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Studies on the Mechanical Properties of Biodegradable Unripe Banana Starch Composites Reinforced with Natural Pineapple Leaf Fibres (*Annas comosus* L. Merr.)

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Abstract

The development of biodegradable composites has gained significant attention due to the environmental concerns associated with synthetic polymers. Unripe banana starch, characterized by its high amylose content, presents excellent film-forming properties and biodegradability, making it a promising matrix for composite fabrication. Despite these advantages, its poor mechanical properties restrict its standalone use in structural applications. To improve its performance, reinforcement with natural fibres such as pineapple leaf fibres has been explored. Pineapple leaf fibres, obtained as agricultural waste, exhibit remarkable tensile strength, flexibility, and low density making them an ideal reinforcement material for starch-based composites. This study focuses on the mechanical characterization of a biodegradable composite derived from unripe banana starch (Musa sapientum L.) and short pineapple leaf fibres (Ananas comosus L. Merr.). The composite was fabricated with varying fibre content (0–5 g), and its mechanical properties were evaluated through tensile strength, flexural strength, compression strength, elongation at break, impact resistance, and hardness testing. Results indicated that fibre reinforcement significantly enhanced the mechanical properties of the starch-based composite. The highest tensile strength and elongation at break were recorded in the sample containing 5g of fibre, demonstrating improved ductility and load-bearing capacity. Compression and flexural tests revealed a progressive increase in mechanical resistance with fibre addition, confirming effective stress distribution within the matrix. Impact and hardness tests further corroborated these findings, with a noticeable improvement in impact resistance and structural integrity. These findings suggest that the incorporation of pineapple leaf fibres into banana starch composites significantly

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improves mechanical properties, making it a viable alternative to conventional plastics in sustainable applications.

Keywords: *Biodegradable composites, Mechanical properties, Unripe banana starch, Pineapple leaf fibre, Tensile strength.*

1. INTRODUCTION

The increasing global awareness of environmental sustainability has driven extensive research into biodegradable alternatives to synthetic plastics (Moshood *et al.*, 2022). Conventional plastics, derived from petrochemical sources, persist in the environment for centuries, contributing significantly to pollution, microplastic accumulation, and ecosystem degradation (Sharma *et al*., 2023). The need for sustainable materials has led to the exploration of biopolymers, particularly starch-based composites, as viable replacements for synthetic plastics in packaging, agriculture, and various industrial applications. However, starch-based materials exhibit inherent limitations, including brittleness, low mechanical strength, and high moisture sensitivity, which hinder their practical applications. To address these challenges, reinforcement with natural fibres has been proposed to enhance the mechanical properties of starch composites (Jiang *et al*., 2019). The incorporation of these fibres into a starch matrix is expected to enhance not only the tensile and flexural properties but also impact resistance, compression strength, and elongation at break, which are critical parameters for assessing mechanical performance (Elfaleh *et al*., 2023).

Several studies have demonstrated the effectiveness of natural fibre reinforcement in improving the mechanical properties of biopolymer composites. Research on cassava starch-based composites reinforced with sisal fibre showed increased tensile strength and improved impact resistance, confirming the reinforcing potential of natural fibres (Lomelí *et al*., 2011). Similarly, studies on corn starch composites blended with jute and kenaf fibres reported significant enhancements in elongation at break and flexural modulus (Hazrol *et al*., 2022). The addition of plant-based fibres has been found to improve stress transfer within the matrix, resulting in better mechanical stability and durability under load-bearing conditions (Li *et al*., 2020). Moreover, research on banana fibre-reinforced starch composites highlighted their increased tensile and flexural strengths, further validating the advantages of fibre reinforcement (Khalid *et al.*, 2021). The elongation at break, which measures the ductility of a material, is a crucial factor in determining its suitability for various applications. Fibre reinforcement is expected to enhance this property by improving the composite's ability to absorb energy before fracture, thereby increasing its flexibility and durability (Mohamed and Haya 2024). Furthermore, the fibre-matrix interaction plays a vital role in load transfer efficiency, stress distribution, and overall mechanical integrity. Understanding these interactions is essential for optimizing the composite formulation to achieve superior mechanical performance (Damanik *et al.*, 2025).

This study investigates the mechanical properties of unripe banana starch pineapple leaf fibre composites with varying fibre content. The key parameters analyzed include tensile strength, flexural strength, compression strength, elongation at break, impact resistance, and hardness. By evaluating these properties, this research aims to provide valuable insights into the structural enhancement of starch-based biodegradable composites. The findings of this study contribute to the growing body of knowledge on sustainable materials, offering potential applications in biodegradable packaging, lightweight construction materials, and eco-friendly consumer products. The integration of agricultural by-products into biopolymer composites not only enhances mechanical performance but also promotes waste valorization, aligning with global efforts to transition toward a circular economy.

2. MATERIALS AND METHOD

The materials used in this study included unripe bananas (**Musa sapientum** L.) and pineapple leaves (**Ananas comosus** (L.) Merr.) as the primary raw materials. Pineapple leaves were sourced from Ohonre Community, Benin City, Edo State (coordinates: 6.1902° N, 5.6097° E) and unripe bananas were obtained from Evbuotubu quarters in Benin City (coordinates: 6.4016° N, 5.6091° E). Analytical grade sodium bisulfite solution (1%), glycerol (used as a plasticizer), sodium hydroxide (3%), and distilled water were all used in this study.

2.1 Extraction of Unripe Banana Starch

The extraction of unripe banana starch was carried out with modification to the method proposed by Islam *et al*, (2024). Fresh unripe bananas were peeled and sliced into uniform pieces using a knife and cutting board. The sliced bananas were spread on clean trays and sun-dried for one week to reduce moisture content. After drying, the slices were washed with a 1% sodium bisulfite solution to inhibit microbial growth and improve starch yield. The treated banana slices were blended with distilled water to form a smooth slurry, which was filtered through cheesecloth to remove fibrous materials. The filtrate was left undisturbed for several hours to allow starch sedimentation, and the supernatant was decanted to collect the starch. The wet starch was thinly spread on trays for air drying for three days. Once dried, it was ground with a mortar and pestle, sieved through a 125-micrometer mesh to ensure uniform particle size, and stored in airtight containers to maintain quality.

2.2 Pineapple leaf fibre extraction

The extraction of pineapple leaf fibre was done by modification of the method proposed by Peng *et al*., (2023). The pineapple leaves were harvested trimmed at both ends and washed to remove dirt. The leaves were then cut into lengths of 50–70 cm for easier processing. For the retting process, the prepared leaves were placed in a container filled with clean water and fully submerged using wooden sticks or weights. The leaves were left to ferment for seven days, allowing microbes to break down the pectin and lignin. The water was observed daily, and if it developed a strong odour or excessive foam, it was replaced with fresh water. After seven days, the softened leaves were removed, and the fibres were extracted using a knife to scrape off the non-fibrous tissues. The extracted fibres were soaked in a 3% sodium hydroxide solution for 30 minutes to remove any remaining plant residues. The NaOH treatment helped further purify the fibres by breaking down and eliminating unwanted materials. After the NaOH treatment, the fibres were thoroughly rinsed with distilled water to neutralize any residual alkali and remove dissolved impurities, ensuring that the fibres were clean and free from contaminants. Finally, the fibres were spread on a rack to air dry for two days before being placed in an oven at 40°C for further drying.

2.3 Fabrication of starch composite from unripe banana starch and pineapple leaf fibre

Pineapple leaves were washed, air-dried, and blended into short fibres using a mechanical blender. The fibres were sieved for uniformity and stored in an airtight container. To prepare the starch composite solution, 10g of unripe banana starch was weighed, and varying amounts of pineapple leaf fibres were added to the beaker based on the following formulations:

Sample A: 0g fibre, 100 mL water, 5 mL glycerol,10g unripe banana starch

Sample B: 1g fibre, 100 mL water, 5 mL glycerol,10g unripe banana starch

Sample C: 2g fibre, 100 mL water, 5 mL glycerol,10g unripe banana starch

Sample D: 3g fibre, 100 mL water, 5 mL glycerol,10g unripe banana starch

Sample E: 4g fibre, 100 mL water, 5 mL glycerol,10g unripe banana starch

Sample F: 5g fibre, 100 mL water, 5 mL glycerol,10g unripe banana starch

The mixture was manually stirred with a glass rod to ensure uniform dispersion of starch, fibre, and glycerol. The solution was transferred to a water bath set at 80°C and continuously stirred using a magnetic stirrer to prevent lumps and achieve proper gelatinization. The hot gelatinized composite was poured into molds and evenly spread using a spatula. After setting at room temperature, the molds were transferred to an oven set at 80°C for 24 hours. The dried composites were carefully removed and stored in a desiccator to prevent moisture absorption before further analysis.

2.4 Mechanical Properties Analysis

The mechanical properties of the composites were evaluated using standardized testing methods. Compression strength was measured using an Electronic Universal Testing Machine (WDW-100KN, Number: 190536), while impact strength was assessed with the Cat.Nr.412 Charpy Impact Testing Machine (15J capacity). Tensile strength and elongation at break were determined using the Tensile Strength Test Machine TM 2101-T7, following ASTM D638, with a maximum force of 10 kN.Hardness testing was conducted using a Muver Durometer (Model: 5019, Serial No.: 01554, Year: 2007). Flexural strength was evaluated using a three-point bending test, following ASTM D790 standards

3. RESULT AND DISCUSSION

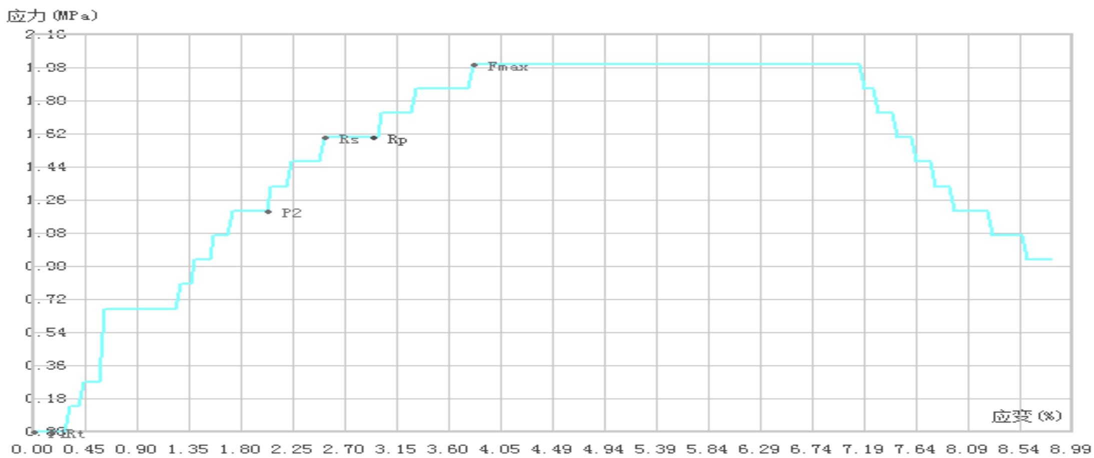

Figure 1: *Compression strength for starch composite from 10g of unripe banana starch containing 0g of pineapple leaf fibre*

Figure 1 provides the control for comparison with fibre-reinforced samples. The compression curve shows a steep initial deformation followed by rapid failure, indicating the brittle nature of the pure starch composite. The absence of fibre reinforcement results in poor load distribution and the formation of microcracks under stress (Plagué, *et al.*, 2017). The figure underscores the necessity of fibre addition to enhance the mechanical properties of starch-based composites.

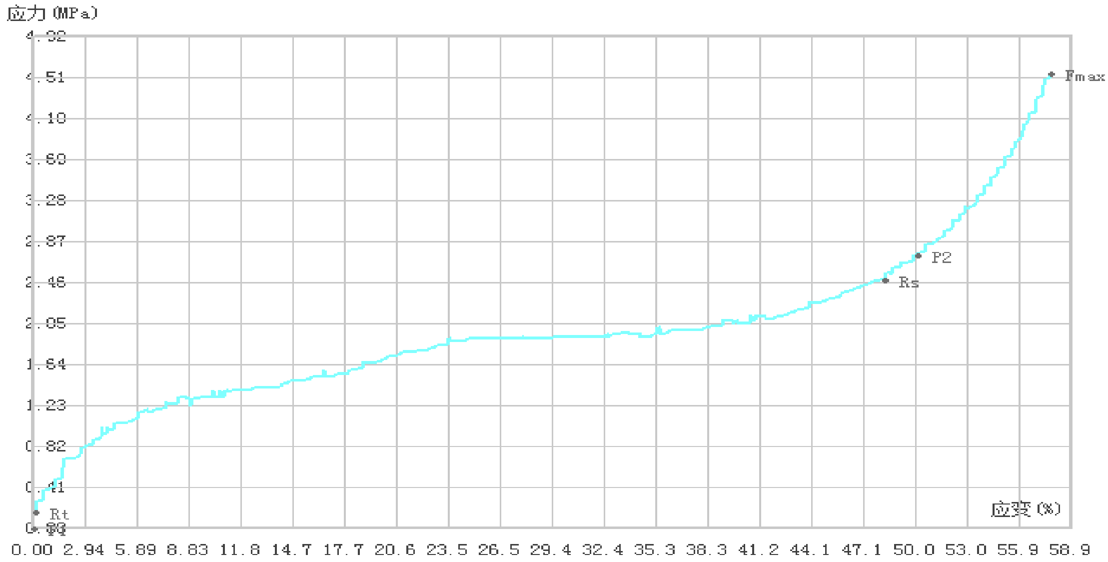

Figure 2: *Compression strength of starch composite from 10g unripe banana starch containing 1g of pineapple leaf fibre*

Figure 2 illustrates the compression properties of the composite containing 1g of pineapple leaf fibre. The introduction of 1g of fibre slightly enhances the composite's rigidity compared to the pure starch composite. During compression testing, the figure shows a gradual initial deformation followed by a steady increase in resistance. The reinforcing effect of the fibre helps distribute stress more evenly, reducing localized deformation points that would typically lead to premature failure in a pure starch matrix. The interfacial bonding between the starch and the fibre at this level appears adequate but may not fully optimize load transfer due to the low fibre content. Potential voids or weak zones in the composite structure might also contribute to minor inconsistencies in compression performance.

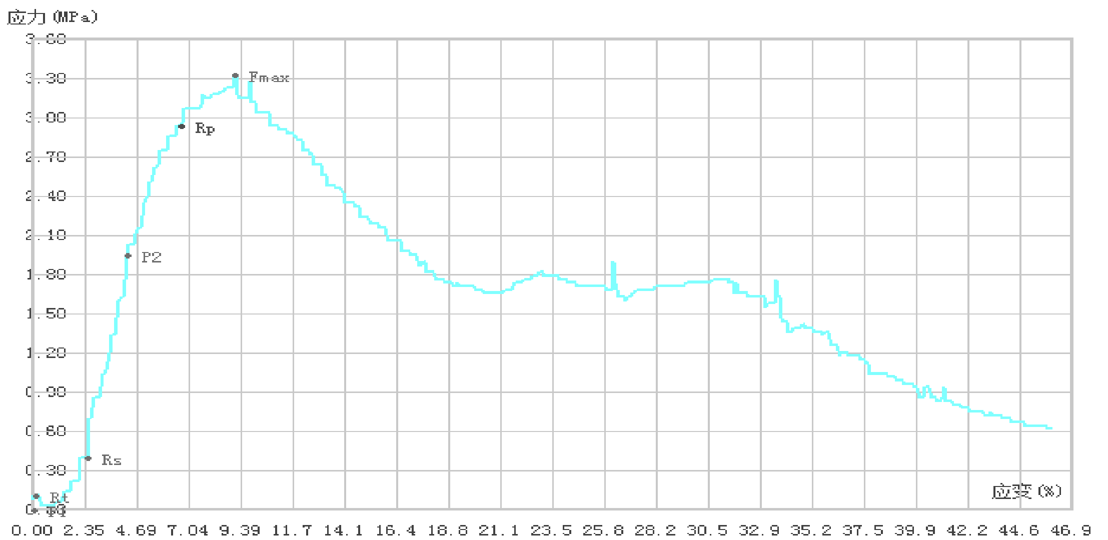

Figure 3: *Compression strength of starch composite from 10g of unripe banana starch containing 2g of pineapple leaf fibre*

Figure 3 for the 2g fibre composite demonstrates a noticeable improvement in compressive strength compared to the 1g sample. The additional fibre content increases the density of the reinforcing network, leading to enhanced load distribution. The curve exhibits a smoother slope, indicating better resistance to deformation. This improvement suggests a stronger interfacial bond between the fibre and the starch matrix, with fewer stress concentration points. The more uniform distribution of fibres may reduce the presence of microvoids, contributing to greater structural integrity under compressive loads.

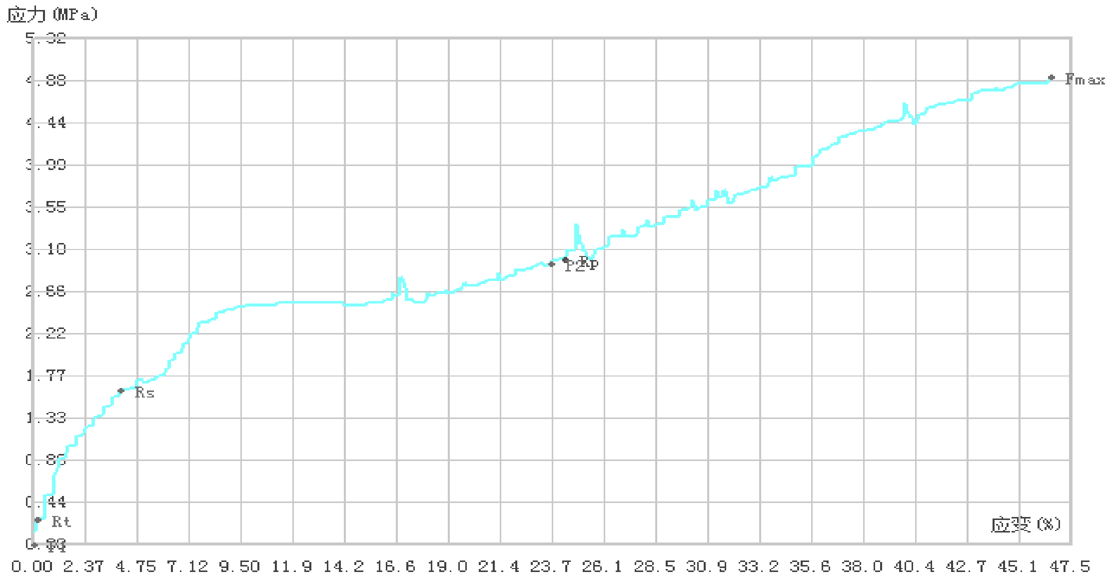

Figure 4: *Compression strength of starch composite from 10g of unripe banana starch containing 3g of pineapple leaf fibre*

Figure 4 shows a higher resistance to compressive forces, with a more gradual deformation profile compared to previous samples. The 3g fibre content appears to provide an optimal balance between fibre reinforcement and matrix cohesion, resulting in improved mechanical properties. The increased fibre network enhances the composite's ability to withstand applied loads without experiencing significant structural failure. The figure also exhibit a plateau phase, indicating effective energy absorption before complete deformation.

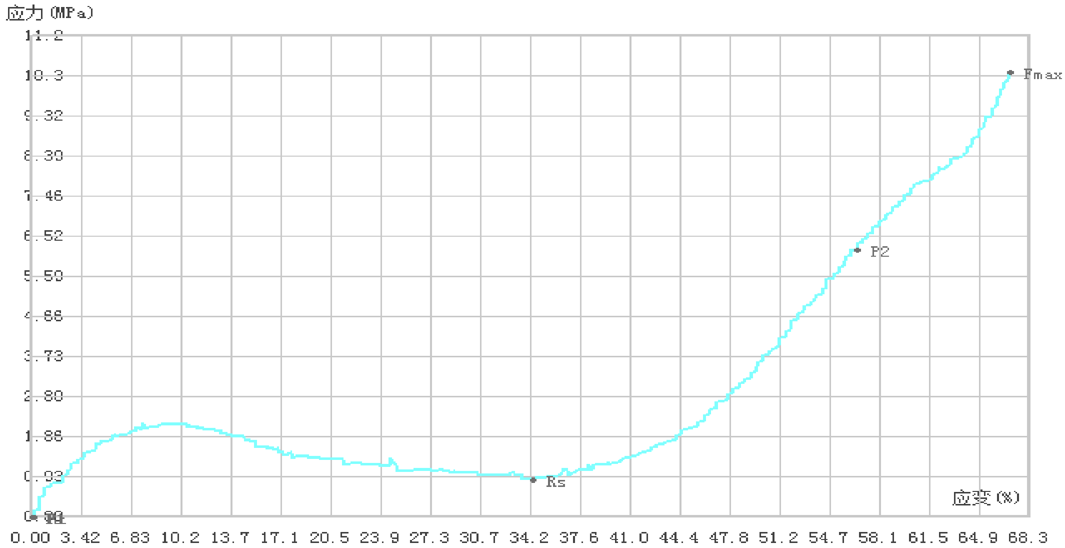

Figure 5: *Compression strength of starch composite from 10g of unripe banana starch containing 4g of pineapple leaf fibre*

Figure 5 for the 4g fibre composite demonstrates a further increase in compression resistance. The curve shows a more linear response with a higher load-bearing capacity. The higher fibre content reinforces the starch matrix more effectively, creating a denser and more interconnected network. However, at this concentration, there is a potential risk of fibre agglomeration, which can lead to non-uniform stress distribution and localized weaknesses. Despite this, the overall mechanical performance remains superior to that of lower fibre content samples.

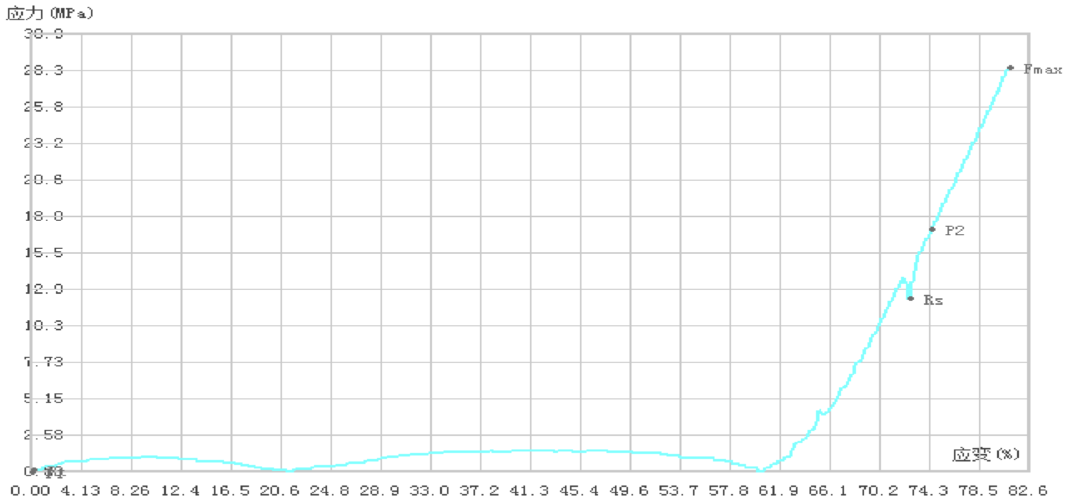

Figure 6: *Compression strength for starch composite from 10g of unripe banana starch containing 5g of pineapple leaf fibre*

The compression results for the 5g fibre composite likely exhibit the highest resistance to deformation among all samples. Figure 6 show a well-defined plateau phase, indicating the composite's ability to absorb and dissipate compressive forces efficiently. The dense fibre network provides maximum reinforcement, enhancing the overall structural integrity. However, the figure may also indicate diminishing returns in performance improvement, suggesting that the matrix is reaching its saturation point for effective fibre reinforcement. Fibre aggregation at this level may also slightly affect the homogeneity of the composite (Li *et al*., 2016).

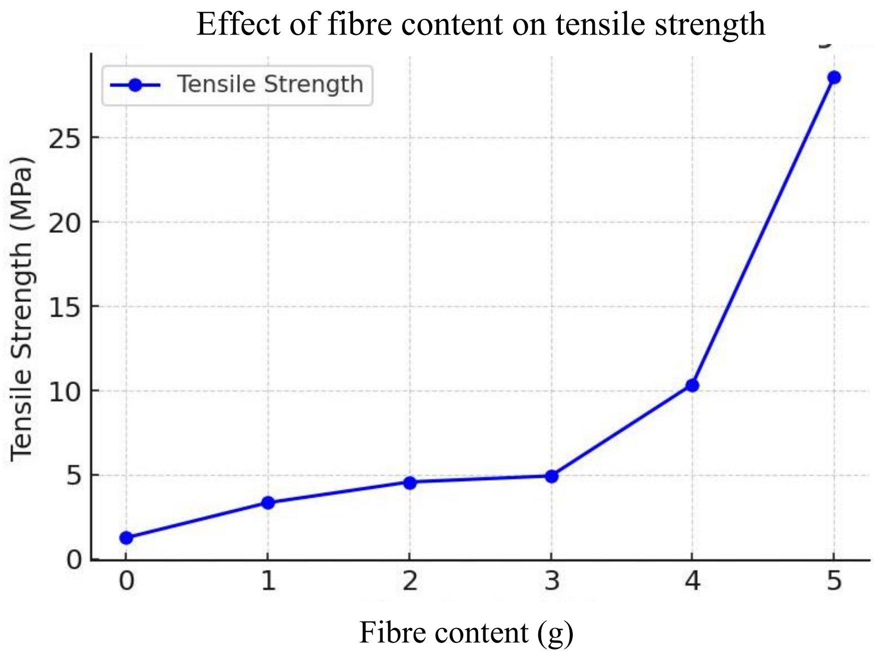

Figure 7: *Tensile Strength of Pineapple Leaf Fibre-Starch Composite (10g Unripe Banana Starch)*

Results in Figure 7 show a non-linear increase in tensile strength with increasing pineapple leaf fibre content in the starch composite containing 10g of unripe banana starch**.** The sample without fibre had the lowest tensile strength (1.25 MPa)**,** but adding 1g of fibre increased it to 3.33 MPa**,** suggesting improved structural integrity. Further increases to 2g and 3g showed moderate improvements (4.56 MPa and 4.92 MPa, respectively), while a significant jump occurred at 4g **(**10.35 MPa**),** indicating better fibre-matrix interaction. The highest tensile strength (28.58 MPa) was recorded at 5g fibre, demonstrating optimal reinforcement. This trend suggests that higher fibre content enhances mechanical strength by improving stress distribution. However, beyond a certain limit, excessive fibre loading could lead to issues like poor dispersion. These findings highlight the potential of pineapple leaf fibre as an effective reinforcement material**,** with 5g fibre yielding the best performance. (Lin *et al*., 2024)

Sample	Max (N) @ 5 % (N)	Max (MPa) @ 5% Strain (MPa)	Username	Timestamp - Start
# 300	28.923	10.482	admin	2025-01-27 14:44:11
• Mean	28.923	10.482		
• SD	0.000	0.000		
• Min	28.923	10.482		
• Max	28.923	10.482		

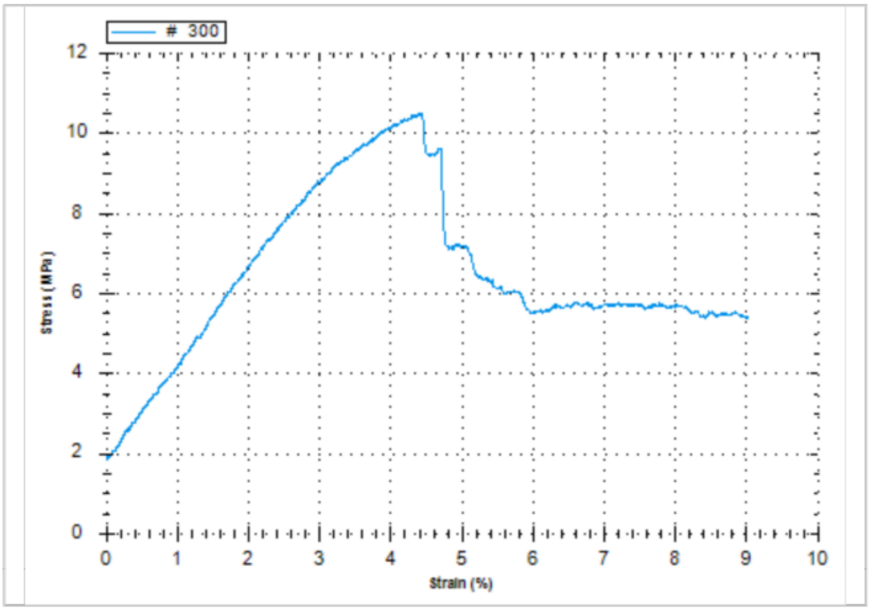

Figure 8: *Flexural Stress -Strain Curve for starch composite from 10g of unripe banana starch containing 0g of pineapple leaf fibre*

The 0g fibre composite (Figure 8) serves as the baseline, exhibiting the weakest flexural performance. The stress-strain curve likely shows a steep initial slope followed by rapid failure, indicative of the brittle nature of pure starch. The absence of fibre reinforcement results in poor structural integrity and early failure under bending forces.

Sample	Max (N) @ 5 % (N)	Max (MPa) @ 5% Strain (MPa)	Username	Timestamp - Start
# 299	6.455	2.340	admin	2025-01-27 14:39:42
• Mean	6.455	2.340		
• SD	0.000	0.000		
• Min	6.455	2.340		
• Max	6.455	2.340		

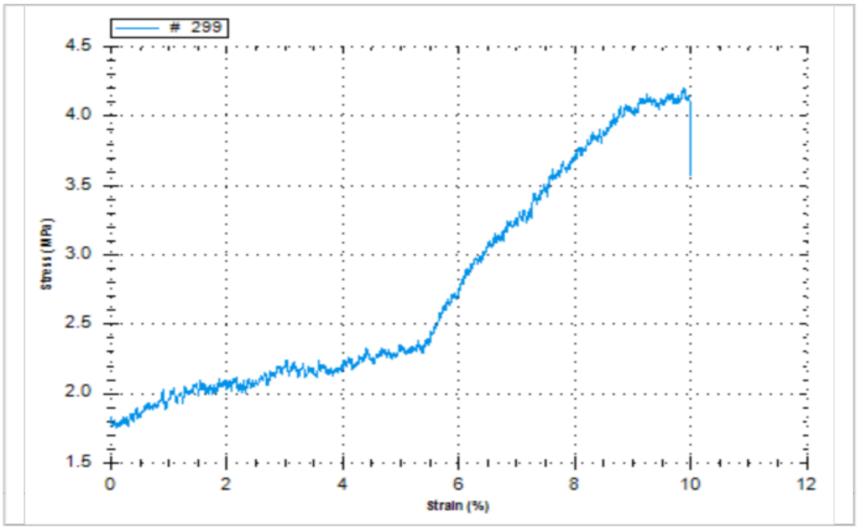

Figure 9: *Flexural Stress -Strain Curve for starch composite from 10g of unripe banana starch containing 1g of pineapple leaf fibre*

With 1g of fibre (Figure 9), the composite shows moderate improvement compared to the 0g sample. The stress-strain curve suggests a gradual increase in load-bearing capacity before failure, demonstrating an initial reinforcement effect. However, the limited fibre content provides only partial resistance to crack propagation, leading to moderate flexural strength.

Sample	Max (N) @ 5 % (N)	Max (MPa) @ 5% Strain (MPa)	Username	Timestamp - Start
# 303	5.504	1.995	admin	2025-01-27 14:53:52
• Mean	5.504	1.995		
• SD	0.000	0.000		
• Min	5.504	1.995		
• Max	5.504	1.995		

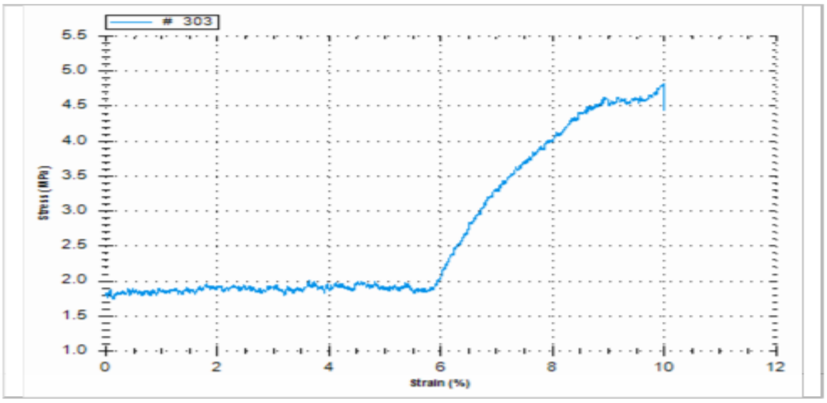

Figure 10: *Flexural Stress -Strain Curve for starch composite from 10g of unripe banana starch containing 2g of pineapple leaf fibre*

With 2g of fibre, the composite demonstrates a smoother stress-strain curve and a higher load-bearing capacity compared to the 1g sample. The additional fibres contribute to better stress distribution and improved resistance to bending forces, reducing the likelihood of sudden fracture. With this fibre content, the composite exhibits enhanced ductility, allowing it to absorb more energy before failure. This indicates an improvement in fibre-matrix interaction, resulting in a more durable and flexible material.

Sample	Max (N) @ 5 % (N)	Max (MPa) @ 5% Strain (MPa)	Username	Timestamp - Start
# 302	8.533	3.092	admin	2025-01-27 14:50:52
• Mean	8.533	3.092		
• SD	0.000	0.000		
• Min	8.533	3.092		
• Max	8.533	3.092		

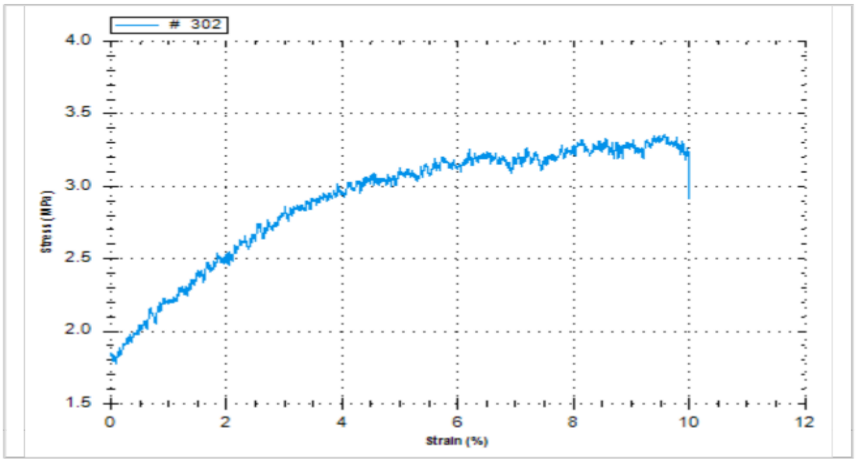

Figure 11: *Flexural Stress -Strain Curve for starch composite from 10g of unripe banana starch containing 3g of pineapple leaf fibre*

At 3g fibre content, the composite exhibits a more extended load-bearing phase before failure, as observed in the stress-strain curve. This suggests that the material can withstand higher flexural stress and absorb more energy before breaking**.** The reinforcement effect at this stage is well-balanced, providing better crack resistance and structural durability**.** The longer deformation phase before failure indicates improved toughness, as the fibres effectively transfer and distribute stress within the composite.

Sample	Max (N) @ 5 % (N)	Max (MPa) @ 5% Strain (MPa)	Username	Timestamp - Start
# 304	6.432	2.331	admin	2025-01-27 14:57:35
• Mean	6.432	2.331		
• SD	0.000	0.000		
• Min	6.432	2.331		
• Max	6.432	2.331		

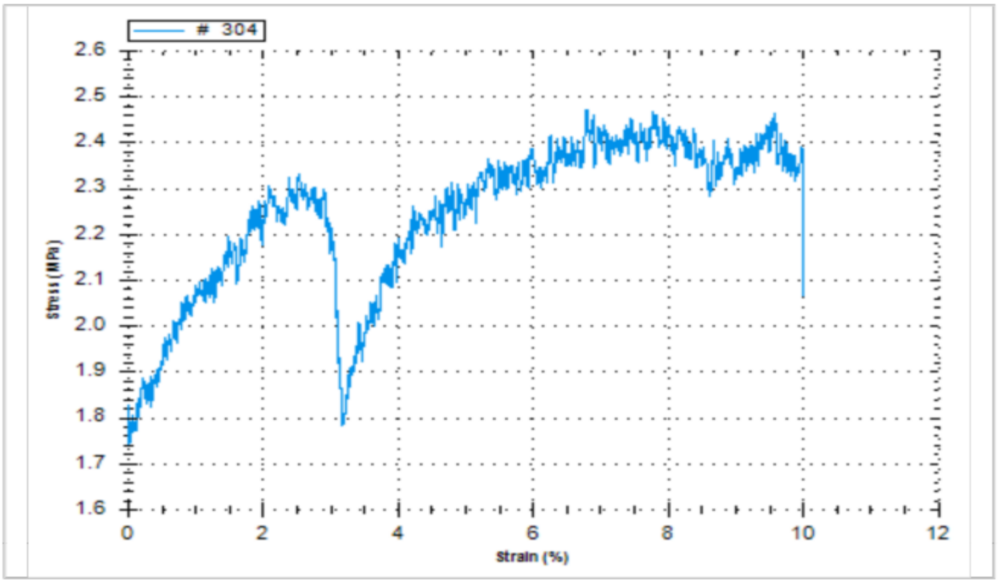

Figure 12: *Flexural Stress -Strain Curve for starch composite from 10g of unripe banana starch containing 4g of pineapple leaf fibre*

A notable enhancement in flexural strength is observed at 4g fibre content, where the stress-strain curve shows higher load-bearing capacity and a gradual failure mode. The denser fibre network at this level contributes to better stress transfer and improved mechanical performance. Unlike lower fibre content samples, the 4g fibre composite demonstrates a more controlled failure, suggesting that the fibres effectively bridge cracks and slow down material degradation under bending forces.

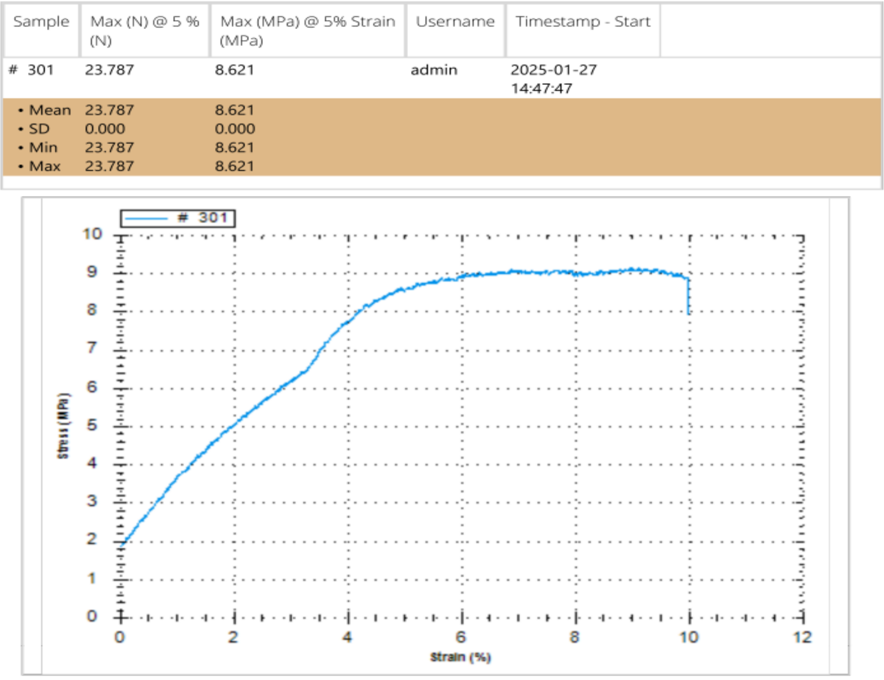

Figure 13: *Flexural Stress -Strain Curve for starch composite from 10g of unripe banana starch containing 5g of pineapple leaf fibre*

The 5g fibre composite exhibits the highest flexural strength among all tested samples. The stress-strain curve reveals a prolonged load-bearing phase and minimal deformation before failure, indicating superior resistance to bending forces. The dense fibre reinforcement at this stage allows the composite to maintain structural stability under significant flexural stress, making it the most mechanically robust sample. However, at high fibre content, there is a possibility of fibre agglomeration, which could lead to uneven stress distribution in future studies.

Table 1: *Hardness test for 10g of unripe banana starch composite containing pineapple leaf fibre*

S/No	Sample (Fibre)	Reading	Reading	Reading	Average Hardness
1	Nil	11	17	21	16.3
2	1 g	48	42	44	44.7
3	2 g	50	45	54	49.9
4	3 g	52	58	56	55.3
5	4 g	63	65	66	64.7
6	5g	68	70	72	70.0

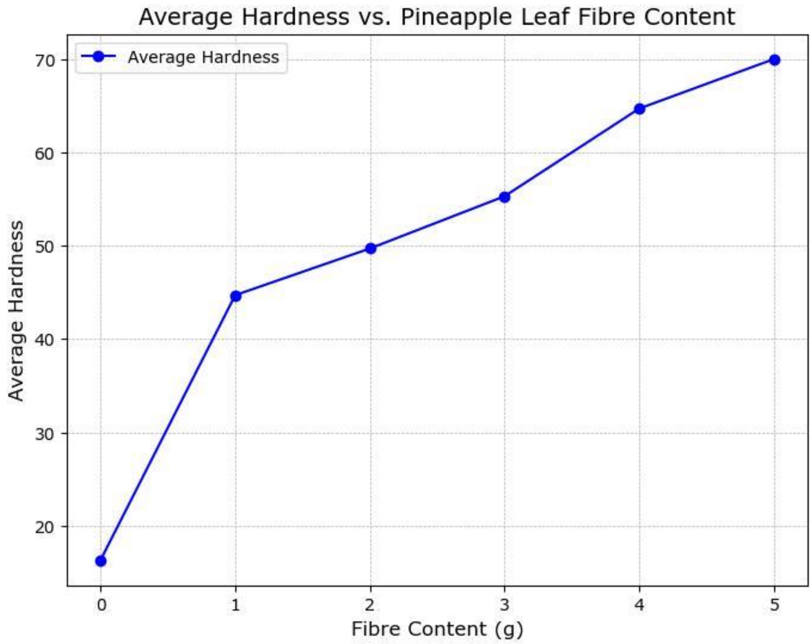

Figure 14: *Graph of the average hardness against pineapple leaf fibre content*

The graph illustrates the relationship between average hardness and pineapple leaf fibre (PLF) content in the starch composite, showing a clear upward trend as fibre content increases. At 0g fibre, the composite has the lowest hardness (~18), but with 1g fibre, it rises sharply to ~45, indicating a 150% improvement due to enhanced structural reinforcement. Beyond this, hardness continues to increase steadily, reaching ~50, 55, 63, and 70 for 2g, 3g, 4g, and 5g fibre, respectively, suggesting that additional fibre enhances mechanical strength through stronger hydrogen bonding and mechanical interlocking between starch and fibre. The highest hardness (~70 at 5g fibre) confirms the reinforcing effect of PLF, making it a promising natural additive for strengthening biopolymer materials. These findings indicate potential applications in biodegradable packaging, eco-friendly construction, and sustainable plastics, though further studies are needed to determine the optimal fibre content to prevent agglomeration and maximize performance.

Table 2: *Impact test for starch composite from 10g of unripe banana starch containing pineapple leaf fibre*

S/No	Sample (Fibre)	Reading
1	Nil	0.60
2	1 g	1.00
3	2 g	1.15
4	3 g	1.25
5	4 g	1.35
6	5 g	2.80

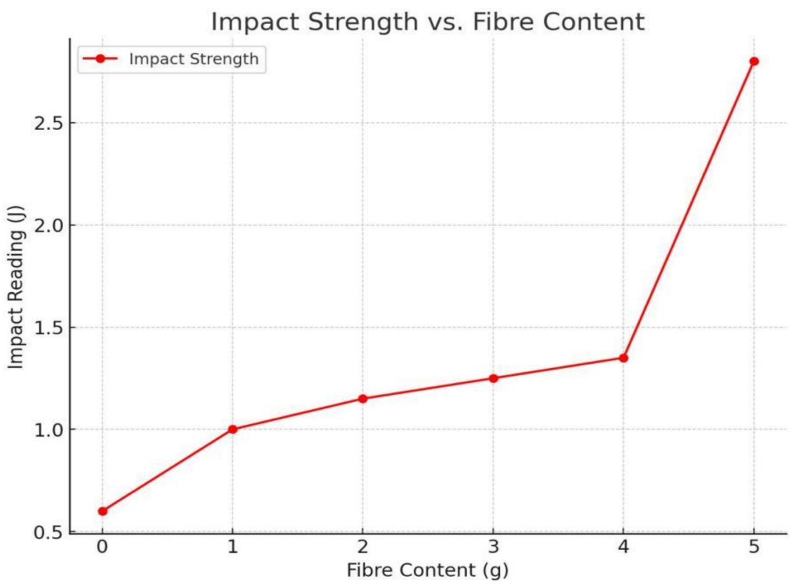

Figure 15: *Graph of impact test against starch composites from 10g of unripe banana starch containing different grams of pineapple leaf fibre*

The graph illustrates the variation of impact strength with pineapple leaf fibre (PLF) content, showing a consistent increase as fibre content rises. At 0g fibre**,** the composite exhibits the lowest impact strength (~0.5 J), but with 1g fibre, it increases to ~1.0 J, indicating a significant improvement due to the fibre's ability to absorb and dissipate impact energy. A gradual increase is observed between 2g and 4g fibre (ranging from ~1.2 J to ~1.5 J), suggesting enhanced toughness and energy absorption within the composite. Notably, at 5g fibre, impact strength rises sharply to ~2.7 J, demonstrating that higher fibre content significantly enhances the material's resistance to fracture. This trend indicates that pineapple leaf fibre effectively reinforces the composite, improving its ability to withstand sudden forces, making it suitable for applications requiring durable and impact-resistant biodegradable materials. However, further research is needed to assess whether excessive fibre loading beyond 5g may lead to diminishing returns due to fibre agglomeration or uneven stress distribution.

Table 3: *Elongation at break for starch composite from 10g of unripe banana starch containing pineapple leaf fibre*

Fibre Loading (g)	Elongation at Break (%)
0	8.81
1	15.23
2	20.45
3	25.67
4	18.34
5	12.89

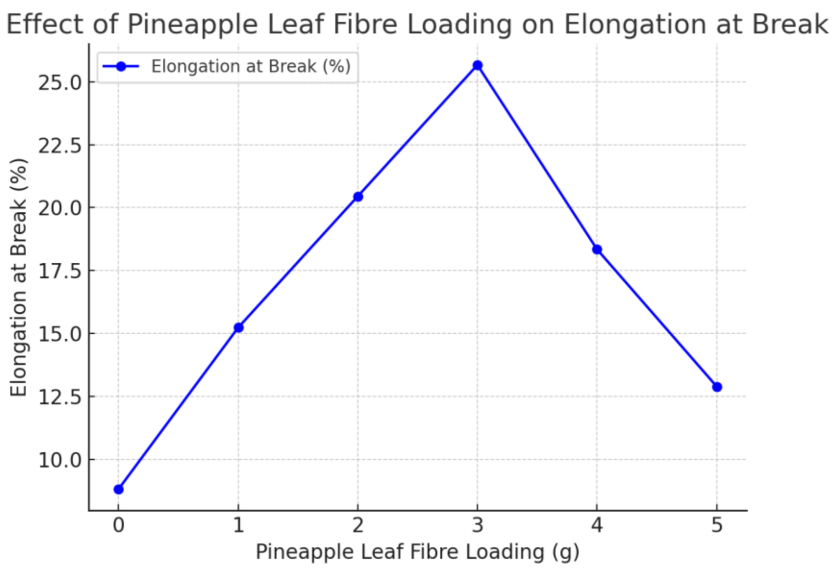

Figure 16: *Graph of elongation at break against pineapple leaf fibre loading for starch composites from 10g of unripe banana starch*

The graph illustrates the effect of pineapple leaf fibre loading on the elongation at break (%) of a starch composite derived from 10g of unripe banana starch. The results indicate an initial increase in elongation at break with increasing fibre content, reaching a peak value of approximately 25.67% at 3g fibre loading. This suggests that moderate fibre incorporation enhances the composite's flexibility and ability to deform under tensile stress. However, further fibre addition beyond 3g results in a decline in elongation at break, with values decreasing to 18.34% at 4g and 12.89% at 5g. The observed trend can be attributed to the dispersion and interaction of fibre within the polymer matrix. At lower fibre contents, the reinforcement effect improves the composite's elasticity, whereas excessive fibre loading likely introduces fibre agglomeration and poor interfacial adhesion, leading to reduced deformability. These findings align with previous studies on natural fibre-reinforced biopolymers, which report an optimal fibre loading threshold for maximizing elongation before a decline due to stiffness and brittle behaviour (McKay *et al*., 2024).

4. CONCLUSION

This study demonstrated the incorporation of pineapple leaf fibre into unripe banana starch composites significantly enhanced their mechanical properties, making them a viable alternative to conventional synthetic polymers. The results showed that fibre reinforcement improved tensile strength, flexural strength, compression strength, impact resistance, elongation at break, and hardness. The optimal mechanical performance was observed at moderate fibre content, particularly from 3 g to 5 g, where the composite exhibited increased load-bearing capacity and improved ductility. However, excessive fibre loading beyond this range led to diminishing returns due to fibre agglomeration and poor matrix-fibre interaction, which reduced elongation at break and overall flexibility. These findings highlight the potential of natural fibre-reinforced biopolymer composites in sustainable applications such as biodegradable packaging, eco-friendly construction materials, and lightweight structural components. Future research should focus on optimizing fibre dispersion and exploring surface modifications to further enhance the mechanical performance and durability of these composites.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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