed to cause product

discoloration and softening, warranting further investigation. Future work should focus on expanding the parameter space for boundary-value factors, conducting scale-up trials, and exploring the long-term recyclability and mechanical property retention of the de-painted PC materials.

Conclusion

This study establishes a systematic laboratory methodology for optimizing paint removal in post-consumer PC recycling, developing two quantitative metrics - de-painting efficiency (δ, Eq. 2) and cost-efficiency index (Δ, Eq. 3) - that bridge the gap between laboratory optimization and industrial implementation. Through L16(45) orthogonal experiments, the optimal cost-efficient process was identified as: no co-solvent (DMSO=0.0%), NaOH 14% (w/w), 80 °C, Solvent A 3.5% (w/w), and surfactant 3.5% (w/w). NaOH concentration exerted the most pronounced influence on de-painting efficiency, followed by reaction temperature. Triplicate validation confirmed that the optimized process achieved a 74.2% improvement in δ (14.089 vs. 8.087), a 43.8% reduction in Δ (9.982 vs. 17.774), a 40% reduction in batch time, and a 4.49% increase in product yield over the current industrial process, with a 2.19% reduction in direct production costs. The cost-weighted dual-metric approach offers a practical methodology readily adoptable for analogous laboratory-to-industrial translation studies in polymer recycling.

Funding

This work was not supported by any funds.

Acknowledgements

The author would like to show sincere thanks to those techniques who have contributed to this research.

Conflicts of Interest

The author declares no conflict of interest.

References

[1] Geyer, R., Jambeck, J. R., Law, K. L. (2017) Production, use, and fate of all plastics ever made. *Science Advances*, 3(7), e1700782.

[2] Johnstone, I. (2022) Organisation for Economic Co-Operation and Development (OECD). *Yearbook of International Environmental Law*, 33(1), 271-276.

[3] Wang, G., Wang, Y., Li, Y., Chen, T. (2023) Identification of urban clusters based on multisource data - an example of three major urban agglomerations in China. *Land*, 12(5), 1058.

[4] Kasiński, S., Szuszkiewicz, J., Rudnicki, M. (2024) Regional strategies for implementing Methane Fermentation technology in waste management: environmental, technological, and social perspectives. *Sustainability*, 16(20), 9034.

[5] Nakatani, J., Maruyama, T., Moriguchi, Y. (2020) Revealing the intersectoral material flow of plastic containers and packaging in Japan. *Proceedings of the National Academy of Sciences*, 117(33), 19844-19853.

[6] Li, M., Shi, X., Li, X., Ma, W., He, J., Liu, T. (2019) Sensitivity of disease cluster detection to spatial scales: an analysis with the spatial scan statistic method. *International Journal of Geographical Information Science*, 33(11), 2125-2152.

[7] Cabrera, G., Li, J., Maazouz, A., Lamnawar, K. (2022) A journey from processing to recycling of multilayer waste films: a review of main challenges and prospects. *Polymers*, 14(12), 2319.

[8] Ali, S. A. S., Ilankoon, I. M. S. K., Zhang, L., Tan, J. (2024) Understanding de-inking in packaging plastic recycling: Bridging the gap in resource conservation and establishing average hazard quotient. *Journal of Hazardous Materials*, 479, 135554.

[9] Ragaert, K., Delva, L., Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste. *Waste Management*, 69, 24-58.

[10] Kim, J. G. (2020) Chemical recycling of poly (bisphenol A carbonate). *Polymer Chemistry*, 11(30), 4830-4849.

[11] Antonakou, E. V., Achilias, D. S. (2013) Recent advances in polycarbonate recycling: a review of degradation methods and their mechanisms. *Waste and Biomass Valorization*, 4(1), 9-21.

[12] Vollmer, I., Jenks, M. J., Roelands, M. C., White, R. J., Van Harmelen, T., De Wild, P., Weckhuysen, B. M. (2020) Beyond mechanical recycling: Giving new life to plastic waste. *Angewandte Chemie International Edition*, 59(36), 15402-15423.

[13] Lee, H. W., Yoo, K., Borchardt, L., Kim, J. G. (2024) Chemical recycling of polycarbonate and polyester without solvent and catalyst: mechanochemical methanolysis. *Green Chemistry*, 26(4), 2087-2093.

[14] Membrives, C. Z., Tamarit, P., Fernandez, A. I., Barreneche, C. (2025) Chemical procedures for paint removal in used thermoplastics for revalorization as a raw material in the automotive industry. *Advances in Polymer Technology*, 2025(1), 8477994.

[15] Li, M., Zhao, Z., Zhao, Z., Li, M. (2025) Review of techniques for the detection, removal, and transformation of environmental microplastics and nanoplastics. *ACS Applied Materials & Interfaces*, 17(14), 20560-20589.

[16] Zhang, Z., Wang, M., Wang, D., Hu, J. (2025) Technological advances in solvents drive a significant decrease in VOC emissions and negative impacts from industrial solvent-use sources. *Environmental Pollution*, 127046.

[17] Wang, L. K., Wang, M. H. S. (2025) Environmental management of electroplating and metal-finishing operations. *Control of Heavy Metals in the Environment*, 325-378.

[18] Guo, J., Luo, C., Wittkowski, C., Fehr, I., Chong, Z., Kitzberger, M., Kuchta, K. (2023) Screening the impact of surfactants and reaction conditions on the de-inkability of different printing ink systems for plastic packaging. *Polymers*, 15(9), 2220.

[19] Ali, S. A. S., Ilankoon, I. M. S. K., Zhang, L., Tan, J. (2025) Response surface methodology optimisation of catanionic surfactant mixtures in de-inking packaging plastic waste. *Journal of Hazardous Materials*, 140244.

[20] Ügdüler, S., Van Laere, T., De Somer, T., Gusev, S., Van Geem, K. M., Kulawig, A., De Meester, S. (2023) Understanding the complexity of deinking plastic waste: an assessment of the efficiency of different treatments to remove ink resins from printed plastic film. *Journal of Hazardous Materials*, 452, 131239.

[21] Uran, F. P., Bila, H., Shah, S., Hlaiem, M., Valizadeh, B., Anderson, S., Ireland, C. P. (2023) Significance of plastic recycling with the focus on polyesters-creating a circular economy. *Chimia*, 77(12), 836-841.

[22] Li, X., Lv, X., Xiang, L. (2023) Review of the state of impurity occurrences and impurity removal technology in phosphogypsum. *Materials*, 16(16), 5630.