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Keywords: Buriti oil; Plasticizer; LLDPE (linear low-density polyethylene); Rheological properties; Thermal properties; Mechanical properties



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Article

Impact of Buriti Oil from *Mauritia flexuosa* Palm Tree on the Rheological, Thermal, and Mechanical Properties of Linear Low-Density Polyethylene for Improved Sustainability

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Abstract: Recent advancements highlight the utilization of vegetable oils as additives in polymeric materials, particularly for replacing conventional plasticizers. Buriti oil (BO), extracted from the Amazon's *Mauritia flexuosa* palm tree fruit, boasts an impressive profile of vitamins, minerals, proteins, carotenoids, and tocopherol. This study investigates the impact of incorporating buriti oil as a plasticizer in linear low-density polyethylene (LLDPE) matrices. The aim of this research was to evaluate how buriti oil, a bioactive compound, influences the thermal and rheological properties of LLDPE. Compositions of buriti oil\LLDPE were prepared via melt intercalation techniques, and the resulting materials were characterized through Thermogravimetric Analysis (TGA), differential scanning calorimetry (DSC), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), mechanical property testing, and contact angle measurement. The addition of buriti oil was found to act as a processing aid and plasticizer, enhancing the fluidity of LLDPE polymer chains. TGA revealed distinct thermal stabilities for buriti oil/LLDPE under different degradation conditions. Notably, buriti oil exhibited an initial weight loss temperature at 402°C, whereas LLDPE at 466.4°C. This indicated a minor reduction in the thermal stability of buriti oil/LLDPE compositions. The thermal stability, as observed through DSC displayed a nuanced response to the oil's incorporation, suggesting a complex interaction between the oil and polymer matrix. Detailed mechanical testing indicated a marked increase in tensile strength and elongation at break, especially at optimal concentrations of buriti oil. SEM analysis showcased a more uniform and less brittle microstructure, correlating with the enhanced mechanical properties. Contact angle measurements revealed a notable shift in surface hydrophobicity, indicating a change in the surface chemistry. This study demonstrates that buriti oil can positively influence the processability and thermal properties of LLDPE contributing to expand its potential applications as an effective plasticizer.

Keywords: buriti oil; plasticizer; LLDPE (linear low-density polyethylene); rheological properties; thermal properties; mechanical properties

1. Introduction

The environmental problems associated with conventional plasticizers have sparked a fervent search for sustainable alternatives in the field of polymer science. As the need for biodegradable materials becomes increasingly urgent, the exploration of biomass-based additives stands out as a promising approach to mitigate the environmental impact of polymeric materials [1,2]. Among these additives, the integration of natural oils as plasticizers has gained considerable prominence in recent years due to several advantages [3].

The International Union of Pure and Applied Chemistry (IUPAC) defines plasticizers as substances added to polymers to enhance certain properties, such as flexibility, malleability, and other characteristics [4]. These additives play a crucial role in modifying the performance characteristics of polymers, allowing their use in a wide range of applications where these properties are essential [5]. Most plasticizers are composed of colorless, odorless liquids, often esters, which are used in mixtures in various proportions. Although their primary function is to improve the processability and mechanical properties of polymers, their presence is so significant that they are considered an integral part of formulations rather than mere additives [5,6].

Historically, thousands of substances have been tested as plasticizers, but fewer than 100 have commercial importance due to performance, cost, and regulatory compliance. The global plasticizer market is closely linked to the polymer market, particularly Polyvinyl chloride (PVC), where more than 90% of plasticizers are used [7,8]. However, as regulation and consumer demand for safer and more sustainable alternatives increase, the development of biomass-based plasticizers, such as buriti oil, andiroba, or copaiba, gains prominence. These natural plasticizers offer a promising route to improve the sustainability of polymeric materials while maintaining or enhancing the desirable properties of polymers [9].

Natural oils, characterized by their diverse chemical compositions and functional attributes, present themselves as viable candidates for augmenting the properties of polymers. The incorporation of these oils into polymer matrices aims not only to enhance mechanical characteristics but also to contribute to a more sustainable and eco-friendly approach to material science [10]. Among the myriad of natural oils, buriti oil, extracted from the fruit of traditional Amazonian *Mauritia flexuosa* palm tree, stands out for its rich content of vitamins, minerals, proteins, carotenoids, and tocopherol. The multifaceted benefits attributed to buriti oil, ranging from antioxidant activity to high oxidative stability, position it as a compelling bio-additive for polymeric materials [11].

Among the classifications of plasticizers, buriti oil can be considered a primary plasticizer, as it can induce softness and elongation when added to the polymer, without the need for other components to enhance its effectiveness [7,12]. Additionally, due to its bioactive properties, buriti oil may offer additional advantages, such as increased thermal stability and oxidation resistance, essential characteristics for applications requiring durability and performance under adverse environmental conditions. Besides compatibility considerations, the thermal stability and volatility of plasticizers are crucial characteristics that influence the durability and safety of final products. The introduction of natural additives, such as buriti oil, presents significant potential to mitigate these challenges [13–15].

An emerging trend in material science is the growing emphasis on incorporating innovative additives that offer multifunctional benefits. Among these, bio-based alternatives like natural oils have gained significant attention due to their potential not only to improve the performance of polymeric materials but also to reduce the environmental footprint associated with synthetic additives. Natural oils, which are often derived from renewable resources, offer a promising sustainable route to enhance the flexibility, toughness, and processability of LLDPE without compromising its environmental profile [16]. The use of such oils as plasticizers or processing aids can lead to polymers that are more adaptable to diverse applications, exhibit improved mechanical properties, and offer a more sustainable alternative to conventional plasticizers. This shift towards bio-based additives aligns with the broader trend in materials science towards the development of eco-friendly and sustainable polymeric systems, thereby contributing to the reduction of dependency on fossil fuel-based materials and promoting the use of renewable resources [17].

Numerous studies are currently underway to develop ecological plasticizers, and many oils stand out when used as plasticizers, notable for their biodegradability, low toxicity, and renewability. For instance, palm oil has been successfully used as a plasticizer in natural rubber (NR) and carbon black (CB) composites, resulting in enhanced properties such as improved CB dispersion and increased tensile strength, especially at lower oil contents compared to traditional petroleum-based plasticizers [18]. Similarly, soybean oil derivatives, particularly methoxy polyethylene glycol-modified epoxidized soybean oil (mPEG-ESBO), have shown promise in PVC applications, providing

superior tensile strength and elongation while lowering the glass transition temperature (T_g) compared to conventional phthalate plasticizers [19]. Additionally, *Moringa oleifera* oil has been investigated as a bioplasticizer for natural rubber vulcanizates, where it has demonstrated improved cure rate, mechanical properties, and enhanced rolling resistance and wet grip behavior, positioning it as a viable green alternative to naphthenic oil in rubber formulations [20]. These examples highlight the potential of plant-derived oils as sustainable plasticizers in various polymer matrices, contributing to a more environmentally friendly approach in material science.

The prevailing trend indicates a shift towards ecological plasticizers potentially replacing synthetic counterparts entirely [21]. Flexibility, workability, and distensibility are crucial properties for polymers as they directly influence their adaptability to various processing conditions and end-use applications. Flexibility enables the polymer to conform to diverse shapes while workability facilitates ease of handling during production, and distensibility is essential for withstanding deformations without compromising structural integrity. These characteristics are fundamental for the polymers' applicability and performance across a wide range of industrial applications [22,23]. Another critical aspect in the selection of plasticizers is its compatibility with the polymer matrix. Inadequate compatibility can lead to plasticizer extraction, compromising the performance of the final material and, in some cases, endangering the health of end-users [24].

One of the pivotal polymeric materials in focus is linear low-density polyethylene (LLDPE). As a widely used thermoplastic, LLDPE exhibits a range of desirable properties, including flexibility, transparency, and ease of processing [25]. These characteristics make LLDPE a material of choice in various applications, ranging from packaging films to containers and pipes. However, despite its advantageous properties, there is a continuous drive to enhance its processability, mechanical strength, and environmental impact. The inherent limitations of LLDPE, such as its relatively low thermal stability and moderate mechanical properties, necessitate the exploration of innovative solutions to meet the evolving demands of industry and sustainability [26,27]. LLDPE stands out among polyethylenes due to its unique molecular architecture, characterized by short, branched chains that result from copolymerization with alpha-olefins. This structure imparts greater flexibility and toughness compared to its high-density counterpart (HDPE), while maintaining a lower density and higher clarity. These attributes are essential in applications like stretch films and flexible packaging, where material performance under stress is critical. However, the same molecular features that confer flexibility also contribute to LLDPE's limitations in thermal stability and mechanical strength under extreme conditions [28,29].

This investigation aims to comprehensively evaluate the influence of buriti oil, extracted from the fruits of *Mauritia flexuosa* palm tree, on the rheological and thermal properties of LLDPE, crucial aspects governing the material's processability and performance. With a particular emphasis on sustainable alternatives, the study seeks to elucidate the role of buriti oil in improving the fluidity of LLDPE polymer chains, subsequently impacting thermal stability and oxidative resistance. The unique attributes of buriti oil, coupled with its versatile applications ranging from cosmetics to food, underscore the potential significance of this research in advancing sustainable practices within the realm of polymeric materials. Through a systematic analysis of processing parameters, thermal behavior, and rheological characteristics, this study aspires to disclose valuable insights to the growing body of knowledge surrounding bioadditives in polymer science.

2. Materials and Methods

2.1. Materials

In this study, linear low-density polyethylene (LLDPE), trade name Dowlex™ GM8480G, was used as the polymer matrix. The LLDPE, acquired from Dow Chemical Company, has a density of 0.917 g/cm³ and a melt flow index (MFI) of 3.0 g/10 min (measured at 230°C with a 2.16 kg load), in accordance with the ASTM D-1238 standard. The buriti oil, used as an additive, was supplied by Mega Plásticos S.A., with a density of 0.97 g/cm³. Both materials were prepared before processing. The LLDPE granules were dried in an oven at 70°C for 24 h to eliminate any moisture, ensuring

optimal mixing and preventing interference in the interfacial adhesion of the composites. The buriti oil was used as received without further purification.

2.2. Methods

2.2.1. Processing of LLDPE and LLDPE/Buriti Oil

LLDPE compositions, incorporating various percentages of buriti oil, were processed using melt intercalation. The compositions were blended at 150°C and 80 rpm for 7 min in a Haake PolyLab torque rheometer connected to a Rheomix mixing chamber equipped with roller rotors (70% fill factor). The addition of the filler occurred after 2 min in a batch mixer. Table 1 shows a detailed overview of the compositions studied.

Table 1. Composition of LLDPE/buriti oil studied.

Samples	LLDPE	Buriti oil (%wt)
LLDPE	100	-
LLDPE/BO-0.1	100	0.1
LLDPE/BO-0.3	100	0.3
LLDPE/BO-0.5	100	0.5
LLDPE/BO-1	100	1.0

2.2.2. Preparation of LLDPE and LLDPE/Buriti Oil Specimens

The preparation of the LLDPE and LLDPE/buriti oil specimens involved several key steps to ensure uniformity and consistency in the final samples. Initially, the compositions were ground using a SEIBT two-knife mill (model MGHS 1.5/85) operating at a rotation speed of 1150 rpm. This milling process was essential to reduce the particle size of the material, ensuring homogeneous mixing of the LLDPE and buriti oil. Following the milling step, the ground compositions were subjected to molding using a heated hydraulic press. The molding process was conducted at a temperature of 150°C for a duration of 10 min, applying a pressure of 10 tons. This temperature was selected based on the melting point of LLDPE, ensuring proper fusion and integration of the buriti oil within the polymer matrix. Once the molding step was completed, the samples were cooled using a water-circulated press to bring the temperature down to 30°C while maintaining the applied pressure of 10 tons. This rapid cooling process helped to stabilize the polymer structure and prevent any deformation or warping in the final product. The final result was polymeric plates with dimensions of 100 x 100 mm and a thickness of 3 mm. These plates were subsequently used for cutting test specimens according to the required dimensions for mechanical, thermal, and other characterization tests.

2.2.3. Fourier-Transform Infrared Spectroscopy (FTIR)

The chemical structure and bonding interactions in the LLDPE and LLDPE/buriti oil compositions were analyzed by FTIR spectroscopy using a Nicolet Nexus 470 spectrometer in transmission mode. The samples were scanned in the range of 4000–400 cm⁻¹ at a spectral resolution of 4 cm⁻¹ using 64 scans. The buriti oil was mixed with dried potassium bromide (KBr) powder and compressed into a disc.

2.2.4. Thermogravimetric Analysis (TGA)

TGA and its derivative curves (TG/DTG) of the weight loss versus temperature of buriti oil, LLDPE and LLDPE compositions was performed on a STA 409 PC Luxx thermogravimetric analyzer from NETZSCH, using approximately 10 mg of sample weighed in aluminum pan, operating from 30°C temperature to 560 °C range at a heating rate of 20 °C/min under a nitrogen atmosphere with steady flow of 60 mL/min.

2.2.5. Differential Scanning Calorimetry (DSC)

Thermal analyses were also performed using a DSC Q100 calorimeter (TA Instruments). Nitrogen was used as purge gas at a flow rate of 20 mL.min⁻¹. Samples of about 5 mg were weighed and used in the analysis. They were first heated from 20 °C to 200 °C at a rate of 10 °C.min⁻¹ to eliminate the thermal history and subsequently cooled to 20 °C at a rate of 10 °C.min⁻¹. The second heating cycle was conducted using the same conditions as the first cycle. From the second heating cycle's curve it was possible to obtain the cold crystallization temperature (T_{cc}), the melting temperature (T_m), the melting enthalpy (ΔH_f), and the cold crystallization enthalpy (ΔH_{cc}).

The degree of crystallinity was determined by Equation (1):

$$X_c = (\Delta H_m / (w \times \Delta [H_m]^{100})) \times 10 \quad (\text{Eq. 1})$$

where, ΔH_m is obtained from the area of the endothermic peak, ΔH_m0 is the enthalpy of fusion of the pure substance with 100% crystallinity, and w is the mass fraction of oil in the compositions. The value of ΔH_m0 for linear low-density polyethylene (LLDPE) is 293 J/g [30].

2.2.6. Scanning Electron Microscopy (SEM)

The morphology of the processed compositions surfaces was observed on a FEI scanning electron microscope, model Inspect S 50, in low vacuum mode using backscattered electron detectors (BEI), at a acceleration voltage of 15 kV. The samples were fixed on aluminum supports and coated with platinum in a EMITEC metalizing apparatus, model SC 7620, at 20 mA for 2 min. The SEM images were collected at a magnification of 1000 x.

2.2.7. Mechanical Properties

Tensile tests of the LLDPE and LLDPE compositions were carry out according to DIN 53504 specifications on a EMIC universal tester, model DL 3000 at 23°C and a cross-head speed of 100 mm/min. Dumbbell-shaped specimens were prepared by compression molding at temperature of 150°C and 10-ton force for 10 min, using MARCONI hydraulic press, model MA098. Five samples were tested from each composition and the average values were reported.

2.2.8. Hydrophobicity (Contact Angle Measurement)

The surface hydrophobicity of LLDPE and compositions was characterized by contact angle and conducted in a Pocket Goniometer (model PGX+). The water was utilized with proper solvent for analyses of samples.

3. Results and Discussion

3.1. Torque-Specific Energy-Time Analysis

The torque and specific energy values, along with the corresponding curves depicted in Figure 1 and Table 2, offer insights into the processing behavior of LLDPE and its compositions with buriti oil (BO).

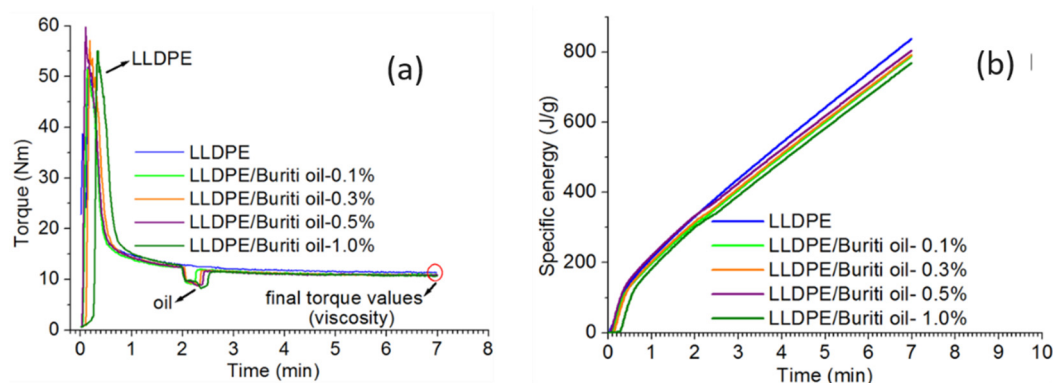


Figure 1. Torque (a) and Specific energy (b) curves as a function of processing time for the LLDPE and compositions.

The torque curves (Figure 1a) demonstrate the torque variations with processing time. Notably, the addition of buriti oil led to a slight reduction in the final torque values. This reduction indicates a subtle decrease in viscosity, emphasizing the impact of oil incorporation on material flow. The torque-time curves for LLDPE exhibited a single loading peak, suggesting a uniform loading process. However, upon introducing buriti oil, a viscosity reduction became apparent, noticeable in the torque decrease after the loading peak. The recorded torque peak at the beginning of mixing is attributed to friction generated between solids (particle-particle and particle-wall) and the plastic deformation of polymeric particles. Subsequently, a torque decrease occurs, linked to polymer material fusion. The reduction in viscosity post-fusion renders the material more fluid, leading to a decrease in force required for rotor movement. The torque stabilizes towards the end of processing, indicating consistent viscosity and suggesting improved processability with the addition of buriti oil [31].

Table 2. Torque (Nm) and Specific energy (J/g) processability values.

Samples	T (Nm)	e (J/g)
LLDPE	11.4	838
LLDPE/BO-0.1	10.9	788.1
LLDPE/BO-0.3	10.8	791.8
LLDPE/BO-0.5	10.8	804.9
LLDPE/BO-1	10.7	768.4

The specific energy curves (Figure 1b) showcase the cumulative energy demand for mixing over time. Initially, there is a substantial increase in energy demand within a short timeframe, reflecting the need to mix the polymer in its solid state. Following polymer fusion, the energy demand shows a nearly constant growth. Importantly, compositions with buriti oil exhibit lower torque and energy demand values, indicating enhanced mechanical workability and a potential plasticizing effect. Both torque and specific energy analyses support the notion that buriti oil improves the processability of LLDPE. The reduced torque values and energy demand imply increased fluidity, suggesting a plastifying effect of the buriti oil. This improvement in processability is consistent across all compositions, with the 1% buriti oil composition demonstrating the most favorable results. These findings align with the expected behavior of a plastifying agent, emphasizing the potential of buriti oil as an enhancer in the processing of LLDPE [32].

3.2. Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectrum of buriti oil reveals distinct absorption bands, as observed in previous studies on similar materials. The spectrum exhibits significant bands associated with saturated alkanes, such as the C–H stretching at 2925 cm⁻¹ and 2852 cm⁻¹. The band at 1745 cm⁻¹ denotes the C=O stretching vibration of carboxylic groups, suggesting the occurrence of carbonyl groups in fatty acid esters [33]. In the range of 1100-1500 cm⁻¹, the absorption profile is influenced by several bands, with contributions from oleic acid (OA) and some from angular triolein (AT). The bands at 2852 cm⁻¹ and 1159 cm⁻¹ can be attributed to aliphatic hydrocarbons and C–H bending vibrations, respectively. These bands contribute to the characterization of long hydrocarbon chains and the scissoring stresses in the C–H₂ groups, aligning with the structural characteristics of fatty acids in buriti oil [33,34].

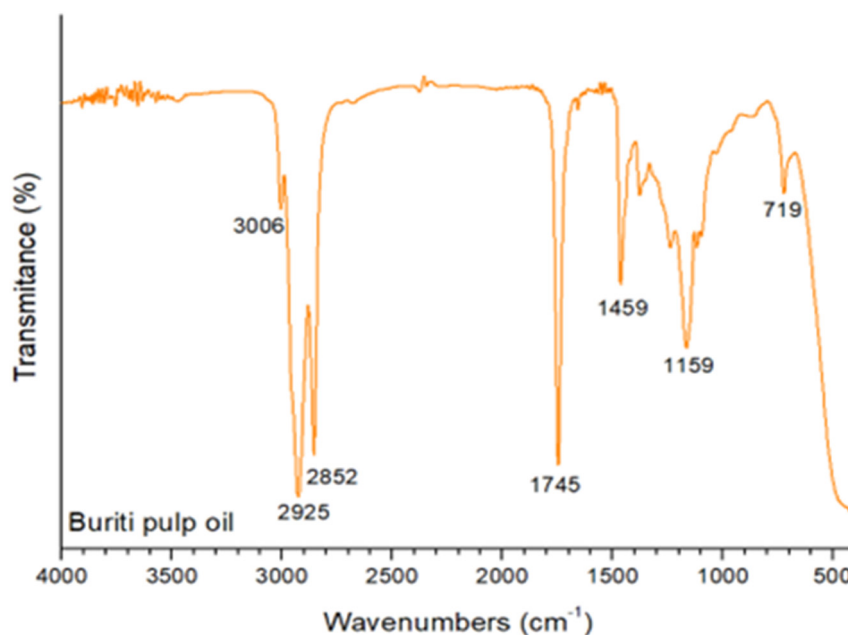


Figure 2. FTIR spectra of buriti oil.

The bands at 1459 cm^{-1} and 719 cm^{-1} correspond to C–H₂ scissoring and asymmetric C–H₃ stretching, respectively. These bands further elucidate the molecular structure of buriti oil, providing insights into the specific vibrations associated with its aliphatic hydrocarbons [34,35]. The band at 3006 cm^{-1} is attributed to C–H stretching related to =C–H bonding. The observed spectral features align with the expected characteristics of long-chain fatty acids found in buriti oil. The presence of ester functions, unsaturation, and specific vibrational modes corroborates the typical composition of vegetable oils. The spectral similarities with oleic and palmitic acids further validate the fatty acid composition of buriti oil. Detailed analyses reveal specific vibrations related to the molecular structure of buriti oil. Bands associated with C=C–C–O stretching and C–C movement provide insights into the molecular arrangement and potential similarities with triglycerides such as triolein [33,35].

3.3. Thermogravimetry Analysis (TGA)

The thermogravimetric decomposition expressed in terms of weight loss as a function of temperature for the compositions is shown in Figure 3. It is very interesting to note that the thermal stabilities of buriti oil and LLDPE under different conditions of degradation tests have shown distinct initial temperatures of weight loss (Tonset).

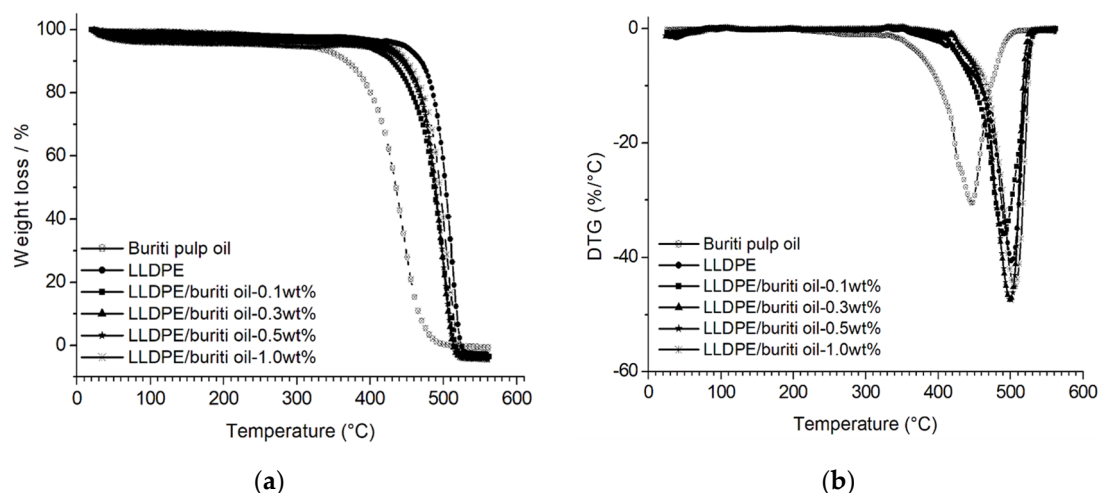


Figure 3. Thermogravimetric analysis (TGA) and differential thermal gravimetry (DTG) of buriti oil, pure LLDPE, and LLDPE/buriti oil compositions. (a) Depicts the weight loss percentage (%) as a function of temperature, highlighting the thermal stability and degradation stages of the materials. (b) Illustrates the DTG (%/°C), indicating the maximum rates of mass loss and corresponding degradation temperatures.

The TGA curves revealed that all samples exhibited a gradual weight loss, with a nearly imperceptible onset of degradation for each sample. However, there was variation in the Tonset among the samples, indicating different thermal behaviors. A slight reduction in Tonset was noted for the LLDPE/buriti oil composition with 0.1 wt%, and a slight increase in Tonset values was observed for other polyethylene compositions with increasing levels of buriti oil subjected to the same analysis conditions. Buriti oil exhibited a distinctive band in the range of 370 to 470 °C, indicating specific decomposition in this temperature range [36,37]. In the LLDPE/buriti samples, this band was preserved, although there was a slight variation, suggesting an interaction between buriti oil and LLDPE.

Comparing pure LLDPE samples with LLDPE/buriti compositions, a proximity in the degradation zones was observed, situated between 460 and 530 °C. This similarity indicates that the addition of buriti oil did not significantly compromise the thermal stability of the polymer. These results are consistent with previous studies on polymers and vegetable oils, where different degradation behaviors were attributed to specific characteristics of the materials [37]. The presence of functional groups in buriti oil, as evidenced in the FTIR analysis, may contribute to the observed thermal variation [33]. Comparative analysis with other polymers suggests that the additives may impact thermal stability [38–40]. Increases in Tonset and maximum temperatures (Tmax) may indicate an improvement in thermal stability, following patterns observed by other authors who used reinforcements in polymers [40].

3.4. Differential Scanning Calorimetry (DSC)

In the Tc curves depicted in Figure 4, we observe that the Tc1 values for the LLDPE and its compositions with buriti oil are approximately 105°C, as shown in the corresponding Table 3. Tc represents the crystallization temperature, indicating the transition from the amorphous to the crystalline phase [41,42].

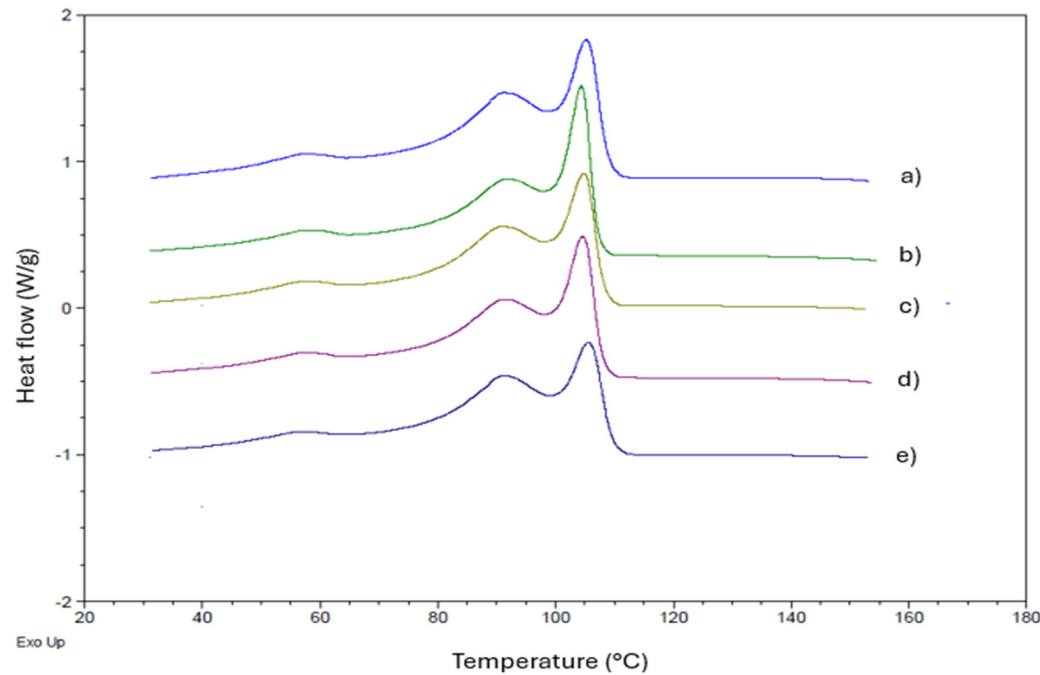


Figure 4. DSC analysis of LLDPE and its compositions with buriti oil: (a) LLDPE, (b) LLDPE/Buriti oil-0.1%, (c) LLDPE/Buriti oil-0.3%, (d) LLDPE/Buriti oil-0.5%, (e) LLDPE/Buriti oil-1.0%. Note: Crystallization temperature (Tc).

The DSC curves exhibit a bimodal endothermic peak for both crystallization and melting processes, with no significant alterations in the values of crystalline melting temperatures (Tm). The crystallization thermograms display an intense exothermic peak, followed by a moderate peak and a weak signal for all compositions. This consistent behavior is observed across all samples, as depicted in Figure 5.

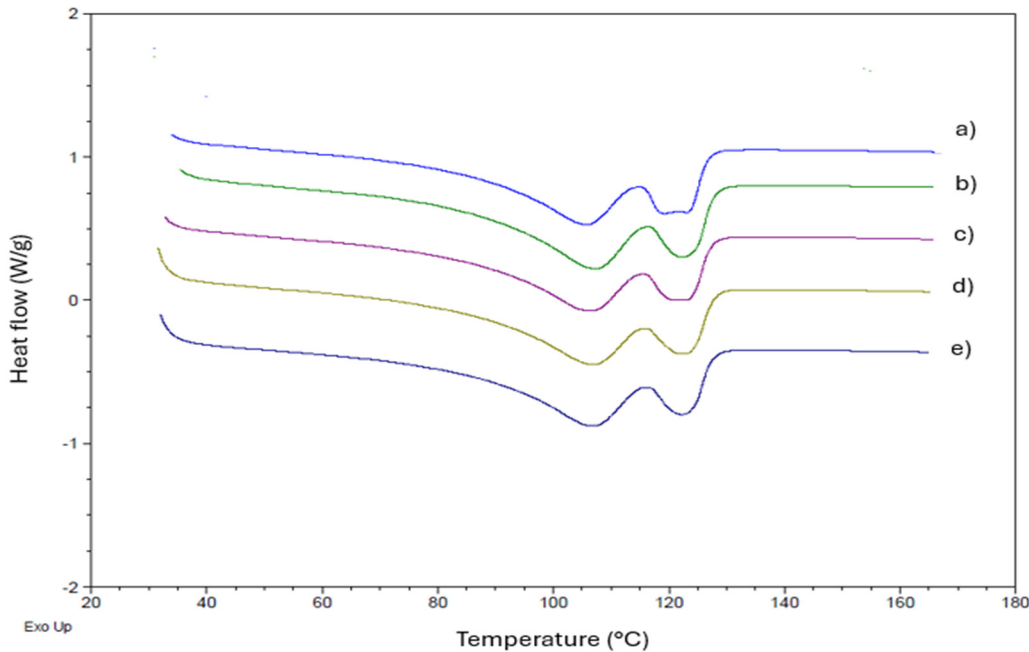


Figure 5. DSC analysis of LLDPE and its compositions with buriti oil: (a) LLDPE, (b) LLDPE/Buriti oil-0.1%, (c) LLDPE/Buriti oil-0.3%, (d) LLDPE/Buriti oil-0.5%, (e) LLDPE/Buriti oil-1.0%. Note: Crystalline melting temperature (Tm).

From the DSC results presented in Table 3, it is evident that there are no substantial changes in the crystallization temperatures (Tc) and melting temperatures (Tm) with the addition of low concentrations of buriti oil. This suggests the preservation of the analyzed thermal behavior. However, a slight decrease in the enthalpy of fusion (ΔH_m) and the degree of crystallinity is observed in the compositions compared to pure LLDPE. This subtle reduction implies that the oil may be acting as a plasticizer, contributing as a processing aid. The DSC findings align with the torque rheometry processability curves, confirming the role of buriti oil as a processing aid.

The observed thermal properties, including crystallization and melting temperatures (Table 3), indicate the potential use of buriti oil as a processing aid without significant alteration in the overall thermal behavior of LLDPE.

Table 3. Detailed Analysis of LLDPE Composition with Buriti Oil: Effects on Crystallization and Thermal Properties.

Samples	T _{c1} (°C)	T _{c2} (°C)	T _{c3} (°C)	T _{m1} (°C)	T _{m2} (°C)	ΔH_m (J/g)	X _c (%)
LLDPE	105.3	91.2	57.7	107.6	122.1	114.2	39.0
LLDPE/BO-0.1	104.4	91.7	57.1	105.1	121.9	103.8	35.4

LLDPE/BO-0.3	104.8	90.9	57.7	107.8	122.5	106.2	36.6
LLDPE/BO-0.5	104.6	91.2	57.4	106.7	123.4	104.1	35.5
LLDPE/BO-1	105.5	91.2	56.9	107.7	122.2	103.8	35.4

3.5. Scanning Electron Microscopy (SEM)

The morphological characteristics of pure LLDPE and the LLDPE/Buriti oil systems were analyzed by SEM, as presented in Figure 6. The micrograph of pure LLDPE is shown in Figure 6 a). A surface characterized by high roughness was noted, a morphological characteristic of the polymer that is also highly influenced by the methodology used in the preparation of the specimens. The morphologies identified in Figure 6 b) refer to the systems containing buriti oil. These micrographs showed smoother and more homogeneous surfaces regardless of the oil content added. Therefore, it was observed that the buriti oil used as a plasticizer during processing helped in the processing and contributed to obtaining smoother and more homogeneous surfaces compared to the pure polymer.

The SEM images of the LLDPE/Buriti oil compositions reveal several critical aspects of the material’s microstructure and dispersion characteristics. The micrographs exhibit a relatively uniform surface morphology, albeit with some irregularities and dispersed particles. In particular, the image 6 a) of the first set shows a smooth surface with minor surface roughness and scattered particles, while the image 6 b) similarly depicts a homogeneous surface interrupted by a few particles. Notably, all compositions exhibit the same pattern in the SEM analysis, indicating consistent dispersion of buriti oil within the LLDPE matrix.

The second set of images presents a more detailed view of the particle dispersion within the LLDPE matrix. Both images, 6 c) and 6 d), indicate the presence of larger particles distributed throughout the polymer matrix. These particles vary in size and shape, suggesting that the mixing process may not have achieved perfect homogeneity. The heterogeneity in particle size and distribution could be indicative of incomplete mixing or agglomeration of the buriti oil within the LLDPE matrix.

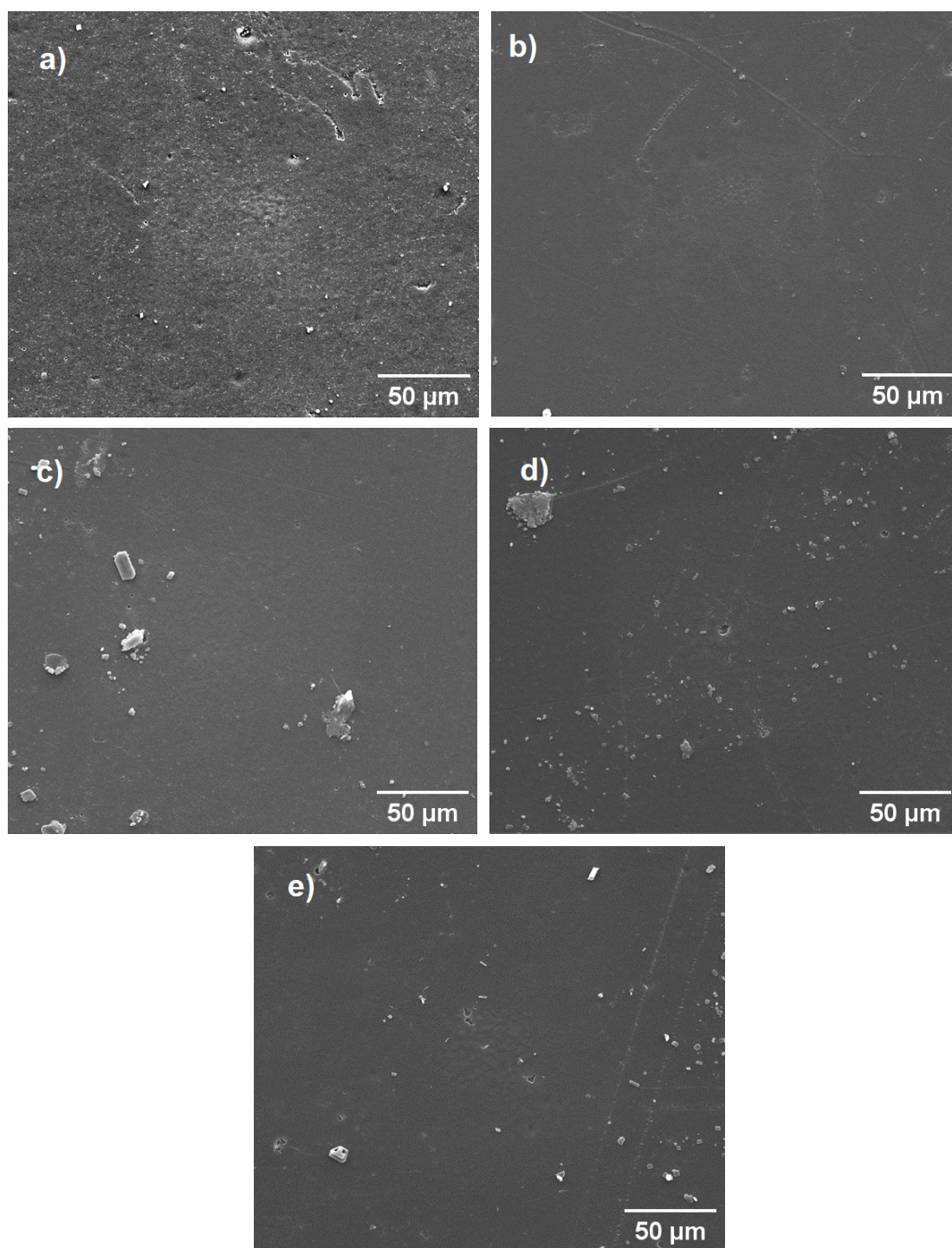


Figure 6. SEM images of LLDPE and LLDPE/Buriti oil compositions: (a) Pure LLDPE showing rough surface morphology; (b) LLDPE/Buriti oil composition displaying smoother and more homogeneous surface; (c) and (d) LLDPE/Buriti oil compositions with dispersed particles of varying sizes, indicating partial agglomeration within the matrix.

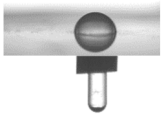
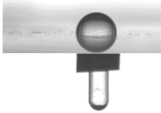
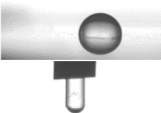
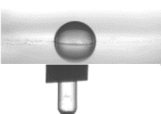
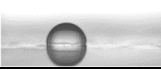
The overall surface morphology appears less brittle and more uniform in the LLDPE/buriti oil composites, which correlates with the improved mechanical properties observed in tensile testing. The presence of dispersed buriti oil particles likely contributes to the enhancement of mechanical properties, such as increased tensile strength and elongation at break. The uniformity in the microstructure, as evidenced by the SEM images, supports the notion that buriti oil acts as a plasticizer, improving the material's flexibility and workability [43,44]. However, the presence of larger, heterogeneous particles suggests that further optimization of the mixing process is necessary

to achieve a more uniform dispersion of buriti oil within the LLDPE matrix. This could involve adjustments to the mixing parameters or the introduction of additional processing steps to reduce particle size and improve distribution.

3.6. Contact Angle Analysis

The measurement of the contact angle serves as a crucial characterization tool, providing insights into the solid surface (substrate) properties. This technique involves determining the angle in degrees formed by a liquid droplet on the surface of the analyzed sample. The obtained angle value is directly related to the surface tension between the interfaces of the analyzed substances. Thus, the response indicates the substrate’s affinity for the analyzed liquid, representing its wettability [45,46]. In this study, water was used as the liquid, and the influence of increasing concentrations of buriti oil in the LLDPE matrix composition was assessed through contact angle measurements, as presented in Table 4. Although there are statistically significant differences in the results, the standard deviation values showed considerable amplitudes, indicating no alteration in the contact angle between pure LLDPE matrix and compositions containing up to 0.5% by mass of buriti oil. However, the value obtained for the composition containing 1.0% by mass of oil exhibited a slight increase in the angle, suggesting that buriti oil favored a reduction in wettability compared to other systems.

Table 4. This is a table. Tables should be placed in the main text near to the first time they are cited.

Sample	Contact Angle [°]	Image
		
PELBD Puro	85,25 (2,01)	
PELBD 0,1	87,08 (3,81)	
PELBD 0,3	88,74 (1,69)	
PELBD 0,5	89,06 (1,58)	
PELBD 1,0	100,96 (3,44)	

3.7. Mechanical Properties

The mechanical properties, including tensile modulus of elasticity, tensile strength, and elongation at break, were evaluated in accordance with ASTM D638 standards. The results of the tensile test for LLDPE with increasing concentrations of buriti oil (0.1%, 0.3%, 0.5%, and 1%) are presented in Figure 7. The values represent the average of the obtained results with their respective standard deviations.

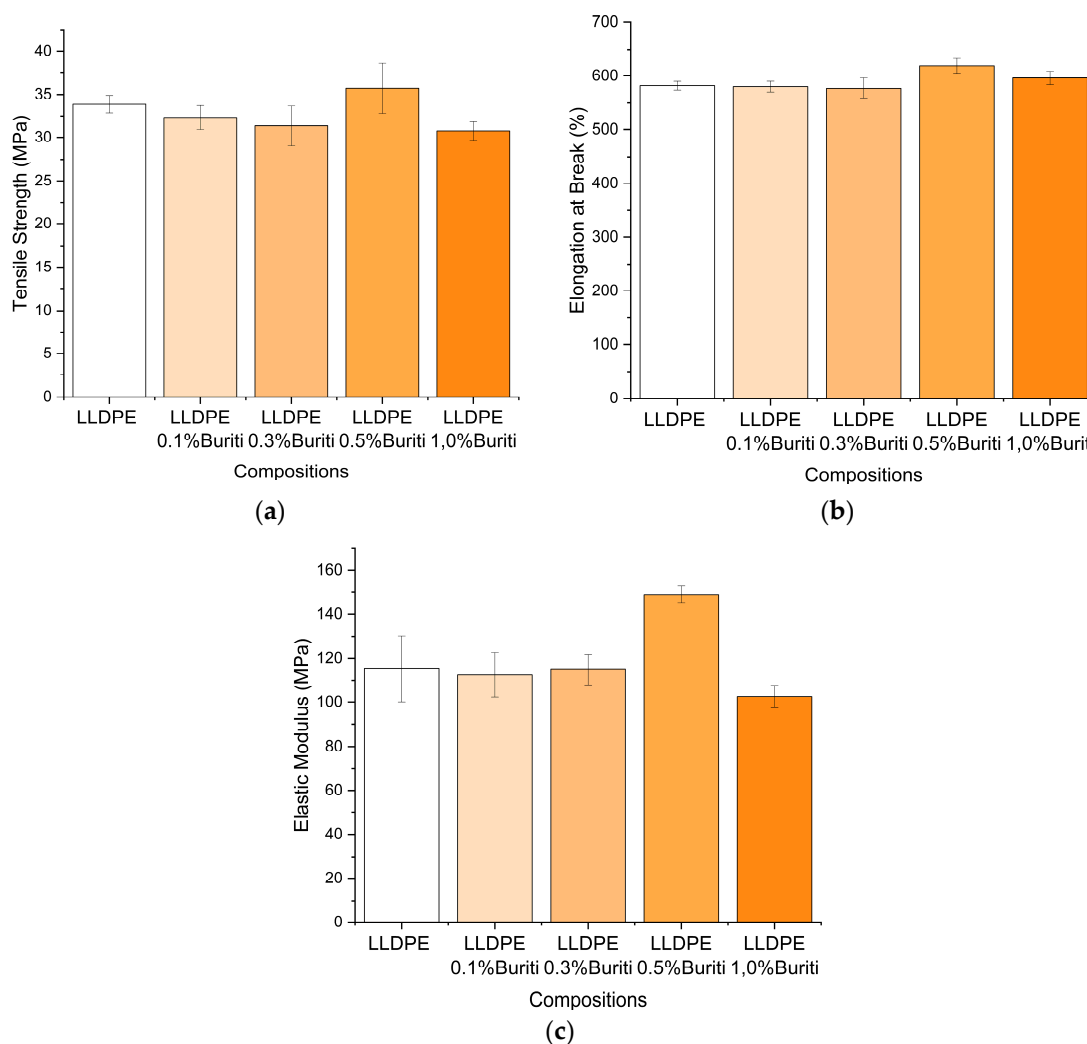


Figure 7. Effect of Buriti Oil Addition on the Mechanical Properties of LLDPE Composites. (a) Tensile strength, (b) Elongation at break, and (c) Elastic modulus of LLDPE composites with varying concentrations of buriti oil (0.1%, 0.3%, 0.5%, and 1%). Error bars represent standard deviations.

The tensile strength results (Figure 7) show that the addition of buriti oil influences the tensile behavior of LLDPE. The composition with 0.5% buriti oil exhibited the highest tensile strength, reaching approximately 35 MPa, which is a significant improvement compared to the other concentrations. This indicates that at this concentration, buriti oil enhances the strength of LLDPE, possibly due to better stress distribution and reduced chain mobility, leading to an overall stronger material. In a similar vein, Ngo et al. [47] discovered that introducing natural oils such as linseed or pine oil into natural fiber-reinforced polyester composites predominantly diminishes surface microhardness and tensile properties but simultaneously augments ductility, indicating a complex interplay between natural oil additives and the mechanical properties of polymer composites.

The modulus of elasticity (Figure 7) follows a similar trend, where the 0.5% buriti oil composition shows a noticeable increase. The enhancement in modulus suggests that buriti oil at this concentration reinforces the polymer matrix, making it stiffer and more resistant to deformation under stress. This improvement in stiffness can be attributed to the interaction between the buriti oil and the LLDPE matrix, which may create a more rigid network structure.

Elongation at break (Figure 7) provides insights into the material's flexibility and ductility. The results indicate that the incorporation of buriti oil generally enhances the elongation at break, with the 1% buriti oil composition showing the highest value. This suggests that buriti oil acts as a plasticizer, increasing the flexibility and ductility of the LLDPE matrix. The increased elongation at break signifies that the material can undergo more deformation before failure, contributing to

improved toughness. Corroboratively, Brunel et al. [48] reported that natural additives, when incorporated into polymers, act as efficient plasticizers. Their studies on PHBV indicated significant enhancements in mechanical properties following the integration of natural oils, which notably decreased the elastic modulus and increased both impact resistance and elongation, thereby underscoring the beneficial effects of natural oil additives on the mechanical behavior of polymers.

The observed mechanical property enhancements, particularly with the 0.5% buriti oil composition, signify a positive impact on the overall tensile behavior of LLDPE. The increase in modulus of elasticity, tensile strength, and elongation at break indicates a favorable combination of stiffness, strength, and flexibility, contributing to improved toughness. This could be attributed to the lubricating and reinforcing effects of buriti oil, influencing the polymer matrix's mechanical response. The lubricating effect of buriti oil reduces internal friction between polymer chains, allowing them to slide more easily past each other, which enhances elongation at break. The reinforcing effect is likely due to the oil's ability to interact with the polymer matrix, creating a more cohesive and robust network that enhances tensile strength and modulus of elasticity. These dual effects contribute to a more balanced mechanical performance, making the LLDPE/buriti oil composites suitable for applications requiring both strength and flexibility.

5. Conclusions

The comprehensive analysis conducted on the LLDPE/buriti oil composites has provided valuable insights into their thermal, rheological, and mechanical behaviors. The thermal analysis, including TGA and DTG, revealed distinct decomposition patterns, with the buriti oil introduction influencing the onset temperatures and decomposition ranges. These findings align with existing literature on the thermal behavior of similar polymer-oil composites, highlighting the significance of the observed trends. Examining the DSC results shed light on the crystallization and melting characteristics of the composites. The variations in crystallization and melting temperatures, as well as enthalpy changes, demonstrated the impact of buriti oil on the polymer's molecular arrangement. This information is vital for understanding the material's processing and potential applications. The torque-specific energy-time analysis offered valuable insights into the processing behavior of the composites. The reduction in torque values with the addition of buriti oil indicated a decrease in viscosity, while the observed peaks and subsequent decline suggested complex interactions during the mixing process. These aspects are crucial for optimizing the processing parameters for composite production. Mechanical property evaluation provided a comprehensive understanding of how buriti oil influences the tensile strength, elongation at break, and elastic modulus of LLDPE, with the 0.5% concentration showing the most promising results in terms of tensile strength and modulus of elasticity, while the 1% concentration excels in elongation at break. The SEM analysis provides valuable insights into the microstructural characteristics of LLDPE/buriti oil composites. The findings indicate that while the buriti oil is generally well-dispersed and contributes positively to the mechanical properties, there is room for improvement in achieving a more homogeneous distribution. These microstructural observations align with the overall enhancement in processability and mechanical performance, reinforcing the potential of buriti oil as an effective bio-based additive in polymer composites. In summary, the systematic investigation of the LLDPE/buriti oil composites encompassed various aspects, offering a holistic perspective on their thermal, rheological, and mechanical characteristics. These findings contribute to the growing body of knowledge on bio-based polymer composites, providing valuable information for further optimization and potential applications in diverse industrial sectors.

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