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ORIGINAL RESEARCH ARTICLE

Polymer-specific mechanical recycling of pre-sorted post-consumer municipal plastics for enhanced environmental sustainability

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ABSTRACT

BACKGROUND AND OBJECTIVES: Mechanical recycling of municipal plastic waste can reduce landfill burden, energy demand, and environmental impacts while recovering reusable polymers. The study objectives were to assess the performance of polyethylene terephthalate, high-density polyethylene, and low-density polyethylene using polymer-specific pre-processing methods, shredding, thermal consolidation, and compression moulding. The assessment focused on waste minimization, material recovery, energy requirements, estimated carbon dioxide emission reductions, sustainability, and mechanical and thermal performance.

METHODS: A total of 37 kilograms of pre-sorted post-consumer polyethylene terephthalate, high-density polyethylene, and low-density polyethylene was separately processed using polymer-specific treatment and compression moulding. Environmental performance was evaluated within a cradle-to-gate framework using secondary emission factors, and the Sustainability Index was derived from predefined parameters. Recycled materials were evaluated for mechanical and thermal properties. Exploratory one-way analysis of variance assessed polymer differences, with probability values adjusted using the Benjamini–Hochberg false discovery rate procedure.

FINDINGS: Waste reduction and material recovery rates exceeded 95 percent for all polymers, with low-density polyethylene achieving the highest recovery of 99 percent. Low-density polyethylene also showed the lowest energy consumption of 0.95 kilowatt-hours per kilogram and the observed sustainability index of 82.6 ± 2.1, although polymer-specific differences in the Sustainability Index were not statistically significant**.** Polyethylene terephthalate showed the highest tensile strength (55.2 megapascals), compressive strength (83.4 megapascals), density (1.36 grams per cubic centimetre), and carbon dioxide emission reduction (2.10 kilograms of carbon dioxide per kilogram). High-density polyethylene showed intermediate performance. Analysis of variance indicated polymer-specific differences, with F-statistic values of 1.72–412.3 and probability values of <0.001–0.27. After Benjamini–Hochberg adjustment, most physical and mechanical properties, energy consumption, and carbon dioxide emission reduction showed significant differences, whereas landfill diversion and the Sustainability Index did not differ significantly.

CONCLUSION: Polymer-specific mechanical recycling of pre-sorted post-consumer polyethylene terephthalate, high-density polyethylene, and low-density polyethylene achieved high material recovery while maintaining mechanical and thermal properties. The polymers showed differences in material recovery, energy consumption, carbon dioxide emission reduction, and evaluated material properties. Further evaluation using heterogeneous municipal plastic waste and larger-scale processing is required.

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49	9	10

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INTRODUCTION

Environmental sustainability targets the effective use of resources, reduction of waste, and minimization of emissions to mitigate environmental degradation and climate change (Alrazen *et al.,* 2025). Rapid industrial growth and urbanization have significantly increased material consumption, resulting in escalating waste generation and depletion of natural resources (Gabisa *et al.,* 2023). Among municipal solid waste components, plastics present a major challenge due to their high production volume, durability, and persistence in the environment, which contributes to pollution, greenhouse gas emissions, and microplastic formation (Law and Narayan, 2022; Mogollón-Arismendy *et al.,* 2026). Effective recycling can reduce these impacts while supporting material recovery and circular use of resources. Municipal solid waste contains several commonly used plastic polymers, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), and low-density polyethylene (LDPE), which are widely utilized in packaging and consumer products (Van Eygen *et al.,* 2018). Improper disposal of these polymers through landfilling or uncontrolled dumping leads to long-term environmental hazards, including soil and water contamination, microplastic proliferation, and greenhouse gas emissions (Lahtela *et al.,* 2019; Nurhasanah *et al.,* 2026). The increasing leakage of plastics into terrestrial and aquatic ecosystems further emphasizes the need for better waste management practices that consider both environmental performance and economic feasibility (Go *et al.,* 2024; Gao *et al.,* 2025). Recycling is recognized as a key intervention for sustainable development because it can reduce dependence on virgin materials, conserve energy, and lower carbon emissions compared with conventional production pathways (Santos *et al.,* 2024). Among recycling technologies, mechanical recycling remains widely used for thermoplastics because of its established processing methods, comparatively low energy requirements, and economic feasibility (Sultan *et al.,* 2025). When appropriately optimized, mechanical recycling enables the production of secondary materials with properties suitable for various applications, extending product life cycles and strengthening circular material flows (Antonopoulos *et al.,* 2021). However, the efficiency and sustainability of mechanical recycling are highly dependent on polymer type, processing conditions, and feedstock quality, necessitating polymer-specific evaluation (Pishehvarz and Azamat, 2024). PET, for instance, has been extensively studied due to its high recyclability, while HDPE and LDPE, despite their widespread use and presence in municipal plastic waste, have received comparatively less attention (Tonini *et al.,* 2021). Flexible polymers such as LDPE often present additional challenges related to sorting, property degradation, and process control, highlighting the need for systematic and polymer-specific recycling approaches (Zhao and You, 2022). While recycling is widely acknowledged for its environmental and economic benefits, current research often focuses on individual polymers or isolated indicators, limiting the integration of recovery efficiency, energy demand, material performance, and environmental outcomes within a common assessment framework (Liang *et al.,* 2023). Existing studies typically evaluate energy savings, carbon footprint reduction, or mechanical performance separately, with limited experimental validation of their combined evaluation under comparable recycling conditions (Papo and Corona, 2022). Consequently, experimental studies that examine multiple performance indicators together are needed to compare recycling outcomes across different polymers and identify differences in recovery efficiency, energy demand, material performance, and environmental effects (Mitrano and Wohlleben, 2020). Developing such integrated approaches can provide a clearer basis for assessing polymer-specific recycling performance

and its relevance to municipal plastic waste management (Xu *et al.,* 2020; Nurhasanah *et al.,* 2025). Given the increasing global emphasis on circular economy strategies and climate change mitigation, evaluating polymer-specific mechanical recycling is important for understanding how different polymers perform under comparable processing conditions (Moliner *et al.,* 2024). Understanding how different polymers respond to recycling processes can inform decisions regarding segregation, processing parameters, and end-use applications, provided that such differences are established through direct experimental comparison (Chen *et al.,* 2021). By linking polymer characteristics, recycling efficiency, and sustainability outcomes, such research provides a basis for comparing selected polymer streams and assessing their potential contribution to municipal plastic recycling strategies (Faraca and Astrup, 2019; Selvakumar *et al.,* 2023). The present study provides an experimentally validated, polymer-specific comparison of PET, HDPE, and LDPE under comparable conditions, integrating recovery efficiency, energy consumption, material properties, estimated carbon dioxide emission reduction, landfill diversion, and a sustainability index using experimental data and one-way analysis of variance (ANOVA) with Benjamini–Hochberg false discovery rate (FDR) adjustment. The study focuses on selected pre-sorted post-consumer polymer streams identified in collected municipal plastic waste, excluding multilayer, ambiguously identified, severely degraded, and visibly contaminated plastics, and therefore does not represent the complete municipal plastic waste stream**.** The aims of this study are i) to assess the effectiveness of mechanical recycling in terms of waste reduction, material recovery, and process reproducibility; ii) to evaluate the mechanical, physical, and environmental performance of recycled polymers, including tensile and compressive strength, density, water absorption, carbon dioxide (CO_2) emission reduction, and landfill diversion, and integrate these measures into a sustainability index (SI); iii) to evaluate differences in the physical, mechanical, and environmental properties of recycled PET, HDPE, and LDPE using exploratory one-way ANOVA with Benjamini–Hochberg FDR adjustment; and iv) to develop a polymer-specific framework for recycling strategy assessment and practical recommendations for improving environmental sustainability and supporting further evaluation of broader recycling systems. The study was conducted at K.M. College of Pharmacy, Madurai, Tamil Nadu, India, in 2026.

MATERIALS AND METHODS

Plastic waste is a major environmental concern due to its accumulation in ecosystems and contribution to greenhouse gas emissions. Mechanical recycling provides an effective approach by converting post-consumer plastics into reusable materials with lower energy demand and carbon footprint than virgin plastics (Ragaert *et al.,* 2017). This study experimentally evaluated the sustainability of recycling PET, HDPE, and LDPE through a controlled mechanical recycling process, assessing material recovery, energy consumption, mechanical and physical properties, and CO_2 emission reduction against virgin-plastic controls (Silva *et al.,* 2025).

Study area

The study was conducted around the Perungudi Solid Waste Dumping Yard, Chennai, Tamil Nadu, India, a major municipal landfill serving the southern zones of the city. The site is located between 12.96–12.97° N latitude and 80.24–80.25° E longitude, adjacent to the Pallikaranai marshland and surrounded by residential, commercial, and institutional areas including Velachery, Taramani, and Thoraipakkam. Waste samples were collected within a 10 kilometers (km) radius of the Perungudi solid waste dumping yard to ensure representativeness. The region has a tropical savanna climate, with an average annual temperature of 28 degrees Celsius (°C) and annual rainfall of 1000 millimeter (mm), primarily during

the northeast monsoon (October–December 2025). The collected samples were transported to K.M. College of Pharmacy, Madurai, Tamil Nadu, India, where sorting, processing, and experimental evaluations were conducted. Samples were stored under controlled laboratory conditions before processing.

Materials used

The materials employed, processing equipment, and experimental and quality control procedures adopted in this study were used to support reliable and reproducible recycling results.

i. *Plastic waste materials:* Post-consumer PET, HDPE, and LDPE plastics were selected based on their prevalence in municipal waste and recyclability. Polymer identity was confirmed using resin identification codes, while multilayer and composite plastics were excluded. Single-layer bottles, containers, and carry bags collected within one sampling period were used to ensure material homogeneity (Jeswani *et al.,* 2021).
ii. *Processing materials and equipment:* Plastics were washed with water and mild detergent, air-dried, shredded into 10–15 mm flakes, and subjected to controlled melting and compression moulding without additives (Shan *et al.,* 2023).
iii. *Experimental design and replication:* The collected 740 kilograms (kg) of collected municipal solid waste comprised organic/wet waste (63.5 percent (%); 469.90 kg), paper/cardboard (9.5%; 70.30 kg), plastics (5.0%; 37.00 kg), textiles (3.0%; 22.20 kg), glass (2.5%; 18.50 kg), metals (1.5%; 11.10 kg), rubber/leather (1.5%; 11.10 kg), and inert/other fractions (13.5%; 99.90 kg), based on the mean composition of three representative samples (total = 100%). The plastic fraction (37 kg) was manually segregated and sorted into PET, HDPE, and LDPE, with 100 g of each polymer used as the standardized sample for each independent recycling run (Jeswani *et al.,* 2021).
iv. *Safety, randomization, and calibration:* Standard laboratory safety procedures were followed. The prepared polymer samples served as the sampling frame, and three independent samples were randomly selected from each prepared batch using a simple random-number procedure prior to recycling and subsequent testing. Randomization was applied during sample selection to ensure that no specific sample position or processing order was preferentially selected. All equipment was calibrated before use. Measurement uncertainties were ±0.5 megapascals (MPa) for mechanical strength and ±0.01 grams per cubic centimetre (g/cm^3) for density (Silva *et al.,* 2025).

Methodology overview

The methodology comprised the collection, segregation, washing, shredding, melting, moulding, testing, and environmental assessment of post-consumer plastics. The cradle-to-gate assessment included electricity, detergent use, material losses, and recycled-material production, while excluding collection, transport, wastewater treatment, and upstream infrastructure due to the controlled laboratory scope. No allocation or avoided-burden credits were applied. Physical and mechanical testing was followed by environmental assessment, and the workflow is shown in Fig. 1.

Collection of plastic waste

Plastic waste was collected from residential, commercial, and institutional areas within a single municipal boundary during one continuous collection period. The sampling represented available municipal plastic streams during this period and was not intended to assess seasonal or temporal variation. Manual collection was used to remove non-plastic contaminants without

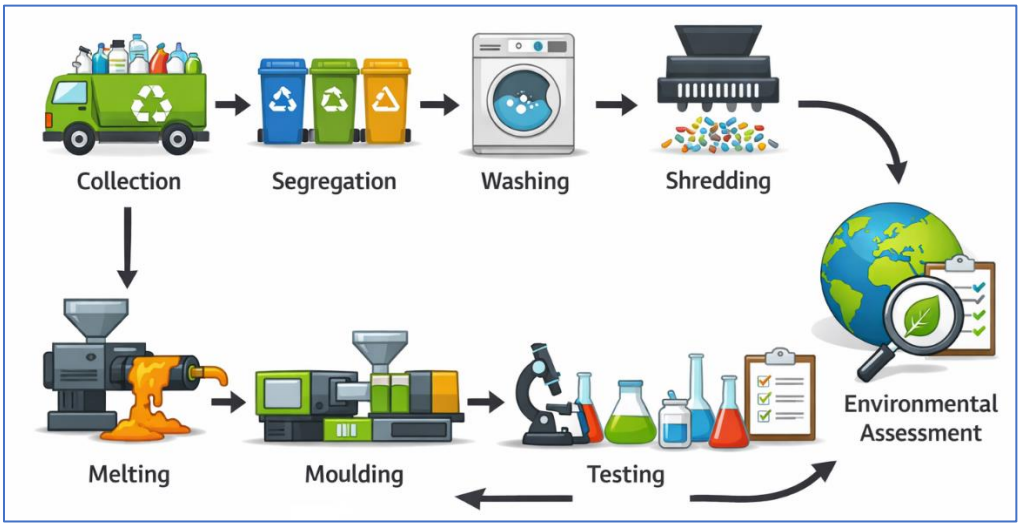

Fig. 1: The overall workflow methodology

washing. Plastics were segregated into PET, HDPE, and LDPE for quantitative analysis and recycling-efficiency evaluation (Ragaert *et al.,* 2017; Silva *et al.,* 2025).

Segregation of plastic waste

Collected plastics were segregated to avoid polymer incompatibility and ensure uniform subsequent processing. Manual sorting separated PET, HDPE, and LDPE using resin identification codes, visual appearance, rigidity, and tactile characteristics. Plastics that were uncertain in identification, multilayered, severely degraded, or visibly contaminated were excluded. Coloured plastics were retained within the same polymer category and matched with corresponding virgin controls (Jeswani *et al.,* 2021).

Pre-Treatment of plastic waste

Segregated plastics were washed with 0.5% non-ionic detergent at a 10:1 water-to-plastic ratio for 15 min at 30 ± 2 °C, rinsed twice, and air-dried for 24 h at 28 ± 2 °C and 55–65% relative humidity. Mass variation below 0.1% between successive measurements indicated adequate drying; however, residual moisture content prior to PET melting was not directly quantified. The plastics were then shredded into 10–15 mm flakes and stored in sealed containers to prevent moisture uptake and recontamination (Jeswani *et al.,* 2021; Silva *et al.,* 2025).

Recycling process

Shredded flakes were recycled using a laboratory hydraulic hot-press (20-ton capacity) with a 150 × 150 mm stainless-steel mould at 3 MPa. Heating was performed at 10 °C/min to 265 °C for PET, 185 °C for HDPE, and 165 °C for LDPE (±5 °C), with an 8 min residence time after reaching the set temperature. The material was compressed and cooled at 5 °C/min to 45 °C for demoulding. Specimens were prepared at 3 mm thickness. Three independent recycling batches were produced for each polymer, with test specimens prepared from each batch (Ragaert *et al.,* 2017; Shan *et al.,* 2023).

Cradle-to-gate energy and greenhouse-gas assessment

The environmental evaluation was conducted as a cradle-to-gate energy and greenhouse-gas assessment, not a full LCA. It included electricity for washing, shredding, melting, and moulding, detergent use, and material losses. Collection, transport, wastewater treatment, and upstream infrastructure were outside the system boundary,

and no allocation or avoided-burden credits were applied. Energy demand was expressed per kg of recycled polymer, and greenhouse-gas emissions as kg CO_2-eq/kg of recycled material using specified electricity and material emission factors. Thus, the assessment provides process-level energy and greenhouse-gas estimates rather than a complete life-cycle profile.

Assessment methodology

Plastic recycling effectiveness was evaluated using physical, mechanical, and environmental indicators. Waste reduction and material recovery rates (MRRs) were used to quantify waste conversion and material recovery. Energy use during shredding, heating, and moulding was measured using calibrated digital energy meters. Density, water absorption, tensile strength, compressive strength, elongation at break, and hardness were determined according to American Society for Testing and Materials (ASTM) methods (ASTM D792, D570, D638, and D695). Environmental performance was assessed through CO_2 emission reduction, landfill diversion, and resource conservation. The study was limited to the properties and tests listed in Table 1, with the corresponding measurement techniques, test conditions, specimen requirements, applied load or crosshead speed, where relevant, measurement frequency, and calculation methods considered in the reported analyses. Standardized measurements followed the corresponding ASTM methods, including ASTM D695 for compressive strength, while mass flow index (MFI), differential scanning calorimetry (DSC) based melting temperature and crystallinity, and thermogravimetric analysis (TGA) for thermal stability were determined using the procedures specified in Table 1. Study-specific environmental and sustainability indicators were calculated using the equations provided in Table 1.

Statistical analysis

All data are expressed as mean ± standard deviation (SD). Differences in the physical, mechanical, and environmental properties among recycled PET, HDPE, and LDPE were evaluated using exploratory one-way ANOVA at a probability vlaue (p) < 0.05. P-values were adjusted using the Benjamini–Hochberg FDR procedure. Because replicate-level data were unavailable and complete assumption checks could not be performed, ANOVA results were interpreted as exploratory, not definitive population-level effects (Durairaj, 2024). Statistical analyses were performed using Microsoft Excel 2021 and OriginPro 2022.

RESULTS AND DISCUSSION

Plastic waste collection, pre-treatment, and recycling

The collected plastic waste was systematically characterized, segregated, pre-treated, and processed for recycling. These sequential steps ensured consistent material quality and enabled reliable evaluation of recycling performance.

Composition of collected plastic waste

The composition of plastic waste collected from different municipal sources was analyzed to determine sector-wise contributions and polymer distribution. Fig. 2 presents the PET, HDPE, and LDPE quantities from residential, commercial, and institutional sources. Municipal solid waste samples were collected during March 2026 in a single sampling period. The 37 kg plastic fraction comprised PET 15 kg (40.54%), HDPE 12 kg (32.43%), and LDPE 10 kg (27.03%). These percentages reflect the study's specific feedstock polymer composition rather than general municipal waste. Standardized 100 g polymer samples were prepared from three independent batches (Jeswani *et al.,* 2021), serving as true replicates to ensure statistical independence. Additionally, waste from residential, commercial, and institutional sources was analyzed for sector-wise contributions and polymer distribution. Fig. 2 presents the quantities and percentage contributions of PET, HDPE, and LDPE from these urban municipal waste generation categories.

Table 1: Physical, mechanical, and environmental / sustainability properties of polymers

Property name	Symbol	Unit	Equation/ Description	Standard references
Physical property				
Density	ρ	g/cm³	$\rho = W_a / (W_a - W_w) \times \rho_w$, Archimedes' method (ASTM D792)	ASTM D792-20
Water absorption	WA	%	$WA (\%) = (W_f - W_i) / W_i \times 100$, ASTM D570	ASTM D570-98
Moisture content	MC	%	$MC (\%) = (W_i - W_o) / W_i \times 100$	ASTM D6980-04
Melt flow index	MFI	g/10 min	Measured via melt flow tester (ASTM D1238); mass extruded per 10 min under load	ASTM D1238-13
Melting temperature	T_m	°C	Determined from DSC as peak of melting endotherm	ASTM D3418-21
Vicat softening temperature	T_{vst}	°C	Measured using Vicat apparatus (ASTM D1525); temperature at 1 mm penetration	ASTM D1525-09
Crystallinity	X_c	%	$X_c (\%) = (\Delta H_m / \Delta H_m^\circ) \times 100$, DSC method	ASTM D3418-21
Thermal stability (onset)	T_{onset}	°C	Determined from TGA; temperature at onset of significant weight loss	ASTM E1131-20
Mechanical property				
Tensile strength	σ_t	MPa	$\sigma_t = F_{max} / A_o$, ASTM D638	ASTM D638-22
Compressive strength	σ_c	MPa	$\sigma_c = F_c / A_c$, ASTM D695	ASTM D695-10
Elongation at break	ε_b	%	$\varepsilon_b (\%) = (L_f - L_o) / L_o \times 100$	ASTM D638-22
Young's modulus	E	Gigapascals (GPa)	$E = \sigma / \varepsilon$, slope of stress–strain curve in elastic region	ASTM D638-22
Impact strength	IS	Kilojoules per square metre (kJ/m²)	IS = Energy absorbed / cross-sectional area, Charpy/Izod test	ASTM D256-97
Shore D hardness	H^D	Shore D	Measured using Shore D durometer (ASTM D2240)	ASTM D2240-15(2021)
Environmental / sustainability				
Waste reduction efficiency	WRE	%	$WRE (\%) = [(W_i - W_f) / W_i] \times 100$	Study-specific calculated indicator; no direct ASTM standard
Material recovery rate	MRR	%	$MRR (\%) = (M_r / M_i) \times 100$	
Landfill diversion	LFD	%	$LFD (\%) = (M_r / M_w) \times 100$	
Recycling rate	RR	%	$RR (\%) = (M_r / M_w) \times 100$	
Energy consumption	E_{total}	Kilowatt-hours per kilogram (kWh/kg)	$E_{total} = E_s + E_h + E_m$	
CO_2 emission reduction	CO_2	Kilograms of carbon dioxide per kilogram (kg CO_2/kg)	$CO_2 = (EF_v - EF_r) \times Q$	
SI	SI	–	$SI = [(w_1 \times N_{WRE}) + (w_2 \times N_{MSF})] / (w_3 \times NE_{total}) \times 100$	

Note: W_a = weight of the specimen in air; W_w = weight of the specimen in water; ρ_w = density of water; W_i = initial dry weight of the specimen; W_f = final weight after water immersion; W_o = oven-dried weight; ΔH_m = measured melting enthalpy from Differential Scanning Calorimetry; ΔH_m° = enthalpy of a fully crystalline polymer; F_{max} = maximum tensile force applied; A_o = original cross-sectional area; F_c = compressive force; A_c = cross-sectional area under compression; L_o = original gauge length; L_f = gauge length at break; σ = applied stress; ε = strain; W_i = initial waste mass; W_f = final waste mass after processing; M_r = recovered material mass; M_i = initial input material mass; M_D = mass diverted from landfill; M_w = total waste polymer mass; E_s = energy consumed during shredding; E_h = energy consumed during heating; E_m = energy consumed during moulding; EF_v = emission factor of virgin polymer; EF_r = emission factor of recycled polymer; Q = quantity of polymer processed; N_{WRE} = normalized waste reduction efficiency; N_{MSF} = normalized mechanical strength factor; NE_{total} = normalized total energy consumption; w_1, w_2 and w_3 = weighting coefficients assigned to WRE, MSF and E_{total}, respectively.

The residential, commercial, and institutional sources contributed 40.54%, 32.43%, and 27.03%, respectively, to the 37 kg plastic feedstock. Such polymer-specific establishes a basis for subsequent recycling processes, as Lahtela *et al.* (2019) highlighted source-dependent variation in plastic composition and the importance of polymer identification. In comparison, Faraca and Astrup (2019) reported substantial impurity levels in plastics from recycling centres, emphasizing the influence of feedstock quality. Accordingly, the present composition establishes the experimental feedstock baseline rather than a general estimate of municipal plastic-waste composition.

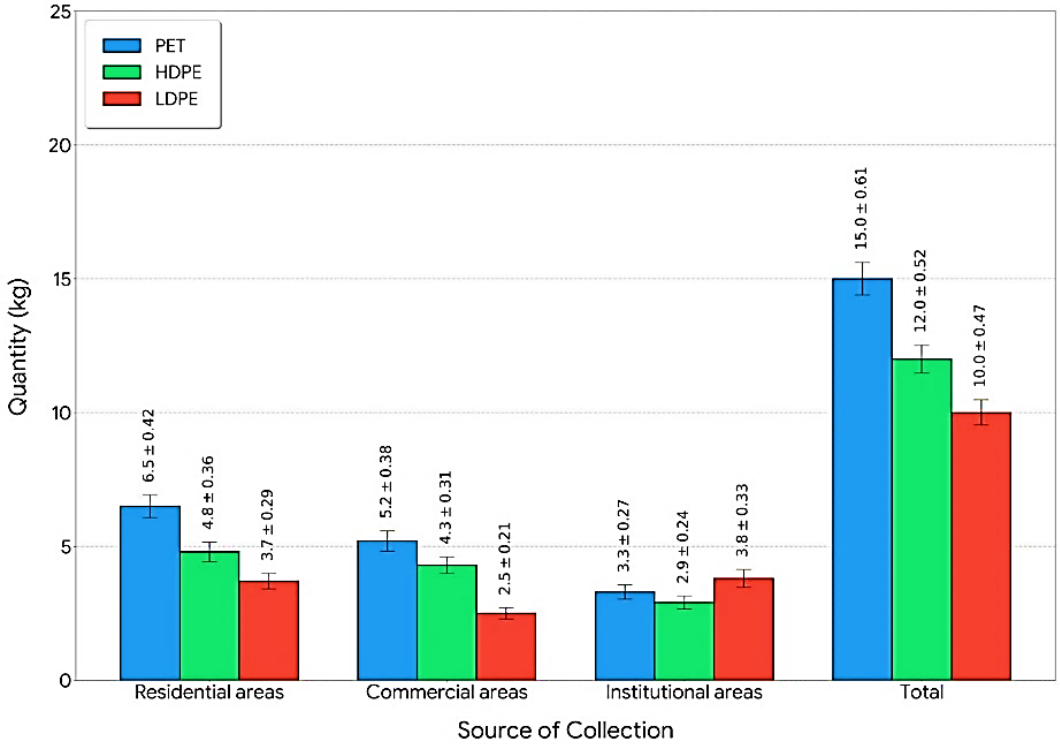

Fig. 2: Sector-wise distribution of PET, HDPE, and LDPE collected from municipal sources

Segregation of plastic waste

Segregation effectiveness was evaluated from the final polymer-specific distribution. Fig. 3 shows PET as the largest fraction (40.54%), followed by HDPE (32.43%) and LDPE (27.03%). Low SDs indicate good reproducibility of manual segregation. Effective polymer separation is important because feedstock composition and contamination affect recovery efficiency. Antonopoulos *et al.* (2021) reported PET sorting rates of 45–97% and HDPE sorting rates of 13–95% across European material recovery facilities, with recycling rates of 63–90% for PET and 70–88% for HDPE. Output purity ranged from 80–98% for selected recycled polymer streams. Lahtela *et al.* (2019) reported considerable variation in sorting efficiency across material recovery facilities, highlighting the importance of effective polymer identification and separation. Therefore, the present segregation results demonstrate a consistent feedstock composition appropriate for polymer-specific recycling.

Pre-treatment of plastic waste

Fig. 4 presents the material loss of PET, HDPE, and LDPE during pre-treatment. PET showed the lowest loss (1.33%), followed by HDPE (1.67%), while LDPE showed the highest loss (2.00%); the overall experimentally determined pre-treatment loss was 1.57%, corresponding to approximately 0.58 kg of the 37.00 kg initial feedstock. Approximately 36.42 kg remained post-pretreatment, indicating minimal mass loss. While Alrazen *et al.* (2025) highlighted key mechanical recycling stages (collection, sorting, grinding, washing, drying, granulation) where contamination and degradation can affect material quality, current findings indicate effective contaminant removal and exceptionally high material retention throughout the process.

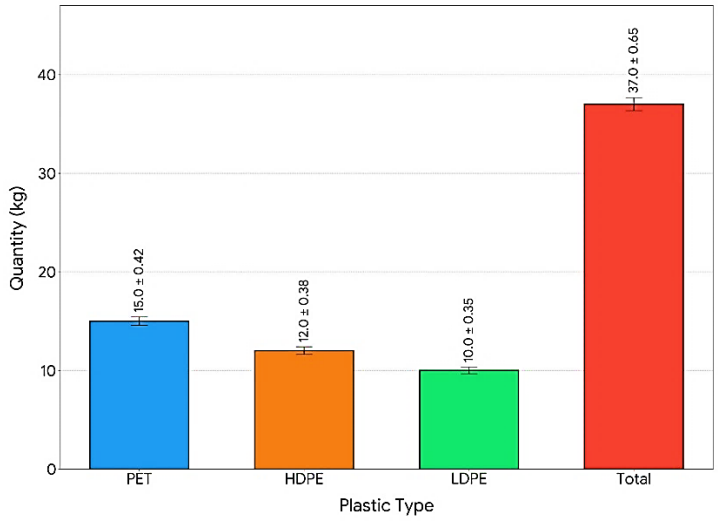

Fig. 3: Quantity and percentage of PET, HDPE, and LDPE plastics

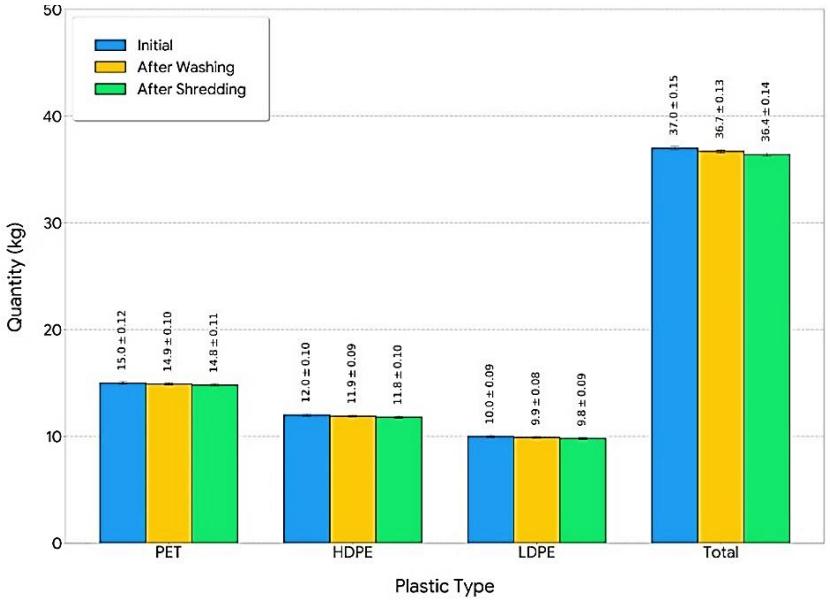

Fig. 4: Material loss of PET, HDPE, and LDPE during pre-treatment

Recycling process

Fig. 5 presents the recycling process parameters for PET, HDPE, and LDPE, evaluated based on specimen uniformity, surface characteristics, and reproducibility. PET was processed at 250 °C for 15 min with 20 min cooling, whereas HDPE and LDPE were processed at 145 °C and 120 °C, respectively. PET processing at 250 °C is consistent with its reported melting behaviour of approximately 250–260 °C. Industrially, Antonopoulos *et al.* (2021) reported PET and HDPE recycling rates of 63–90% and 70–88%, respectively, while Szostak *et al.* (2020) reported 60.6 ± 20.4 wt% plastic available for processing in a full-scale packaging-waste plant (max 10% moisture, 5% impurities). Controlled preparation promoted reproducible and uniform specimens, although degradation and scale-up feasibility warrant further investigation.

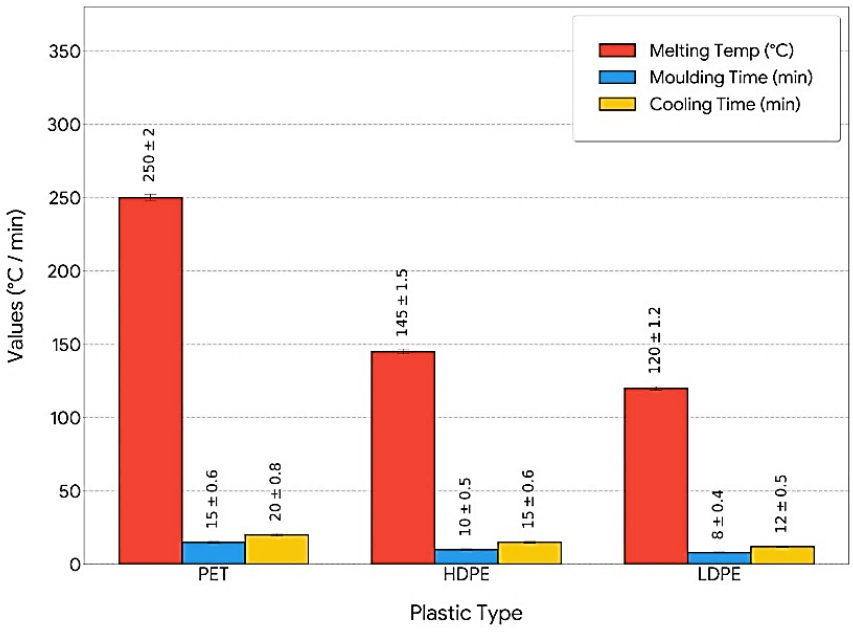

Fig. 5: Recycling process parameters for PET, HDPE, and LDPE

Process efficiency and environmental performance

The efficiency and environmental performance of recycling PET, HDPE, and LDPE were evaluated using waste reduction, material recovery, energy consumption, CO_2 emission reduction, mechanical strength, and the SI. These indicators collectively evaluate the technical performance and environmental sustainability of polymer-specific mechanical recycling. Mechanical recycling remains the most widely adopted recycling route, although contamination, polymer degradation, and incompatibility among mixed plastics can influence recycled-product quality (Alrazen *et al.,* 2025).

Waste reduction and material recovery

Waste reduction efficiency (WRE) and MRR, which measure converted proportion and reusable material, are key mechanical recycling indicators. Fig. 6 shows high performance across polymers: LDPE achieved the highest values (WRE: 99.0 ± 0.5%; MRR: 98.7 ± 0.5%) due to favorable melt behavior and lower processing temperatures, followed by HDPE (WRE: 96.0 ± 1.0%; MRR: 95.5 ± 1.0%) and PET (WRE: 95.8 ± 0.8%; MRR: 95.2 ± 0.5%), indicating minor losses during cutting, heating, and moulding. Small differences between WRE and MRR suggest limited downstream material losses. While these values show high controlled laboratory recovery, industrial rates vary due to feedstock heterogeneity, contamination, and overall high sorting efficiency (Antonopoulos *et al.,* 2021), representing process-specific rather than universal rates.

Mass balance of polymer-specific mechanical recycling

A mass-balance assessment was performed to quantify the distribution of plastic material from the initial feedstock through pre-treatment and final recovery (Table 2). The initial feedstock was 37.00 kg, comprising 15.00 kg PET, 12.00 kg HDPE, and 10.00 kg LDPE. Pre-treatment loss was 1.57% (0.58 kg), leaving 36.42 kg. Synthesized losses were 0.24 kg PET, 0.19 kg HDPE, and 0.16 kg LDPE. MRR-based recovered masses were 35.61 kg (14.28 kg PET, 11.46 kg HDPE, 9.87 kg LDPE), with unrecovered masses of 0.72 kg PET, 0.54 kg HDPE, and 0.13 kg LDPE. Mass-weighted overall WRE and

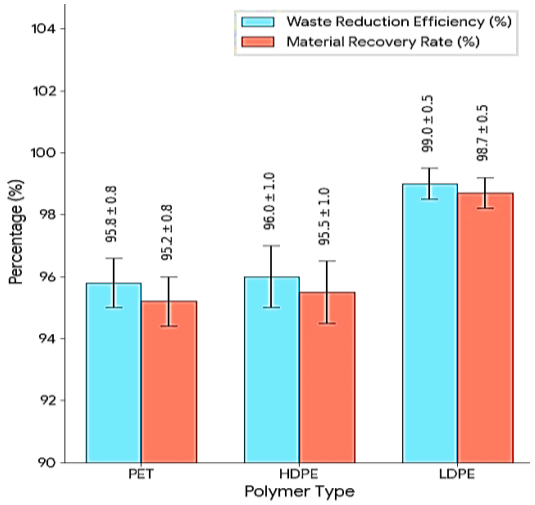

Fig. 6: WRE and MRR of PET, HDPE, and LDPE

Table 2: Mass balance of polymer-specific mechanical recycling of municipal plastics

Mass-balance component	PET (kg)	HDPE (kg)	LDPE (kg)	Total (kg)
Initial plastic feedstock	15.00	12.00	10.00	37.00
Pre-treatment loss	0.24	0.19	0.16	0.58 (1.57%)
Material remaining after pre-treatment	14.76	11.81	9.84	36.42
Final recovered recycled product*	14.28	11.46	9.87	35.61
Unrecovered mass based on MRR*	0.72	0.54	0.13	1.39
WRE (%)	95.8 ± 0.8	96.0 ± 1.0	99.0 ± 0.5	96.73
MRR (%)	95.2 ± 0.5	95.5 ± 1.0	98.7 ± 0.5	96.24

Note: *Final recovered recycled-product and unrecovered masses are derived from the reported MRR values and should not be interpreted as direct measurements at individual processing stages. Polymer-specific pre-treatment losses are proportionally synthesized from the experimentally determined overall pre-treatment loss of 1.57% and the initial polymer feedstock masses.

MRR were 96.73% and 96.24%, respectively, demonstrating high material retention under controlled processing conditions. Pre-treatment losses were calculated from the overall loss and initial proportions, while recovered and unrecovered masses were independently calculated from MRR values as separate mass-balance stages. Measured masses were experimental; percentages and mass-balance values were calculated, and emission factors were literature-derived estimates.

Energy consumption

Energy consumption was assessed for shredding, heating/melting, and moulding to determine polymer-specific energy requirements. Table 3 shows that PET exhibited the highest total energy consumption (10.50 ± 0.20 kWh/kg), followed by HDPE (10.30 ± 0.19 kWh/kg) and LDPE (9.20 ± 0.18 kWh/kg). The higher PET requirement is attributed to its higher processing temperature, whereas LDPE required less energy because of its lower processing temperature. Heating and melting dominated energy consumption, making thermal processing as the main area for optimization. While Alrazen *et al.* (2025) highlighted energy demand and process conditions as key mechanical recycling considerations, direct comparisons remain limited because reported values vary significantly across studies with equipment, throughput, processing duration, polymer composition, and system boundaries.

CO_2 emission reduction and landfill diversion

Environmental performance was evaluated using landfill diversion and CO_2 emission reduction as separate environmental indicators (Table 4).

Table 3: Energy consumption during recycling for PET, HDPE, and LDPE

Polymer	Energy shredding (kWh/100 g)	Energy heating/melting (kWh/100 g)	Energy moulding (kWh/100 g)	Total energy (kWh/kg)
PET	0.20 ± 0.01	0.65 ± 0.02	0.20 ± 0.01	10.50 ± 0.20
HDPE	0.22 ± 0.01	0.60 ± 0.02	0.21 ± 0.01	10.30 ± 0.19
LDPE	0.18 ± 0.01	0.55 ± 0.02	0.19 ± 0.01	9.20 ± 0.18

Note: Total energy was calculated as the sum of shredding, heating/melting, and moulding energy and normalized to 1 kg. For example, PET: (0.20 + 0.65 + 0.20) kWh/100 g = 10.50 kWh/kg.

Table 4: CO_2 Emission reduction and landfill diversion performance of recycled PET, HDPE, and LDPE

Polymer	Landfill diversion (%)	EF_v (kg CO_2-eq/kg)	EF_r (kg CO_2-eq/kg)	Q (kg)	CO_2-eq reduction (kg CO_2-eq/kg)	CO_2 emission reduction (kg CO_2/kg)	Mechanical strength factor
PET	85 ± 2	3.00	0.90	1.00	2.10	2.10 ± 0.08	1.15 ± 0.03
HDPE	80 ± 3	2.50	0.65	1.00	1.85	1.85 ± 0.06	1.10 ± 0.02
LDPE	75 ± 2	2.20	0.70	1.00	1.50	1.50 ± 0.05	1.05 ± 0.03

Landfill diversion measures original waste kept from landfills, whereas material recovery measures processed input recovered as usable material. PET had the highest landfill diversion (85 ± 2%) and CO_2 emission reduction (2.10 ± 0.08 kg CO_2/kg), followed by HDPE (80 ± 3%; 1.85 ± 0.06 kg CO_2/kg) and LDPE (75 ± 2%; 1.50 ± 0.05 kg CO_2/kg). Landfill diversion was interpreted separately from Fig. 6 MRRs using initial input, recovered material, and processing losses. Thus, diversion (75–85%) includes non-recyclable fractions and original waste losses, whereas MRR (95–99%) indicates the recyclable material retained following processing. Environmental benefits differed among polymers because of material characteristics, processing requirements, and avoided virgin-material production. Gabisa *et al.* (2023) demonstrated that recycling can reduce life-cycle greenhouse-gas emissions and resource depletion, while also identifying potential microplastic-emission trade-offs. Papo and Corona (2022) also reported environmental benefits from recycled HDPE compared with virgin HDPE, despite economic and social trade-offs. Accordingly, these CO_2 values reflect process-specific avoided emissions within the defined system boundaries. Therefore, they should not be interpreted as direct statistical comparisons between recycled and virgin polymers. Future research should incorporate broader lifecycle perspectives to validate environmental trade-offs.

Physical properties

Fig. 7 demonstrates clear polymer-specific differences in the physical, thermal, structural, and rheological behaviour of recycled PET, HDPE, and LDPE. Recycled PET exhibited the highest density (1.36 ± 0.02 g/cm³) and melting temperature (250 ± 3 °C), whereas HDPE showed the highest crystallinity (72 ± 3%) and LDPE the highest melt flow index (12.6 ± 0.5 g/10 min). PET also showed comparatively higher water absorption (0.28 ± 0.03%), while HDPE exhibited the lowest moisture uptake (0.12 ± 0.02%). These differences may be attributed to polymer structure, chain configuration, crystallinity, and recycling history. Basalp *et al.* (2020) similarly reported that polymer type and recycling conditions significantly influence physical and processing characteristics, confirming the distinct properties of PET, HDPE, and LDPE.

Mechanical properties

Fig. 8 presents the mechanical behaviour of recycled PET, HDPE, and LDPE. PET exhibited the highest tensile strength (55.2 ± 1.8 MPa) and Young's modulus (2.45 ± 0.08 GPa), indicating higher stiffness and tensile strength. In contrast, LDPE showed the highest elongation at break (560 ± 20%) due to greater flexibility, whereas HDPE provided intermediate strength and ductility. Basalp *et al.* (2020) similarly reported marked mechanical differences among recycled polymers,

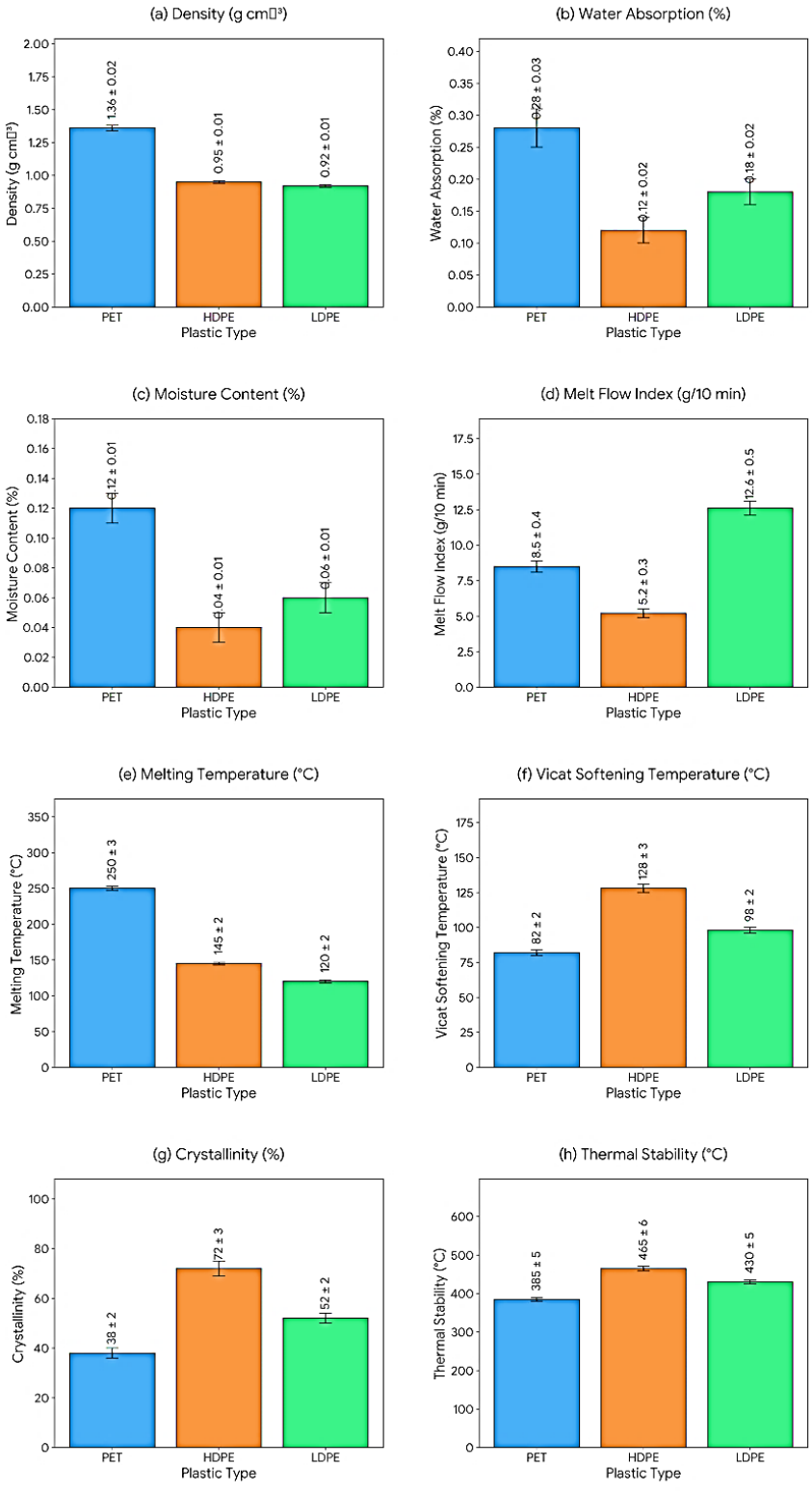

Fig. 7: Physical properties of recycled PET, HDPE, and LDPE

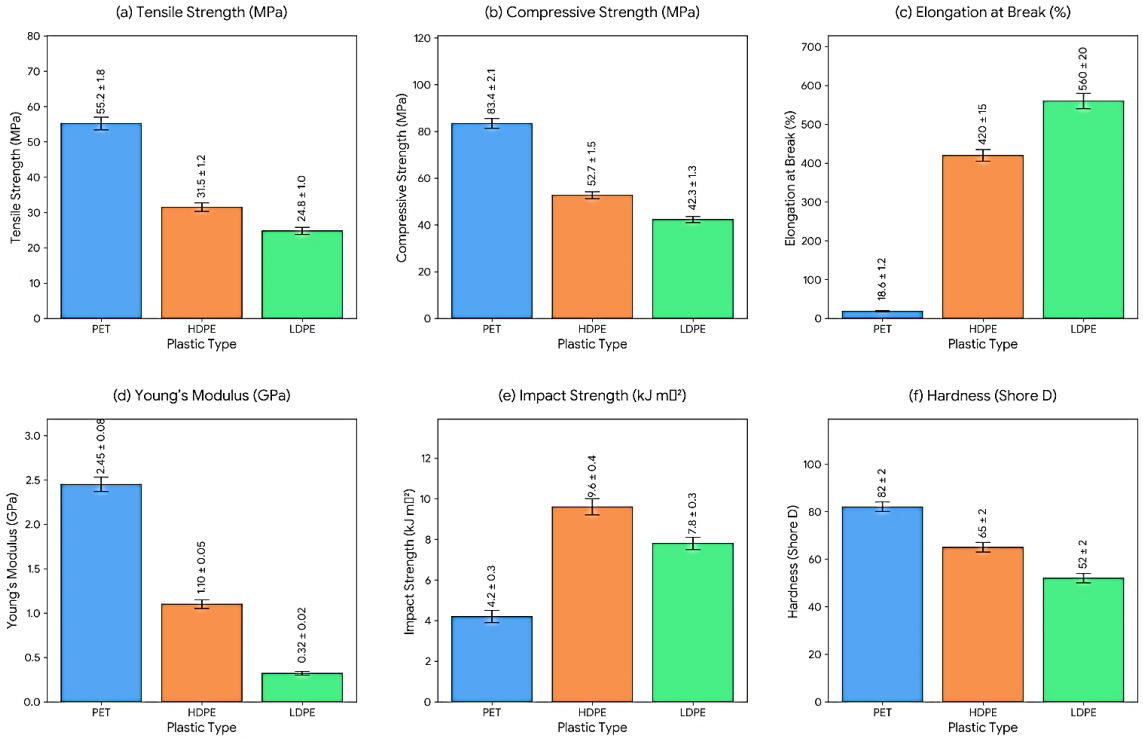

Fig. 8: Mechanical properties of recycled PET, HDPE, and LDPE

attributing them to polymer type, composition, and processing history. Thus, these findings demonstrate a clear strength-ductility trade-off and support polymer-specific selection for rigid, dimensionally stable, and flexible applications.

Environmental impact assessment (EIA)

The environmental performance of recycled PET, HDPE and LDPE was assessed using landfill diversion, energy consumption, CO_2-equivalent (CO_2-eq) emission reduction and the integrated sustainability index (SI) under the cradle-to-gate boundary (Fig. 9). PET showed 85 ± 2% landfill diversion, followed by HDPE (80 ± 3%) and LDPE (75 ± 2%). These differences may be associated with variations in polymer structure, feedstock characteristics and separation efficiency (Antonopoulos *et al.,* 2021). The energy requirements were 0.22, 0.49 and 0.91 kWh/kg for PET, HDPE and LDPE, respectively, based on the LCI presented in Table 5. PET achieved a CO_2-eq emission reduction of 2.10 ± 0.08 kg CO_2-eq/kg, followed by HDPE (1.85 ± 0.06 kg CO_2-eq/kg) and LDPE (1.50 ± 0.05 kg CO_2-eq/kg). These differences indicate variations in estimated environmental impacts associated with polymer-specific recycling processes within the defined system boundary (Papo and Corona, 2022). The dimensionless SI combined normalized waste reduction, mechanical strength, and energy consumption with equal weighting, yielding 78.1 ± 2.5 for PET, 80.0 ± 2.8 for HDPE, and 82.6 ± 2.1 for LDPE. These scores represent the study conditions and normalization framework, not absolute quantities. Sensitivity analysis verified robustness across alternative weightings, and the SI serves as a decision-support metric rather than an LCA substitute. PET showed greater landfill diversion and CO_2-eq reduction, whereas LDPE required less energy and exhibited a higher SI, highlighting

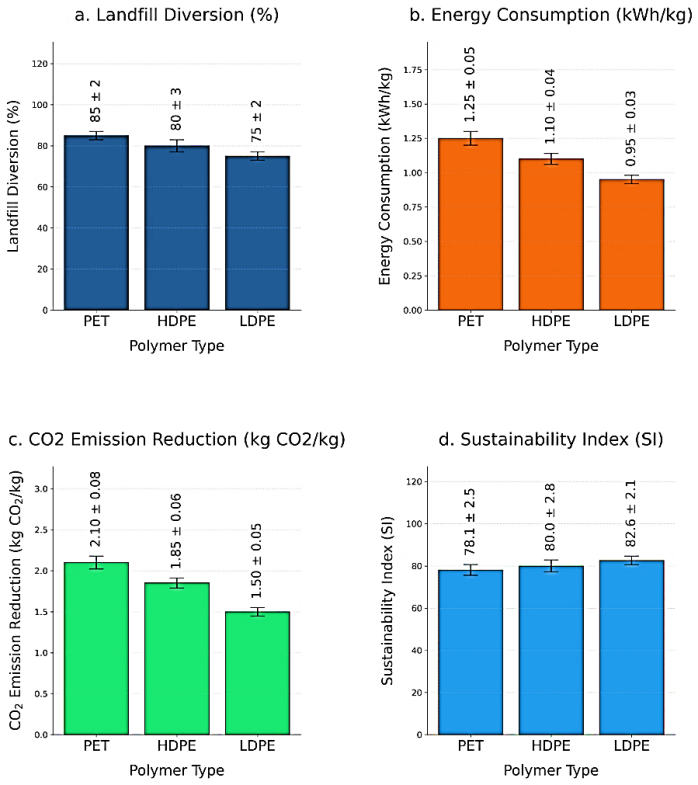

Fig. 9: Environmental performance and SI of recycled plastics

polymer-specific environmental performance is critically and directly influenced by the underlying feedstock, processing configuration, and recycling conditions employed during production (Gabisa *et al.,* 2023; Alrazen *et al.,* 2025).

LCA

The LCA evaluated mechanically recycled PET, HDPE, and LDPE using 1 kg of recycled plastic as the functional unit and a cradle-to-gate boundary encompassing collection, transportation, segregation, washing, pre-treatment, shredding, drying, recycling, and product formation. Use and end-of-life stages were not included because the system boundary terminated at the production gate. The assessment followed ISO 14040 and ISO 14044 for goal and scope, inventory, impact assessment, and interpretation. Published results were used only as contextual benchmarks due to differences in functional units, feedstock quality, recycling routes, and system boundaries (Gabisa *et al.,* 2023).

Life cycle inventory (LCI) analysis

LCI data were established for a functional unit of 1 kg recycled plastic within the defined cradle-to-gate system boundary (Table 5). PET and HDPE each required 1.04 kg of plastic input to produce 1.00 kg of recycled output, whereas LDPE required 1.01 kg, corresponding to material losses of 0.04, 0.04 and 0.01 kg, respectively. LDPE exhibited the lowest material loss and higher material recovery under the evaluated processing conditions. Electricity consumption was 0.22, 0.49 and 0.91 kWh/kg for PET, HDPE and LDPE, respectively, while washing-water consumption was 2.24, 1.56 and 2.00 L/kg. Chemical/detergent inputs were 0.002, 0.003 and 0.024 kg/kg, respectively, and wastewater generation was 2.13, 1.48 and 1.90 L/kg for PET, HDPE and LDPE, respectively.

Table 5: LCI data for recycled plastics (per kg)

Parameter	PET	HDPE	LDPE
Plastic input (kg/kg recycled plastic)	1.04	1.04	1.01
Recycled output (kg/kg recycled plastic)	1.00	1.00	1.00
Material loss (kg/kg recycled plastic)	0.04	0.04	0.01
Electricity consumption (kWh/kg)	0.22	0.49	0.91
Washing-water consumption (L/kg)	2.24	1.56	2.00
Chemical/detergent input (kg/kg)	0.002	0.003	0.024
Wastewater generation (L/kg)	2.13	1.48	1.90
Transport requirement (km)	60	60	50
Material-loss treatment	Process loss	Process loss	Process loss
Functional unit for recycle plastic	1 kg	1 kg	1 kg
System boundary	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate

Transport requirements were 60 km for PET and HDPE and 50 km for LDPE. These inventory differences indicate variations in polymer characteristics, feedstock requirements and processing conditions. Feedstock quality and contamination can further influence material recovery and recycling efficiency in heterogeneous plastic streams. Faraca and Astrup (2019) identified feedstock quality and contamination as key constraints in mechanical recycling, while Alrazen *et al.* (2025) highlighted processing configuration and feedstock quality as important determinants of recycling performance.

Life cycle impact assessment (LCIA)

Environmental and sustainability indicators are presented in Table 6. PET recorded the highest landfill diversion (85 ± 2%) and CO_2-eq emission reduction (2.10 ± 0.08 kg CO_2-eq/kg), followed by HDPE (80 ± 3%; 1.85 ± 0.06 kg CO_2-eq/kg) and LDPE (75 ± 2%; 1.50 ± 0.05 kg CO_2-eq/kg). Energy savings relative to virgin plastic increased from 62% for PET to 65% for HDPE and 68% for LDPE. The mechanical strength factor decreased from 1.15 ± 0.03 for PET to 1.10 ± 0.02 for HDPE and 1.05 ± 0.03 for LDPE, whereas SI increased from 78.1 ± 2.5 to 80.0 ± 2.8 and 82.6 ± 2.1, respectively. SI was calculated using the complete study-specific formulation, with the mechanical strength factor defined as the ratio of recycled to corresponding virgin-polymer compressive strength. These environmental benefits are consistent with Papo and Corona (2022) and Gabisa *et al.* (2023). Differences among polymers reflect material recovery, feedstock characteristics, energy requirements, and processing conditions. Faraca and Astrup (2019) highlighted the effects of feedstock quality and contamination, while Alrazen *et al.* (2025) emphasized processing configuration and feedstock characteristics. Direct numerical comparison remains limited by variations in functional units, system boundaries, feedstock composition, recycling efficiency, transport assumptions, and processing conditions.

Insights and implications of LCA findings

The life cycle assessment linked polymer characteristics to energy demand and sustainability, with heating and melting identified as the main hotspots (58 to 62%). PET required the highest heating energy (0.65 ± 0.02 kWh/100 g), while shredding contributed 17 to 20% and moulding 18 to 21%, identifying thermal processing as the main energy-reduction opportunity, consistent with Alrazen *et al.* (2025). A ±10% change in heating energy altered the Sustainability Index (SI) by ±6% for PET, ±5% for HDPE, and ±4% for LDPE, whereas material-loss changes caused less than ±2% variation, confirming energy demand as the dominant driver. These SI sensitivity were obtained by recalculating the complete SI equation after independently varying heating energy by ±10%, while keeping other components unchanged, representing net SI changes rather than direct inverse proportionality.

Table 6: LCIA Indicators

Impact category	PET	HDPE	LDPE
Landfill diversion (%)	85 ± 2	80 ± 3	75 ± 2
CO_2 emission reduction (kg CO_2/kg)	2.10 ± 0.08	1.85 ± 0.06	1.50 ± 0.05
Energy savings vs virgin (%)	62	65	68
Mechanical strength factor	1.15 ± 0.03	1.10 ± 0.02	1.05 ± 0.03
SI	78.1 ± 2.5	80.0 ± 2.8	82.6 ± 2.1

The environmental assessment applied polymer-specific emission factors for virgin plastics (2.75 kg CO_2-eq/kg for PET, 1.82 for HDPE, 1.95 for LDPE) and recycled counterparts (0.65 for PET, 0.64 for HDPE, 0.45 for LDPE) on a cradle-to-gate basis using India-relevant conditions for 2025, with electricity emissions at 0.70 kg CO_2-eq/kWh and greenhouse gases expressed on a 100-year global warming basis. Compared to virgin plastics, recycled PET, HDPE, and LDPE achieved energy savings of 62%, 65%, and 68%, respectively, with CO_2 reductions of 2.10, 1.85, and 1.50 kg CO_2/kg. PET provided the highest CO_2 reduction, while LDPE achieved the highest energy saving and SI. Gabisa *et al.* (2023) similarly reported greenhouse gas benefits. Low standard deviations for energy consumption (±0.03 to 0.05 kWh/kg) and material loss (0.01 to 0.04 kg) indicate good repeatability, though LCA outcomes remain sensitive to the electricity mix, transport, allocation, and feedstock quality (Faraca and Astrup, 2019). The findings support polymer-specific approaches targeting thermal energy reduction, material recovery, feedstock quality, and virgin-material substitution rather than a generalized recycling approach.

Polymer-specific mechanical recycling pathway for municipal plastics

The polymer-specific recycling pathway achieved effective material recovery, with low pre-treatment losses (1.33–2.00%) and satisfactory recycled-material performance, highlighting the importance of controlled segregation and feedstock quality. These findings support the observations of Faraca and Astrup, 2019, who identified contamination and sorting quality as critical constraints in municipal plastic recycling, while Alrazen *et al.* (2025) highlighted the influence of polymer properties and process configurations. Heating and melting accounted for 58 to 62% of energy demand, with PET requiring the highest heating energy (0.65 ± 0.02 kWh/100 g). LDPE achieved the highest SI (82.6 ± 2.1), whereas PET showed the greatest carbon reduction (2.10 kg CO_2/kg), indicating that energy efficiency and carbon mitigation vary by polymer type. The results indicate that polymer-specific optimization of thermal processing and material recovery is superior to a generalized municipal strategy.

Statistical analysis of recycled plastics

Exploratory one-way ANOVA with Benjamini–Hochberg FDR adjustment identified significant polymer-specific differences across most physical, mechanical, energy, and carbon-reduction properties. However, landfill diversion and the Sustainability Index did not show statistically significant differences.These findings are consistent with the polymer-specific performance characteristics reported by (Alrazen *et al.,* 2025), while providing quantitative evidence under controlled mechanical recycling conditions.

One-way ANOVA and Tukey post-hoc analysis of polymer properties

The physical, mechanical, and environmental properties of recycled PET, HDPE, and LDPE were evaluated to assess material performance and sustainability. The study provides an integrated, polymer-specific assessment linking process efficiency, physical and mechanical properties, environmental indicators, ANOVA, and the sustainability index. Original one-way ANOVA results are retained in Table 7 as exploratory

Table 7: One-way ANOVA and Benjamini–Hochberg FDR-adjusted comparison of polymer properties

Property category	Evaluated parameter	F-statistic (F)	p-value (p)	FDR-adjusted p	Significance level
Physical	Density (g/cm³)	152.3	<0.001	0.0023	***
	Water absorption (%)	9.42	0.016	0.0192	*
	Moisture content (%)	12.58	0.010	0.0138	*
	Melt flow index (g/10 min)	18.35	0.005	0.0082	**
	Melting temperature (°C)	246.7	<0.001	0.0023	***
	Vicat softening temperature (°C)	27.8	0.002	0.0040	**
	Crystallinity (%)	96.4	<0.001	0.0023	***
	Thermal stability (Onset °C)	14.2	0.008	0.0120	**
Mechanical	Tensile strength (MPa)	178.6	<0.001	0.0023	***
	Compressive strength (MPa)	148.1	<0.001	0.0023	***
	Elongation at break (%)	412.3	<0.001	0.0023	***
	Young's modulus (GPa)	203.5	<0.001	0.0023	***
	Impact strength (kJ/m²)	21.7	0.004	0.0072	**
	Shore D hardness	165.4	<0.001	0.0023	***
Environmental / Sustainability	Landfill diversion (%)	2.18	0.22	0.2329	ns
	Energy consumption (kWh/kg)	6.03	0.033	0.0371	*
	CO_2 emission reduction (kg CO_2/kg)	10.52	0.014	0.0180	*
	SI	1.72	0.27	0.2700	ns

Note: ***Highly significant (p < 0.001); **Significant (p < 0.01); *Moderately significant (p < 0.05); ns: Not significant.

statistical descriptors, with multiple-testing adjustment using the Benjamini–Hochberg FDR procedure. Complete replicate-level observations, sample sizes, residual diagnostics, normality tests, and homogeneity-of-variance assessments were not available for all parameters; consequently, the ANOVA results are interpreted as exploratory rather than definitive evidence of population-level effects.

i. *Physical properties:* The evaluated physical properties included density, water absorption, moisture content, melt flow index, melting temperature, Vicat softening temperature, crystallinity, and thermal stability. The F-statistic ranged from 9.42 to 246.7, with p-values from <0.001 to 0.016. After FDR adjustment, values remained below 0.05 for all eight parameters (0.0023–0.0192), indicating consistent polymer-level differences across the evaluated properties. PET had a density of 1.36 g/cm³, compared with 0.95 g/cm³ for HDPE and 0.92 g/cm³ for LDPE. PET also showed higher thermal resistance, while HDPE and LDPE showed greater flexibility. These differences are consistent with reported influences of polymer type, crystallinity, degradation history, and processing conditions, although the experimental design does not demonstrate causal relationships among these factors Alrazen *et al.* (2025).

ii. *Mechanical properties:* All mechanical parameters showed exploratory differences, with F-statistics of 21.7–412.3 and p-values of ≤0.004; FDR-adjusted p-values remained below 0.01. PET showed higher tensile strength (55.2 MPa) and compressive strength (83.4 MPa) than HDPE (31.5 and 52.7 MPa) and LDPE (24.8 and 42.3 MPa), respectively. PET had lower elongation at break (18.6%) than HDPE (420%) and LDPE (560%), indicating greater stiffness and lower ductility. However, molecular weight, intrinsic viscosity, oxidation indices, molecular-weight distribution, branching, and other direct degradation indicators were not evaluated; consequently, specific molecular or structural mechanisms cannot be established. These results describe polymer differences under the study conditions without establishing causal structure–property relationships. Published studies similarly report that recycled-polymer performance is influenced by polymer type, recycling history, molecular changes, crystallinity, contamination, and processing conditions (Das and Ali, 2025).

iii. *Environmental and sustainability properties:* The exploratory analysis indicated differences in energy consumption and CO_2 emission reduction, whereas landfill diversion and SI showed no clear differences after multiple-testing adjustment. The reported F-statistic were 2.18, 6.03, 10.52, and 1.72 for landfill diversion, energy consumption, CO_2 emission reduction, and SI, respectively. The corresponding FDR-adjusted p-values were 0.2329, 0.0371, 0.0180, and 0.2700. The CO_2 emission reduction values were 2.10 kg CO_2/kg for PET, 1.85 kg CO_2/kg for HDPE, and 1.50 kg CO_2/kg for LDPE, while energy consumption showed a smaller polymer-level difference. These sustainability characteristics should be interpreted in relation to collection, sorting, contamination, feedstock quality, recycling efficiency, and process configuration rather than attributed solely to polymer type, as these factors can collectively influence recycling performance and environmental outcomes (Faraca and Astrup, 2019).

PET exhibited higher density, tensile strength, and compressive strength, but lower elongation at break, whereas HDPE and LDPE showed greater ductility and flexibility. Sustainability indicators showed less polymer-level differentiation than physical and mechanical properties. The reported statistics are retained for transparency but treated as exploratory because the available information does not permit complete verification of inferential ANOVA assumptions prior to drawing definitive statistical conclusions.

Sustainability assessment

This section evaluates the environmental sustainability of polymer-specific mechanical recycling for PET, HDPE, and LDPE by integrating landfill diversion, energy consumption, carbon reduction, and material performance indicators. The findings provide an experimental basis for supporting circular economy practices and climate mitigation, with comparisons made against previous global and regional studies.

Contribution of recycling to environmental sustainability

Mechanical recycling significantly reduced landfill burden while generating reusable secondary materials. Landfill diversion efficiencies reached 85 ± 2% for PET, 80 ± 3% for HDPE, and 75 ± 2% for LDPE, exceeding typical previous studies ranges for post-consumer recycling (50–85%, Edjabou *et al.,* 2021). WRE and material recovery exceeded 95% for all polymers, with LDPE achieving 99 ± 0.5%, compared to typical industrial recovery rates of 60–90% (Tonini *et al.,* 2021). These high recovery values reflect the selected feedstock, as severely degraded, contaminated, ambiguous, and multilayer plastics were excluded and therefore should not be interpreted as representative of unsorted municipal plastic recycling. Pre-treatment losses remained minimal (total loss: 1.57%), which is lower than the 2–10% commonly reported (Van Eygen *et al.,* 2018). Additionally, microplastic mitigation is relevant: well-managed recycling reduces microplastic release by 56.8 million particles per year, whereas uncontrolled processes can increase particle release up to 2.4×10^9 particles per year (Gabisa *et al.,* 2023), emphasizing the importance of optimized pre-treatment and handling.

Reduction in carbon footprint

Substantial CO_2 emission reductions were achieved, strongly dependent on polymer-specific embodied carbon and recovery efficiency. PET exhibited the highest reduction (2.10 ± 0.08 kg CO_2 per kg), followed by HDPE (1.85 ± 0.06 kg CO_2 per kg) and LDPE (1.50 ± 0.05 kg CO_2 per kg), within the previous studies range for mechanical recycling (0.37–0.65 kg CO_2 per kg, Vollmer *et al.,* 2020) and consistent with global GHG mitigation scenarios of 67 Megatonnes of carbon dioxide equivalent (Mt CO_2-eq) (Gabisa *et al.,* 2023). Despite lower landfill diversion, LDPE achieved the highest SI (82.6 ± 2.1) due to its lower energy requirement, confirming that environmental performance depends on recovery efficiency, carbon intensity, and energy consumption. Mechanical recycling can provide greater greenhouse-gas benefits than alternative

treatment pathways under optimized conditions, while the European Union (EU) recycling rate of only 19.6% (Amadei *et al.,* 2025b) highlights the continuing gap in plastic recycling performance.

Energy savings through recycling

Total energy consumption varied by polymer and processing requirements. PET required 1.25 ± 0.05 kWh per kg, HDPE 1.10 ± 0.04 kWh per kg, and LDPE 0.95 ± 0.03 kWh per kg, which is consistent with previous studies ranges for mechanical recycling (0.9–1.5 kWh per kg, Szostak *et al.,* 2020). Heating and melting accounted for approximately 58–62% of total energy consumption. Lower LDPE processing temperature reduced energy requirements while maintaining mechanical performance. Effective process control during shredding, heating, and moulding helped minimize energy losses, reinforcing the environmental advantage of mechanical recycling relative to chemical recycling, which can consume similar or higher energy under pyrolysis/gasification scenarios (0.37–0.65 kg CO_2 per kg, Vollmer *et al.,* 2020). These results demonstrate that polymer-specific optimization of energy use is crucial for maximizing sustainability.

Long-term sustainability implications

Sustainability outcomes were assessed using landfill diversion, mechanical performance, energy efficiency, and carbon mitigation. Exploratory one-way ANOVA with Benjamini–Hochberg FDR adjustment identified polymer-specific differences in most physical and mechanical properties, energy consumption, and CO_2 emission reduction, but not for landfill diversion or the sustainability index. These differences are observational and do not establish causal or long-term sustainability effects. The findings provide a controlled experimental baseline within the defined system boundary. CO_2-eq reductions were 2.10, 1.85, and 1.50 kg CO_2-eq/kg for PET, HDPE, and LDPE, respectively, relative to corresponding virgin polymers. These are not directly comparable with absolute recycling impacts of 0.37–0.65 kg CO_2-eq/kg from previous LCA studies. Facility-scale recovery comparisons were interpreted cautiously because feedstock, contamination, sorting losses, process scale, and system boundaries differ. The high recovery reflects controlled laboratory process efficiency rather than municipal-scale recycling performance. Similarly, the material-recovery yield is process-level, whereas the EU recycling rate of 19.6% represents broader post-consumer waste management outcomes. These values were therefore considered contextual benchmarks. Recycling outcomes vary with feedstock composition, process configuration, energy sources, and system boundaries (Nordahl and Scown, 2024; Tonini *et al.,* 2021). Table 8 provides broader evidence from previous studies on climate impacts, recycling rates, resource use, and potential environmental risks associated with plastic recycling.

Sustainability context

Mechanical recycling is widely recognized as the most environmentally favorable plastic waste management pathway when polymer purity and process efficiency are adequately controlled. Previous LCA and material flow analysis studies have shown that sustainability outcomes are highly polymer-dependent, reflecting trade-offs among energy demand, greenhouse gas mitigation, material recovery, and mechanical performance (Tonini *et al.,* 2021; Van Eygen *et al.,* 2018). Literature values in Table 9 are used as contextual references, not universal performance thresholds. The comparison assesses whether experimental indicators fall within or exceed reported ranges without implying comparative performance. Differences among studies may reflect feedstock quality, process configuration, functional units, and system boundaries. Similarly, SI values depend on the selected indicators and weighting formulation and should not be interpreted as universally valid inherent sustainability rankings across polymers without comprehensive sensitivity and uncertainty analyses.

Table 8: Previous studies benchmarks for sustainability metrics of plastic recycling

Aspect	Recycling pathway / Context	Reported value (Range)	Key Interpretation	Source
Global GHG reduction	Substitution of virgin plastics with recycled polymers	67 Mt CO_2-eq (global scenario)	Large climate benefit from replacing virgin polymers	Gabisa *et al.* (2023)
Mechanical recycling GWP	Mechanical recycling of plastics (LCA studies)	0.37–0.65 kg CO_2 per kg	Lower climate impact compared with incineration and virgin production	Vollmer *et al.* (2020)
Chemical recycling GWP	Pyrolysis / gasification routes	0.37–0.65 kg CO_2 per kg	Can be competitive with mechanical recycling under optimized conditions	Vollmer *et al.* (2020)
Emission reduction vs incineration	Chemical recycling (pyrolysis)	Up to 70% GHG reduction	Strong advantage over energy-recovery incineration	Krell *et al.* (2025)
EU recycling rate	Post-consumer plastic waste (EU-27)	19.6%	Indicates limited circularity despite policy efforts	Amadei *et al.* (2025a)
Recycled plastic use in EU	Secondary plastics used in new products	5.5 Mt/y	Highlights gap between waste generation and recycled content demand	Amadei *et al.* (2025b)
Microplastic reduction	Use of recycled materials (system-level)	56.8 million particles per year	Recycling reduces leakage when well managed	Gabisa *et al.* (2023)
Microplastic increase (risk)	Mechanical recycling without mitigation	2.4×10^9 particles per year	Emphasizes need for improving process controls	Gabisa *et al.* (2023)

Table 9: Sustainability performance of mechanical recycling previous studies and present study

Indicator	Previous studies benchmark	Present study	Interpretation	Source
MRR (%)	60–90	PET 95.2; HDPE 95.5; LDPE 98.7	Recovery exceeds typical industrial values	Tonini *et al.* (2021)
Pre-treatment loss (%)	2–10	Total loss 1.57	Highly efficient washing and shredding	Van Eygen *et al.* (2018)
Energy consumption (kWh/kg)	0.9–1.5	PET 1.25; HDPE 1.10; LDPE 0.95	Consistent with optimized systems	Szostak *et al.* (2020)
CO_2 reduction (kg CO_2/kg)	1.1–3.0	PET 2.10; HDPE 1.85; LDPE 1.50	Within global mitigation ranges	Gabisa *et al.* (2023)
Landfill diversion (%)	50–85	PET 85; HDPE 80; LDPE 75	PET reaches upper benchmark	Edjabou *et al.* (2021)
Tensile strength trend	PET > HDPE > LDPE	55.2 > 31.5 > 24.8 MPa	Confirms polymer hierarchy	Das and Ali (2025)
SI	Energy–quality trade-off	PET 78.1; HDPE 80.0; LDPE 82.6	LDPE favored by low energy demand	Nordahl and Scown (2024)

Contextual comparison of material recovery and process efficiency

The comparison of material recovery and process efficiency is primarily relevant to feedstock condition and process control rather than numerical performance ranking. Previous studies report substantial variation in sorting efficiency, contamination, and recovery across heterogeneous plastic streams (Faraca and Astrup, 2019; Antonopoulos *et al.* 2021). The controlled, pre-segregated feedstock used in this study therefore represents a defined experimental condition distinct from heterogeneous municipal or industrial streams. The processing sequence and polymer-specific thermal conditions are considered in Table 10 to distinguish methodological effects from material-specific observations. Table 10 demonstrates that methodological and system-level differences affect recycling-result interpretation. The 1.57% overall processing loss was lower than impurity levels reported in previous studies, reflecting the manually segregated, controlled feedstock (Faraca and Astrup, 2019), while broad sorting and recycling ranges show that industrial recovery depends on feedstock and facility conditions (Antonopoulos *et al.,* 2021). Thus, the present polymer proportions indicate feedstock composition, not solely recovery efficiency within the analyzed industrial recovery streams.

Table 10: Comparison of previous studies with the present polymer-specific recycling results

Parameter	Previous study result	Present study result	Critical comparison	Source
Waste source & composition	PP and PE were consistently represented in CDW plastic; 86.11 kg manually separated and 57.74 kg mechanically sorted.	37 kg collected: PET 40.54%, HDPE 32.43%, LDPE 27.03%.	Confirms source-dependent polymer composition.	Lahtela *et al.* (2019)
Feedstock quality and loss	Impurities up to 28%; recycling potential 52% hard plastics, 59% films and 79% PVC.	PET 1.33%, HDPE 1.67%, LDPE 2.00% loss; overall 1.57%.	Lower loss reflects controlled, pre-segregated feedstock.	Faraca and Astrup (2019)
Sorting and recycling	PET sorting 45–97%, recycling 63–90%; HDPE sorting 13–95%, recycling 70–88%; purity 80–98%.	PET 40.54%, HDPE 32.43%, LDPE 27.03%.	Present values are composition data, not recovery rates.	Antonopoulos *et al.* (2021)
Recycling pathway	Collection → sorting → grinding → washing → drying → granulation.	Segregation → washing → drying → shredding → polymer-specific thermal processing.	Follows established mechanical recycling with polymer-specific processing.	Alrazen *et al.* (2025)
Processing conditions	No directly comparable polymer-specific conditions reported.	PET 250 °C/15 min; HDPE 145 °C/10 min; LDPE 120 °C/8 min.	Provides differentiated polymer-specific process control.	Alrazen *et al.* (2025)
Mechanical performance	Recycled MixPO WPC 5.8 MPa and recycled LLDPE WPC 5.5 MPa tensile strength.	PET 55.2, HDPE 31.5, LDPE 24.8 MPa.	Higher values are not directly comparable due to different material formulations.	Basalp *et al.* (2020)
Application potential	Recycled PP rebar showed 12.2 ± 0.6 kN maximum load.	Tensile strengths: PET 55.2, HDPE 31.5, LDPE 24.8 MPa.	Indicates reuse potential, but geometry and testing metrics differ.	Das and Ali (2025)
Energy consumption	Recycled-HDPE bottle system: 0.08 kWh/FU for 58.20 g HDPE.	PET 1.25, HDPE 1.10, LDPE 0.95 kWh/kg.	Different functional units and boundaries prevent direct comparison.	Papo and Corona (2022)
CO_2 reduction	Global recycling scenario indicated −67 Mt CO_2-eq and about 50 Mt resource savings.	PET 2.10, HDPE 1.85, LDPE 1.50 kg CO_2/kg.	Both indicate benefits, but scales and boundaries differ.	Gabisa *et al.* (2023)
Landfill diversion	No directly comparable polymer-specific value reported.	PET 85 ± 2%, HDPE 80 ± 3%, LDPE 75 ± 2%.	Provides polymer-specific landfill-diversion evidence.	Present study
LCA energy hotspot	No directly comparable hotspot percentage reported.	Heating/melting 52.6–56.0%; washing/shredding 28–30%; moulding/cooling 16–18%.	Heating and melting are the principal energy hotspots.	Present study
Energy savings	Recycled-material systems generally reduce impacts relative to virgin materials.	PET 62%, HDPE 65%, LDPE 68% savings.	Demonstrates polymer-specific energy savings within the defined boundary.	Present study
Statistical significance	No directly comparable three-polymer dataset.	Most physical/mechanical properties significant; energy and CO_2 significant; landfill diversion and SI non-significant.	Shows stronger polymer effects on material properties than sustainability indicators.	Present study
SI	No directly comparable integrated SI reported.	PET 78.1 ± 2.5, HDPE 80.0 ± 2.8, LDPE 82.6 ± 2.1.	Shows that sustainability is not determined solely by mechanical strength.	Present study
Overall performance	Previous studies emphasize feedstock heterogeneity, sorting limitations, contamination and environmental benefits.	Polymer-specific processing produced differentiated material, energy, environmental and sustainability outcomes.	Supports differentiated recycling strategies for municipal plastics.	Present study

PET showed the highest tensile strength (55.2 MPa), whereas HDPE and LDPE showed greater flexibility; comparisons indicate reuse potential, although differences in formulation, geometry, and testing metrics limit direct comparison (Basalp *et al.,* 2020; Das and Ali, 2025). Environmental comparisons are similarly affected by functional units, system boundaries, process assumptions, and impact categories. The present system required 0.95–1.25 kWh/kg and achieved 1.50–2.10 kg CO_2/kg reduction, while previous studies reported broader life-cycle outcomes under different conditions (Papo and Corona, 2022; Gabisa *et al.,* 2023). Heating and melting contributed 52.6–56.0% of total energy demand, making thermal processing the principal hotspot. Physical and mechanical properties showed greater differentiation than selected sustainability indicators. PET had the highest mechanical performance, while LDPE had the lowest energy demand (0.95 kWh/kg) and highest SI (82.6 ± 2.1). The SI a study-specific composite indicator rather than an inherent polymer property. Overall, the results indicate a trade-off between performance and sustainability and support polymer-specific segregation and processing under controlled conditions.

Circular economy perspective

In the context of circular economy implementation, polymer-specific mechanical recycling supported material utilization, resource efficiency, and reduced environmental burden. MRRs (95.2–98.7%) exceeded industrial benchmarks (60–90%), while pre-treatment loss (1.57%) was below reported ranges (2–10%), indicating effective material retention through segregation and pre-treatment (Van Eygen *et al.,* 2018; Tonini *et al.,* 2021). Energy consumption (0.95–1.25 kWh/kg) was within optimized ranges (0.9–1.5 kWh/kg), with lower LDPE demand demonstrating the importance of polymer-specific processing (Szostak *et al.,* 2020). CO_2 reductions (1.50–2.10 kg CO_2/kg) were within reported ranges (1.1–3.0 kg CO_2/kg), while landfill diversion (75–85%) aligned with benchmarks (50–85%) (Edjabou *et al.,* 2021; Gabisa *et al.,* 2023). The SI trend (LDPE > HDPE > PET) highlighted the role of energy efficiency, with LDPE showing higher sustainability despite lower landfill diversion (Nordahl and Scown, 2024). High recovery, low material losses, optimized energy use, and substantial carbon dioxide reduction support polymer-specific recycling for material recovery, reduced virgin-material dependence, and climate mitigation.

Implications for environmental sustainability

Mechanical recycling under controlled feedstock conditions reduced landfill burden, material losses, energy consumption, and carbon dioxide emissions while maintaining mechanically robust recycled materials. PET achieved the greatest CO_2 reduction, whereas LDPE showed the highest SI due to its lower energy demand. These findings indicate that sustainable polymer-specific recycling requires a balance among material recovery, mechanical performance, and energy efficiency rather than maximizing diversion alone. However, the experimental feedstock excluded multilayer, composite, severely degraded, and visibly contaminated plastics; therefore, the findings may not fully capture the variability present in heterogeneous municipal plastic waste.

Limitations of the study

Recovery values exceeding 95% were obtained under controlled laboratory conditions using well-sorted, relatively homogeneous PET, HDPE, and LDPE feedstocks. Multilayer, composite, severely degraded, and visibly contaminated plastics were excluded. Polymer identification was based on resin codes and physical characteristics with pre-segregation cross-checking, while independent FTIR confirmation was not performed. Therefore, recovery and environmental performance may not reflect heterogeneous municipal waste or industrial conditions. The study also lacked pilot- or industrial-scale validation and detailed techno-economic assessment. Thus, the polymer-specific recycling framework provides a basis for potential broader application rather than direct evidence of

large-scale implementation. Further research should include heterogeneous feedstocks, scale-up trials, techno-economic assessment, and LCA. As sampling occurred during a single collection period in March 2026, seasonal variation could not be assessed, and the reported PET, HDPE, and LDPE proportions are specific to the study feedstock rather than representative of year-round or regional composition. Uncertainty in energy-meter measurements, material-property testing, and CO_2-eq emission factors may also propagate into the overall energy, environmental, and sustainability indicators. Therefore, these vital resulting metrics should be interpreted strictly within the defined experimental conditions and system boundary.

Novelty and research gap

This study addresses an important research gap by integrating process efficiency, energy demand, physical and mechanical performance, CO_2 reduction, recovery, and overall sustainability into a polymer-specific assessment of PET, HDPE, and LDPE under controlled mechanical recycling conditions.

i. *Research gap:* Unlike previous studies that often examine individual material, process, or environmental indicators, the present study combines physical and mechanical performance with experimentally measured energy and environmental outcomes under common controlled recycling conditions.
ii. *Novel knowledge:* The experiment provides directly measured polymer-specific relationships among stage-specific energy demand, material properties, recovery, CO_2 reduction, and sustainability indicators that cannot be inferred from established intrinsic differences among PET, HDPE, and LDPE alone.
iii. *Statistical contribution:* Exploratory one-way ANOVA with Benjamini–Hochberg FDR adjustment provides a systematic assessment of polymer-specific differences across measured performance, energy, and sustainability indicators.
iv. *SI contribution:* The integrated framework provides a quantitative basis for assessing polymer-specific recycling performance through the study-specific SI, while its formulation, normalization, weighting, units, and mathematical consistency are explicitly clarified and the SI is not presented as the sole basis of novelty.
v. *Practical significance:* The findings provide a controlled laboratory baseline for evaluating polymer-specific recycling performance and energy-environment trade-offs, supporting further investigation of resource-efficient recycling strategies without implying direct municipal-scale optimization or large-scale implementation.

The principal novelty lies in the experimentally resolved polymer-specific dataset and integrated comparative framework developed under common controlled recycling conditions, providing a quantitative baseline for future pilot- and industrial-scale validation.

Recommendations and future perspectives

Processing conditions should be polymer-specific, particularly temperature, moulding time, and cooling. Energy-saving strategies such as preheating and optimized mechanical processing should focus on energy-intensive polymers such as PET. Future work should evaluate hybrid recycling streams and validate these findings through industrial-scale trials. These strategies can improve material quality, energy efficiency, and environmental performance while supporting circular plastic management.

CONCLUSION

Mechanical recycling of municipal plastic waste enhances environmental sustainability while producing reusable materials with preserved mechanical integrity and supporting circular economy objectives through material utilization (material recovery: 95.2–98.7%) and low process losses (1.57%). PET, HDPE, and LDPE were processed through polymer-specific pre-treatment, shredding, thermal consolidation, and

compression moulding, allowing systematic evaluation of WRE, material recovery, energy consumption, CO_2 emission reduction, mechanical performance, and SI. High process efficiency was observed, with waste reduction and material recovery exceeding 95% across all polymers, with LDPE achieving the highest recovery of 99%. PET exhibited the highest tensile strength (55.2 MPa), compressive strength (83.4 MPa), density (1.36 g/cm^3), and CO_2 emission reduction (2.10 kg CO_2/kg), while LDPE showed the lowest energy consumption (0.95 kWh/kg) and the highest observed SI (82.6 ± 2.1). HDPE displayed intermediate values across several evaluated parameters. Exploratory one-way ANOVA showed polymer-specific differences, with F-statistics of 1.72–412.3 and p-values of <0.001–0.27. After Benjamini–Hochberg FDR adjustment, most physical and mechanical properties, energy consumption, and CO_2 emission reduction were significant, whereas landfill diversion and SI were not. These differences represent observed polymer-specific variation under the experimental conditions and do not establish causal structure–property relationships. Density, crystallinity, mechanical performance, energy consumption, and carbon mitigation were therefore treated as observed recycling-performance indicators. The study's novelty lies in integrating mechanical, physical, and environmental indicators within a unified sustainability framework. The evaluated ranges were 0.95–1.25 kWh/kg energy consumption, 1.50–2.10 kg CO_2/kg CO_2 emission reduction, and 75–85% landfill diversion. The laboratory-scale design and well-sorted feedstocks limit extrapolation to mixed municipal waste and industrial conditions. Thus, the findings do not establish climate-change mitigation, industrial-scale performance, long-term sustainability, or broader circular-economy outcomes. PET showed higher tensile and compressive strength, HDPE intermediate mechanical characteristics, and LDPE greater flexibility and the highest observed SI. These findings support polymer-specific pre-treatment and processing. Future studies should evaluate mixed polymer streams, additional polymer types, low-energy processing, industrial-scale validation, and comprehensive life cycle assessment to examine broader environmental and economic implications.

AUTHOR CONTRIBUTIONS

D. Shankar conceived and designed the study, developed the methodology, conducted the investigation and experimental work, collected and analysed the data, and prepared the original manuscript draft. J. Nouri supervised the study, coordinated the project, and critically revised the manuscript. Ho Soonmin supervised the study, critically evaluated the work, interpreted the data, validated the scientific findings, and conducted the final review of the manuscript. B. Hitesh contributed to the literature review, analytical interpretation, and manuscript revision. M. Sankaramuthukumar contributed to methodological development, environmental sustainability analysis, supervision, and project coordination. All authors contributed to the interpretation of the findings, critically reviewed the manuscript, approved the final version, and agreed to all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests. Furthermore, the authors confirm that all ethical guidelines, including the prevention of plagiarism, misconduct, data falsification and fabrication, and redundant or duplicate submissions, were fully observed and maintained.

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POSITIVE AI STATEMENT

During the preparation of this work, the authors used QuillBot and Grammarly for English grammar and language improvement. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

ABBREVIATIONS

εb	Elongation at break
p	Probability value
ρ	Density
σc	Compressive strength
σ_t	Tensile strength
T_m	Melting temperature
T_{onset}	Thermal stability onset temperature
T_{vst}	Vicat softening temperature
%	Percent
°C	Degree Celsius
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
CO_2	Carbon dioxide
CO_2-eq	CO_2-equivalant
DSC	Differential scanning calorimetry
E	Young's modulus
EIA	Environmental impact assessment
EU	European Union
FDR	False discovery rate
GPa	Gigapascals
GHG	Greenhouse gas
g	Gram
g/cm^3	Grams per cubic centimetre
H^D	Shore D hardness
h	Hours
HDPE	High-density polyethylene
IS	Impact strength
kg	Kilograms
kg CO_2/kg	Kilograms of carbon dioxide per kilogram
kg CO_2-eq/kg	Kilogram carbon dioxicde-equivalant per kg
kJ/m^2	Kilojoules per square metre
km	Kilometre
kWh/kg	Kilowatt-hours per kilogram
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFD	Landfill diversion
LDPE	Low-density polyethylene
MFI	Melt flow index
MC	Moisture content
min	Minutes
mm	Millimetre
MPa	Megapascals
MRR	Material recovery rate
Mt CO_2-eq	Megatonnes of carbon dioxide equivalent
Mt/y	Megatonnes per year
PET	Polyethylene terephthalate
SD	Standard deviation
SI	Sustainability index
TGA	Thermogravimetric analysis
WA	Water absorption
Xc	Crystallinity

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