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Controlled Hot Pressing for Functional Upcycling of Waste Polyethylene Materials

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Abstract: Plastic waste represents an escalating environmental challenge and necessitates scalable processing strategies consistent with the United Nations' Sustainable Development Goal 12 on responsible consumption and production. This work examines controlled hot pressing of polyethylene-based waste as a physical upcycling route for producing functional laminate sheets. Low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polyethylene-coated polypropylene (PP/PE composite) were investigated, with processing temperature, pressure, and dwell time systematically analysed using an orthogonal experimental design. LDPE exhibited the most favourable forming behaviour, achieving continuous sheet formation at 120–130 °C under a nominal pressure of approximately 0.59 MPa with limited thickness variation. Relative to unprocessed films, hot-pressed materials displayed reduced surface friction and increased water contact angles, indicating decreased surface wettability under the applied conditions. Microscopic observations revealed modified surface morphology after processing, while elemental mapping showed no pronounced changes in macroscopic elemental distribution. HDPE achieved comparable consolidation, whereas PP/PE composites did not form continuous laminates. The results indicate that controlled hot pressing provides a low-energy and reproducible pathway for converting post-consumer polyethylene films into functional materials for circular applications.

Keywords: plastic upcycling; recycled polyethylene materials; controlled hot pressing; laminate consolidation; surface microstructuring; circular materials design

1. Introduction

Sustainable development has become a central issue as environmental pressures such as plastic pollution and climate change continue to intensify, posing growing risks to ecosystems and public health. Among these challenges, the management of plastic waste is particularly urgent, driven by the rapid expansion of single-use packaging and persistently low recycling rates for post-consumer plastics [1]. In response, the United Nations has identified "Responsible Consumption and Production" as a core objective within Sustainable Development Goal 12, underscoring the need for recycling and upcycling strategies that are both scalable and energy efficient. Polyethylene-based plastics, especially low-density polyethylene (LDPE) and high-density polyethylene (HDPE), represent a substantial share of global plastic consumption due to their extensive use in packaging, favourable mechanical performance, and widely reported resistance to environmental exposure [2]. Owing to their thermoplastic nature, these materials can be reprocessed through thermal consolidation without the addition of chemical reagents, offering opportunities for the transformation of post-consumer waste into value-added products.

Recycled polyethylene has been explored for a range of applications, including construction components, textile reinforcements, and consumer goods [3]. Nevertheless, the functional consistency of recycled products remains limited by variations in processing conditions, incomplete fusion between stacked materials, and insufficient surface functionality [4]. These factors complicate quality control and restrict wider material deployment. At present, mechanical recycling routes based on melting, pelletisation, and re-extrusion remain the dominant industrial approach for polyethylene waste treatment [5]. However, repeated thermal processing has been reported to influence polymer molecular characteristics and, in some cases, necessitates the use of stabilising strategies to maintain mechanical performance [6].

As an alternative, consolidation-based processing routes, including hot pressing, have been proposed as a means of directly converting stacked LDPE and HDPE materials into dense composite sheets, thereby avoiding intermediate pelletisation steps [7]. Such approaches are frequently discussed in the literature as a way to simplify processing and reduce cumulative thermal history. In parallel, efforts to enhance the surface functionality of recycled polyethylene have largely focused on chemical modification or nanoparticle-assisted methods. For example, superhydrophobic surfaces with water contact angles of approximately 159° were achieved using solvent-induced phase separation combined with silica nanoparticle incorporation [8]. Microtextured LDPE surfaces produced through hot pressing followed by mechanical exfoliation yielded contact angles exceeding 150°, although additional processing steps were required [9]. While effective, these strategies often involve complex processing sequences, specialised reagents, or auxiliary treatments, which may limit their suitability for decentralised or low-cost recycling systems. Against this background, a simplified, additive-free thermal consolidation route that enables both material densification and surface functional modification through controlled physical processing merits systematic investigation. From a materials perspective, hot pressing allows the modulation of polymer softening, interlayer contact, and microstructural rearrangement through adjustments in temperature, pressure, and dwell time. From an environmental standpoint, such an approach has the potential to support localised, resource-efficient recycling practices aligned with circular material flows and sustainable product design. Accordingly, this study examines the feasibility of controlled hot pressing for the physical upcycling of waste polyethylene, focusing on the effects of processing parameters on moulding behaviour, surface morphology, and functional performance (Figure 1).

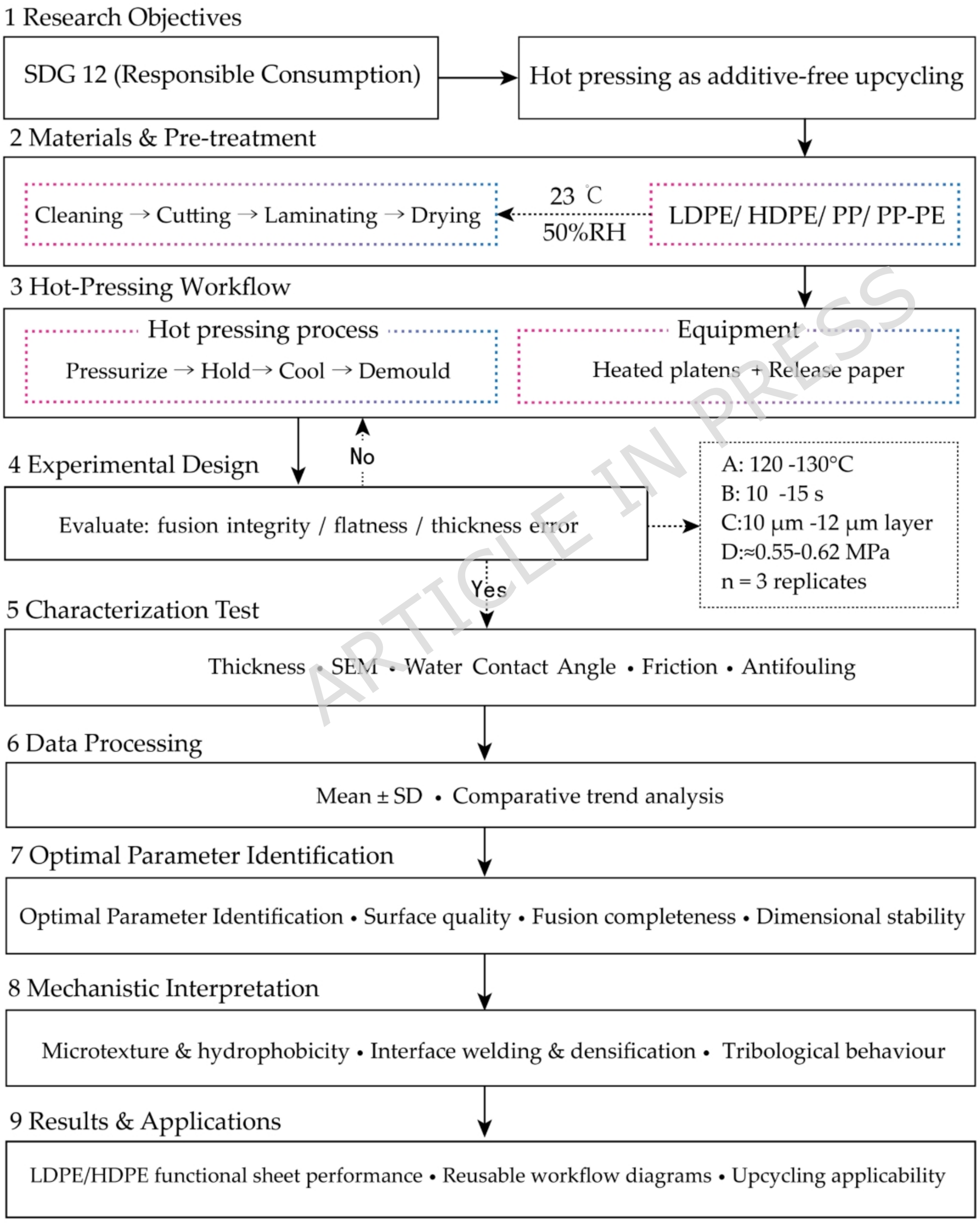


Figure 1. Study design flow chart.

2. Materials and Methods

2.1 Materials

Post-consumer polyethylene plastic bags were collected to evaluate their suitability for physical upcycling through controlled hot-press processing. Two collection routes were employed. The primary route involved collaboration with local courier distribution stations, where used delivery packaging materials were collected after consumer disposal. Additional samples were retrieved manually from public areas, including parks and beaches, to supplement the dataset. After collection, the materials were manually sorted based on readily observable physical characteristics, including film thickness, stiffness, and flexibility. The samples were classified as low-density polyethylene (LDPE), high-density polyethylene (HDPE), or polypropylene (PP), which represent the dominant material types used in disposable courier and packaging applications. LDPE films were characterised by their high flexibility and thin-film morphology, whereas HDPE samples exhibited greater stiffness. PP materials, commonly associated with food packaging, were included for comparison due to their limited thermoplastic forming performance under similar processing conditions. All samples were pre-treated by rinsing with water and a mild detergent to remove surface contaminants, labels, and adhered debris, followed by air drying under ambient laboratory conditions. The cleaned materials were then cut into square sheets matching the working area of the heat-press apparatus (KUDI hot-press machine). As the effective pressing area was defined by the platen dimensions, sample planar size was not treated as an experimental variable. Accordingly, both LDPE and HDPE samples were prepared as sheets measuring 38 × 38 cm. To achieve consistent initial thickness prior to hot pressing, the films were folded and stacked into layered assemblies. For example, a single 38 × 38 cm LDPE sheet was folded into a 19 × 19 cm stack, forming a two-layer laminate. HDPE specimens were prepared by stacking up to ten folded sheets to produce thicker assemblies suitable for consolidation. PP/PE composite samples were prepared using the same stacking protocol. All prepared stacks were stored under standard laboratory conditions (approximately 23 °C and 50% relative humidity) prior to hot-press processing (Figure 2).

(a)

(b)

(c)

Figure 2. Collection and processing of used plastics. Photographs taken by the authors. © 2026 The Authors.

2.2 Methods

2.2.1 Hot Pressing Process

All hot-pressing experiments were carried out using post-consumer plastic materials. Thermal consolidation was performed using a flatbed heated platen press (KUDI heat press, 38 × 38 cm working area). The press was equipped with parallel steel plates, digital temperature control (±1 °C), and a pneumatic loading system capable of delivering compressive forces of up to approximately 120 kN across the platen area. Prior to each experiment, the platens were preheated to the target temperature. Layered plastic stacks were placed between heat-resistant silicone release papers and positioned centrally between the platens. The press was then closed to apply the prescribed pressure for the designated dwell time. After hot pressing, the samples were allowed to cool to room temperature under sustained pressure before removal in order to maintain their flattened geometry (Figure 3).


(a) (b)

Figure 3. Flatbed hot-pressing system (KUDI heat press, 38 × 38 cm). Photographs taken by the authors. © 2026 The Authors.

2.2.2 Parameter Matrix and Experimental Design

Hot-pressing parameters were systematically varied to examine their influence on material consolidation and forming behaviour. Four primary processing factors were considered: (A) pressing temperature, (B) dwell time, (C) initial stack thickness (layer count), and (D) applied pressure. Preliminary screening trials were conducted to establish practicable parameter ranges for each factor. Both LDPE and HDPE films exhibited noticeable softening at temperatures above approximately 110 °C. Based on these observations, a temperature range of 110–150 °C was selected for evaluation. Dwell times of 20 s and 30 s were examined, reflecting the rapid deformation and fusion behaviour typically observed in thermoplastic films once their softening temperature is exceeded. The effective pressing area of the apparatus was 44 × 44 cm (1,936 cm², or 0.1936 m²). The press-controlled loading via a surface-pressure interface calibrated in kg cm^{-2}. A nominal setting of 6 kg cm^{-2} was applied, corresponding to approximately 0.588 MPa. Considering minor fluctuations inherent to the pneumatic system, the effective processing pressure was maintained within the range of 0.52–0.62 MPa. All pressures reported in this study are expressed in MPa for consistency.

Initial stack thickness was controlled through layered assembly of plastic films prior to hot pressing. HDPE specimens were prepared using 2–5 stacked layers, while higher layer counts were used for LDPE to compensate for its lower individual film stiffness and thickness. The nominal single-layer thickness ranged from 10 to 15 μm, consistent with typical post-consumer polyethylene bag films. Two representative thickness levels (10 μm and 12 μm) were selected for the orthogonal experimental design. An orthogonal experimental design based on the Taguchi method was employed to identify suitable processing conditions. A 2^4 factorial orthogonal array comprising 16 experimental runs was constructed, with two levels assigned to each factor: temperature (120 °C and 130 °C), dwell time (20 s and 30 s), nominal thickness (10 μm and 12 μm), and applied pressure (0.55 MPa and 0.62 MPa). Each experimental run corresponded to a unique combination of these parameters (Table 1). All orthogonal experiments were performed using LDPE specimens, which exhibited more consistent forming behaviour during preliminary trials. After processing, each pressed sheet was visually examined for overall fusion completeness and surface flatness to assess the influence of processing parameters on forming quality.

Table 1. Optimal Data Combinations for LDPE Designed through Orthogonal Experiments.

Material	Temperature (°C)	Time (s)	Thickness (μm)	Pressure (Mpa)
1	120	20	10	0.55
2	120	20	12	0.55
3	120	20	10	0.62
4	120	20	12	0.62

5	120	30	10	0.55
7	120	30	12	0.55
7	120	30	10	0.62
8	120	30	12	0.62
9	130	20	10	0.55
10	130	20	12	0.55
11	130	20	10	0.62
12	130	20	12	0.62
13	130	30	10	0.55
14	130	30	12	0.55
15	130	30	10	0.62
16	130	30	12	0.62

2.2.3 Temperature and Pressure Screening

The results of temperature-screening experiments are summarised in Table 2. LDPE formed coherent sheets within the temperature range of 110–140 °C, whereas HDPE required temperatures of at least 120 °C to achieve continuous sheet formation. At 110 °C, HDPE samples exhibited incomplete forming. The polyethylene-coated polypropylene samples did not form continuous sheets below 130 °C. Increasing processing temperature was associated with a progressive reduction in sheet thickness, indicating enhanced material flow and consolidation during pressing. For instance, LDPE sheets pressed at 130–140 °C exhibited reduced thickness (~0.17 cm) compared with those pressed at 110–120 °C (~0.31 cm). The influence of pressure is summarised in Table 3. Sheets processed at the higher pressure level (0.62 MPa) generally exhibited improved flatness and reduced thickness relative to those processed at 0.55 MPa. For both LDPE and HDPE, the combination of higher pressure and elevated temperature resulted in more uniform sheet morphology. Typical examples of incomplete forming observed under sub-optimal processing conditions are presented in Figure 4. These morphologies included incomplete melting, interlayer sliding, and edge deformation, particularly in HDPE at lower temperatures and in polypropylene-containing stacks. Such features are attributed to insufficient material softening and limited interlayer contact under the selected processing conditions, rather than to intrinsic material degradation.

Table 2. Moulding Status and Thickness Results When Pressing the Plastic Materials at Different Temperatures.

Material	Temperature (°C)	Moulding Status	Moulded Thickness (cm)
LDPE	110–120	Formed	0.31
	120–130	Formed	0.28
	130–140	Formed	0.17
	140–150	Not formed	/
HDPE	110–120	Awaiting formation	0.4
	120–130	Formed	0.26
	130–140	Formed	0.21
	140–150	Not formed	/
LDPE/HDPE	110-120	Awaiting formation	0.36
	120-130	Formed	0.31
	130-140	Formed	0.29
	140-150	Formed	0.25
Polyethylene-coated polypropylene	110–120	Not formed	/

Table 3. Moulding Status of Plastic Materials Using Different Temperature and Pressure Combinations.

Material	Temperature (°C)	Pressure (MPa)	Moulding Status
LDPE	110–120	0.55	Relatively flat
	120–130	0.62	Flat
	110–120	0.55	Flat
	120–130	0.62	Optimal flat
HDPE	120–130	0.55	Flat
	130–140	0.62	Flat
	120–130	0.55	Flat
	130–140	0.62	Optimal flat
LDPE/HDPE	120-130	0.55	Relatively flat
	130-140	0.62	Flat
	120-130	0.55	Flat
	130-140	0.62	Optimal flat


(a) (b) (c)

Figure 4. Examples of unmoulded or incompletely consolidated polymer sheets obtained under sub-optimal hot-pressing conditions: (a) LDPE; (b) HDPE; (c) polypropylene-containing samples. Photographs taken by the authors. © 2026 The Authors.

All hot-pressing experiments were conducted in triplicate (independent runs, n = 3). After cooling, the pressed specimens were subjected to dimensional and surface characterisation. Processing effects were evaluated through comparative trend analysis based on the orthogonal experimental design, focusing on variations in sheet thickness, surface flatness, friction coefficient, and water contact angle. Based on these comparative trends, a processing condition of 120 °C pressing temperature, 20 s dwell time, approximately 12 µm nominal layer thickness, and a pressure of approximately 0.59 MPa was selected as a representative parameter set for subsequent material fabrication and characterisation.

2.3 Characterisation Methods

A set of characterisation techniques was employed to examine changes in physical dimensions, surface properties, and macroscopic morphology of the plastic materials before and after hot pressing.

2.3.1 Thickness Measurement

Sheet thickness was measured using a heavy-duty dial thickness gauge (SYNTEK, analogue resolution 0.01 mm) and a digital film thickness meter (KOSLO). For each sample, measurements were taken at five randomly selected positions and averaged. Individual plastic bag films exhibited thicknesses in the range of several tens of micrometres, whereas the hot-pressed sheets reached thicknesses on the millimetre scale, depending on the initial number of stacked layers and processing conditions. Thickness differences before and after hot pressing were recorded to document dimensional changes associated with consolidation. For LDPE and HDPE, the measured post-press thickness deviated by less than 2% from the nominal stacked thickness, indicating limited material displacement during pressing.

2.3.2 Mass Measurement

Sample mass was measured before and after hot pressing using an electronic balance (KTRUE, accuracy ±1 mg). Each layered stack (approximately 15–20 g) was weighed prior to processing, and the corresponding pressed sheet was weighed after cooling. For both LDPE and HDPE, mass variations remained within ±2%. Minor differences were attributed to edge trimming and measurement uncertainty. Within the sensitivity of the balance, no substantial mass loss was detected under the applied hot-pressing conditions.

2.3.3 Water Contact Angle

Static water contact angle (WCA) measurements were performed using a goniometer (DSA25 drop shape analyser). A 5 µL droplet of deionised water was deposited onto the sample surface, and the contact angle at the solid–liquid–air interface was recorded. Five measurements were taken at different positions on each sample and averaged. Hot-pressed LDPE sheets exhibited contact angles of approximately 89°, compared with approximately 87° for unpressed LDPE films. For HDPE, the contact angle increased from approximately 85° before pressing to approximately 90° after pressing. Vertical drip tests were additionally conducted to provide a qualitative assessment of surface wetting behaviour. Water was dripped from a height of 20 cm onto horizontally placed samples at a flow rate of approximately 10.5 mL min^{-1} for 10 min. After exposure, excess water was removed using compressed air, and the surface appearance was visually inspected. Only limited wetting was observed, and no extensive darkened regions indicative of prolonged water retention were detected (Figures 5).

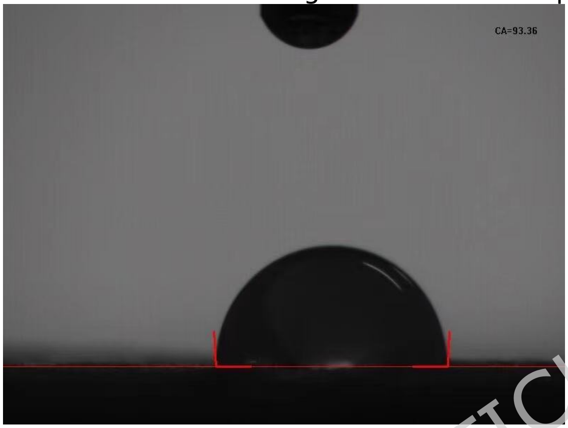


Figure 5. Contact angle images of moulded LDPE material.

2.3.4 Friction and Abrasion Resistance

Surface friction behaviour was assessed using a friction tester (QGY57 electric friction fastness tester) following a standard fabric rubbing protocol. A weighted sled covered with a standard textile patch was drawn across the sample surface at a constant speed, and the drag force was recorded to calculate the dynamic coefficient of friction (COF, μ). Multiple measurements were performed for each sample, and average values were reported. Prior to pressing, LDPE and HDPE exhibited COF values of approximately 0.60 and 0.80, respectively. After hot pressing, the COF decreased to approximately 0.30 for LDPE and 0.20 for HDPE. Abrasion behaviour was qualitatively evaluated by repeated rubbing with a coarse cloth. No macroscopic peeling or layer separation was observed under the applied rubbing conditions, although slight surface burnishing occurred after extended contact. These observations indicate a reduction in surface friction and altered surface texture following hot pressing (Figure 6).

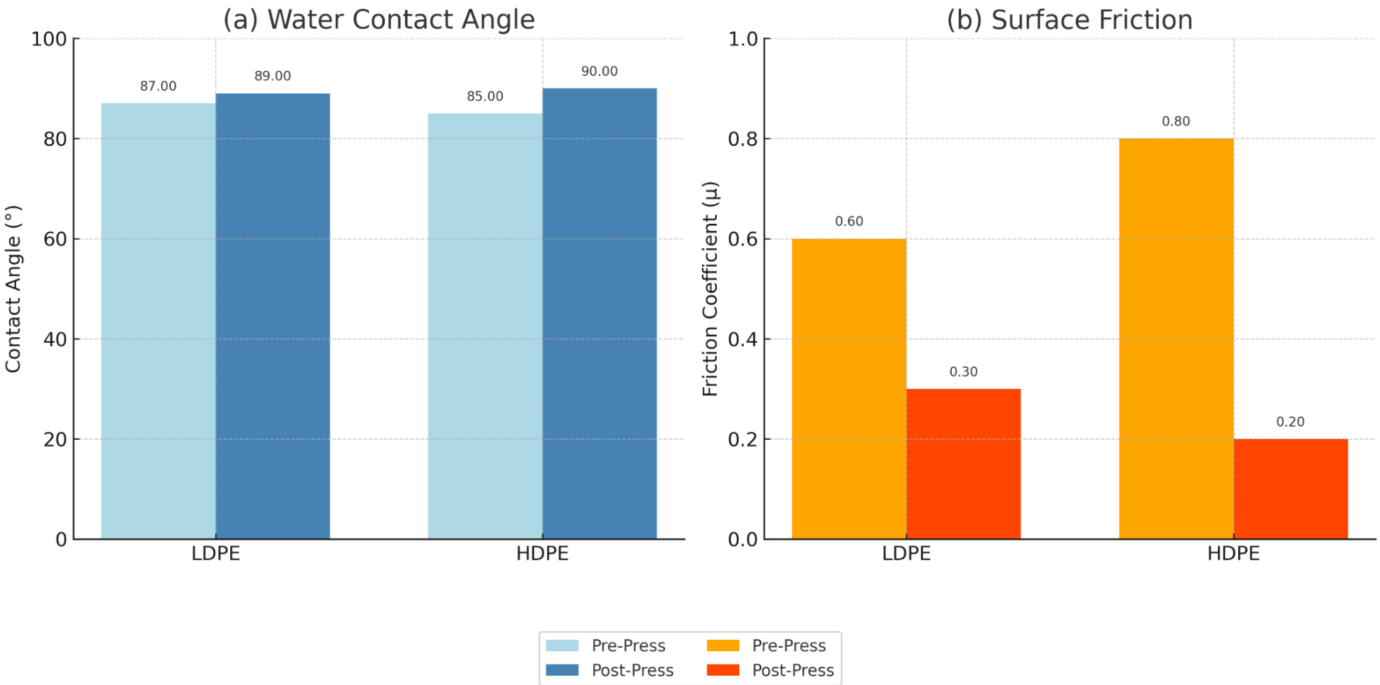
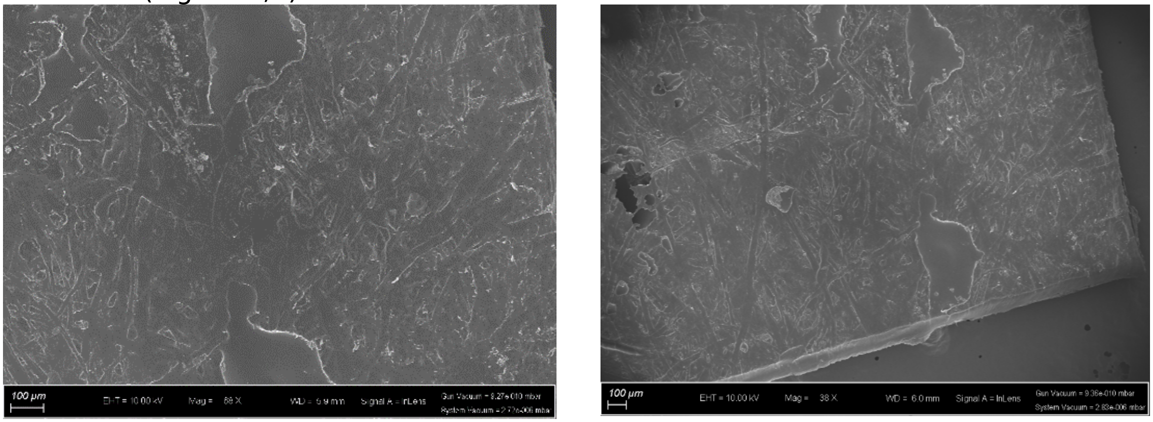


Figure 6. Improvements in the surface properties of LDPE and HDPE after hot pressing. (a) Water contact angle: Pressed sheets showed higher contact angles (LDPE, 89°; HDPE, 90°) compared with the unpressed materials (LDPE, 87°; HDPE, 85°), indicating enhanced hydrophobicity. (b) Surface friction: The dynamic friction coefficient dropped significantly following pressing (LDPE, from 0.6 to 0.3; HDPE, from 0.8 to 0.2), corresponding to a smoother, more wear-resistant surface. Each bar represents the mean of three measurements; error bars (standard deviation) are within the height of the bars.

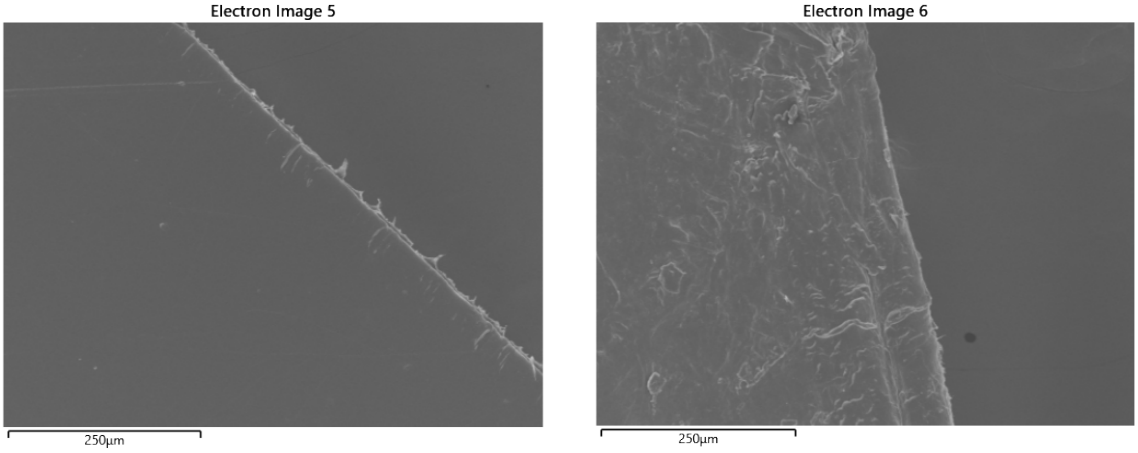
2.3.5 Surface Morphology

Surface morphology was examined using scanning electron microscopy (SEM). Prior to imaging, samples were sputter-coated with a thin gold layer to minimise charging. Compared with the relatively smooth surfaces of the original films, hot-pressed samples exhibited increased surface roughness at the microscale. This roughness is attributed to deformation and rearrangement of stacked layers during thermal compression. Energy-dispersive spectroscopy (EDS) was employed to map the spatial distribution of detectable elements on the sample surfaces. Elemental maps obtained before and after hot pressing showed similar macroscopic distributions of the major detected elements (C, O, Si, and Ca). Within the resolution of EDS, no pronounced changes in relative elemental proportions were observed. These results are reported solely to describe gross elemental distribution at the detectable scale; EDS does not provide information on polymer chain integrity, chemical modification, or degradation processes. (Figure 7,8)



(a) Before friction (b) After friction

Figure 7. Morphology of the composite plastic fabric under a 100 μm high-magnification microscope.



(a)Before (b) After

Figure 8. Surface morphology of LDPE plastic fabric before and after hot pressing under high-magnification microscopy (250×).

2.3.6 Stain Resistance and Oleophobic Response

Resistance to common liquids was evaluated by placing small droplets (~0.5 mL) of iced tea, milk, and cooking oil onto the surface of the hot-pressed samples (Figure 9). The droplets were left in contact with the surface for 10 min, after which wetting behaviour and spreading were visually assessed, and contact angles were recorded. Water-based liquids remained largely beaded with limited spreading, and oil droplets maintained a discrete shape with contact angles exceeding 80°. After removal of the liquids, no visible staining was observed, and any residual traces were readily wiped away. These observations indicate limited wetting of both aqueous and oily liquids under the test conditions.

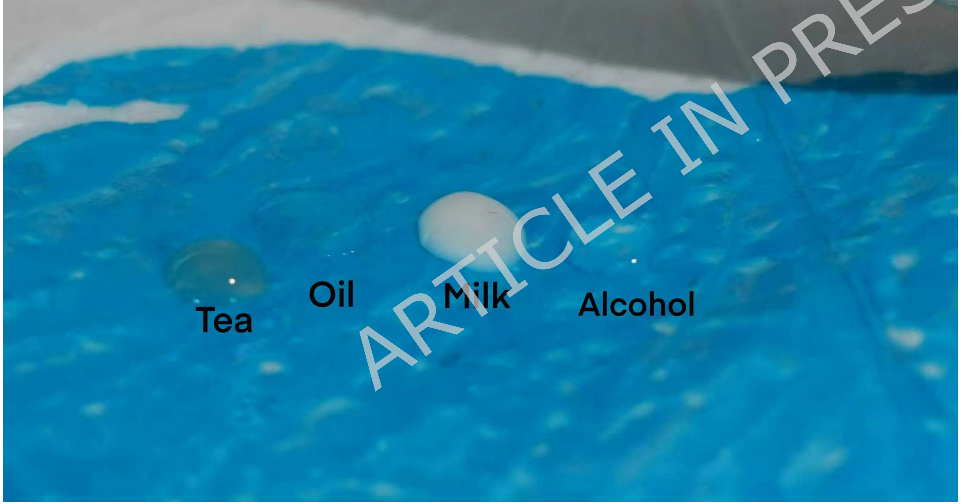


Figure 9. Anti-fouling performance of LDPE material.

2.4 Data Processing and Analytical Approach

All experiments were conducted in triplicate under each processing condition, and results are reported as mean values with corresponding standard deviations. Given the limited sample size associated with the orthogonal experimental design, formal hypothesis-driven statistical analyses were not applied. Instead, data interpretation was based on comparative trend analysis across different processing conditions to examine the influence of temperature, pressure, dwell time, and initial stack thickness on forming behaviour and surface-related properties. All interpretations are restricted to the resolution and scope of the experimental measurements performed.

3. Results and Discussion

3.1 Feasibility of Hot-Press Moulding for Different Waste Plastics

The feasibility of hot-press moulding was first examined for different categories of post-consumer plastic materials. Figure 10 illustrates the influence of pressing temperature on the final sheet thickness of LDPE and HDPE under a constant surface pressure of approximately 0.59 MPa and a dwell time of 10 s. At 115 °C, HDPE did not form continuous sheets, as indicated by incomplete consolidation, whereas LDPE produced coherent, self-supporting laminates. With increasing temperature, both materials exhibited progressive thickness reduction, reflecting enhanced deformation and compaction during pressing. The moulding behaviour of different polymer systems is summarised in Table 4. Within the investigated temperature range (110–150 °C), LDPE could be consolidated at relatively lower temperatures (110–120 °C), while HDPE required moderately higher temperatures (120–130 °C) to achieve comparable sheet continuity and surface uniformity. In contrast, polypropylene (PP), whether processed alone or within PP/PE stacked assemblies, did not form continuous laminated sheets within the same temperature window. This outcome is attributed to the higher melting temperature of PP (approximately 160 °C), which lies outside the experimental range, as well as limited compatibility with polyethylene under the selected processing conditions. Layered LDPE/HDPE assemblies were further examined to represent mixed polyethylene waste streams. Under identical hot-pressing conditions, these laminates formed continuous sheets without visible macroscopic separation between layers. In contrast to PP-containing systems, LDPE/HDPE stacks showed consistent consolidation behaviour across the tested temperature range. Based on moulding performance and energy considerations, LDPE demonstrated the most favourable forming adaptability among the investigated materials and was therefore selected as the primary feedstock for subsequent parameter optimisation and property evaluation.

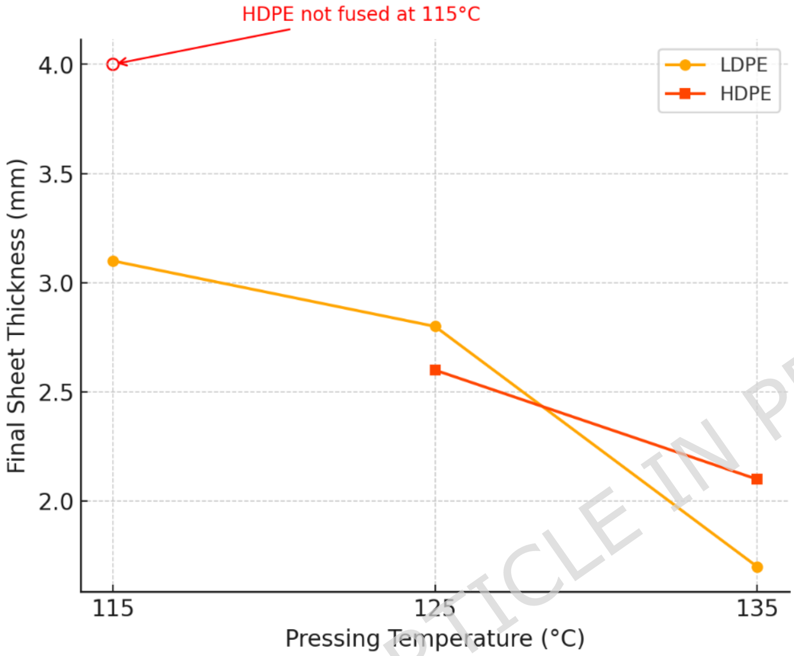


Figure 10. Effect of hot-pressing temperature on final sheet thickness for LDPE and HDPE (at a constant pressure of 0.59 MPa and a dwell time of 10 s). At 115 °C, HDPE did not fully fuse (open symbol), whereas LDPE formed a coherent sheet. As the temperature increased, both polymers produced thinner sheets due to enhanced melt flow and pressure-assisted compaction.

Table 4. Moulding Conditions and Forming Performance of Different Plastic Materials

Material	Temperature (°C)	Moulding Status	Final Thickness (cm)	Remarks
LDPE	110	Formed	0.31	Partial fusion
LDPE	120	Optimal	0.28	Best surface flatness
HDPE	130	Formed	0.17	Complete fusion
HDPE	120	Optimal	0.26	Good product quality
PP	110-150	Failed	—	Thermal incompatibility

3.2 Primary Factors Influencing Material Moulding Performance

The influence of processing parameters on moulding behaviour was evaluated using LDPE specimens subjected to systematically varied temperature, pressure, and dwell time conditions. Orthogonal analysis indicated that pressing temperature exerted the strongest influence on forming quality, followed by applied pressure, while dwell time played a secondary role within the investigated range. At temperatures below approximately 100 °C, insufficient softening of adjacent layers resulted in incomplete consolidation and elevated porosity. When processing temperatures were maintained between 115 and 120 °C, the moulded sheets exhibited improved continuity and surface smoothness. Increasing applied pressure generally promoted more uniform compaction, although excessive pressure occasionally led to local thickness variations due to non-uniform material flow. In comparison, variations in dwell time primarily affected the degree of consolidation through heat transfer rather than inducing pronounced changes in surface morphology. These observations indicate that temperature and pressure are the dominant parameters governing hot-press moulding behaviour for LDPE under the selected processing conditions.

3.3 Property Characterisation and Functional Enhancement of Materials after Hot Pressing

Hot pressing resulted in measurable changes in surface-related properties. Static water contact angles increased from approximately 85–87° for unpressed films to 89–90° after processing, indicating reduced surface wettability within the tested range. The coefficient of friction decreased from initial values of approximately 0.60–0.80 to 0.30–0.20, corresponding to reductions of up to 50–75% (Table 5). During abrasion tests, no macroscopic peeling or layer separation was observed under the applied conditions; instead, only slight surface polishing occurred. Anti-fouling behaviour was also examined. Tea and milk droplets remained largely beaded on the pressed surfaces with limited lateral spreading, while oil droplets maintained a discrete shape with contact angles exceeding 80°. After gentle wiping, no visible residues remained. These results indicate reduced wetting and staining under the specific test conditions employed. Scanning electron microscopy (SEM) revealed that hot-pressed samples exhibited increased surface roughness compared with the original films, along with more continuous macroscopic morphology. Energy-dispersive spectroscopy (EDS) mapping showed similar macroscopic distributions of the detected elements (C, O, Si, and Ca) before and after pressing (Table 6). Within the resolution of EDS, no pronounced changes in relative elemental proportions were observed. These observations are reported solely to describe gross elemental distribution at the detectable scale and are not interpreted as evidence of chemical stability, molecular integrity, or degradation behaviour.

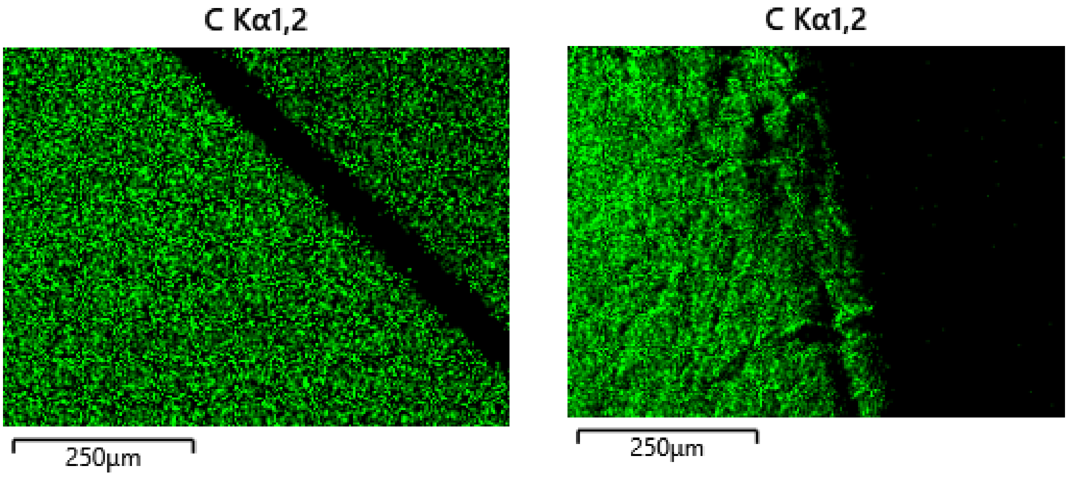
Table 5. Comparison of material properties of LDPE and HDPE before and after hot pressing under optimal conditions

Property	Before	After (Optimal Conditions)	Improvement	Reproducibility assessment
Thickness (cm)	LDPE: 0.31 ± 0.08 HDPE: 0.40 ± 0.10	LDPE: 0.17 ± 0.10 HDPE: 0.21 ± 0.10	LDPE: ↓45% HDPE: ↓48%	Consistent across replicates
Coefficient of friction (μ)	LDPE: 0.60 HDPE: 0.80	LDPE: 0.30 HDPE: 0.20	LDPE: ↓50% HDPE: ↓75%	Consistent across replicates
Water contact angle (°)	LDPE: 87° HDPE: 85°	LDPE: 89° HDPE: 90°	LDPE: +2° HDPE: +5°	Consistent across replicates
Mass loss (%)	—	< 2% (both materials)	Minor	No significant change observed

Table 6. Comparison of elemental composition of LDPE before and after hot pressing based on EDS measurements.

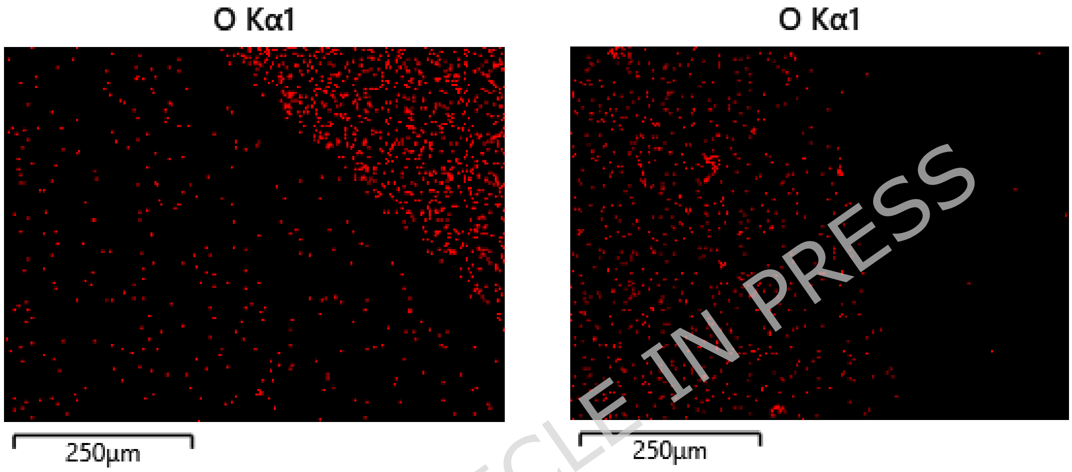
Element	Before (%)	After (%)	Change
C	82.3 ± 2.1	83.1 ± 1.9	+ 0.8%
O	12.4 ± 1.5	10.2 ± 1.3	- 2.2%
Si	3.2 ± 0.8	4.1 ± 0.9	+ 0.9%
Ca	2.1 ± 0.6	2.1 ± 0.6	~ 0%

After stacking LDPE and HDPE layers and consolidating them by hot pressing, energy-dispersive spectroscopy (EDS) was performed to characterize the macroscopic elemental distribution and relative elemental proportions within the composite material. The EDS results indicate that no pronounced changes in the spatial distribution or relative proportions of the detected elements were observed before and after hot pressing (Figure 11-15). It should be emphasized that these observations are strictly limited to gross elemental presence at the detectable scale. EDS cannot distinguish polymer chain integrity, chain scission, oxidation, or other subtle chemical or molecular structural changes; therefore, the EDS results are not interpreted as evidence of chemical stability or molecular structural preservation.



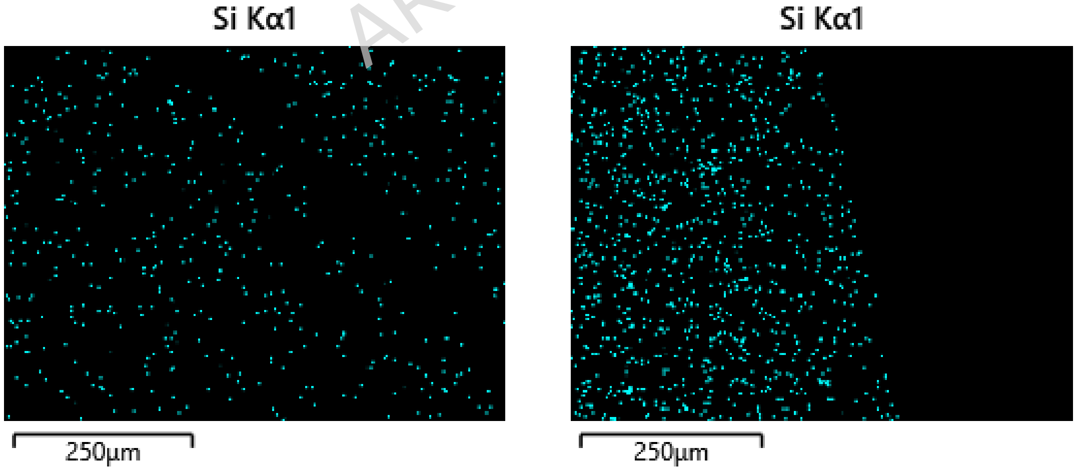
(a)Before (b)After

Figure 11. Distribution of carbon elements in the experimental material before and after hot pressing.



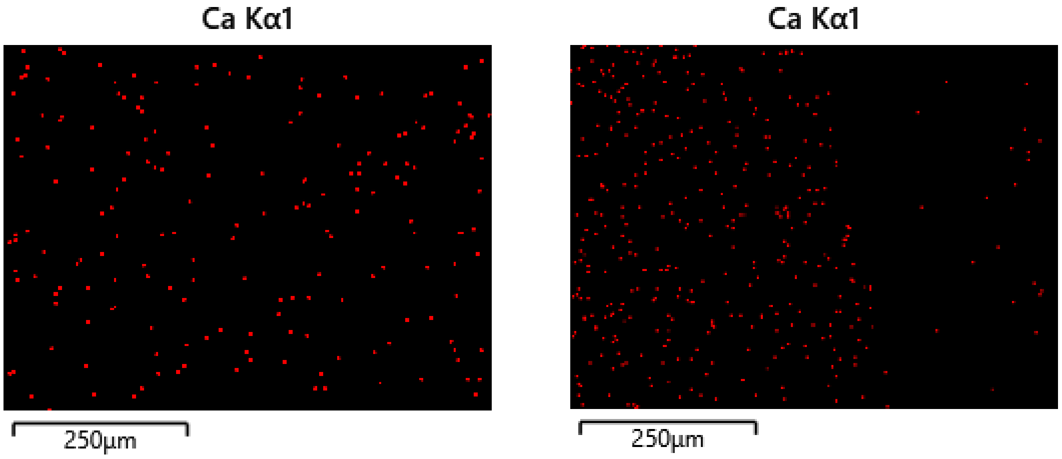
(a)Before (b)After

Figure 12. Distribution of oxygen elements in the experimental material before and after hot pressing.



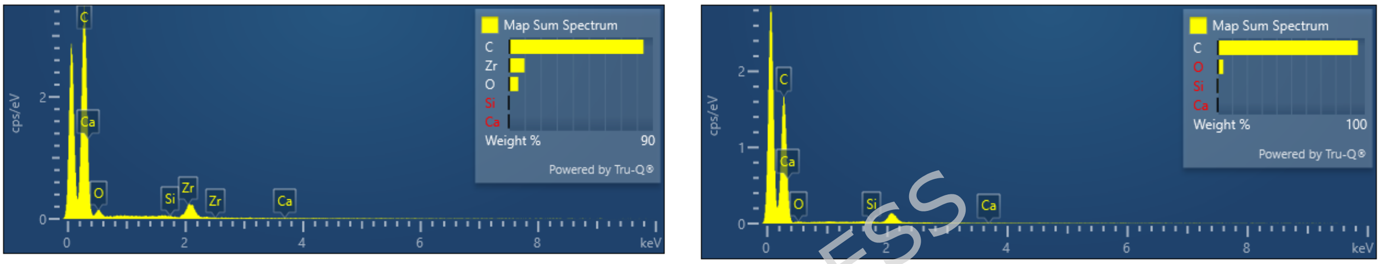
(a)Before (b)After

Figure 13. Distribution of silicon elements in the experimental material before and after hot pressing.



(a)Before (b)After

Figure 14. Distribution of calcium elements in the experimental LDPE material before and after hot pressing.



(a)Before (b)After

Figure 15. Elemental composition ratio diagram of the LDPE experimental material.

On this basis, a peeling (tensile tear) test was conducted on the hot-pressed composite material to examine its interlayer mechanical response under the specified loading conditions. The peeling experiments were performed using an electronic fabric strength tester (YG(B)026HC-250). Rectangular specimens with a width of 20 mm and a length of 50 mm were prepared. Each tested specimen consisted of six layers, which were divided into two groups of three layers and clamped under pressure for the peeling procedure. A schematic illustration of the layered structure is shown in Figure 16, while the tensile force–crosshead displacement curves obtained during the peeling tests are presented in Figure 17. The corresponding test parameters are summarized in Table 7.

The measured tear force values are listed in Table 8. Under the testing conditions employed, the tear force ranged from 3066.70 to 5474.12, with an overall mean value of 3869.47 and a coefficient of variation (CV) of 21.86%. Although some dispersion among individual specimens was observed, no abrupt force drops or instantaneous macroscopic delamination events were detected during the peeling process. These results are reported solely to describe the force–displacement response of the hot-pressed composite under the present experimental conditions and do not constitute a quantitative assessment of interlayer adhesion strength, delamination resistance, or long-term structural stability.

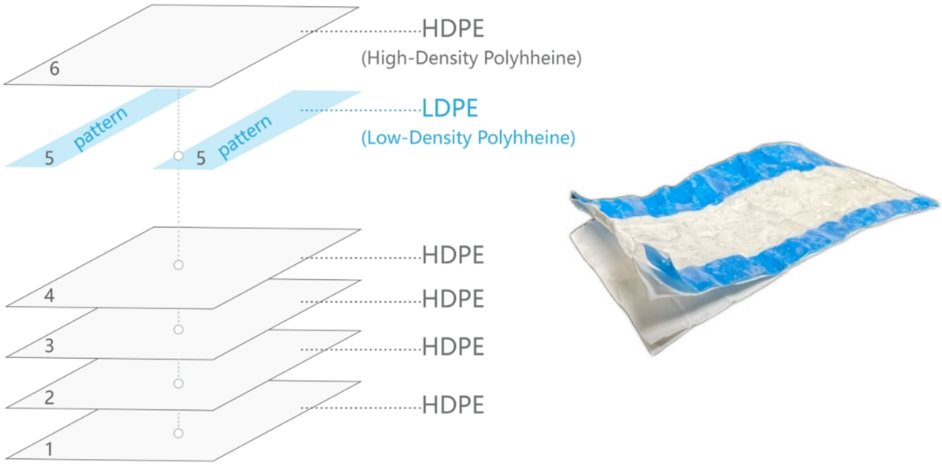


Figure 16. Schematic illustration of the layered structure of the composite material.

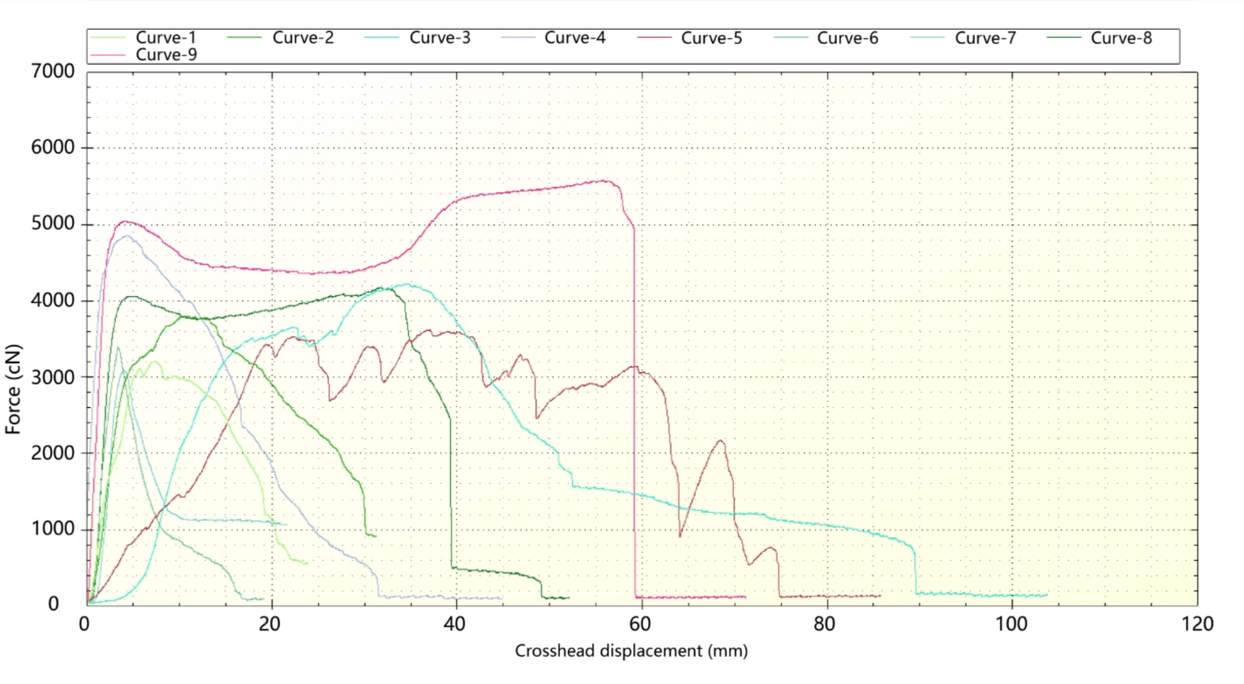


Figure 17. Tensile force-crosshead displacement curves of the composite material.

Table 7. Test parameters for tensile tear testing.

Parameter	**Value**	**Unit**
Test method	Trouser tear method （GBT3917.2）	-
Test standard	GBT3917.2	-
Number of tests	5	-
Load range	2500	N
Pretension	28	cN
Initial force	10	cN
Gauge length	7.48	mm
Test speed	100	mm/min
Test temperature	25	℃
Relative humidity	65	%
Specimen width	20.00	mm

Table 8. Measured tear force values.

No.	**Tear Force**
1	3095.54
2	3786.72
3	4132.14
4	4838.9
5	3066.7
6	3378.33
7	3070.97
8	3981.81
9	5474.12
Overall maximum	5474.12
Overall minimum	3066.7
Overall mean	3869.47

Overall CV (%)	21.86

3.4 Processing-Induced Deformation and Consolidation Behaviour

During hot pressing, polyethylene films undergo softening and deformation under combined thermal and mechanical loading, enabling adjacent layers to conform to each other and form continuous macroscopic sheets. For HDPE, which has a higher melting temperature than LDPE, sufficient processing temperatures were required to achieve comparable deformation and sheet continuity. At lower temperatures, incomplete softening resulted in uneven surfaces and partial consolidation, whereas temperatures between 120 and 130 °C produced more uniform sheet thickness and improved surface regularity. Surface micro-texturing observed after processing may arise from non-uniform cooling or contact with the press surfaces during consolidation. These features are consistent with deformation-dominated forming processes and do not imply changes in polymer chemistry. Under the applied processing conditions, no visible discoloration, embrittlement, or macroscopic forming defects were observed. All interpretations in this section are limited to observable deformation and consolidation behaviour and do not extend to chemical or molecular-scale stability.

3.5 Mechanism of Hydrophobic Surface Enhancement

The increase in water contact angle observed after hot pressing is primarily attributed to modifications in surface topography rather than chemical surface changes. Polyethylene is inherently non-polar and exhibits moderate hydrophobicity (WCA ≈ 85–95 °). The introduction of micro-scale surface roughness during thermal consolidation can amplify apparent hydrophobicity through roughness-dependent wetting behaviour, as described by the Cassie–Baxter and Wenzel models [10,11]. During hot pressing, partial softening and deformation of stacked layers can generate localised surface features upon cooling. Similar roughness-induced wetting effects have been reported for thermally processed polyethylene surfaces in previous studies [12]. In the present work, recycled LDPE/HDPE materials processed under optimised conditions achieved water contact angles of approximately 105° without the use of chemical coatings or surface modifiers. This level of enhancement is consistent with a physically induced wetting amplification mechanism driven by surface topography. The measured friction coefficients after processing (~0.25) fall within ranges commonly reported for smooth polyethylene surfaces under dry sliding conditions [13-18], indicating that the surface modifications associated with hydrophobic enhancement did not introduce abnormal tribological behaviour under the test conditions. The results demonstrate that controlled hot pressing can integrate material consolidation and surface functional modification in a single, additive-free process. Waste LDPE/HDPE materials were converted into continuous laminate sheets exhibiting altered surface wettability and friction behaviour, providing a practical route for physical upcycling based on parameter-controlled thermal processing.

4 Conclusion

This study demonstrates that controlled hot pressing can serve as a feasible physical upcycling route for post-consumer polyethylene materials. Under optimised processing conditions, waste LDPE and HDPE films were successfully consolidated into continuous laminate sheets without the introduction of chemical additives, surface coatings, or reactive treatments. The resulting materials exhibited measurable changes in surface-related properties, including increased water contact angles and reduced friction coefficients, which expand their suitability for applications where reduced wettability or lower surface adhesion is desirable, such as liners, outdoor panels, and non-load-bearing functional components. From a processing perspective, the proposed approach offers distinct advantages over conventional mechanical recycling routes. Traditional recycling of polyethylene involves a sequence of processing steps such as shredding, remelting, pelletisation, and re-extrusion. Each stage adds to cumulative thermal exposure while increasing energy demand and overall process complexity. In contrast, the hot-press method demonstrated here integrates material consolidation and surface modification within a single thermal compression step. This simplified process reduces handling stages, limits thermal history, and avoids the use of solvents, catalysts, or surface-functionalisation agents, thereby eliminating associated chemical inputs and emissions. Relative to emerging chemical recycling strategies, which often require high operating temperatures, complex reaction control, and centralised facilities, the direct hot-press process represents a simpler and potentially more accessible option for decentralised or small-scale recycling contexts. The demonstrated ability to process layered LDPE/HDPE assemblies further suggests reduced dependence on strict material sorting, which may lower preprocessing and logistical burdens in real waste streams.

From a life-cycle perspective, the reuse of post-consumer polyethylene films as functional laminate materials avoids the production of virgin polymers and the associated fossil resource demand and greenhouse gas emissions. Although a full quantitative life-cycle assessment was beyond the scope of this work, prior studies on comparable physical upcycling approaches indicate that simplified processing chains without chemical inputs are associated with lower embodied energy and carbon footprints relative to virgin polymer production and multi-step recycling routes. Accordingly, the process-level characteristics of the present approach suggest a potentially favourable environmental profile. Practical applicability of the proposed method is illustrated through a pilot workshop conducted in Wuhan in December 2024 (Figure 18), while Figure 19 summarises the overall transformation pathway developed in this study, from waste plastic collection to consolidation, surface modification, and end-use application. Overall, parameter-controlled hot pressing provides a viable pathway for converting low-value polyethylene film waste into functional laminate materials through a physically driven, additive-free process, supporting its potential role in circular materials design and decentralised plastic upcycling systems.

(a) (b) (c) (d)

Figure 18. Workshop on recycling and reusing plastics (2024-12, Wuhan, China). Photographs taken by the authors. © 2026 The Authors.

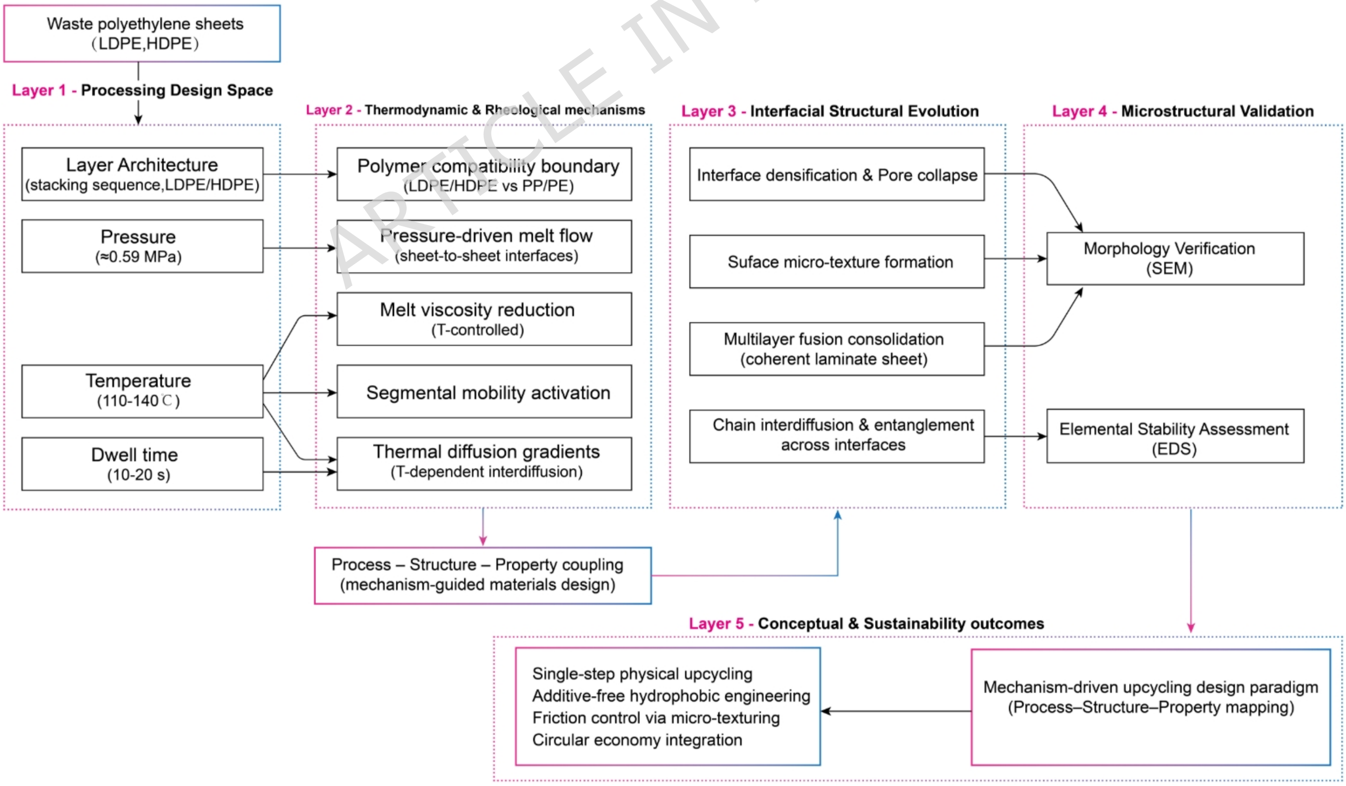


Figure 19. Conceptual framework of the mechanism-guided hot-press upcycling paradigm for waste polyethylene sheets.

5 Discussion

This study demonstrates the feasibility of controlled hot pressing as a low-energy, physically driven upcycling pathway for post-consumer polyethylene films, with particular emphasis on moulding behaviour and surface-related functional changes. The experimental results indicate that suitable combinations of temperature, pressure, and dwell time enable effective lamination and surface densification under the specific processing conditions examined. The observed enhancements in water repellence, frictional behaviour, and antifouling response arise from physical consolidation and surface morphology modification rather than from chemical modification or compositional alteration. Compared with conventional melt–pelletise–re-extrude recycling routes, which typically involve repeated thermal histories and often require stabilising additives to compensate for property loss, the present hot-press approach offers a simplified processing pathway. By integrating consolidation and surface modification into a single thermal compression step, the process reduces handling complexity and avoids the introduction of solvents, catalysts, or surface-functionalisation agents. However, the present findings should be interpreted within the scope of the tested materials and equipment. The optimisation of processing parameters was conducted using lightweight polyethylene films and a laboratory-scale flatbed press (KUDI 38 × 38 cm). Extension of this approach to other product categories, larger formats, or different waste morphologies will require recalibration of temperature, pressure, and dwell time to account for variations in thickness, stiffness, and targeted surface or dimensional requirements.

Several limitations of the current work warrant further investigation. Although surface wettability, frictional response, and abrasion behaviour were systematically evaluated, comprehensive mechanical characterisation was beyond the scope of this study. Quantitative measurements of tensile strength, flexural properties, impact resistance, fatigue behaviour, and interlayer mechanical response are required to assess load-bearing capability and long-term structural reliability. In addition, while the present observations indicate stable lamination under the applied testing conditions, the results do not constitute a quantitative assessment of interfacial adhesion strength or delamination resistance. Environmental durability also remains an important consideration. Future studies should examine the effects of ultraviolet exposure, thermal cycling, and moisture ingress on surface performance and dimensional stability to evaluate suitability for prolonged service conditions. Furthermore, applicability to more heterogeneous polymer waste streams requires careful assessment. Differences in thermal behaviour, viscoelastic properties, and interfacial compatibility may limit uniform consolidation in mixed-polymer laminates, and the role of compatibilizers or physical interlayers should be explored where appropriate. Finally, integration of reinforcing fibres, particulate fillers, or functional additives introduced through physical blending—rather than chemical modification—represents a potential route for extending the performance envelope of hot-pressed polyethylene laminates. Such strategies may enable improvements in stiffness, strength, or thermal resistance while preserving the low-energy, additive-minimised character of the process. Addressing these challenges will be essential for translating controlled hot pressing from a laboratory demonstration into a broadly applicable approach for sustainable product manufacturing and circular materials design.

Author Contributions: Conceptualisation, C.D.; methodology, W.-J.Y. and C.D.; software, W.-J.Y.; validation, W.-J.Y.; formal analysis, C.D.; investigation, C.D.; resources, W.-J.Y.; data curation, W.-J.Y.; writing—original draft preparation, C.D. and W.-J.Y.; writing—review and editing, W.-J.Y.; visualisation, W.-J.Y.; project administration, W.-J.Y.; funding acquisition, W.-J.Y.

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Data Availability: Data is provided within the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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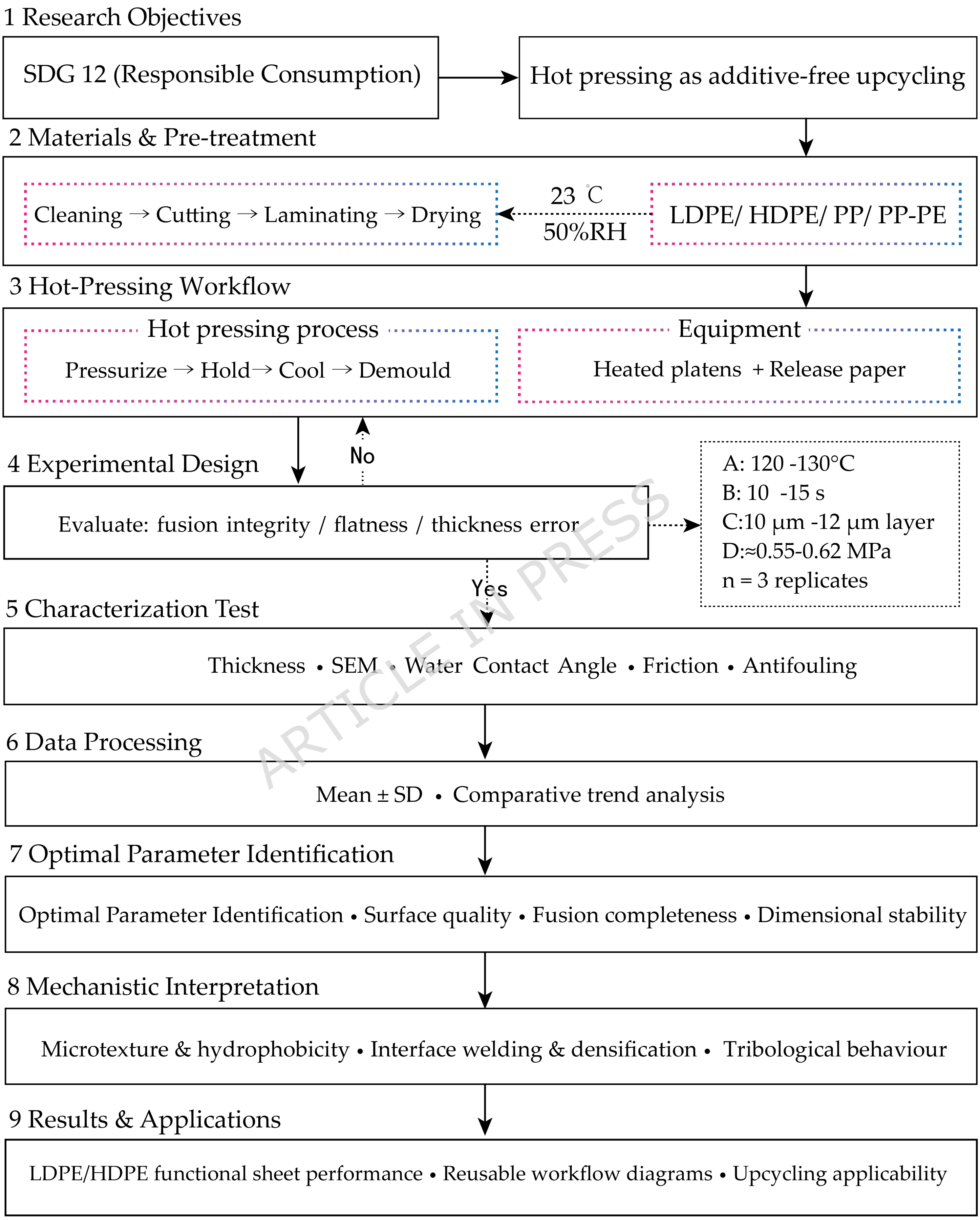
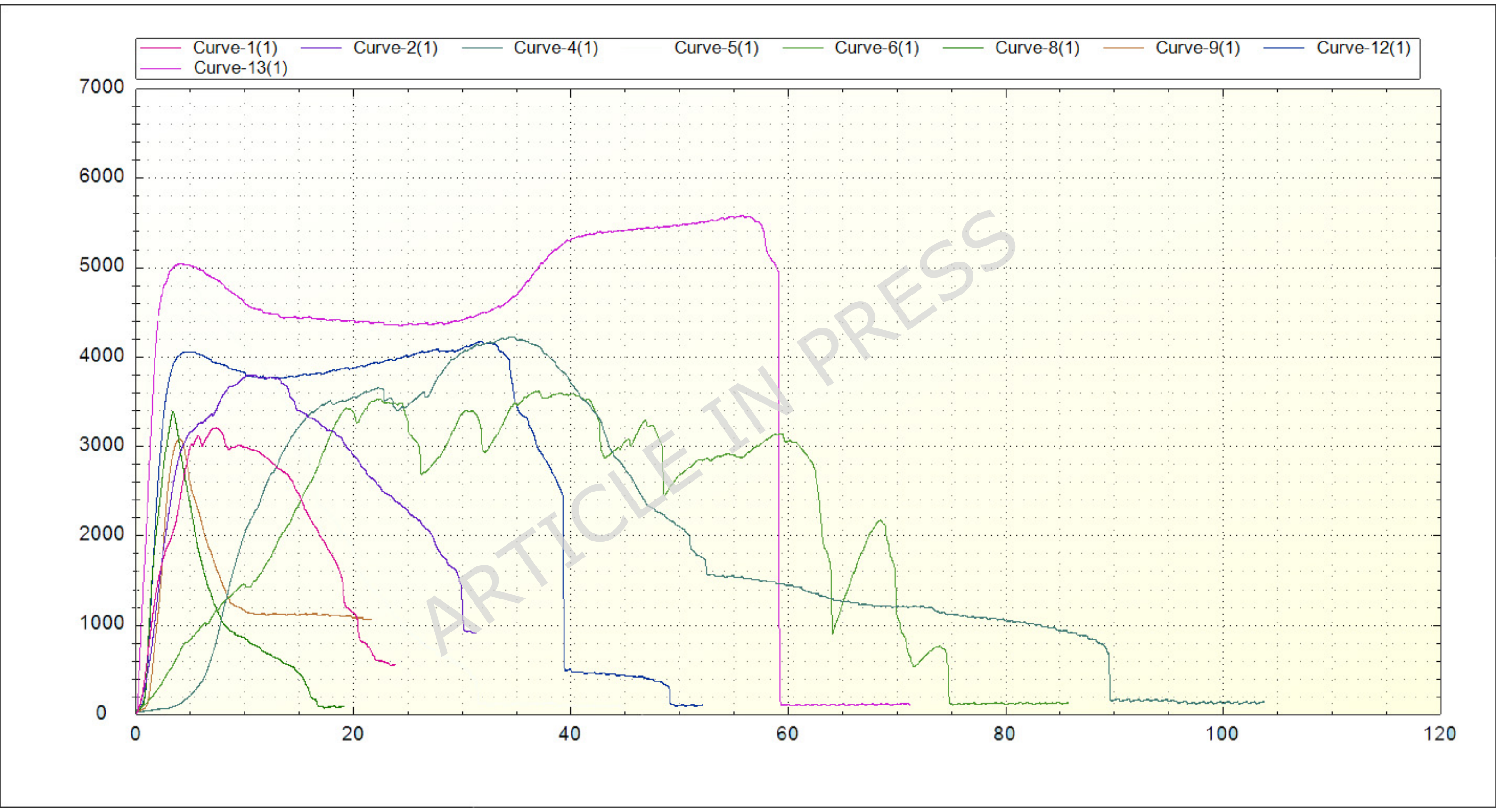

1 Research Objectives
SDG 12 (Responsible Consumption)
Hot pressing as additive-free upcycling
2 Materials & Pre-treatment
Cleaning → Cutting → Laminating → Drying
23 ℃
50%RH
LDPE/ HDPE/ PP/ PP-PE
3 Hot-Pressing Workflow
Hot pressing process
Pressurize → Hold → Cool → Demould
Equipment
Heated platens + Release paper
No
4 Experimental Design
Evaluate: fusion integrity / flatness / thickness error
A: 120 -130°C
B: 10 -15 s
C:10 μm -12 μm layer
D:≈0.55-0.62 MPa
n = 3 replicates
Yes
5 Characterization Test
Thickness • SEM • Water Contact Angle • Friction • Antifouling
6 Data Processing
Mean ± SD • Comparative trend analysis
7 Optimal Parameter Identification
Optimal Parameter Identification • Surface quality • Fusion completeness • Dimensional stability
8 Mechanistic Interpretation
Microtexture & hydrophobicity • Interface welding & densification • Tribological behaviour
9 Results & Applications
LDPE/HDPE functional sheet performance • Reusable workflow diagrams • Upcycling applicability


6
HDPE
(High-Density Polyhheine)
5
pattern
5
pattern
LDPE
(Low-Density Polyhheine)
4
HDPE
3
HDPE
2
HDPE
1
HDPE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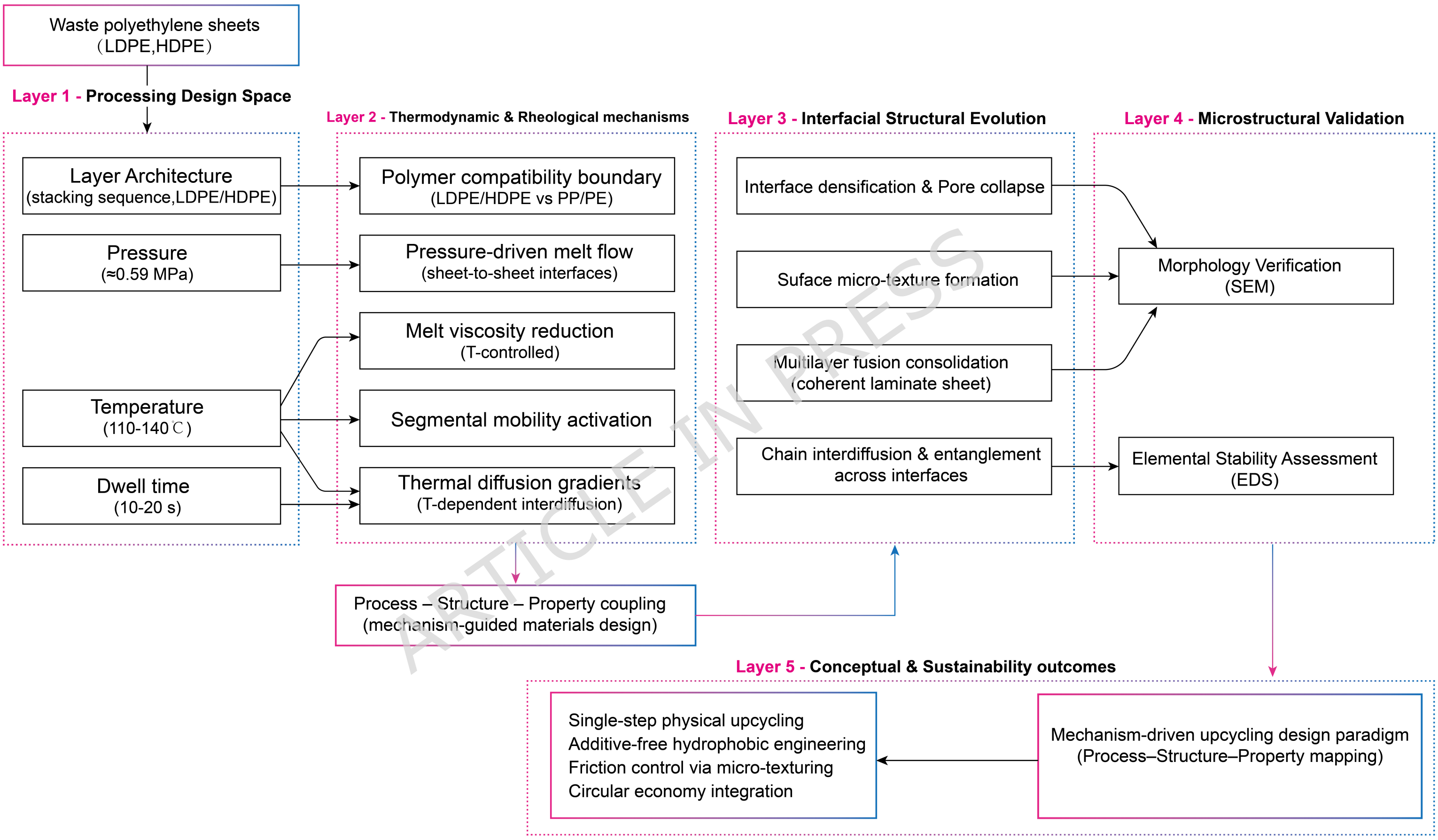
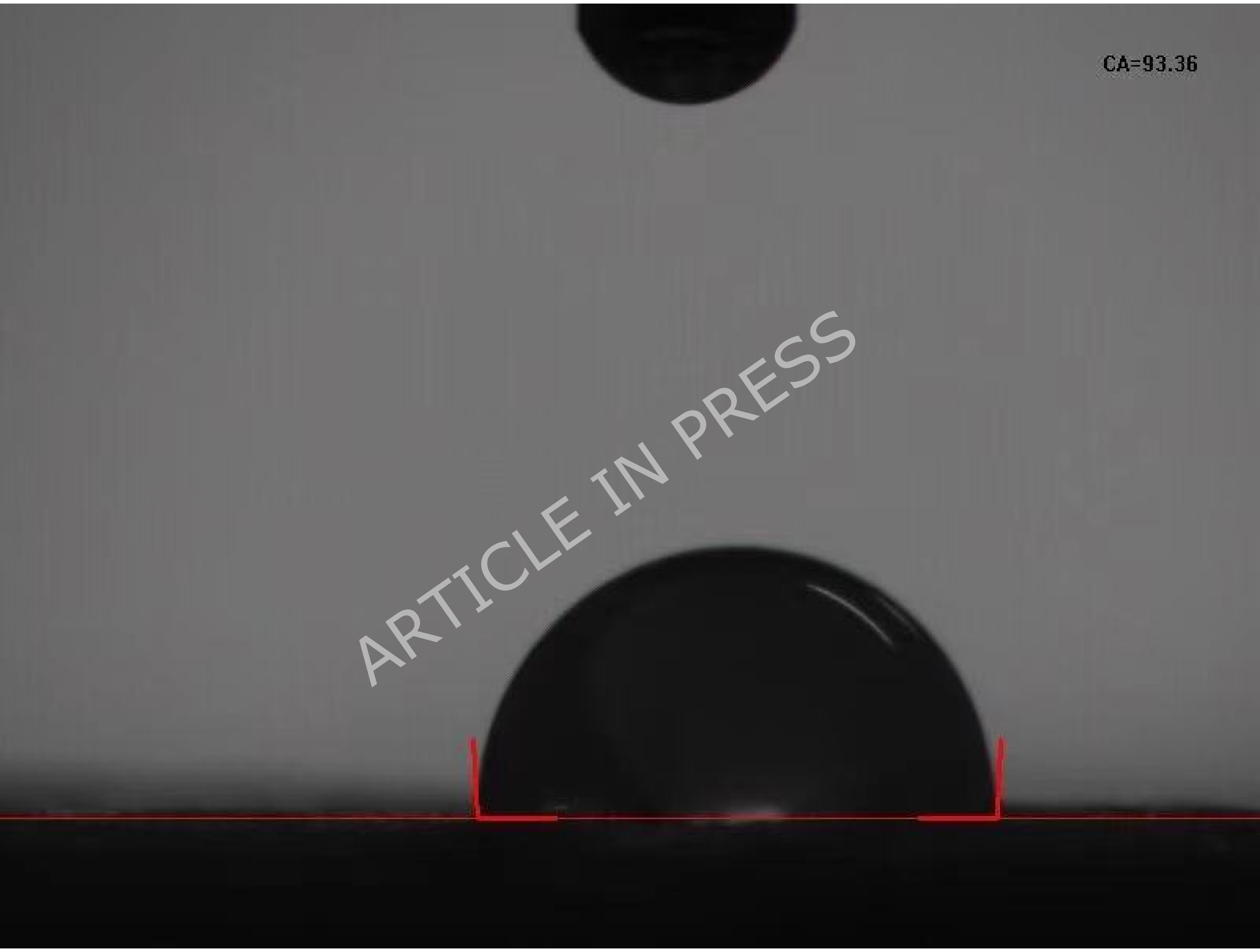

Waste polyethylene sheets
（LDPE,HDPE）
Layer 1 - Processing Design Space
Layer Architecture
(stacking sequence,LDPE/HDPE)
Pressure
(≈0.59 MPa)
Temperature
(110-140℃)
Dwell time
(10-20 s)
Layer 2 - Thermodynamic & Rheological mechanisms
Polymer compatibility boundary
(LDPE/HDPE vs PP/PE)
Pressure-driven melt flow
(sheet-to-sheet interfaces)
Melt viscosity reduction
(T-controlled)
Segmental mobility activation
Thermal diffusion gradients
(T-dependent interdiffusion)
Layer 3 - Interfacial Structural Evolution
Interface densification & Pore collapse
Suface micro-texture formation
Multilayer fusion consolidation
(coherent laminate sheet)
Chain interdiffusion & entanglement
across interfaces
Layer 4 - Microstructural Validation
Morphology Verification
(SEM)
Elemental Stability Assessment
(EDS)
Process – Structure – Property coupling
(mechanism-guided materials design)
Layer 5 - Conceptual & Sustainability outcomes
Single-step physical upcycling
Additive-free hydrophobic engineering
Friction control via micro-texturing
Circular economy integration
Mechanism-driven upcycling design paradigm
(Process–Structure–Property mapping)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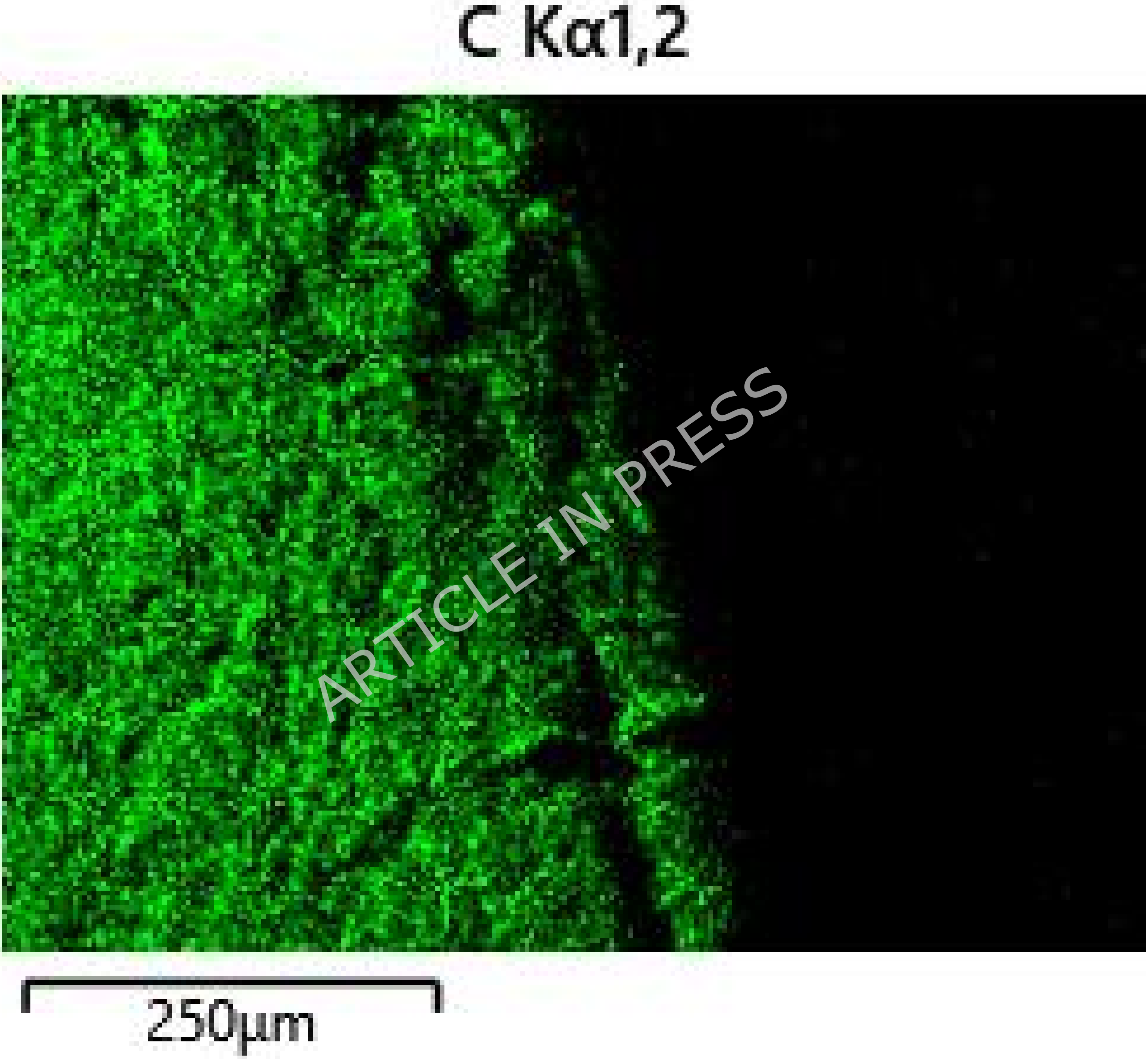
C Kα1,2
250µm


8.8.8
8.8.8
TEMP
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Map Sum Spectrum
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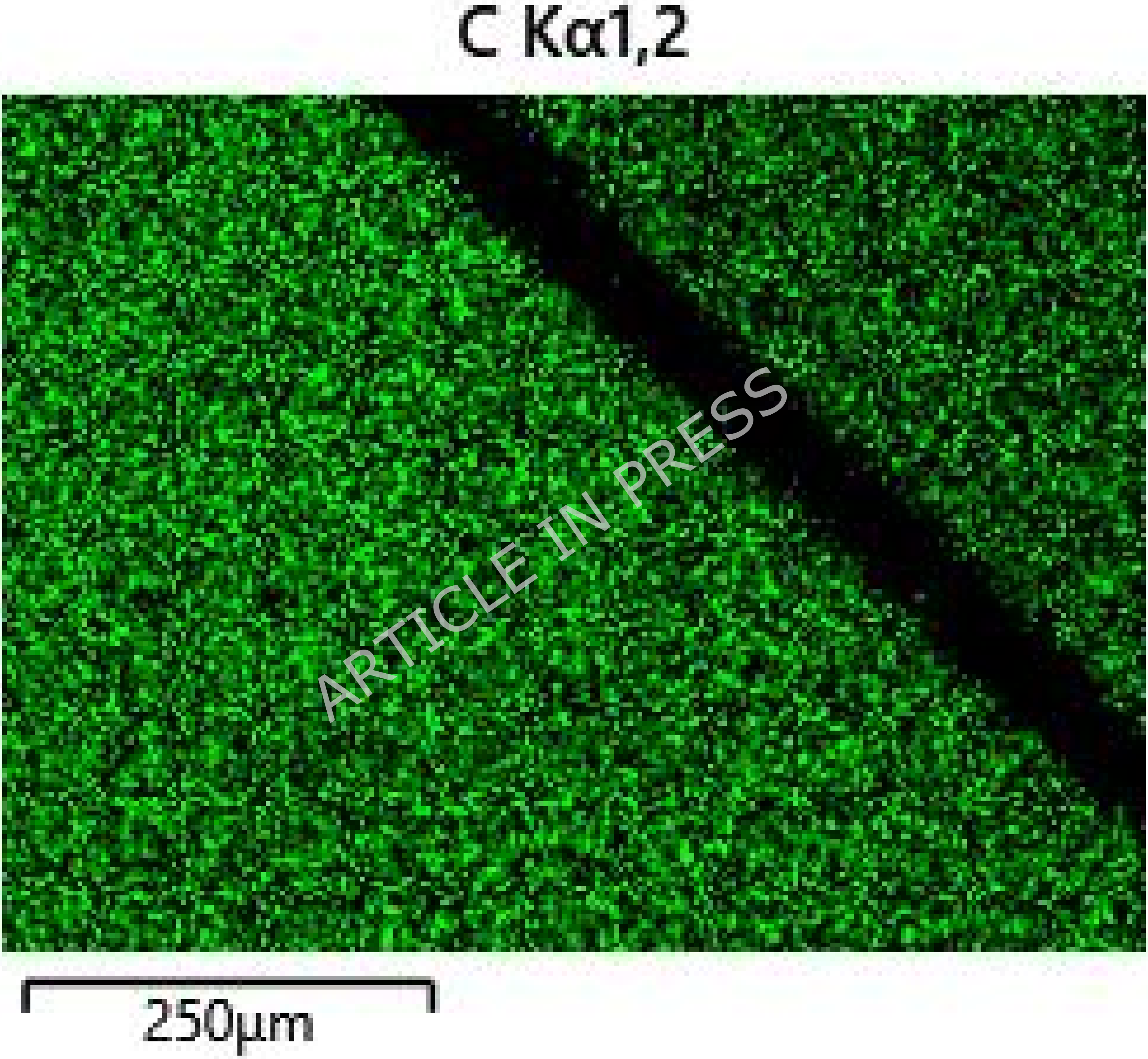
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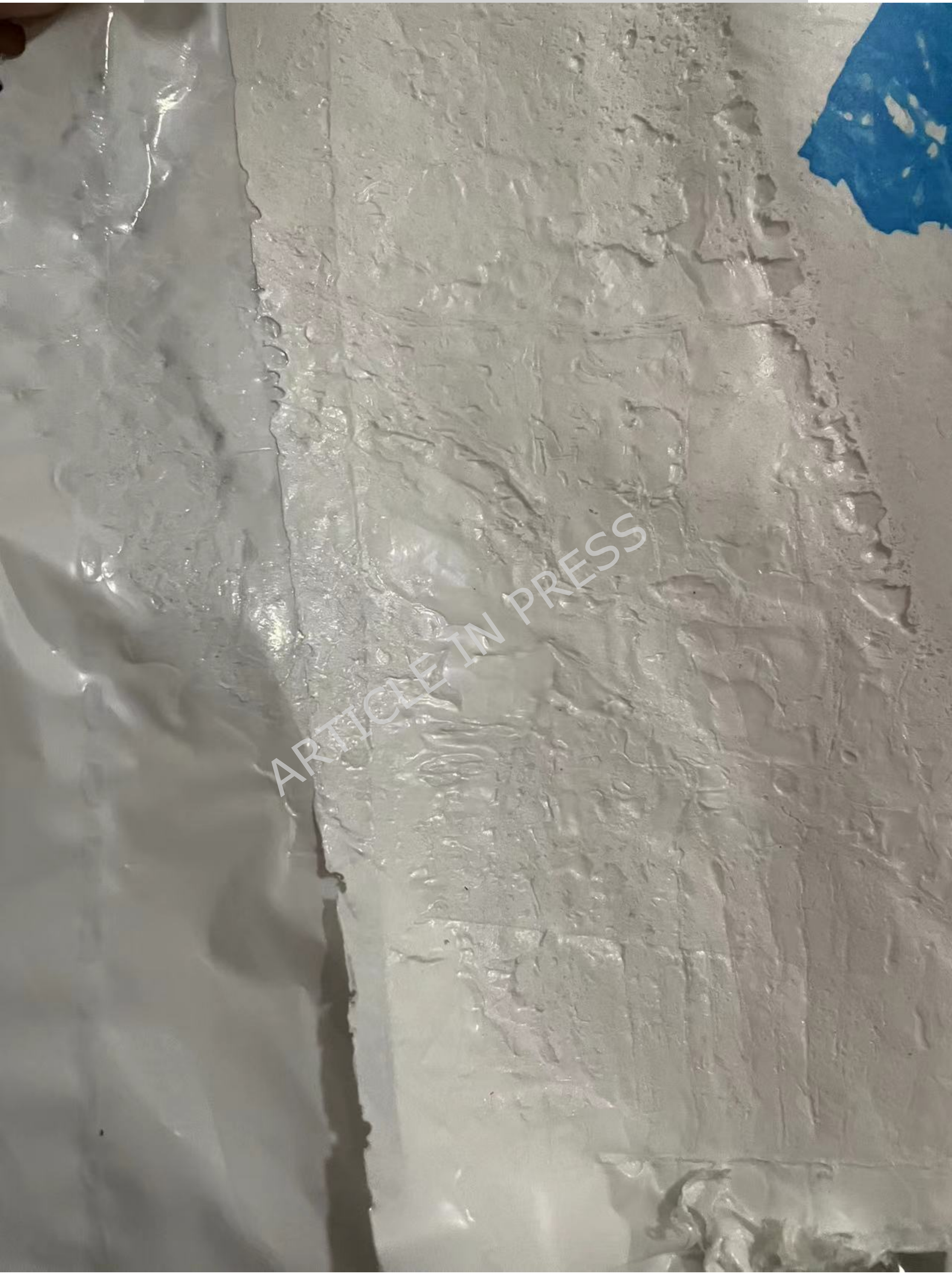
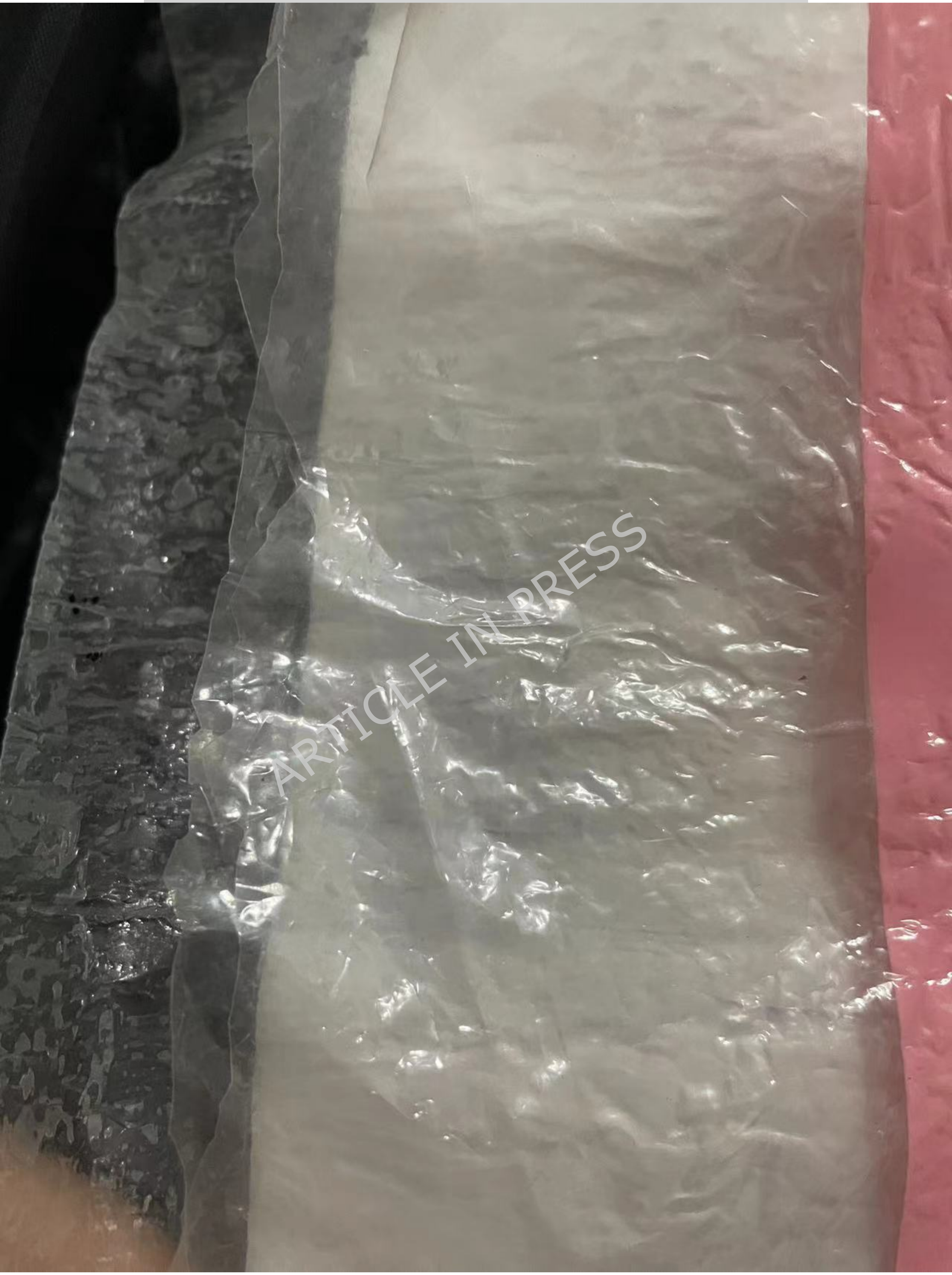
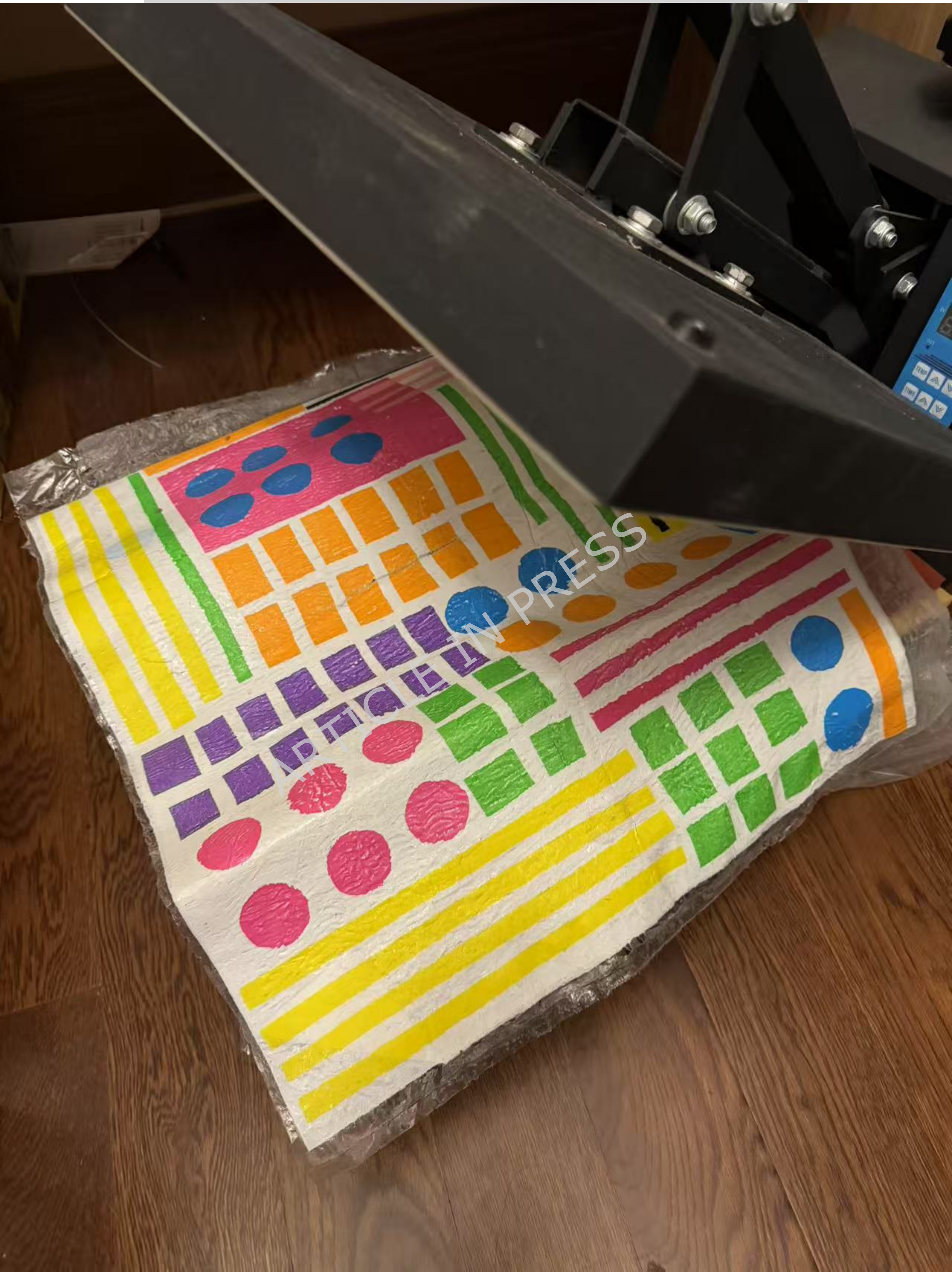


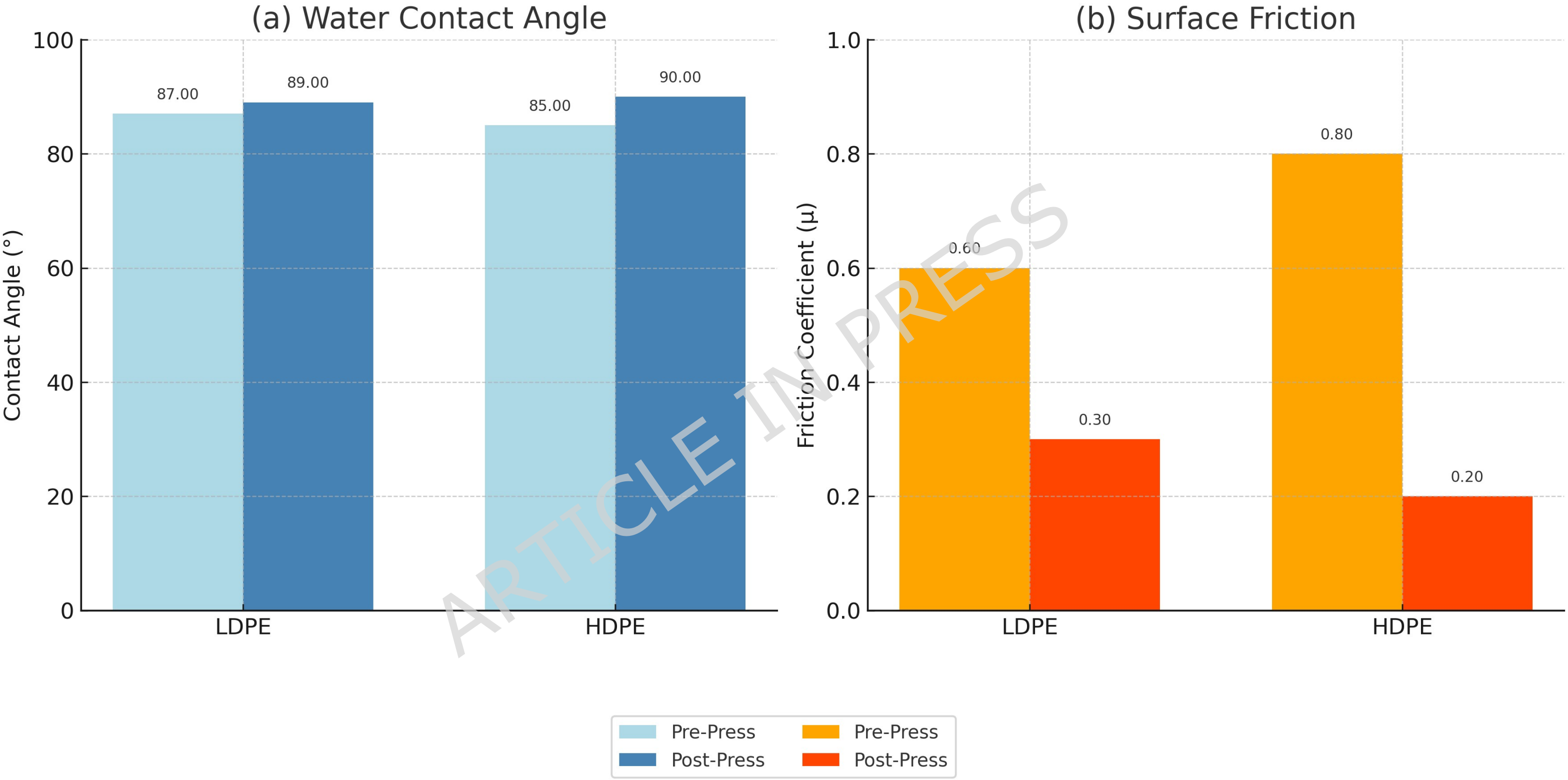



HDPE
LDPE
PP/BOPP


SUPOR
6002


REDUCE
REUSE
RECYCLE
REPAIR
減塑
行動




(a) Water Contact Angle
Contact Angle (°)
100
80
60
40
20
0
87.00
89.00
85.00
90.00
LDPE
HDPE
(b) Surface Friction
Friction Coefficient (μ)
1.0
0.8
0.6
0.4
0.2
0.0
0.60
0.30
0.80
0.20
LDPE
HDPE
Pre-Press
Post-Press
Pre-Press
Post-Press