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Influence of extrusion blow moulding profile temperature on physical, melt flow behaviour, mechanical, morphological and thermal properties of LDPE bottle

Cee Kee Lim[a], Mohd Hanif Mohd Pisal[a,b*], Tan Soo Jin[c,d], Lim Kean Chong[a], Mohamad Aiman Asyraf Mohamad Aznan[a] and Muchammad Tamyiz[e]

[a]*Faculty of Chemical Engineering & Technology, University Malaysia Perlis (UniMAP), Arau, Perlis 02600, Malaysia*
[b]*Center of Excellence Biomasse Utilization, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia*
[c]*Faculty of Mechanical Engineering & Technology, University Malaysia Perlis (UniMAP), Arau, Perlis 02600, Malaysia*
[d]*Center of Excellence Geopolymer and Green Technology (CEGeoGTech), Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia*
[e]*Department of Environmental Engineering, Faculty of Engineering, Universitas Nahdlatul Ulama Sidoarjo (UNUSIDA), 61234 Sidoarjo, Jawa Timur, Indonesia*
** Corresponding author. Tel.: +604-9798751; fax: +604-9798755; e-mail: hanifpisal@unimap.edu.my*

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ABSTRACT

Low-density polyethylene (LDPE) is widely used in bottle manufacturing due to its excellent flexibility and processability; however, manufacturers often face difficulties in optimizing and balancing mechanical performance and thermal stability when adjusting processing temperatures of extrusion blow moulding (EBM). This study investigates the effect of EBM profile temperatures on the physical, melt flow behaviour, mechanical, morphological, and thermal properties of LDPE. Profile temperatures ranging from 130 °C to 140°C were systematically evaluated. The moisture content of LDPE decreased by 13.22% as the profile temperature increased, enhancing processability. Density showed a modest rise of 0.33%, while the melt flow index (MFI) improved by 21.49%, indicating enhanced polymer chain mobility. Mechanical testing revealed that tensile strength, tensile modulus, impact strength, and flexural strength declined by 22.7%, 20.85%, 21.59%, and 22.75%, respectively, as temperature increased, due to reduced crystallinity and increased amorphous behaviour with field emission scanning electron microscopy (FESEM) further revealing brittle fracture features. In contrast, tear strength improved by 20.94% and tear force by 26.78%, attributed to better molecular alignment at higher temperatures. Differential scanning calorimetry (DSC) indicated enhancement in ΔHm and Xc, suggesting more efficient molecular packing and improved chain alignment at higher profile temperatures, with thermogravimetric analysis (TGA) further confirming the improved thermal stability, with the onset degradation temperature at 5% weight loss (T_5 wt.%) increasing by 13.19% and the maximum degradation temperature (T_{max}) by 3.18%. Statistical analysis using the Tukey test identified 135 °C as the optimum profile temperature, balancing mechanical integrity, tear resistance, and thermal performance. These findings provide valuable guidance for optimizing EBM conditions to achieve superior LDPE product quality with enhanced thermal stability and durability.

Keywords: *Low-density polyethylene, Extrusion blow moulding, Profile temperature, Tukey's test, Crystallinity.*

1. INTRODUCTION

EBM is a widely utilized technique for fabricating hollow plastic components, offering high production efficiency and design flexibility. Among thermoplastics, LDPE is a material of choice in EBM due to its easy processability [1] high flexibility, low melting point, and excellent chemical resistance. However, achieving consistent product quality is often hindered by inadequate control of processing conditions most notably, the profile temperature across the extrusion barrel. Despite being a crucial factor influencing melt viscosity, parison formation, and polymer chain mobility, the impact of barrel zone temperature variation on the comprehensive properties of LDPE remains underexplored [2-5]. Despite the critical role of profile temperature in determining melt flow behaviour, parison stability, and polymer crystallinity, its specific influence on the physical, mechanical, and thermal properties of LDPE remains underexplored. Most existing studies have focused on broader processing conditions such as parison thickness, chiller temperature, melt temperature, and extrusion speed [6-8] or on recycled and composite materials [9-11], rather than isolating the thermal profile variable in LDPE systems.

Moreover, literature on MFI as a function of profile temperature variation in EBM is scarce, even though MFI is a critical indicator of processability and polymer chain mobility [12]. While some studies suggest that elevated temperatures can enhance flowability and reduce internal stress, they also risk inducing thermal degradation or reduced mechanical strength if not optimized [8,13]. This presents a technical gap in understanding how nuanced thermal control along the extruder barrel influences the multidimensional performance of LDPE in EBM applications. The objective of this study is to investigate the effect of profile temperature variations in the EBM process on the physical, melt flow, mechanical, morphological, and

thermal properties of LDPE. The research involves controlled temperature settings across multiple zones and applies standardized testing methods in moisture and density measurements, MFI evaluation, mechanical testing, and thermal analysis. The investigation includes moisture content and density measurements, MFI, tear, tensile, flexural, and impact strength assessments, along with TGA and DSC. By correlating these results to specific temperature zones, this study offers novel insights into thermal–property relationships in EBM for LDPE bottles.

The scope is to generate empirical data that can contribute to the optimization of EBM processing conditions, thereby enhancing product performance and consistency. The novelty of this work lies in its integrated property evaluation under varying profile temperatures, a domain that remains underrepresented in current polymer processing literature. Blow pressure, cooling time, and mould temperature remain pivotal manufacturing processes for producing hollow plastic components across industries ranging from packaging to automotive and consumer goods. Among the various thermoplastics utilized in EBM, LDPE stands out due to its excellent processability, chemical resistance, and cost-effectiveness. However, achieving optimal physical and mechanical properties in LDPE bottle-based products remains a critical challenge, particularly as product performance is increasingly tied to processing precision.

2. THEORETICAL BACKGROUND

EBM is a widely used thermoforming process for producing hollow plastic products such as LDPE bottles. Among its critical parameters, profile temperature plays a pivotal role in controlling melt viscosity, flow behaviour, crystallization, and interlayer bonding. Theoretical models in thermorheology and polymer physics explain how increasing temperature reduces viscosity and improves flowability but also accelerates thermal degradation such as chain scission and oxidation. LDPE is a semicrystalline polymer with long-chain branching and is highly sensitive to thermal conditions. Its mechanical and thermal properties depend on entanglement density and crystallinity, which can be compromised by excessive processing temperatures. A higher profile temperature generally increases the MFI, but often at the cost of reduced tensile strength, impact resistance, and crystallinity, as confirmed by DSC, TGA, and FESEM observations.

Therefore, optimizing the profile temperature is essential to balance processability with structural integrity in EBM-processed LDPE. While past studies have examined thermal effects in general extrusion or injection moulding, focused research on profile temperature's impact in EBM for LDPE bottles remains limited. This study addresses that gap by systematically linking processing conditions to performance outcomes.

3. METHODOLOGY

3.1. Materials

This research requires LDPE; commercial-grade Cosmothene LDPE F210 in pellet form was supplied by The Polyolefin Company (Singapore) Pte Ltd.

3.2. Sample Preparation

LDPE was first processed using an extrusion blow moulding (EBM) machine, model W3-2017 (WY Group, Perak, Malaysia), based on the profile temperatures listed in Table 1. The resulting bottles were subsequently cut into test specimens, and the overall schematic flow of the process is illustrated in Figure 1. The LDPE samples used in this study were directly obtained from ready-made EBM bottles without any additional cleaning or pretreatment. Each bottle measured 144 mm in height, 95 mm in width, and 79.5 mm in depth, with a wall thickness of approximately 1 ± 0.2 mm. For physical and thermal characterizations, including moisture content, density, MFI, TGA, and DSC, specimens were prepared from the side surface of the bottle. For mechanical tests such as tensile, flexural, tear, and impact tests, the front flat surface was used to ensure uniform geometry and flatness. Structural analysis using FESEM was performed on the fracture surface of impact-tested samples. Cutting dimensions and specimen configurations adhered to relevant standard testing protocols and are detailed in Section 4. All tests were conducted in triplicate for statistical reliability, except for FESEM, TGA, and DSC, which were conducted on single representative samples.

Table 1. Profile temperature of EBM machine

Zone	1	2	3	4	5	6	7(Die)
D1 (°C)	110	115	120	125	130	135	130
D2 (°C)	112	117	122	127	132	137	132
D3 (°C)	115	120	125	130	135	140	135
D4 (°C)	117	122	127	132	137	142	137
D5 (°C)	120	125	130	135	140	145	140

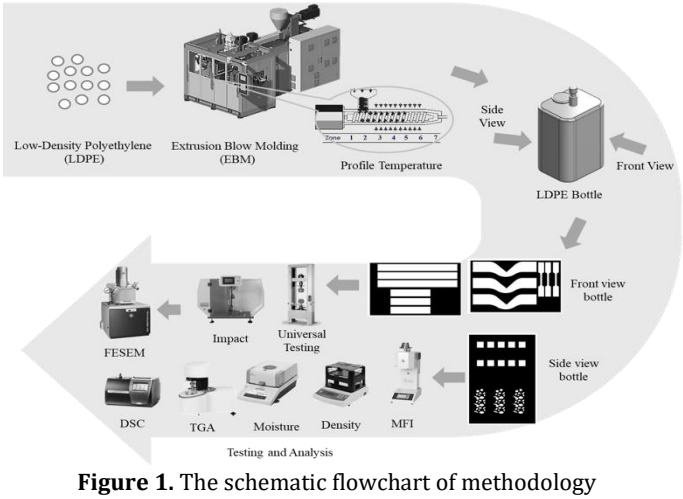

Figure 1. The schematic flowchart of methodology

4. DATA COLLECTION AND ANALYSIS

Tukey's Honestly Significant Difference (HSD) test was employed using Minitab 17 to assess the statistical significance of differences among group means. This post hoc analysis enabled a clear evaluation of the effects of processing parameters by identifying which group comparisons showed meaningful variation. Non-overlapping confidence intervals indicated statistically significant differences, while overlaps suggested similarity. The use of Minitab 17 ensured robust statistical validation, reinforcing the reliability of the findings.

4.1. Moisture Content and Density Test

The moisture content of the LDPE (ASTM D6980) was determined by using a moisture analyzer (HE53 Mettler Toledo, USA). The samples were placed in the chamber at 105 °C for moisture analysis. The samples were placed in the chamber at 105 °C for moisture analysis. The density of the LDPE (ASTM D792) was determined by using a plastic density testing machine (Quarrz AU300RP, Shenzhen). For density measurement, the samples were positioned both on the top tray and inside the chamber. Both samples were cut to 2 mm x 1 mm x 1±0.2 mm in size (length x width x thickness). Moisture content and density were automatically calculated, and the results were averaged from three samples.

4.2. Melt Flow Index

MFI (ASTM D1238) was tested using plastometer model GT-7 100-MI (GOTECH, Taichung, Taiwan) to study the flow properties of LDPE. The primary test uses a single dead weight to measure the quantity of material released over a predetermined period of time. The testing was conducted with a weight of 3.8 kg at a standard temperature of 223 °C, and the material was collected every 10 minutes for determination of MFI [11]. The average of three samples' data was collected. The melt flow index is obtained using Equation (1), where the weight of extrudate is in grams, t is the time interval in seconds, and 10 minutes (600 seconds).

$$\mathrm{MFI} = \left(\frac{g}{10}minutes\right) = \frac{600\,\mathrm{sec} \times \text{weight of extrudate (g)}}{\mathrm{t}} \quad (1)$$

4.3. Tear Test

The die C tear test, as outlined in ASTM D624, focuses on evaluating the tear resistance of materials, particularly for flexible plastics. In this test, specimens were prepared in a distinctive "C" shape to facilitate controlled tearing. The standard dimensions for these specimens are generally 100 x 19 mm (length x width), providing a suitable size for reliable testing. The critical feature of this specimen is the "C" shaped notch, which serves as the initiation point for tearing. This notch typically measures about 6 mm in depth and 15 mm in width, allowing for a consistent path for the tear to propagate. Three specimens, with a thickness of 1 mm, were tested at a speed of 50 mm/min, in line with material characteristics and test requirements.

4.4. Tensile Test

Tensile properties were determined following ASTM D638 using the Instron 5569 and the universal testing machine model AG-XD plus (Shimadzu, Kyoto, Japan). The tests will be conducted on samples with varying profile temperatures. The test was carried out at 25 ± 3 °C with a crosshead speed of 10 mm/min and dimensions of 9.5 mm for width and 63 mm for length. Tensile strength, tensile modulus, and elongation at break were measured for three dumbbell-shaped specimens with a thickness of 1±0.2 mm [14].

4.5. Impact Test

The notched impact resistance of LDPE samples was measured using the Izod method (ASTM D256). To ensure brittle fracture behaviour, the samples were first cooled in liquid nitrogen before testing. In standard Izod tests, a pendulum swings at a controlled speed of 2.45 m/s, making it suitable for smaller specimens. The pendulum used in this study had a maximum impact energy of 15 J, with a 120° initial drop angle and an effective weight of 5 kg. The impact point on the specimen was set 204 mm from the pendulum's pivot, while the notch at the base of the sample was positioned 22 ± 0.5 mm from the hammer's strike point. Although impact test dimensions can vary based on material and method, the Izod test typically requires specimens sized 63.5 mm × 12.7 mm × 1±0.2 mm, with three replicates tested for consistency.

4.6. Morphology Analysis

The impact-fractured morphology of the LDPE at D1 and D5 was examined using FESEM, with equipment model number NOVA NanoSEM 450 (Hillsboro, Oregon, USA). Prior to imaging, a thin layer of platinum was sputter-coated onto the sample to prevent charging during observation, and the magnification used was 100x.

4.7. Flexural Test

This study evaluated the flexural properties of LDPE samples using a three-point bending test, conducted on an AG-XD Plus universal testing machine (Shimadzu, Kyoto, Japan) in accordance with ASTM D790. The test measured both flexural strength and flexural modulus. To ensure failure occurred purely due to tension and compression, the span-to-thickness ratio was maintained at a minimum of 16:1 by setting the support span at 50 mm. The crosshead speed was fixed at 10 mm/min with a maximum load capacity of 10 kN. The specimens, cut to dimensions of 127 mm × 12.7 mm × 1±0.2 mm (length × width × thickness), were subjected to bending, and the resulting flexural strength and modulus were recorded [14].

4.8. Thermal Analysis

DSC using a DSCQ-10 model (TA Instruments, New Castle, Delaware, USA) was utilized to measure the thermal properties. Approximately 5 mg of each sample was heated to 200 °C and cooled to 50 °C during the 1st cycle. TA Instruments Universal Analysis 2000 software was used to analyze the crystallization kinetics, and the degree of crystallinity (X_c) was ascertained according to the heat of fusion (ΔH_f) using Equation (2): Where, X_c: Degree of crystallinity, ΔHf: Measured heat of fusion from DSC, and ΔH_0: Heat of fusion for a perfect crystal (290 J/g for polyethylene) [15].

$$X_C = \frac{\Delta H_f}{\Delta H_0} \times 100 \quad (2)$$

Then TGA was conducted using a PerkinElmer TGA 8000 thermogravimetric analyser (Waltham, MA, USA) under a nitrogen atmosphere to prevent oxidative degradation. Approximately 5 ± 1 mg of each sample was weighed and placed into a platinum crucible. The samples were then heated from 30 °C to 700 °C at a constant heating rate of 10 °C/min. Nitrogen gas was purged at a flow rate of 20 °C/min throughout the analysis. The TGA curves were recorded as mass loss (%) versus temperature (°C), while the first derivative of the TGA curve (DTG) was plotted. The key thermal degradation parameters extracted from the curves included the temperature at 5% weight loss (T5 wt.%), temperature at 50% weight loss (T50 wt.%), maximum decomposition temperature (T_{max}), and residual mass at 700 °C.

5. RESULTS AND DISCUSSION

5.1. Moisture Content and Density

The effect of different profile temperatures on the moisture content and density of LDPE is shown in Figure 2. As the profile temperature increases from D1 to D5, the moisture content of LDPE steadily decreases, while density gradually rises, demonstrating a complementary relationship between thermal energy input and material transformation. It becomes evident that heat simultaneously enhancing moisture removal and promotes molecular ordering, thereby improving density. Specifically, the moisture content decreases from 1.77% at D1 to 1.53% at D5, representing an overall reduction of 13.22%. The most pronounced drop, 5.69%, occurs between D2 and D3, highlighting a critical temperature window for efficient moisture removal. This behaviour can be attributed to the enhanced water evaporation as elevated temperatures increase the kinetic energy of both water molecules and polymer chains, enabling moisture to overcome intermolecular forces within the polymer matrix [16].

As the profile temperature rises, the LDPE melt's viscosity decreases, facilitating the diffusion of water from the bulk to the surface, consistent with Fick's law of diffusion [17]. Moreover, at temperatures near or above D3, the branched structure of LDPE becomes increasingly flexible, further aiding the release of trapped moisture. Notably, at D5, thermal energy reaches an optimal level, achieving the lowest residual moisture content of 1.53% and marking the most efficient moisture removal under the studied conditions. Parallel to moisture reduction, the density of LDPE shows a gradual increase with rising profile temperatures, from 0.919 g/cm^3 at D1 to 0.922 g/cm^3 at D2, reflecting an overall 0.33% increase. This slight but consistent gain reflects improved molecular ordering and crystallization, promoted by enhanced chain mobility and alignment during extrusion at higher temperatures. As the chains reorganize into more tightly packed structures, overall material density increases. This observation aligns with Doran and Choi [18], who reported that the degree of branching in polyethylene significantly affects chain packing, crystallinity, and, consequently, density. Additionally, Al-Salem *et al.* [19] found that elevated profile temperatures during compounding influence not only degradation but also the physical attributes of polyethylene blends. Together, these findings underscore the dual role of profile temperature in optimizing both moisture content and density in LDPE in EBM. The progressive moisture reduction and density enhancement with increasing temperature highlight the importance of precise thermal control in achieving superior properties. While elevated temperatures improve drying efficiency and molecular organization, careful temperature selection is crucial to balance moisture removal, polymer stability, and processing performance, which ultimately achieves optimum properties.

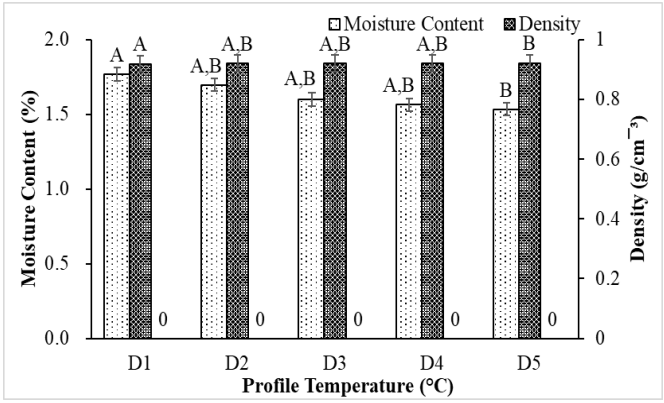

Figure 2. The effect of different profile temperatures of LDPE on moisture content and density

The Tukey test indicates that profile temperature significantly influences the moisture content and density of LDPE as shown in Figure 2. The lowest profile temperatures of 130 °C at D1 consistently falls into Group A for both density and moisture content, indicating that at the lowest temperature, LDPE exhibits the lowest density with the highest moisture content. The overlap in groupings for intermediate temperatures (D2, D3, and D4), which were classified into both Groups A and B, suggests that the differences in moisture content and density under these conditions are not statistically significant when compared with either D1 or D5. In contrast, the highest

profile temperature of 140 °C at D5, falls solely into Group B for both properties. These results emphasized the interdependent effects of profile temperature on moisture content and density. As the profile temperature rises, the improved flowability and molecular orientation not only enhance crystallinity and packing density but also reduce the material's capacity to retain moisture.

5.2. Melt Flow Index (MFI)

The MFI of LDPE exhibits a clear and progressive increase as the profile temperature rises from D1 to D5, as shown in Figure 3. Between D1 and D2, the MFI rises sharply from 4.56 g/10 min to 4.92 g/10 min, marking the largest single-step change of 7.89%. As profile temperature increases to D3, the MFI reaches 5.19 g/10 min (5.49% rise), followed by a slight increase to 5.23 g/10 min at D4 (0.77%), and finally peaks at 5.54 g/10 min at D5 with a 5.93% gain. Overall, the MFI shows a remarkable 21.49% increase across the studied temperature range, revealing a strong temperature sensitivity in LDPE flow behaviour. This trend directly reflects the thermal softening of the polymer melt, where elevated temperatures reduce viscosity, weaken intermolecular interactions, and enhance chain mobility, all of which promote smoother flow under pressure. This inverse relationship between MFI and viscosity aligns with fundamental principles of polymer melt rheology [20].

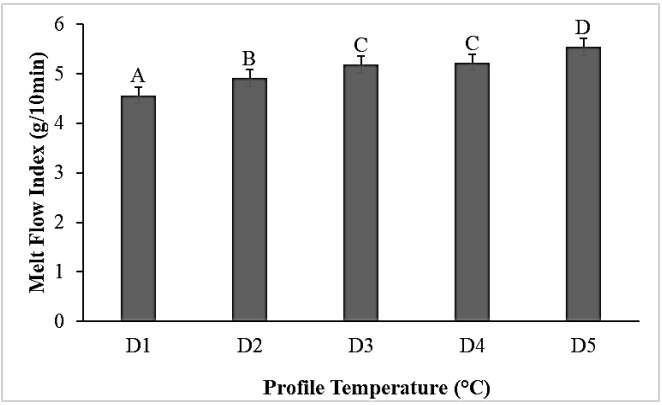

Figure 3. The effect of different profile temperatures on melt flow index

According to Arrhenius' equation, polymer viscosity decreases exponentially with increasing temperature, providing a solid mechanistic explanation for the observed MFI rise [21]. This behaviour is further supported by Yuan and Sakai [22], who demonstrated that greater free volume at high temperatures accelerates molecular motion while reducing entanglement density and intermolecular forces. Similarly, Pielichowski [23] emphasized the critical role of temperature in driving thermal degradation in polyolefins, highlighting the need to balance flow enhancement with potential risks like chain scission. Importantly, the increase in MFI indicates improved processability of LDPE, yet it also signals a trade-off that excessive temperatures can lower molecular weight and compromise final product strength. Moisture content plays an additional role, as water can act as a plasticizer, further reducing viscosity and boosting MFI, making moisture control essential during processing. Thus, while D5 achieves the highest MFI, lowest moisture content, and increased density, careful optimization of profile temperature is crucial to achieve a balance between ease of extrusion, mechanical integrity, and product quality. Collectively, these findings reinforce established polymer rheological theories and underscore the vital importance of precise thermal control in EBM of LDPE.

D5 has the highest MFI and is significantly different from all other profile temperatures, categorized under Group D. D4 and D3 share Group C, indicating no significant difference in their MFI values. D2 is in Group B, indicating that its MFI is distinct from higher and lower temperatures. D1 has the lowest MFI and is significantly different from all other temperatures, forming its own Group A. The Tukey's test reveals clear distinctions in MFI across the five profile temperatures. MFI increases with higher profile temperatures, with significant differences observed between D5 and all other groups. This trend aligns with the theoretical understanding that higher profile temperatures reduce the viscosity of LDPE, thereby enhancing its flowability during processing. Conversely, the lowest MFI at D1 reflects the impact of lower temperatures on restricting polymer chain mobility.

5.3. Tear Properties

The effect of profile temperature on the tear performance of LDPE is presented in Figure 4, with a consistent increase with rising profile temperature from D1 to D5. Specifically, tear strength increased from 4.167 MPa at D1 to 5.04 MPa at D5, reflecting an overall enhancement of 20.89%. The largest percentage increase was observed between D2 and D3, from 4.341 to 4.688 MPa, at 7.99%, followed by smaller but steady gains at higher temperatures. Similarly, tear force rose from 3.141 N at D1 to 3.984 N at D5, representing a 26.82% overall increase. The progressive increase in tear strength and force with temperature can be attributed to improvements in the polymer's microstructure under optimized thermal conditions. At elevated profile temperatures, reduced moisture content, enhanced molecular alignment, and increased density all contribute to superior mechanical integrity. As shown in the earlier moisture content results, residual moisture decreased from 1.77% to 1.53% as temperature increased, which is critical because moisture acts as a plasticizer that can weaken inter-chain bonding and lower tear resistance [24]. The concurrent rise in density (from 0.919 g/cm^3 to 0.922 g/cm^3) suggests improved crystalline packing of LDPE chains, reinforcing the material's resistance to tear propagation.

Additionally, the increase in MFI with temperature (21.49% overall) indicates enhanced chain mobility during extrusion, allowing the material to form a more homogeneous and defect-free structure upon cooling. This molecular uniformity strengthens the material against localized stress concentrations during tear loading. Prior studies have shown that higher processing temperatures

improve the cohesive energy density and tear resistance of thermoplastic films by promoting optimal chain entanglement and reducing void formation [25]. Tukey's test grouped each temperature condition into distinct significance Groups from A to E, confirming that the differences between all temperature levels were statistically significant.

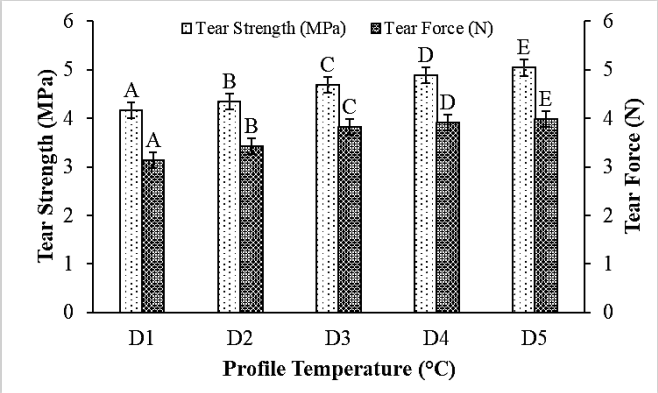

Figure 4. The effect of different profile temperatures on tear strength and tear force

5.4. Tensile Properties

The results in Figure 5 reveal a clear and progressive decline in both tensile strength and tensile modulus of LDPE as profile temperature increases from 130 °C to 140 °C. Tensile strength drops from 11.31 MPa at 130 °C to 8.74 MPa at 140 °C, marking an overall 22.7% reduction, with the sharpest decline of 9.63% occurring between 130 °C and 132 °C. Similarly, tensile modulus decreases from 136.07 MPa to 107.73 MPa over the same temperature range, reflecting a 20.85% total decrease, with the largest single drop (8.17%) between 132 °C and 135 °C. This consistent downward trend reflects the sensitivity of LDPE's mechanical integrity to thermal conditions during processing. As profile temperature increases, the decline in tensile strength and modulus can be attributed to the combined effects of reduced crystallinity, diminished polymer chain alignment, and greater amorphous content within the material. Elevated profile temperatures extend the melt's residence time, slowing solidification and inhibiting the formation of ordered crystalline domains, ultimately weakening the material's stiffness and load-bearing capacity [26].

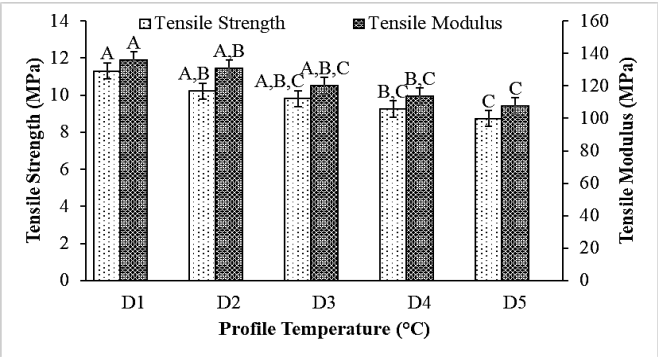

Figure 5. The effect of different profile temperatures on tensile strength and tensile modulus

Interestingly, the mechanical decline mirrors earlier observations on moisture content, MFI, and density. While higher temperatures reduced moisture content and increased MFI, enhancing flow and molecular mobility, they also compromised tensile properties by lowering the degree of structural order. High MFI indicates reduced viscosity and better chain mobility, but when coupled with rapid cooling at lower temperatures, it promotes stronger inter-chain interactions and higher tensile performance. At lower temperatures (130 °C), high moisture content creates voids and interfacial defects, weakening tensile properties. As moisture is driven off at higher temperatures, however, the polymer becomes prone to thermal degradation and reduced crystallinity, which further erodes tensile strength [27]. These findings highlight the complex trade-off between processability and mechanical performance in LDPE, underscoring the need to optimize profile temperature to balance moisture removal, molecular alignment, and final product strength.

The elongation at break of LDPE demonstrates a clear and progressive enhancement with rising profile temperature, as illustrated in Figure 6. Specifically, elongation increases from 450.9 MPa at 130 °C to 465.3 MPa at 132 °C, marking a moderate 3.19% rise. A more pronounced increase follows between 132 °C and 135 °C, where elongation reaches 494.6 MPa, representing the largest single-step gain of 6.30%. This positive trajectory continues with elongation climbing to 513.37 MPa at 137 °C (3.79% increase) and peaking at 542.09 MPa at 140 °C (5.60% increase). Overall, the elongation at break increases by 20.23% across the studied temperature range, highlighting the material's enhanced ductility at elevated profile temperatures.

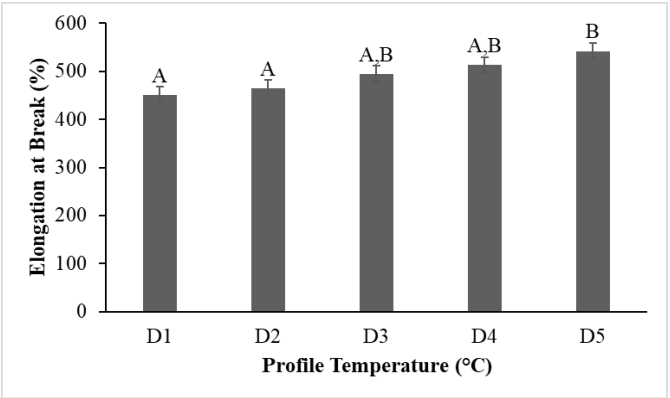

Figure 6. The effect of different profile temperatures on elongation at break

This improvement can be attributed to the synergistic effects of reduced moisture content, lower crystallinity, and decreased viscosity at higher processing temperatures, which collectively expand the amorphous regions within the LDPE matrix and elevate the melt flow index (MFI). The increased amorphous fraction promotes greater polymer chain mobility, enabling the material to undergo larger deformations prior to fracture. Furthermore, the reduction in stiffness at elevated temperatures facilitates enhanced strain accommodation, aligning with the ductility

improvements observed. These findings agree with the work [28] reported that rising temperatures reduce the degree of crystallinity in LDPE spherulites without significantly altering spherulite size, further explaining the material's enhanced capacity for elongation under tensile stress.

The Tukey's test results reveal clear and meaningful trends across tensile strength, tensile modulus, and elongation at break in relation to profile temperature. D1 shows the highest tensile strength and belongs solely to Group A, reflecting superior mechanical performance compared to D5, which is grouped in C. D2 falls into overlapping Groups A and B, while D3 and D4 share Groups B and C, indicating gradual rather than abrupt changes. Importantly, the overlapping groupings show that D1, D2, and D3 can be considered statistically part of the same performance cluster, with no significant differences among their tensile strength and modulus despite rising profile temperatures. Similarly, for tensile modulus, D1 again holds the top position in Group A, while D5 occupies Group C with the lowest modulus, and D2 to D4 show intermediate, overlapping groupings, reinforcing that D1, D2, and D3 belong to a statistically cohesive group. In contrast, the elongation at break shows a reversed trend: D5 achieves the highest elongation and is placed in Group B, while D1 and D2 fall into Group A, and D3 to D4 overlap both A and B, again demonstrating that D1, D2, and D3 form a shared statistical grouping due to their overlapping Tukey's classifications. These results collectively illustrate that while increasing profile temperatures significantly reduces tensile strength and modulus, they simultaneously enhance ductility, as reflected in elongation at break. The overlap in statistical groupings at mid-range temperatures (D1 to D3) suggests a transitional window where mechanical properties remain relatively stable, emphasizing the need for precise optimization to balance strength and flexibility in LDPE processing.

5.5. Impact Properties

The impact strength of LDPE demonstrates a clear declining trend with increasing profile temperature, as illustrated in Figure 7. Specifically, the impact strength drops from 250.35 J/m^2 at D1 to 242.17 J/m^2 at D2 (a 3.27% decrease), then to 235.94 J/m^2 at D3 (2.57% reduction), followed by a sharper decline to 215.77 J/m^2 at D4 (8.53% decrease), and finally reaching 196.27 J/m^2 at D5 (the largest single-step drop of 9.05%). Overall, this represents a significant 21.59% reduction across the studied temperature range. The decline in impact strength can be attributed to reduced crystallinity, lower molecular packing efficiency, and diminished chain entanglement at higher profile temperatures, all of which weaken LDPE's capacity to absorb and dissipate impact energy.

At lower profile temperatures, particularly 130°C at D1, LDPE exhibits the highest impact strength due to enhanced crystallinity and superior molecular alignment, allowing the material to better resist crack initiation and propagation. This behaviour is consistent with prior findings where an increase in moisture content improved impact strength by promoting flexibility through weakened dipole–dipole interactions [29]. Crystallinity plays a crucial role in the material's ability to absorb energy during impact, as lower-temperature-processed LDPE retains a more ordered microstructure, which strengthens its resistance. However, as profile temperature rises, the associated increase in melt flow index (MFI) reflects reduced viscosity and enhanced molecular mobility, allowing LDPE to flow more easily but also reducing chain entanglements, thereby lowering impact strength.

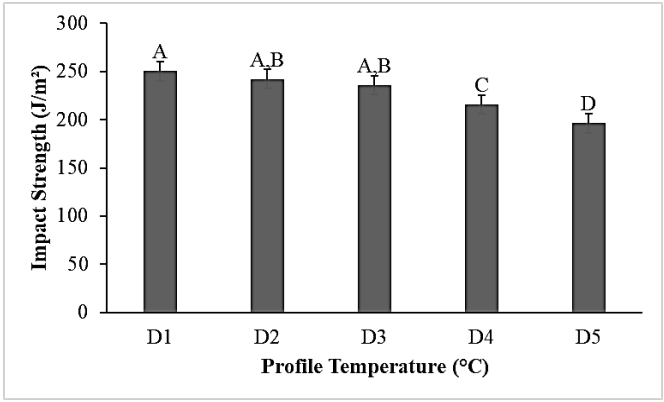

Figure 7. The effect of profile temperature on impact strength

At the highest studied temperature of 140 °C at D5, the pronounced 21.59% decrease in impact strength is primarily due to the disruption of the polymer's crystalline regions and the shift toward a more amorphous morphology. While excessive crystallinity can lead to brittleness, a loss of crystalline integrity compromises the polymer's ability to effectively dissipate impact energy, making it more susceptible to deformation and failure under dynamic loading. Kong *et al*. [30] further explain that elevated processing temperatures modify entanglement density, directly contributing to reduced impact strength, while Zhang *et al*. [31] noted that relaxation time, proportional to complex viscosity and entanglement density, decreases as temperature increases. Additionally, Harnnarongchai *et al*. [32] highlighted that higher profile temperatures increase molecular mobility, further diminishing the material's resistance to deformation under impact. Together, these results underscore the critical importance of optimizing profile temperature to balance processability, crystallinity, and mechanical integrity in LDPE systems.

D1 exhibits the highest impact strength and forms its own Group A, indicating the most robust resistance to impact. D2 and D3 belong to overlapping Groups A and B, respectively, showing intermediate impact strength values. D4 belongs to Group C, indicating a marked reduction in impact strength compared to lower temperatures. D5 shows the lowest impact strength and belongs to a distinct Group D, reflecting significantly reduced resistance to impact at higher profile temperatures. Tukey's test results clearly demonstrate a significant reduction in impact strength as profile temperature increases from grouping A

to D. This decline underscores the importance of optimizing profile temperatures to balance the mechanical properties of LDPE for applications requiring impact resistance.

5.6. Field Emission Scanning Electron Microscopy (FESEM)

Profile temperatures were examined using FESEM to reveal distinct differences in the fracture surfaces, which correlate with changes in mechanical properties such as impact strength and ductility. As shown in Figure 8(a), it displayed a relatively rough fracture surface with minimal voids characterized by significant plastic deformation. This indicates ductile fracture behaviour, where the LDPE may retain a high degree of chain entanglement and cohesive strength, which allowed it to absorb and dissipate energy effectively. This observation is consistent with the relatively higher impact strength measured at D1, 130 °C.

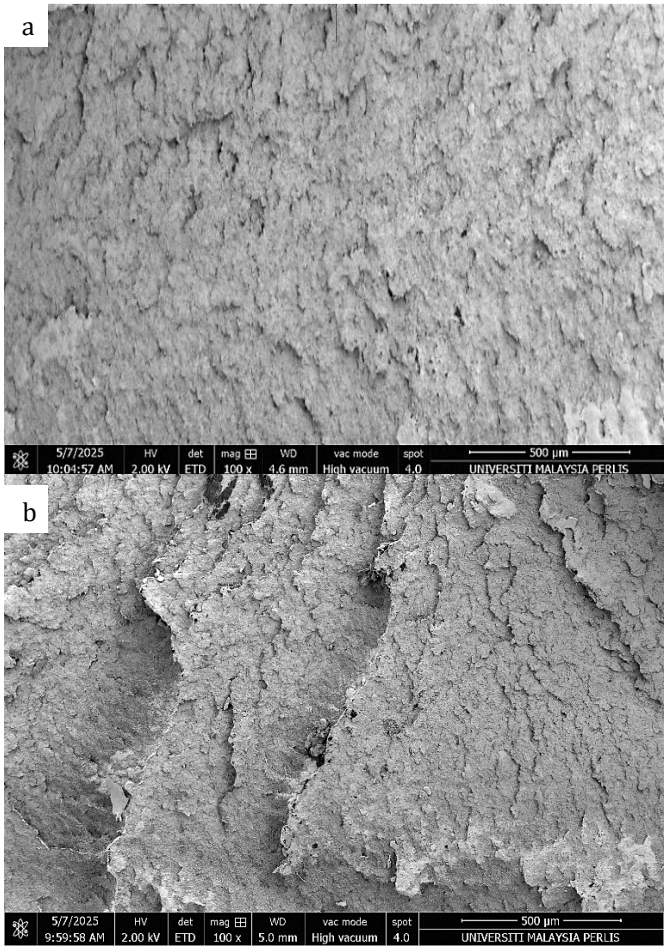

Figure 8. FESEM images of (a) D1 and (b) D5 at magnification of 100x

In contrast, as shown in Figure 8(b), LDPE samples processed at a higher profile temperature at D5, 140 °C displayed markedly different fracture features. The fracture surfaces were noticeably smoother, with fewer signs of plastic deformation and a more planar appearance. The presence of layering indicates a transition toward brittle fracture. This brittle morphology corresponds with the reduced impact strength observed in mechanical testing and is attributed to the thermal degradation and chain scission occurring at elevated processing temperatures [33]. Additionally, the higher melt flow index (MFI) observed at elevated processing temperatures reflects increased melt fluidity, which may lead to incomplete or weakened interlayer fusion during blow moulding, ultimately contributing to reduced structural integrity and fracture susceptibility [34].

5.7. Flexural Properties

The flexural strength of LDPE shows a clear and progressive decline as the profile temperature increases from D1 to D5, as depicted in Figure 9. At D1, the flexural strength is 23.66 MPa, decreasing to 22.68 MPa at D2 (4.14% reduction), 21.90 MPa at D3 (3.44% reduction), then dropping sharply to 19.86 MPa at D4 (9.32% decrease), and finally reaching 18.28 MPa at D5 (7.95% decrease). Overall, the flexural strength decreases by 22.75% across the temperature range, highlighting a substantial loss in the polymer's ability to resist bending as profile temperature rises. This trend reflects the diminished stiffness of the polymer matrix at elevated temperatures, where reduced crystallinity, molecular packing, and chain orientation compromise the material's flexural performance.

At lower temperatures like D1, LDPE exhibits enhanced crystallinity and molecular alignment, which reinforces the polymer's rigidity and flexural strength. However, as the temperature increases from 132 °C in D2 to 140 °C in D5, the enhanced molecular mobility restricts crystallization, enlarges the amorphous phase, and ultimately lowers mechanical integrity. This is consistent with the findings of Salakhov *et al*. [35], who reported that an increase in the amorphous fraction leads to decreased crystallinity and ductility. Similarly, Huo *et al*. [36] emphasized that water content significantly affects flexural strength, noting that increased moisture at lower temperatures promotes flexural strength growth, underscoring the complex interplay between thermal and moisture effects in polymer systems.

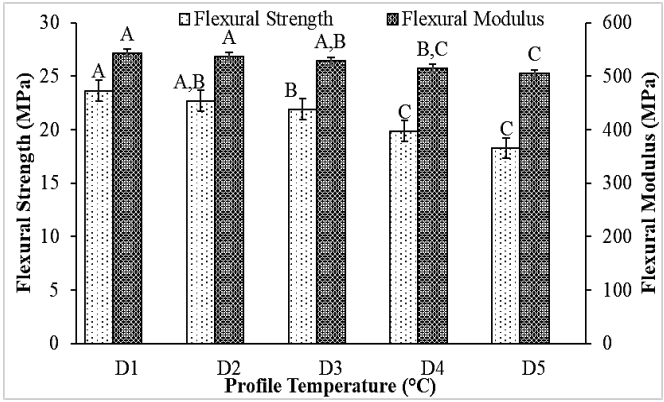

Figure 9. The effect of profile temperature on flexural strength and flexural modulus

The flexural modulus of LDPE also declines consistently with rising profile temperatures, as shown in Figure 9.

Starting from 543.40 MPa at D1, the modulus decreases slightly to 536.77 MPa at D2 (1.22% reduction), drops further to 528.57 MPa at D3 (1.53% reduction), then declines to 515.23 MPa at D4 (2.53% decrease), and ultimately falls to 504.72 MPa at D5 (2.04% reduction). In total, the flexural modulus decreases by 7.11% across the temperature range. This reduction is primarily attributed to the rise in molecular mobility, lower molecular packing density, and reduced crystallinity at elevated processing temperatures, which collectively diminish the stiffness and rigidity of the polymer matrix. Increased thermal energy disrupts molecular packing, weakens intermolecular forces, and enhances chain flexibility, rendering the material less capable of withstanding bending stresses. Darras *et al*. [37] similarly observed that polymers processed above their crystallization temperatures exhibit loss of intermolecular cohesion, resulting in reduced flexural strength and modulus.

Importantly, these flexural trends are closely interrelated with the previously observed moisture content, density, and MFI results, which at higher profile temperatures, the reduced moisture content and density, combined with the increased MFI, reflect a more amorphous and less crystalline structure. This transformation leads to greater molecular mobility but compromises the material's mechanical rigidity, ultimately explaining the consistent decrease in flexural strength and modulus with rising processing temperatures.

D1 achieves the highest flexural strength, forming a distinct Group A, indicating robust structural performance. D2 and D3 overlap Groups A and B, showing a slight reduction in strength. D4 and D5 exhibit the lowest values, forming Group C. Meanwhile, D1 and D2 exhibit the highest modulus values in Group A, indicating maximum rigidity. D3 belongs to Groups A and B, showing a moderate decrease. D4 shows further reduction and overlaps with Groups B and C. D5 has the lowest modulus and belongs to Group C, reflecting a substantial loss in rigidity. The Tukey's test results underscore the importance of profile temperature in determining the flexural properties of LDPE. Lower profile temperatures of D1 at 130 °C are favourable for achieving higher flexural strength and modulus, making them suitable for applications requiring structural rigidity. Conversely, higher profile temperatures of D4 at 137 °C and D5 at 140 °C result in statistically significant reductions, limiting their utility in such applications.

5.8. Differential Scanning Calorimetry (DSC)

DSC was conducted to examine the thermal transitions and crystalline structure development of LDPE under varying die profile temperatures during the extrusion blow moulding (EBM) process. The critical thermal parameters evaluated include the T_{onset}, T_m, ΔHm, and %Xc. The results are presented in Figure 10 and Table 2. The results demonstrate a consistent trend of increasing ΔHm and Xc with rising profile temperature, suggesting that thermal energy imparted during the EBM process influences the crystallization behaviour of LDPE. Notably, the T_{onset} and T_m remained relatively stable across all temperature profiles, with T_{onset} ranging from 93.85 °C to 94.73 °C and T_m ranging narrowly between 108.95 °C and 109.96 °C. This stability in melting temperatures implies that the crystalline structure of LDPE is thermally resilient to moderate changes in processing temperature.

Table 2: The onset melting temperature (T_{onset}), peak melting temperature (T_m), enthalpy of melting (ΔHm), and degree of crystallinity (Xc) of D1, D3, and D5.

Profile Temperature	T_{onset} (°C)	T_m (°C)	ΔHm (J/g)	%Xc (%)
D1	93.85	108.95	140.2	47.97
D3	94.03	109.66	142.6	49.17
D5	94.73	109.96	145.1	50.34

However, the melting enthalpy (ΔHm) increased from 140.2 J/g at D1 to 145.1 J/g at D5, corresponding to a rise in the degree of crystallinity from 47.97% to 50.34%. This enhancement in ΔHm and Xc suggests more efficient molecular packing and improved chain alignment at higher profile temperatures. The increase in crystallinity is attributed to the enhanced mobility of polymer chains and prolonged exposure to elevated thermal conditions, which facilitate better formation of ordered crystalline domains during the cooling phase. These observations agree with findings by Wang *et al*. [38] and Toda A. [39], which indicate that higher profile temperatures during melt processing promote the reorganization of polymer chains into crystalline structures. The increase in crystallinity may also contribute to improved stiffness and mechanical strength of the moulded bottles, as observed in related mechanical property analyses.

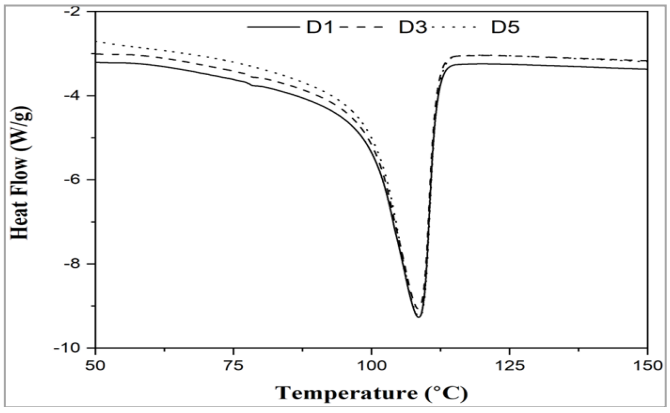

Figure 10. DSC curves of the D1, D3, and D5.

From a processing perspective, the results suggest that a profile temperature of D5 (140 °C) may enhance crystalline structure formation without compromising thermal stability. Nevertheless, excessive crystallinity can sometimes lead to embrittlement, and thus, optimal thermal settings must balance processability, crystallinity, and desired mechanical performance. Among all profile temperature profiles tested, D3 consistently delivered balanced properties across physical and mechanical performance without significant trade-offs.

5.9. Thermogravimetric Analysis (TGA)

The TGA results of LDPE processed at different profile temperatures are shown in Figure 11 and Table 3. The TGA results reveal that the thermal stability of LDPE improves progressively as the profile temperature increases. Specifically, T_5%wt increases from 381.84 °C at D1 to 432.21 °C at D5, indicating enhanced onset of thermal degradation. Likewise, T_{50}%wt rises from 466.56 °C at D1 to 483.08 °C at D5, and T_{max}%wt increases from 477.07 °C to 492.24 °C. The residual mass also increases from 1.4% at D1 to 5.5% at D5, suggesting greater formation of thermally stable char at higher profile temperatures. This progressive improvement in thermal resistance can be attributed to changes in molecular arrangement and packing during processing. As the profile temperature increases, the LDPE chains experience greater mobility, facilitating more efficient packing and partial cross-linking that enhance thermal stability [1]. Additionally, higher profile temperatures promote the formation of more densely packed amorphous regions, which can resist degradation up to higher temperatures despite the reduction in crystallinity [2].

Table 3: The temperature at 5% weight loss (T_5%wt), 50% weight loss (T_{50}%wt), maximum degradation rate temperature (T_{max}%wt), and residual mass of D1, D3, and D5.

Profile Temperature	T_5%wt (°C)	T_{50}%wt (°C)	T_{max}%wt (°C)	Residual Mass (%wt)
D1	381.84	466.56	477.07	1.4
D3	408.25	478.12	489.13	4.6
D5	432.21	483.08	492.24	5.5

Interestingly, these thermal stability improvements correlate with previously discussed results. The observed reduction in moisture content with increasing profile temperature likely contributes to better thermal resistance, as moisture can catalyze early thermal degradation [29]. The increase in density observed at higher profile temperatures suggests tighter chain packing, consistent with the rise in degradation temperatures. Moreover, the increase in MFI with profile temperature reflects enhanced chain mobility, which paradoxically contributes to both reduced mechanical strength (tensile, flexural, impact) and improved thermal stability due to more efficient thermal relaxation and redistribution of stresses in the amorphous matrix. Mechanically, while tensile and flexural strengths decreased with increasing profile temperature, likely due to reduced crystallinity and weaker intermolecular interactions. The improved thermal resistance suggests that the material's backbone remains stable at elevated temperatures. The lower impact strength observed at higher temperatures may be partially offset by the increased thermal resistance, reflecting a trade-off between toughness and thermal durability.

Overall, the TGA results highlight that while higher profile temperatures may not be suitable for bottle application as they compromise LDPE's mechanical performance, they simultaneously enhance its thermal stability, which could be advantageous for applications requiring heat resistance. In contrast, medium-profile temperatures offer a more balanced performance, maintaining adequate mechanical properties while achieving acceptable thermal resistance. Notably, the Tukey's test results statistically confirmed that the mechanical performance at medium profile temperatures shows no significant difference compared to low profile temperatures. This finding is particularly valuable for industrial applications, as it suggests that lower profile temperatures can be used without compromising product quality. Operating at lower temperatures offers clear advantages in terms of energy efficiency, process stability, and cost control, making it a highly attractive choice for manufacturers aiming to optimize both performance and sustainability.

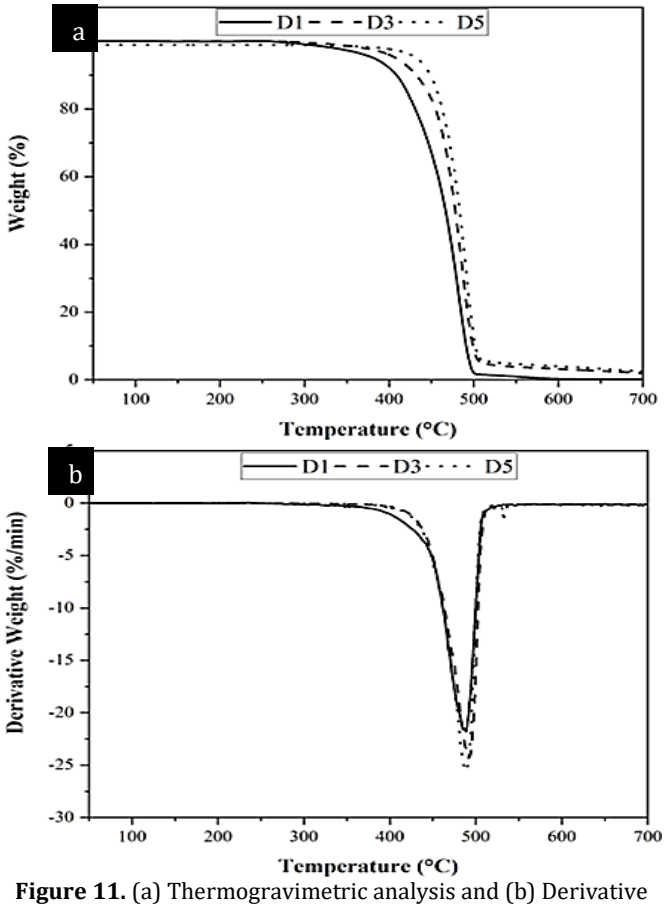

Figure 11. (a) Thermogravimetric analysis and (b) Derivative thermogravimetric curves at D1, D3, and D5.

6. CONCLUSION

This study establishes 135 °C (D3) as the optimal profile temperature for processing LDPE via extrusion blow moulding (EBM), offering a balanced improvement in physical, mechanical, structural, and thermal properties. At this temperature, the material exhibited reduced moisture content, higher density, optimal melt flow behaviour and enhanced crystallinity, indicating improved molecular packing and thermal stability. Mechanically, D3 maintained tensile, impact, and flexural strength within acceptable ranges, as validated through Tukey's statistical analysis. The findings emphasize that precise thermal control is critical in optimizing LDPE's processability and

performance. Nonetheless, the outcomes present promising applications in industrial polymer processing, especially in the production of blow-moulded bottles where both dimensional consistency and mechanical durability are essential. Manufacturers can adopt 135 °C as a process setpoint to optimize throughput without compromising product quality. Future research should expand upon this work by investigating long-term aging and fatigue resistance tests. In summary, this work underscores the critical importance of precise thermal control in EBM and offers a foundational guideline for optimizing LDPE processing toward improved sustainability, performance, and manufacturability.

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