

Synthesis, Characterization, and Thermogravimetric Analysis of Polylactic Acid-Based Bio-Adhesive for Industrial Applications

Salisu Nuhu^{1,*}, Haruna Abubakar Danyaya²

Abstract

This study investigated the synthesis, characterization, and thermogravimetric analysis of polylactic acid (PLA)-based bio-adhesives for industrial applications. The adhesive was synthesized using an emulsion polymerization method with varying compositions of PLA and vinyl acetate. The physicochemical, mechanical, and thermal properties of the synthesized adhesives were assessed through pH analysis, viscosity measurement, peel strength evaluation, tack tests, biodegradability investigations, Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC), and Thermogravimetric Analysis (TGA). The results revealed that increasing PLA concentration improved adhesion strength, viscosity, thermal stability, and water resistance. FTIR analysis confirmed successful polymer formation through the presence of ester functional groups, while DSC and TGA analyses demonstrated enhanced thermal behavior with higher PLA content. The biodegradability study also showed increased degradation with increasing PLA concentration, indicating environmental sustainability. Among the formulations, Sample C exhibited the best overall performance, making it the most suitable candidate for industrial applications such as packaging and labeling. The findings confirm that PLA-based bio-adhesives can serve as environmentally friendly alternatives to petroleum-based adhesives.

Keywords: polylactic acid (PLA) bio-adhesives, emulsion polymerization, thermogravimetric analysis (TGA), biodegradable adhesives, industrial packaging applications

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INTRODUCTION

Despite its advantages, the application of PLA in adhesive formulations is not without challenges. For industrial relevance, adhesives must exhibit adequate thermal stability, mechanical strength, and resistance to environmental conditions. These properties determine their effectiveness in real-world applications where temperature variations and mechanical stress are common.

To better understand and improve the performance of PLA-based bio-adhesives, it is essential to investigate their thermal behavior and structural characteristics. Characterization techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and other

analytical methods provide insights into the chemical structure and morphology of the material. Additionally, thermogravimetric analysis (TGA) is a critical technique used to evaluate the thermal stability and decomposition patterns of materials by monitoring weight changes as a function of temperature. [1].

This study, therefore, focuses on the synthesis, characterization, and thermogravimetric analysis of polylactic acid-based bio-adhesives, with the aim of developing a sustainable material that can meet the demands of industrial applications while minimizing environmental impact.[2]

Problem Statement

The continued reliance on petroleum-based adhesives in industrial applications presents significant environmental and sustainability challenges. These materials originate from non-renewable resources and contribute to persistent environmental contamination due to their resistance to degradation. Furthermore, the emission of harmful substances during their production and use raises additional concerns regarding occupational safety and environmental health.

Although bio-based adhesives have been proposed as alternatives, many existing formulations do not yet meet the performance standards required for industrial use. In particular, limitations in thermal stability and durability hinder their widespread adoption. Polylactic acid-based adhesives show considerable promise; however, there is still a need to optimize their synthesis and enhance their performance characteristics.

Moreover, insufficient data on the thermal degradation behavior and structural properties of these materials limits their practical application. Without proper characterization and analysis, it becomes difficult to predict their behavior under industrial conditions.

This study seeks to address these gaps by developing a PLA-based bio-adhesive and conducting comprehensive characterization and thermogravimetric analysis to evaluate its suitability for industrial applications.

Aim of the Study

The main aim of this study is to synthesize, characterize, and evaluate the thermal properties of polylactic acid-based bio-adhesives for industrial applications.

The specific objectives of this research are to:

1. Synthesize a polylactic acid-based bio-adhesive
2. Characterize the synthesized adhesive using appropriate analytical techniques
3. Determine the thermal stability of the adhesive using thermogravimetric analysis (TGA)
4. Analyze the structural and morphological properties of the adhesive
5. Evaluate the potential applicability of the adhesive in industrial settings

This study is significant due to its contribution to the expanding domain of sustainable materials. By exploring the potential of polylactic acid as a base material for bio-adhesives, this research supports the development of environmentally friendly alternatives to conventional adhesives.

The findings from this study will provide valuable information on the thermal stability and structural characteristics of PLA-based adhesives, which are critical factors in determining their industrial applicability. This can serve as a foundation for further research and development aimed at improving the performance of bio-based adhesive systems.

Furthermore, the study corresponds with international sustainability objectives by advocating for the utilization of renewable resources and mitigating environmental damage linked to synthetic materials. It may also have practical implications for industries seeking cost-effective and eco-friendly bonding solutions.

Scope of the Study

This study concentrates on the synthesis, characterisation, and thermogravimetric assessment of bio-adhesives derived from polylactic acid. The study covers the preparation of the adhesive, evaluation of its chemical and structural properties, and assessment of its thermal behavior.

However, the study does not extend to large-scale industrial production or long-term field performance testing. The results obtained are therefore limited to laboratory-scale analysis and evaluation

LITERATURE REVIEW

The increasing demand for environmentally sustainable materials has led to extensive research into bio-based alternatives for conventional industrial products. Adhesives, which are essential in a wide range of applications, are among the materials being re-evaluated because of their environmental footprint. This chapter reviews existing literature on bio-adhesives, polylactic acid (PLA), synthesis methods, characterization techniques, and thermo gravimetric analysis, with the aim of providing a solid foundation for the present study.

Overview of Adhesives

Adhesives are materials that bond surface together through attachment. They are widely used in industries such as packaging, construction, automotive, and electronics due to their ability to provide strong and durable bonds without the need for mechanical fasteners [3].

Typical conventional adhesives come from petroleum-based polymers like epoxy resins, polyurethanes and acrylics. While, these materials offer excellent bonding strength and durability, they are associated with several drawbacks, including environmental pollution, toxicity, and non-biodegradability [4].

Bio-Adhesives

Bio-adhesives are derived from natural and renewable resources such as starch, proteins, lignin, and other biopolymers. They are regarded as eco-friendly because they biodegrade have low toxicity and offer a smaller carbon footprint [5].

Historically, natural adhesives were used before the advent of synthetic polymers; however, their application declined due to inferior mechanical properties and poor resistance to environmental conditions. Recent advancements in material science have led to renewed interest in bio-adhesives, with efforts focused on improving their performance to meet industrial standards [6].

Bio-adhesives offer several advantages, including sustainability and reduced environmental impact, but challenges such as low thermal stability and limited durability still restrict their widespread adoption in demanding industrial applications. (skeist&miron 2019).

Polylactic Acid (PLA)

Polylactic acid (PLA) is one of the most widely studied biodegradable polymers due to its excellent biocompatibility and ease of production from renewable resources. It is produced from lactic acid which comes from fermenting carbohydrate like corn starch or sugarcane [7].

PLA possesses several desirable properties, including biodegradability, good mechanical strength, and processability. These attributes render it appropriate for diverse uses, such as packaging, medical devices, and more recently, adhesive compositions [8].

However, PLA also has certain limitations, such as brittleness and relatively low thermal resistance. These limitations can affect its performance in adhesive applications, particularly in environments involving high temperatures or mechanical stress [6].

Poly lactic acid, often known as poly (lactic acid) or polylactide (PLA), is a thermoplastic polyester officially generated by condensation of lactic acid $C(CH_3)(OH)HCOOH$ with water loss (hence its name). Lactide ring opening polymerization can also be used to make it [9]. This is shown in Figure 1 below



Synthesis of PLA-Based Bio-Adhesives

The synthesis of PLA-based bio-adhesives typically involves the modification of PLA to improve its adhesive properties. This may include blending with plasticizers, copolymerization, or incorporation of other bio-based materials to enhance flexibility and bonding strength. Different synthesis techniques have been explored, including solvent casting, melt blending, and chemical modification methods. These approaches aim to optimize the physical and chemical properties of the adhesive to meet specific application requirements [10].

The selection of synthesis method greatly influences the adhesive's final characteristics, such as thermal stability, viscosity, and bonding performance.

Characterization of Bio-Adhesives

Characterization is essential in understanding the properties and performance of synthesized bio-adhesives. Various analytical techniques are used to evaluate their chemical structure, morphology, and physical properties [10].

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is a common method for identifying functional groups and verifying the chemical structure of polymers. It provides information about the molecular interactions and bonding within the adhesive material [11].

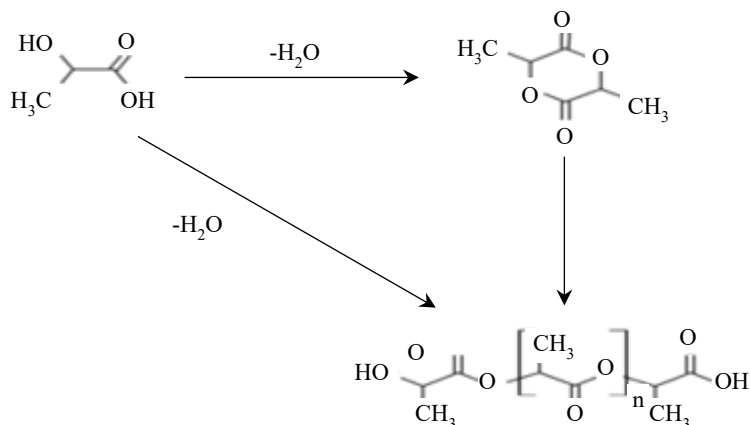


Figure 1. Chemical structure and polymerization of polylactic acid (PLA).

Scanning Electron Microscopy (SEM)

SEM is employed to study the surface morphology of materials. It helps in understanding the texture, porosity, and structural uniformity of the adhesive, which can influence its bonding performance [12].

Mechanical Properties

Mechanical testing evaluates properties such as tensile strength, elasticity, and adhesion strength. These attributes are crucial for determining the adhesive's suitability for industrial uses.

Thermo gravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is a common method for assessing the thermal stability of substances. It measures the change in mass of a sample as it is heated over time, providing insights into its decomposition behavior [13].

TGA is particularly important for adhesive materials because it helps determine:

- Decomposition temperature
- Thermal stability range
- Weight loss patterns

These parameters are essential for understanding how the material will perform under different temperature conditions in industrial environments.

For PLA-based materials, TGA typically shows a single-stage degradation process, although this can vary depending on the composition and modifications made during synthesis [14].

Industrial Applications of Bio-Adhesives

Bio-adhesives are increasingly being explored for use in industries such as packaging, woodworking, and textiles. Their ability to biodegrade makes them especially appealing when environmental impact is a key concern. PLA-based adhesives, in particular, have shown potential in packaging applications due to their compatibility with biodegradable materials. However, further improvements in thermal and mechanical properties are required for broader industrial adoption [15].

Research Gap

Despite significant progress in the development of bio-based adhesives, several challenges remain. Many studies have focused on the synthesis of PLA-based materials, but fewer have provided comprehensive analysis combining synthesis, characterization, and thermal evaluation.

In particular, there is limited data on the thermogravimetric behavior of PLA-based bio-adhesives in relation to their industrial applicability. This lack of information hinders understanding of how these materials behave in real-world conditions.

This study aims to bridge this gap by providing a detailed investigation into the synthesis, characterization, and thermal properties of PLA-based bio-adhesives.

MATERIALS AND METHODS

All reagents and chemicals employed in this study were of analytical grade and obtained from a certified chemical supplier based in Kano, Nigeria. The materials were transported to the Science Laboratory Technology Department of Hussaini Adamu Federal Polytechnic, Kazaure, where all experimental procedures were carried out.

The major materials used include:

- Polylactic acid (PLA)
- Vinyl acetate (VAc)
- Potassium per sulfate (initiator)
- Sodium hydrogen carbonate (buffer)
- Surfactant solution
- Additives/modifiers
- Solvent (e.g., chloroform or dichloromethane)
- Plasticizer (e.g., glycerol or polyethylene glycol)
- Distilled water

All chemicals were used as received without further purification.

Preparation of Solutions

A buffer solution was prepared by dissolving 0.12 g of sodium hydrogen carbonate in 10 mL of distilled water in a 50 mL beaker. Similarly, an initiator solution was prepared by dissolving 0.12 g of potassium persulfate in 10 mL of distilled water in another 50 mL beaker. Both solutions were stirred thoroughly until complete dissolution was achieved.

Synthesis of PLA-Based Bio-Adhesive

The bio-adhesive was synthesized via an emulsion polymerization process. Measured volumes of polylactic acid (PLA) and vinyl acetate (VAc) were introduced into a polymerization bottle, followed by the addition of 20 mL of surfactant solution. The mixture was tightly sealed and shaken vigorously for approximately 20 seconds to ensure proper mixing.

Subsequently, the prepared initiator and buffer solutions were added to the reaction mixture. The polymerization bottle was tightly sealed, labeled, and placed in a thermostatically controlled agitator at 60°C for 15 hours to allow complete polymerization.

Formulation Design

Different formulations of the adhesive were prepared by varying the ratio of PLA to vinyl acetate, as shown in Table 1.

Characterization of Synthesized Adhesive

The synthesized adhesives were subjected to various physicochemical and thermal analyses to determine their performance characteristics.

Determination of pH

The pH of each adhesive sample was measured using a calibrated digital pH meter. The instrument was standardized using buffer solutions of pH 4.01 ± 0.01 and pH 7.00 ± 0.01 at 25°C before measurement.

Table 1. Formulation of PLA-based bio-adhesive.

Sample	PLA (mL)	VAc (mL)	Initiator/Buffer (mL)	Surfactant (mL)
A	40	30	10	20
B	50	20	10	20
C	55	15	10	20

Determination of Viscosity

The viscosity of the adhesive samples was measured at 25°C using a Brookfield rotational viscometer. Appropriate spindle speeds were selected depending on the viscosity range of each sample.

Adhesion Performance Tests

Peel Strength Test

The peel strength of the adhesive was assessed using a 180° peel test. Adhesive-coated paper strips (25 × 25 mm²) were applied to clean glass substrates and allowed to set for 20 minutes. The test was carried out with a universal testing machine at a steady speed of 300 mm/min. The force required to detach the adhesive from the substrate was recorded, and the average value was calculated.

Tack Test

The tack property, which represents the ability of the adhesive to form an instant bond, was determined using the loop tack method.

A loop of adhesive-coated material was brought into contact with a glass surface under controlled conditions. The maximum force required to detach the loop was measured using a tensile testing machine.

Water Resistance Test

The water resistance of the adhesive was evaluated using an immersion test. Adhesive-coated labels were applied to glass bottles and allowed to cure for 24 hours.

The bottles were then immersed in an ice-water bath (1:1 ratio) for another 24 hours. After removal, the adhesion performance was evaluated based on:

- Degree of peeling
- Surface defects
- Retention of adhesion

Biodegradability Test

The biodegradability of the synthesized adhesives was assessed by immersing samples in phosphate-buffered saline (PBS) at 37°C.

The samples were monitored over a specified period, and degradation was evaluated based on:

- Percentage weight loss
- Visual changes (cracks, deformation)
- Surface morphology

Enzymatic degradation studies were also conducted using lipase and protease enzymes to simulate biological conditions.

Thermal Analysis

Differential Scanning Calorimetry (DSC)

DSC was used to analyze thermal transitions of the adhesive samples. Around 2–5 mg of each sample was placed in a sealed aluminum pan and heated from 80°C to 200°C at a rate of 10°C/min. The glass transition temperature (T_g) and melting temperature (T_m) were obtained from the resulting thermograms.

Thermogravimetric Analysis (TGA)

Thermal stability was evaluated using TGA. Samples were heated from 25°C to 600°C at a heating rate of 10°C/min under a nitrogen atmosphere. The change in weight with temperature was recorded to determine:

Decomposition temperature

- Thermal stability
- Residual mass

Fourier Transform Infrared (FTIR) Analysis

FTIR analysis was performed to determine the functional groups present in the synthesized adhesives. Samples were analyzed using an FTIR spectrometer (ATR mode) within a wavenumber range of 4000–400 cm^{-1} . Before analysis, samples were dried in an oven at 80°C to remove moisture.

Expected Outcomes

The study is expected to:

- Successfully synthesize a PLA-based bio-adhesive with enhanced performance properties
- Establish the relationship between composition and adhesive performance
- Demonstrate improved thermal stability and biodegradability
- Identify suitable industrial applications for the developed adhesive
- Support the advancement of sustainable and eco-friendly adhesive systems

RESULTS AND DISCUSSION

The synthesized poly lactic acid (PLA)-based bio-adhesives were successfully prepared using emulsion polymerization techniques. Three formulations (A, B, and C) with varying PLA/vinyl acetate compositions were analyzed to evaluate their physicochemical, mechanical, and thermal properties. The obtained findings are presented and discussed with reference to adhesive performance and possible industrial uses.

Physicochemical Properties

The pH values of the synthesized adhesives fall within a mildly acidic to near-neutral range, which is typical for polymer-based adhesive systems in Table 2. The slight increase in pH from Sample A to C can be attributed to the higher PLA content, which stabilizes the polymer matrix and reduces residual acidity from initiators as shown in Figure 2.

This pH range is favorable for industrial applications such as paper labeling and packaging, where extreme acidity or alkalinity could damage substrates [16, 17].

Viscosity

A progressive increase in viscosity was observed with increasing concentration of Poly(lactic acid) (PLA) in the adhesive formulations. This behavior is primarily attributed to increased molecular chain entanglement and higher solid content within the adhesive matrix. As presented in Table 3, Sample A exhibited a viscosity of 1450 cP, while Samples B and C showed higher viscosities of 1820 cP and 2150 cP, respectively. Higher viscosity contributes to improved adhesive film formation and enhanced bonding strength; however, it must be carefully controlled to maintain suitable processability during application. Among all formulations, Sample C demonstrated the highest viscosity, indicating stronger internal cohesion and better suitability for heavy-duty industrial applications, as illustrated in Figure 3.

Table 2. pH of synthesized adhesives.

Sample	pH Value
A	5.8
B	6.2
C	6.5

Table 3. Viscosity Values of Synthesized PLA-Based Bio-Adhesive Formulations

Sample	Viscosity (cP)
A	1450
B	1820
C	2150

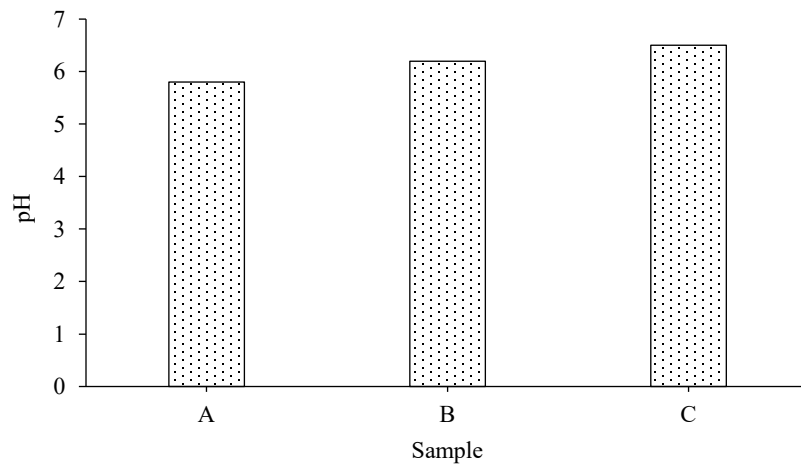


Figure 2. pH of adhesives.

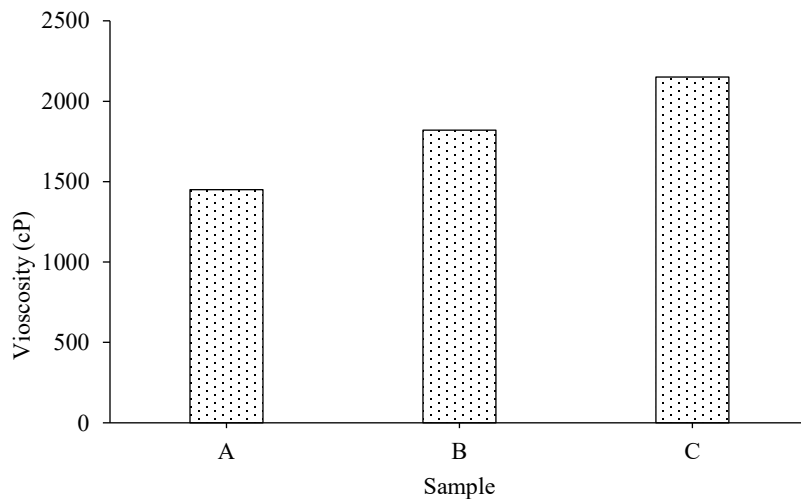


Figure 3. Viscosity of adhesives

Adhesion Properties

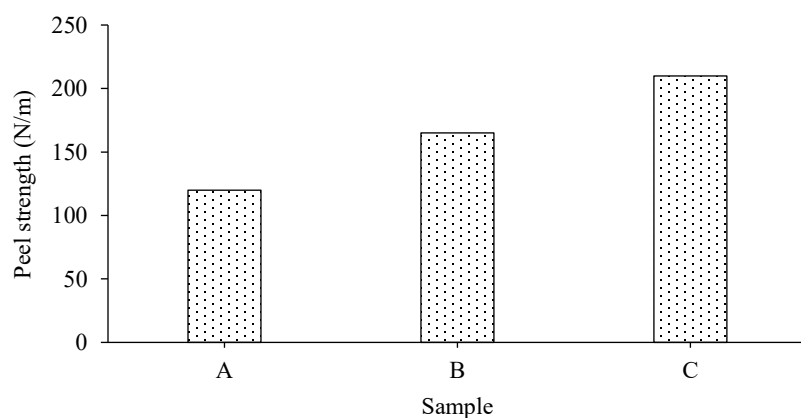
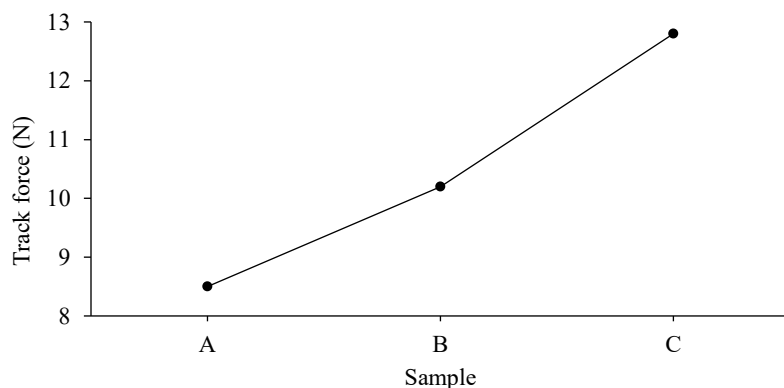
The peel strength of the synthesized Poly(lactic Acid) (PLA)-based bio-adhesives increased significantly with increasing PLA concentration. This improvement can be attributed to enhanced intermolecular interactions and better mechanical interlocking between the adhesive and substrate surfaces. As shown in Table 4, Sample A exhibited a peel strength of 120 N/m, while Sample B showed an increased value of 165 N/m. Sample C demonstrated the highest adhesion performance among all formulations, indicating its strong suitability for industrial bonding applications such as packaging and labeling, as illustrated in Figure 4 [18, 19].

Table 4. Peel Strength evaluation of synthesized PLA-based bio-adhesive formulations.

Sample	Peel Strength (N/m)
A	120
B	165
C	210

Table 5. Tack force measurement of synthesized PLA-based bio-adhesive formulations.

Sample	Tack Force (N)
A	8.5
B	10.2
C	12.8

**Figure 4.** Peel strength.**Figure 5.** Tack properties

Tack Properties

The tack performance of the synthesized Polylactic Acid (PLA)-based bio-adhesives followed a trend similar to that observed for peel strength. Increasing PLA concentration enhanced the surface wetting ability of the adhesive and promoted rapid bond formation under light pressure. As shown in Table 5, Sample A exhibited a tack force of 8.5 N, while Samples B and C demonstrated higher tack forces of 10.2 N and 12.8 N, respectively. The improved tack behavior confirms that PLA contributes significantly to adhesive responsiveness during initial contact, thereby enhancing bonding efficiency, as illustrated in Figure 5.

Biodegradability Test

The biodegradation results revealed that increasing the concentration of Poly-lactic Acid (PLA) significantly enhanced the degradability of the synthesized bio-adhesives. This behavior can be attributed to the presence of hydrolysable ester linkages in PLA and its increased susceptibility to enzymatic and microbial attack. As presented in Table 6, Sample A exhibited a weight loss of 18% after 14 days, while Samples B and C showed higher degradation rates of 24% and 31%, respectively. Among all formulations, Sample C demonstrated the highest biodegradation rate, indicating superior environmental compatibility and making it a promising candidate for sustainable material development, as illustrated in Figure 6 [20–21].

Water Resistance Test

The water resistance of the synthesized Poly-lactic Acid (PLA)-based bio-adhesives improved with increasing PLA concentration. Sample C maintained strong adhesion under wet conditions, which can be attributed to improved film integrity and reduced water penetration into the adhesive matrix. As shown in Table 7, Sample A exhibited partial peeling after 24 hours of exposure, while Sample B showed minor edge defects. In contrast, Sample C remained fully adhered, demonstrating superior moisture resistance and adhesive stability. These results indicate that Sample C is highly suitable for applications requiring moisture durability, such as bottle labeling and cold-storage packaging.

Table 6. Percentage weight loss of synthesized PLA-based bio-adhesive formulations after 14 days.

Sample	Weight loss (%) after 14 days
A	18%
B	24%
C	31%

Table 7. Observational adhesion stability of synthesized PLA-based bio-adhesive.

Sample	Observation after 24 hrs
A	Partial peeling
B	Minor edge defects
C	Fully adhered

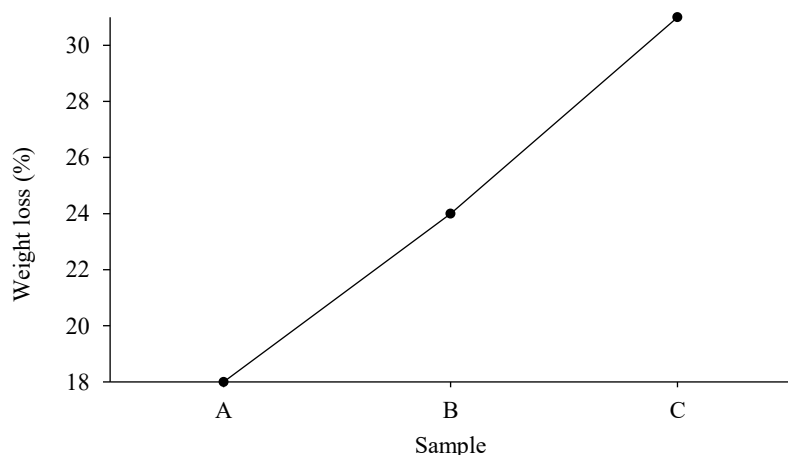


Figure 6. Biodegradability.

Thermal Analysis

Thermogravimetric Analysis (TGA)

The Thermogravimetric Analysis (TGA) results of the synthesized Polylactic Acid (PLA)-based bio-adhesives revealed a multi-stage degradation pattern that is characteristic of polymeric materials. The first stage, occurring below 200°C, corresponds to the loss of absorbed moisture and volatile components present in the adhesive matrix. The second stage, between 200°C and 400°C, represents the major thermal degradation of the polymer backbone. The final stage involves the formation of residual char after decomposition. Among all formulations, Sample C exhibited the highest thermal stability, as evidenced by its higher degradation onset temperature and greater residual mass percentage. As presented in Table 8, Sample A showed an initial degradation temperature of 220°C and a maximum degradation temperature of 350°C with 8% residual mass, while Sample B exhibited values of 240°C, 370°C, and 10%, respectively. Sample C demonstrated the best thermal performance with an initial degradation temperature of 260°C, maximum degradation temperature of 390°C, and 12% residual mass. These findings indicate stronger polymer interactions and improved structural integrity, making Sample C suitable for high-temperature industrial applications, as illustrated in Figure 7. [22, 23]

Differential Scanning Calorimetry (DSC)

The Differential Scanning Calorimetry (DSC) analysis of the synthesized Polylactic Acid (PLA)-based bio-adhesives showed a gradual increase in both glass transition temperature (T_g) and melting temperature (T_m) with increasing PLA concentration. This behavior indicates reduced polymer chain mobility and the presence of stronger intermolecular interactions within the adhesive matrix. As presented in Table 9, Sample A exhibited a T_g of 52°C and a T_m of 148°C, while Samples B and C showed progressively higher values. Sample C demonstrated the highest T_g and T_m values of 58°C and 156°C, respectively, indicating enhanced thermal resistance and structural stability. Higher T_g values suggest improved resistance to deformation during storage and application, whereas higher T_m values indicate better thermal endurance and structural integrity at elevated temperatures, as illustrated in Figure 8. [24–26]

Table 8. Thermal degradation characteristics of synthesized PLA-based bio-adhesive formulations.

Sample	Initial degradation temp (°C)	Maximum degradation temp (°C)	Residual mass (%)
A	220	350	8
B	240	370	10
C	260	390	12

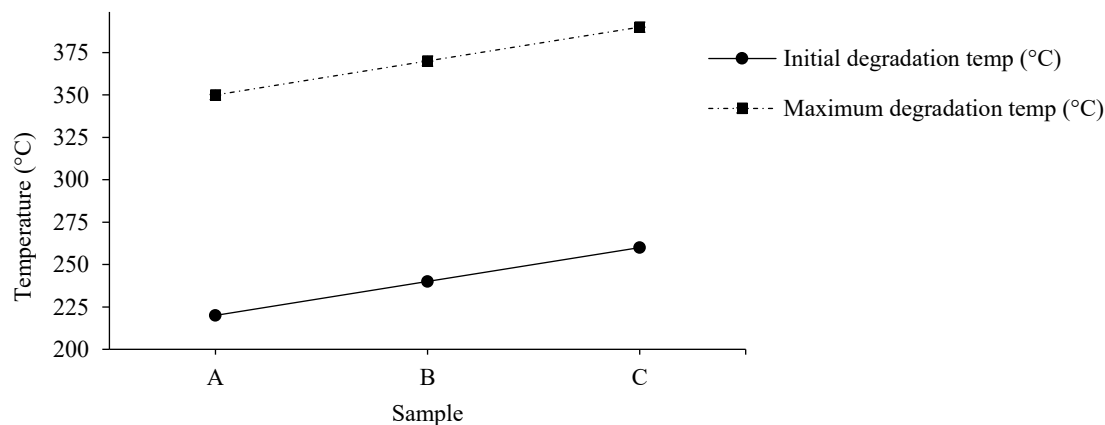


Figure 7. TGA Analysis.

Table 9. Glass transition and melting temperatures of synthesized PLA-based bio-adhesive formulations

Sample	Glass transition temp (T _g °C)	Melting temp (T _m °C)
A	52	148
B	55	152
C	58	156

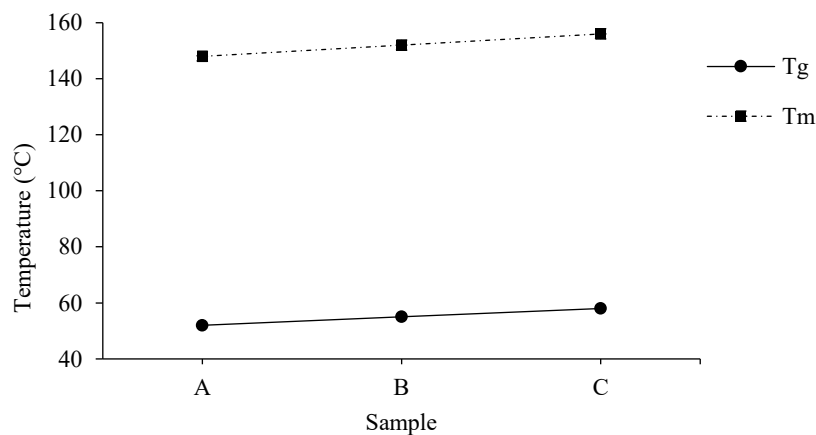


Figure 8. DSC analysis.

Wavenumber (cm ⁻¹)	Functional Group	Interpretation
~1750	C=O (Ester)	Presence of PLA backbone
~2950	C-H Stretch	Alkyl groups
~1080	C-O Stretch	Ester linkage confirmation
~3400	O-H Stretch	Moisture/hydroxyl groups

Table 10. FTIR peak assignments and functional group identification of synthesized PLA-based bio-adhesive formulations.

FTIR Analysis

The FTIR spectra of the synthesized Poly(lactic Acid) (PLA)-based bio-adhesives confirmed the successful formation of the polymeric adhesive system. The observed absorption peaks correspond to the characteristic functional groups present in PLA and related polymer structures. As presented in Table 10, the strong absorption peak around 1750 cm⁻¹ corresponds to the C=O stretching vibration of ester groups, confirming the presence of the PLA backbone. The peak observed near 2950 cm⁻¹ is attributed to C-H stretching vibrations associated with alkyl groups, while the absorption band around 1080 cm⁻¹ corresponds to C-O stretching, indicating successful ester linkage formation during polymerization. Additionally, the broad peak near 3400 cm⁻¹ represents O-H stretching vibrations, suggesting slight moisture absorption or the presence of residual hydroxyl groups within the adhesive matrix. These FTIR results confirm the successful incorporation of PLA and validate the intended polymerization process.

CONCLUSION

This study focused on the synthesis, characterization, and thermal evaluation of poly(lactic acid) (PLA)-based bio-adhesives developed as environmentally sustainable alternatives to conventional petroleum-based adhesives. The adhesive formulations were prepared using an emulsion polymerization technique with varying compositions of PLA and vinyl acetate to evaluate the effect of PLA concentration on adhesive performance and material properties.

The experimental results demonstrated that increasing PLA content significantly improved the physicochemical, mechanical, and thermal properties of the adhesives. The viscosity of the formulations increased progressively with PLA concentration, indicating enhanced internal cohesion and structural integrity within the adhesive matrix. Adhesion studies revealed improved peel strength and tack performance, suggesting stronger intermolecular interactions and better surface wetting characteristics. Water resistance tests further confirmed that higher PLA concentrations enhanced adhesive stability under moist conditions.

Biodegradability analysis showed measurable degradation of the adhesives, confirming their eco-friendly nature and suitability for sustainable material applications. Thermal characterization using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) indicated improved thermal stability, higher degradation temperatures, and increased resistance to thermal deformation with increasing PLA content. FTIR analysis verified the successful incorporation of characteristic functional groups associated with PLA and vinyl acetate.

Among all formulations, Sample C consistently exhibited superior overall performance, including enhanced adhesion strength, thermal resistance, water stability, and biodegradability. The findings confirm that PLA-based bio-adhesives possess strong potential for industrial applications such as packaging and labeling while supporting environmental sustainability.

Recommendations

Based on the findings obtained from this study, several recommendations are proposed for future research and development of Polylactic Acid (PLA)-based bio-adhesives. Future investigations should focus on optimizing the PLA-to-monomer composition ratio to achieve an ideal balance between adhesion strength, flexibility, viscosity, and processability for different industrial applications. The incorporation of functional additives such as plasticizers, crosslinking agents, and nanofillers including nanoclay and cellulose nanocrystals is also recommended to improve the mechanical properties, flexibility, and durability of the adhesive formulations.

In addition, extended biodegradation studies under real environmental conditions such as soil burial, composting systems, and aquatic environments should be conducted to better understand long-term environmental behavior and degradation mechanisms. Advanced characterization techniques including Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Dynamic Mechanical Analysis (DMA) are recommended to provide deeper insight into the structural, morphological, and viscoelastic properties of the adhesives.

Furthermore, pilot-scale production and industrial application testing should be carried out to evaluate adhesive performance under practical operating conditions involving humidity, temperature fluctuations, and mechanical stress. Economic and commercial feasibility studies are also essential to determine the cost-effectiveness of large-scale production compared to conventional petroleum-based adhesives. Finally, application-specific formulations should be developed for sectors such as packaging and labeling, wood and furniture manufacturing, and biomedical or other eco-friendly material applications.

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