

EFFECT OF FIBRE LENGTH AND FIBRE LOADING ON IMPACT, HARDNESS AND WATER ABSORPTION RESISTANCE OF LUFFA CYLINDRICA FIBRE REINFORCED POLYLACTIC ACID COMPOSITE

Bukar, M.^{1,2*}, Aji, I.S.¹, Mshelia, Z.A.¹ and Hammajam, A.A.¹

¹Department of Mechanical Engineering, Faculty of Engineering, University of Maiduguri, Borno State, Nigeria

²Maiduguri Flour Mills Limited, Maiduguri, Borno State, Nigeria

*Corresponding email: mohammedbukar61@gmail.com

ABSTRACT

The increasing demand for sustainable and environmentally friendly materials has driven the development of biopolymer composites reinforced with natural fibres. Among these, Luffa cylindrica has gained attention due to its lightweight, high cellulose content, and desirable mechanical properties, making it a promising alternative to synthetic reinforcements. Similarly, polylactic acid (PLA), a biodegradable polymer derived from renewable agricultural sources, exhibits broad application potential but suffers from brittleness and poor impact resistance. This study investigates the mechanical and physical properties of Luffa cylindrica-reinforced polylactic acid (PLA) composites, focusing on the effects of fibre length (1 mm, 2 mm, and 3 mm) and fibre loading (10% to 50%). Luffa cylindrica fibres were sourced from Maiduguri, treated with sodium hydroxide, and incorporated into PLA matrices using melt-mixing and hot compression techniques. The composites were characterized for impact strength, hardness, and water absorption according to ASTM standards. Results indicated that the impact strength of the composites decreased as filler loading increased, with the best performance observed at 30% loading for 1 mm fibres. Hardness increased with higher material content, with the 30% filler content of 1 mm fibre showing the highest hardness. Water absorption increased with both fibre length and filler content, with the 3 mm fibre composites displaying the highest water uptake. These trends were attributed to the fibre's natural hydrophilicity and the increased surface area for water absorption. This study highlights the potential of Luffa cylindrica as a reinforcing agent in biodegradable PLA composites, particularly in enhancing hardness, though its addition reduced impact strength and increased water absorption. The findings suggest that while Luffa cylindrica fibres improve certain mechanical properties, modifications such as surface treatments may be necessary to optimize performance for industrial applications.

Keywords: Characterization, polymer matrix, Hydrophilicity, Waste material, Agricultural waste

1 INTRODUCTION

The development of composite materials reinforced with natural fibres have gained increasing attention due to the need for more sustainable, environmentally friendly materials. In recent years, natural fibres have emerged as viable alternatives to synthetic fibres, offering benefits such as biodegradability, lower cost, and reduced environmental impact. Among the natural fibres explored, *Luffa cylindrica*, also known as sponge gourd, has gained prominence due to its light weight, high cellulose content, and mechanical properties that make it suitable for reinforcing polymers. As a renewable resource,

Luffa cylindrica holds potential for reducing the environmental footprint of synthetic materials in a range of applications, including automotive components, packaging, and construction materials [1, 2]. Polylactic acid (PLA), a biopolymer derived from renewable agricultural products such as corn starch and sugarcane, has been widely studied for its biodegradability and biocompatibility. PLA is used in various industries, including medical, packaging, and agriculture [3]. However, despite its favourable environmental properties, PLA exhibits several limitations, particularly its brittleness and poor impact resistance [4, 5]. As a result, there is a growing interest in enhancing the mechanical properties of PLA through reinforcement with natural fibres. The addition of fibres to the PLA matrix can improve its strength, flexibility, and thermal stability, making it more versatile for engineering applications. Several studies have investigated the use of natural fibres such as kenaf, jute, sisal, and hemp as reinforcements in biopolymer composites [6, 7, 8]. There is also no paucity of research on *Luffa cylindrica* as a filler in PLA-based composites [9, 10]. Previous research has demonstrated that the incorporation of natural fibres can improve the mechanical properties of biopolymers, but the results have varied depending on factors such as fibre type, fibre length, fibre-matrix adhesion, and filler loading. There is a need for further investigation into how the combination of fibre length and filler loading of *Luffa cylindrica* impacts the mechanical performance of PLA composites. In particular, understanding the interaction between fibre and matrix at different filler loadings is crucial for optimizing the composite's properties, especially in terms of impact resistance, hardness, and water absorption. Thus, the objectives of this research are to determine the effect of *Luffa cylindrica* fibre length on the impact strength, hardness, and water absorption of PLA composites; to evaluate the influence of filler loading on the mechanical and physical properties of *Luffa cylindrica*-PLA composites; and to assess the suitability of *Luffa cylindrica* as a reinforcing agent for biodegradable PLA composites. Specifically, the study examines how different fibre lengths (1 mm, 2 mm, and 3 mm) and filler loadings (10%, 20%, 30%, 40% and 50%) influence the impact strength, hardness, and water absorption behavior of the composite.

2 MATERIALS AND METHODS

2.1 Materials

Luffa cylindrica was sourced from Maiduguri Metropolis. It was sorted, washed, sun-dried, shredded into smaller pieces, and cut into short fibres of 1 mm, 2 mm, and 3 mm using a Laboratory Milling Machine at the Quality Control Laboratory, Nilest, Zaria, Kaduna State. The polylactic acid was acquired from Abams Chemicals Plc, Ojota, Lagos State, Nigeria, while sodium hydroxide and distilled water were obtained from the Chemistry Laboratory at the Nigerian Institute of Leather and Science Technology, Zaria, Kaduna State.

2.2 Methods

2.2.1 Treatment of *Luffa Cylindrica*

The *Luffa cylindrica* fibres were treated with a 5% sodium hydroxide (NaOH) solution for one hour at 50 degrees Celsius. The solution was prepared by dissolving 5 grams of NaOH pellets in 100 ml of distilled water. After treatment, the fibres were rinsed thoroughly with distilled water until the pH of the rinsing water became neutral. The treated fibres were then dried in a hot air oven at 70°C for six hours. The weight of the fibres was monitored every 30 minutes until it remained constant following a procedure used by [11].

2.2.2 Melt-mixing of Composite

The formulation shown in Table 1 was followed in the melt-mixing process. Sample A, B, C, D and E were replicated for fibre length 1 mm, 2 mm and 3 mm.

Table 1. Composite Formulation

| Material | Neat Sample (PLA) | Sample A | Sample B | Sample C | Sample D | Sample E |
|------------|-------------------|----------|----------|----------|----------|----------|
| LCF (wt %) | 0 | 10 | 20 | 30 | 40 | 50 |
| PLA (wt %) | 100 | 90 | 80 | 70 | 60 | 50 |

2.2.3 Hot Compression

The composite material was placed into a metal mould with dimensions of 120 mm x 100 mm x 3.2 mm. The mould was then placed on a hydraulic hot press and heated to 150 degrees Celsius while applying a pressure of 2.5 MPa for five minutes. After cooling, the composite was removed from the mould and labelled. This process was repeated for all of the composites produced.

2.3 Characterization of the Composites

Impact Strength: The impact test was carried out according to the standard specified by ASTM D-156. The specimen was cut to dimensions 64 mm x 12.7 mm x 3.2 mm and 45° notched was inserted at the middle of the test specimens from all the produced composite samples. The impact energy test was carried out using Izod Impact Tester (Resil impactor testing machine). The specimen was clamped vertically on the jaw of the machine and hammer of weight 1500 N was released from an inclined angle 150°. The impact energy for corresponding tested specimen was taken and recorded. To guarantee reliability, three replicas were tested for each sample composition.

Hardness: The hardness test was carried out in accordance with ASTM D2240 on a Mico Vicker Harness Tester. Three replicas of each sample composition were tested to confirm reliability.

Water Absorption Test: The water absorption test was carried out in accordance with ASTM D570. Specimens were prepared with dimension 50mm x 50mm x 3.2 mm. Water absorption test was done by total immersion of specimens in distilled water at room temperature for 7 days. The water absorbed was determined by weighing the samples at regular intervals of 24 hours, with the aid of digital weighing balance.

2.4 Statistical Analysis

All data presented are expressed as means of the triplicate tests. Single factor analysis of variance was carried out to compare the means of different data sets, and a value of $P < 0.05$ was considered statically significant.

3 RESULTS AND DISCUSSION

3.1 Impact Strength

Impact strength describes the capacity of a material to withstand a suddenly applied load. Figure 1 shows the impact strength of the luffa fibre filled PLA composites. The control sample recorded the highest impact strength and was significantly ($P < 0.05$) different from all other samples. The results show that the impact strength of the composites decreased from 0.219 J/mm to 0.182 J/mm, 0.214 J/mm to 0.157 J/mm and 0.229 J/mm to 0.180 J/mm for the composites filled with luffa fibre 1 mm, 2 mm and 3 mm fibre length respectively as the filler loading increased from 10% to 50%. It is expected that the impact strength decreased since the matrix is a brittle polymer and clearly, the fibre incorporation did not improve the impact strength of the PLA and addition of the filler could have made the composite more brittle [11].

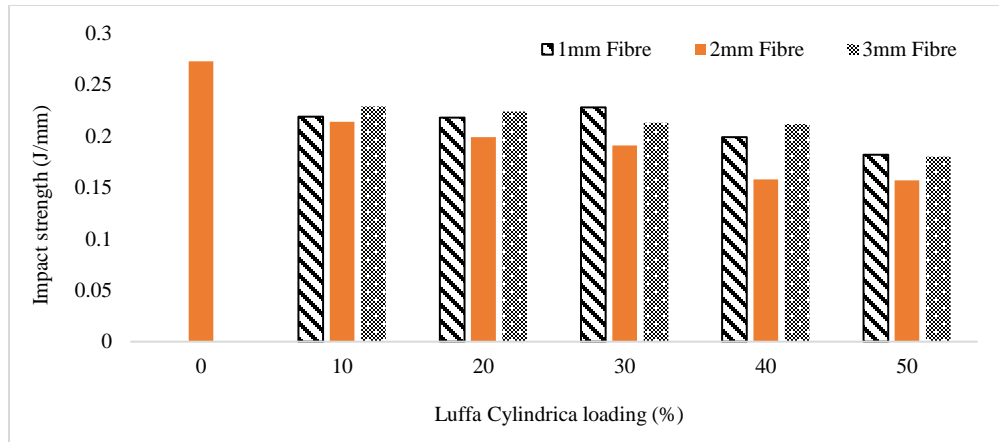


Figure 1. Effects of fibre loading and fibre length on the impact strength of PLA composites

Overall, 1mm fibre length at 30% loading gave a better performance among the composites formulated. The presence of the fibre only made the matrix more brittle and therefore could not resist stress on impact which caused the failure [12]. The SEM result obtained from the failed samples of the test is presented in Figure 2a and b. Even though the SEM showed good adhesion of the matrix to the fibre, the brittle nature of the composite did not allow the composite to resist a lot of stress on impact. This is usually expected in a brittle material [13, 14].

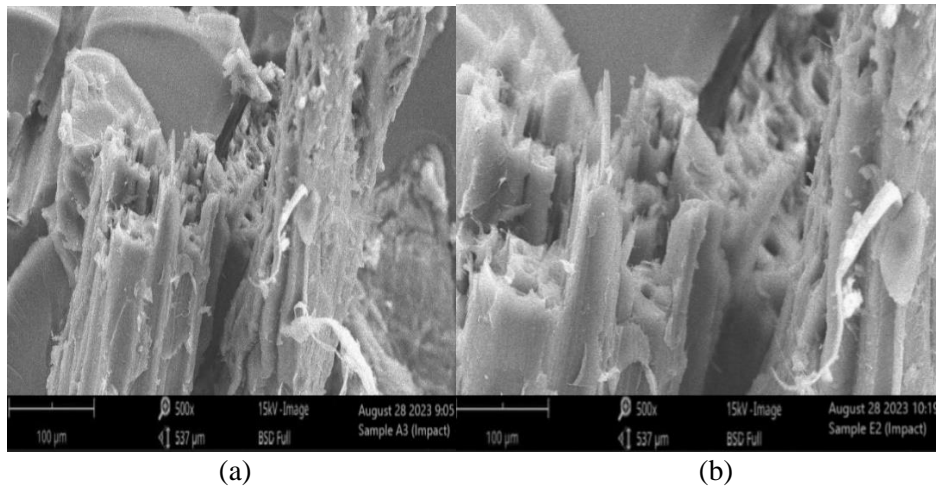


Figure 2. (a) Impact Strength Sample (A3); (b) Impact Strength Sample (E2)

3.2 Hardness

Hardness property is a measure of the resistance of material to deformation induced by either mechanical indentation or abrasion [15]. Figure 3 shows the hardness results of the produced luffa fibre filled PLA composites. It was found that there is a gradual increase in the hardness of the composites with the increase filler loading with sample of 30% loading at 1 mm fibre having the highest hardness and is significantly different ($P < 0.05$) from the other samples followed by sample at 50% luffa loading at 2 mm fibre loading. This is expected because the matrix is a hard and brittle polymer whereas the fillers incorporated in the polymer as evident by impact strength results. The incorporation of the fibre further improved the resistance to indentation of the polymer especially the composite formulated with 3mm fibre length. This is usually evident in brittle materials; they usually show strength in hardness but poor on impact [16].

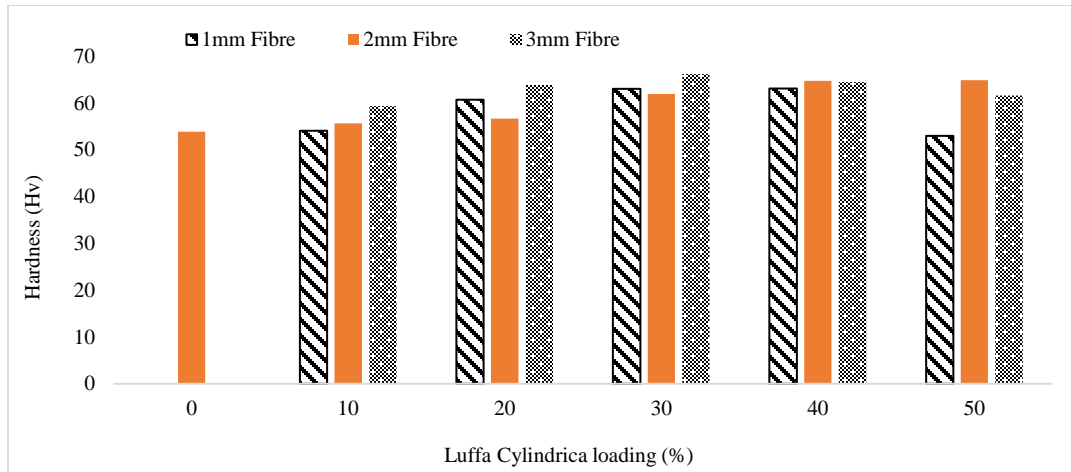


Figure 3. Effects of fibre loading and fibre length on the hardness of PLA composites
The results of the SEM of failed samples are presented in Figure 4 (a and b).

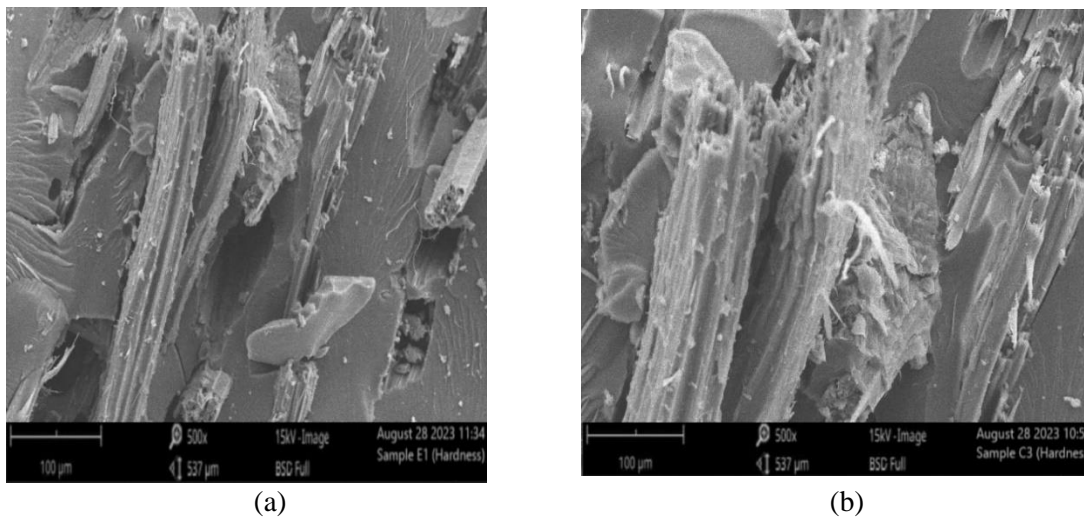


Figure 4. (a) Hardness Sample (C3); (b) Hardness Sample (E1)

Figure 4a and 4b are results for sample C3 (sample loaded with 30 %, 3 mm luffa fibre length) and sample E1 (sample loaded with 50 %, 1 mm luffa fibre length) respectively which represents the best and the poor performing samples from hardness test results. Uniform fibre embedded matrix with few surface contours could be seen in Figure 4a whereas a dense fibre loading with excessive surface contour could be seen in Figure 4b. The contours could be responsible for the low hardness value of the sample E1 as the indenter might have fallen on the contours during testing [17].

3.3 Water Absorption

Water absorption test results for the luffa fibre filled PLA composites is shown in Figure 5. It can be seen that the water absorption of the composites increases from 0.12 % to 1.23 %, 0.12 % to 1.28 % and 1.35 % to 2.42 % for the samples filled with 1 mm, 2 mm and 3 mm luffa fibre respectively as the filler loading increased from 10 % to 50 %. This trend could be related to the inherent hydrophilic property of the fillers being an agro-waste material. Moreover, it was observed that the samples containing 3 mm fibre length exhibit highest water absorption than those filled with 1 mm and 2 mm fibre length. This could be since the higher the fibre length the more the surface area of the filler in the matrix exposed to absorb water which gave rise to higher water absorption of the composite. Moreover, the high cellulose content of Luffa cylindrica may have also contributed to the high-water absorption observed [18].

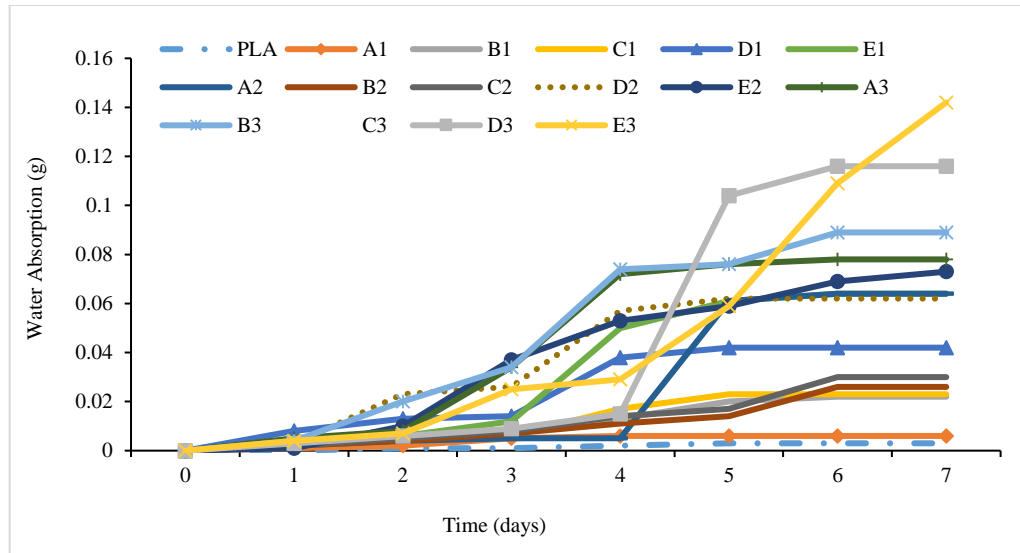


Figure 5. Effects of fibre loading and fibre length on water absorption of PLA composites

4 CONCLUSIONS

This study explored the mechanical and water absorption properties of *Luffa cylindrica*-reinforced PLA composites, focusing on the effects of fibre length and filler loading. The experimental results demonstrated that both fibre length and filler loading play crucial roles in determining the overall performance of *Luffa cylindrica*-PLA composites. Longer fibre lengths, particularly 2 mm and 3 mm, showed a significant improvement in impact strength of the composite, likely due to better stress transfer between the fibre and matrix. However, increasing filler loading beyond 30% led to a decrease in impact strength, suggesting that excessive filler content may compromise the composite's mechanical integrity due to agglomeration and poor fibre dispersion in the matrix. In terms of hardness, higher filler loadings generally enhanced the composite's resistance to surface deformation, making it more suitable for applications requiring rigid materials. Water absorption tests indicated that the composites' hydrophilicity increased with higher filler content, likely due to the natural fibres tendency to absorb moisture. However, the impact of fibre length on water absorption was less pronounced, indicating that filler loading is the dominant factor influencing the composite's moisture uptake. While *Luffa cylindrica* fibre improved the overall mechanical properties of PLA, strategies to mitigate its water absorption characteristics, such as surface treatments or the use of water-resistant coatings, may be necessary for applications in humid environments.

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