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ORIGINAL ARTICLE

Fabrication of raw and chemically treated biodegradable *Luffa aegyptica* fruit fibre-based hybrid epoxy composite: a mechanical and morphological investigation

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Abstract

This study investigated the manufacturing and characteristics of luffa fibre reinforced epoxy composites with different stacking sequences and fibre treatments. The composites were created using a manual lay-up approach mixed with compression moulding. Three laminates were tested: L1 with untreated luffa fibres, L2 with HCl-treated fibres, and L3 with NaOH-treated fibres. Mechanical tests demonstrated that chemical treatments considerably increased tensile, flexural, interlaminar shear, and impact strengths when compared to the untreated L1 laminate. L3 with NaOH-treated fibres had the highest tensile strength of 16.47 N/mm^2, flexural strength of 11.205 N/mm^2, interlaminar shear strength of 4.105 N/mm^2, and improved impact energy absorption. The alkali treatment was more successful than the acid treatment at improving fibre-matrix adhesion by removing hemicellulose and lignin. Scanning electron microscopy analysis revealed enhanced interfacial bonding and decreased debonding in the treated fibre laminates. Water absorption experiments revealed that the NaOH-treated L3 laminate absorbed the least amount of moisture after 28 days of immersion, at approximately 6–7%. The results show that chemically treated luffa fibre reinforced composites can be tailored for medium load structural applications by adjusting the fibre surface characteristics.

Keywords Flax · *Luffa aegyptica* fibre · Epoxy resin · Mechanical properties · Morphology

1 Introduction

The importance of biodegradable materials has increased in recent years due to the demand for eco-friendly disposal methods. This change has resulted in an increased emphasis on natural fibres, which are crucial in tackling modern biological and ecological issues. The fibres offer a sustainable substitute for synthetic reinforcing fibres commonly utilised in numerous industries now. Composites using natural fibres have advanced greatly since their beginning and are now used in several industries including consumer products and high-tech production. New manufacturing methods have been developed in pursuit of economically attractive composite parts. The automotive industry has acknowledged the significant commercial opportunities presented by composites, exceeding those of the aerospace sector. Natural fibres have competitive benefits over glass fibres, especially in terms of specific strength and specific stiffness. The advancement of engineering materials led to the creation of composites, addressing issues related to inflexible polymers.

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In the mid-1960s, industries such as automotive and aviation began to investigate natural fibres more extensively because of their excellent characteristics and widespread availability. Natural fibres are more cost-effective and less irritating to the skin compared to manufactured fibres such as glass and aramid. Hybrid composites, which blend natural and synthetic fibres, possess a wider array of favorable characteristics, rendering them suitable for usage in several industries such as aerospace, marine, and household appliances. Researchers are currently investigating the potential of bamboo for long-lasting furniture, creative support systems, and parts for bicycles and cars. Sisal fibres, found in many forms, are used in braking materials due to their remarkable thermomechanical characteristics and mechanical properties. Natural fibre-reinforced composites are increasingly used in sustainable construction, providing advantages for buildings, livestock, and living beings. Wood fibre-reinforced composites are used in furniture, while epoxy-based composites improve the structural strength of airframes. Engineers are using bio-based materials more often to lessen environmental harm. Natural fibre-reinforced composites are becoming popular as a sustainable option since they are inexpensive, recyclable, biodegradable, lightweight, and have excellent mechanical qualities.

The limited mechanical properties of natural fibre-reinforced composites in comparison to synthetic fibres provide a challenge. Hybridisation, which combines two or more different types of fibres, is a successful technique for overcoming this constraint. Weight-to-volume ratio, chemical fibre treatment, stacking order, ambient conditions, and individual fibre characteristics are key factors that impact the performance of hybrid composites [1–4]. Since the middle of the 1960s, there has been a growing need for materials that are both more grounded and more rigid for use in a variety of industries, including automotive and aviation manufacturing. These domains of application are increasingly becoming interested in natural fibres as a result of the exceptional features that they possess and the vast supply of natural fibres on the planet. Synthetic fibres are a form of man-made, better-imitated fibres, such as glass, aramid, and other similar materials. Natural fibres are more cost-effective than synthetic ones, and they do not irritate the skin or other parts of the body. Synthetic fibres, on the other hand, are becoming more expensive as time goes on [5–8]. The advantages of this type of fibre in comparison to synthetic fibres are more numerous. Hybrid composites made from natural and synthetic fibres provide a wider range of desirable qualities than those of composites made from just one type of fibre. Fibre-reinforced polymer composites, or FRPCs for short, are polymer framework composites that have reinforcing materials embedded inside them in the form of fibres. These fibres have high strength. There are a wide variety of industries that make use of composites made from natural and synthetic fibres, such as the aerospace industry, marine, and the household appliance industry. Research is being conducted on the viability of using bamboo for long-lasting furniture, innovative geometrical auxiliary structures, and even bicycles, tricycles, and automobile parts [9]. The sisal fibres are commercially available in a variety of forms, including cloth, strings, strips, wire, rolls, and so on. In the case of braking materials, a substance must not only possess remarkable thermomechanical qualities and a high level of chemical stability, but it must also have adequate mechanical properties. Because of the brake parts' potential impact on the driver's overall health, ensuring that they are of sufficient quality and are resistant to damage is of the utmost importance. Natural fibre composites have gained popularity in recent years as a means to develop and sustain buildings, livestock, and other living organisms. Wood fibre reinforced composites are being used in the production of profiles for use in a variety of furniture applications, including windows and doors. Epoxy-based composites are increasingly being used to enhance the structural integrity of airframes. To reduce their impact on the environment, engineers have begun using bio-based materials in their construction projects. Recent efforts in the scientific community have focused on the creation of sustainable materials made from renewable and biodegradable natural resources. Natural fibre-reinforced composites are one of these materials that can replace synthetic materials and reduce harmful effects on the environment. They also have advantages such as low cost, recyclability, biodegradability, low density, and better mechanical properties, making them one of the most sustainable materials for a variety of industrial applications. Natural fibre-reinforced composites are one of these materials that can replace synthetic materials and reduce harmful effects on the environment. They also carry advantages such as low cost. As a result, bio-based composites have become increasingly significant as a means of making use of the fibres that are readily accessible in nature in the form of plants, animals, and minerals [10–13]. Plants are harvested for their fibres, which are then utilised in conjunction with polymers for structural and lightweight applications. The poor mechanical capabilities of natural fibre-reinforced composites, in comparison to those of synthetic fibres, is a major drawback of these materials. This challenge can be conquered by producing hybrid fibre-reinforced polymer composites with two or more different types of fibres. To get around the disadvantages of using natural fibres, hybridisation is a viable option, and one of the most successful strategies for overcoming the limitations of natural fibres is the use of hybridisation. The weight-to-volume ratio, the chemical treatment of the fibres, the stacking order of the fibres, the circumstances of the surrounding environment, and the qualities of the individual fibres are the most critical aspects that influence hybrid composites. Hybrid polymer composites made from synthetic and natural components have the potential to improve upon a number of aspects of traditional polymers, including their mechanical qualities, moisture absorption, cost,

and environmental impact by decreased carbon content. Natural fibres can be combined with synthetic fibres such as carbon, Kevlar, glass, and aramid, as well as mineral fibres such as basalt, in order to improve the performance of composite materials. Stacking sequence can aid in modifying the qualities of the composite material; this was shown by an examination of the impact and mechanical properties of the hybrid basalt/flax with various stacking sequences. As a result, composite materials may be tailored to fulfil the intended purposes. Since, the basalt mat has a long-lasting nature, that's why it was utilised for the outside layers. Long-term ageing experiments on flax reinforced epoxy composites demonstrated that hybridisation of basalt with flax improved the durability of natural fibres composites. This was discovered through the testing of flax reinforced epoxy composites. The utilisation of composites made from a combination of natural and synthetic fibres has many practical uses in vehicle design due to its lightweight and cost-effective nature [2, 14–20]. The three-body abrasive wear and water absorption responses of Luffa fibre-reinforced polyester composites were tested with and without the inclusion of micro-fillers of Al_2O_3, $CaCO_3$, and TiO_2. The use of micro fillers into Luffa-fibre based composites has resulted in significant improvements to both their physical and mechanical characteristics [21]. Materials scientists and engineers can benefit from using both natural and synthetic fibres to create lightweight, high-performance polymer composite materials. Natural fibres are renewable materials that offer several benefits, including cheap production costs, biodegradability, low density, high specific modulus, abundance, and little environmental impact. According to the literature review, *Luffa aegyptica* fruit fibre (Fig. 1) has been used as a reinforcement for vinyl ester matrix based composite. It needs additional research. The inner fibre of the luffa cylindrical fruit was employed. A previous study shows that as a composite reinforcement *Luffa aegyptica* fruit fibre exhibits better mechanical, physical, and thermal qualities. Despite these findings, *Luffa aegyptica* as a strengthening component for epoxy matrix composite has not been studied, thus, requiring more research. Hence, the present study explores its possibilities with epoxy matrix and different chemical treatments The current study aims to assess the effectiveness of epoxy composites reinforced with *Luffa aegyptica* fruit fibres of varying stacking sequences for use in structural engineering.

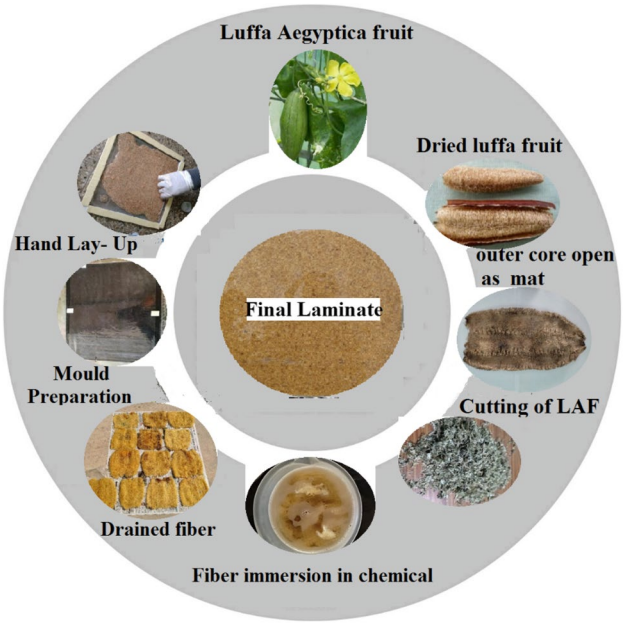

Fig. 1 Composite laminates fabricated in the present study

2 Materials and methods

2.1 Materials

2.1.1 Luffa aegyptica

The mature fruits of the luffa plant, which belongs to the Cucurbitaceae (cucumber) family, are harvested and utilised as natural sponges, while the young fruits are consumed as vegetables. Its distribution spans the entirety of Asia, from the south to the east and central regions. Both Vietnam and China have a significant demand for luffa vegetables. The luffa fibre possesses substantial toughness, strength, and stiffness, which are comparable to those found in a variety of metals with density ranges that are comparable. Luffa's chemical constitution is predominantly made up of lignin and hemicellulose/cellulose, but it also contains certain inorganic elements, including glycosides, polypeptides, amino acids, and proteins. In addition, luffa does include some organic compounds. The chemical composition of luffa or lignocellulosic agricultural fibre (LAF) is as follows: cellulose (%): LAF typically contains cellulose in the range of 55 to 90%. Cellulose is a fundamental component of plant cell walls, providing structural integrity and strength. Hemicellulose (%): The hemicellulose content in LAF falls between 8 and 22%. Hemicellulose is another type of polysaccharide found in plant cell walls, contributing to the overall flexibility and binding of plant fibres. Lignin (%): LAF comprises lignin in the range of 10 to 23%. Lignin is a complex polymer that enhances the rigidity of plant cell walls, playing a crucial role in providing resistance to decay. Ash (%): The ash content in LAF is approximately 0.4%. Ash represents the inorganic residue remaining after complete combustion and includes minerals and other inorganic components. Extractives (%): LAF contains extractives in the range of 3–3.2%. Extractives are organic compounds that can be extracted from the plant material using solvents and may include substances such as resins and waxes.

2.1.2 Epoxy resin

The use of epoxy resin in adhesives is among the most prevalent of its many applications [22–24]. Epoxy is a material that may be utilised for structural and technical adhesives due to its robust qualities [25–27]. Epoxy resin is a versatile material that finds widespread application in a variety of industries, including the automotive, metal plating, and electrical component manufacturing industries. Epoxy resin acts as a binding and adhesive agent in composite manufacturing, offering protective encapsulation, stress transfer, chemical resistance, thermal stability, and electrical insulation to improve material performance. The curing process enhances dimensional stability and results in a strong, rigid composite structure.

2.1.3 Hardener

Epoxy resins, by themselves, are fluids that are exceptionally stable and have relatively lengthy shelf life [28, 29]. It is impossible for it to adequately cure without being combined with an epoxy hardener [30, 31]. If the resin was not allowed to become brittle before it was placed to the floor, it would continue to be close to liquid for an unlimited amount of time and would not turn into a resilient flooring system.

2.1.4 Sodium hydroxide (NaOH)

One of the inorganic compounds, sodium oxide is most often encountered in its solid form at normal temperature [32]. It is also white in colour. This chemical molecule is composed of the cations Na^+ found in sodium and the anion OH^- found in hydroxide. The formula for sodium oxide in chemical notation is NaOH. NaOH induces mercerisation, a chemical process that modifies the structure of natural fibres, enhancing their strength, durability, and affinity for dyes. This treatment improves the overall performance and applicability of natural fibres in various industrial applications. Additionally, it is commonly used in the production of a variety of items, such as explosives, liquid drain and oven cleaners, paper, soap and detergents, pulp, and many others. There are a few other names for it, including Iye and caustic soda.

2.1.5 Hydrochloric acid (HCl)

When hydrogen chloride is diluted with water, HCl is produced as a by-product of the reaction. It is an uncomplicated diatomic molecule. HCl is an extremely potent corrosive irritating acid that is commonly used in industry and labs and is also found in gastric juice in diluted form.

2.2 Fabrication of composites

Raw luffa fruit is obtained by harvesting the fruit from the plant and then drying it after the outer layer has been partially peeled off. After the fruit has been dried, it is simple to separate the fruit from its skin. If there is any leftover fibre in the fruit form, it is first made into a mat by cutting it straight, and then any resulting fibre bits are finely powdered or diced, according to what is depicted in the Fig. 1a. The surface area of LAF is able to be significantly increased by the use of chemical treatments using a variety of chemicals including NaOH and HCl. Improvement in overall qualities is achieved by removing unwanted contaminants and decreasing water absorption. Treatment with alkaline NaOH and HCl demonstrated its capacity to enhance the microstructure of LAF by altering its chemical composition and eliminating all contaminants. Distilled water was used to do multiple washings on the LAF to get rid of any remaining dirt or debris. The luffa is given an alkaline treatment by being rinsed in a NaOH solution for 24 h at room temperature. This solution is generated by dissolving 100 g of NaOH in 2 L of distilled water. To eliminate any pollutants that may have been present in the LAF, it was given many washes in water that had been distilled. Later, a 6% HCl solution is made by dissolving 120 mL of HCl in 2 L of distilled water. Subsequently, an acidic treatment is performed on luffa by washing 250 g of luffa in an HCl solution for 24 h while the temperature is kept at room temperature. Following the application of a chemical treatment, the fibre is washed and then allowed to dry in the light of the sun. Fabrication of composite materials is accomplished using the hand layup process by making a mould measuring 250 mm by 250 mm. The mould is left to dry, and once it is dry, silicon spray used as the mould releasing agent is applied. The measured amount of chopped LAF is placed by hand inside the mould, and then an epoxy-hardener liquid is added. The epoxy-hardener mixture, which is made in a 1:10 ratio, is thoroughly stirred with a motorised stirrer before it is slowly poured into the fibre beds and spread out. Rollers or brushes were used to impregnate materials with glue. But nip roller-type impregnators are becoming more and more popular. These impregnators work by using rotating rollers that are covered in a resin bath to push resin into the chopped fibres. This method works well to wet the fibres and get rid of any air that is stuck in the lay-ups. The laminates are allowed to cure under conditions that are typical of the atmosphere. After that, the laminate was taken out of the mould, transferred to the oven, and left there for 24 h to air cure at 80 °C. The untreated, HCl, and NaOH-treated fibres, as well as the untreated fibre, are all subjected to this procedure again. Chemical treatment with

HCl and NaOH is critical for optimising luffa natural fibres for a variety of applications. This process effectively eliminates contaminants, waxes, and non-cellulosic components, resulting in a cleaner starting material. The procedure alters the fibre surface, resulting in enhanced adhesion to polymer matrices in composite materials and improved mechanical properties. Increased porosity improves applications such as water filtration, while increased dye affinity makes dyeing easier in textiles. Chemical treatment also makes luffa fibres more biocompatible, expanding their potential applications in biomedical disciplines. Overall, these treatments help adapt luffa fibres to specific uses, increasing their versatility across various sectors. After curing, samples were cut from them and prepared for analysis of their mechanical characteristics in accordance with the ASTM standards, as shown in the Table 1.

2.3 Experimentation methods

The laminates were manufactured utilising the ASTM D2734-94 standard, and the results of this approach were analysed to find out the hybrid composites' densities as well as their void percentages. Calculating the experimental density required the application of the Archimedes principle. Performing the calculations is needed to determine the specimen's weight in both air and liquid.

Equation (1) was utilised to arrive at the results of the experiment.

$$\rho_{ex} = \frac{w_a}{w_a - w_l} \times \rho_l \tag{1}$$

Table 1 Specimen dimensions

S. no	ASTM code	Mechanical test	Sample dimensions (mm^3)
1	ASTM D638	Tensile	254 × 25.4 × 3
2	ASTM D790	Flexural	90 × 10 × 3
3	ASTM D2344	Interlaminar shear	60 × 10 × 3
4	ASTM D256	Impact	63 × 12.7 × 3

where,

ρ_{ex} represents experimental density,
w_a represents weight of the specimen in air,
w_l represents weight in liquid, and
ρ_l represents density of the liquid.

Each laminate's theoretical density was computed, and then five tests were run on each laminate to determine its actual density; the average of these tests was then recorded. For the purpose of determining the theoretical density based on weight fraction, Eq. (2) was utilised.

$$\rho_{th} = \frac{100}{\frac{W_m}{\rho_m} + \frac{W_f}{\rho_f}} \tag{2}$$

where, W_m indicates the weight fraction (%) of matrix phase, ρ_m represents the density of the matrix phase, W_f indicates weight fraction (%) of fabric, and ρ_f indicates the density of the fabric.

Laminates having more than 5% voids are regarded as being of low quality, in contrast to excellent composites, which have less than 1% of void space. As the amount of voids in the composite grows, the attributes of the composite exhibit decreasing values, namely a decrease in its water-resistant quality. In Tables 2 and 3, the density, void, weight, and volume fractions are displayed.

The % of void was determined by applying Eq. (3) to both the theoretical and experimental values of density.

$$V_v = \frac{\rho_{th} - \rho_{ex}}{\rho_{th}} \tag{3}$$

where V_v indicates the void percentage, ρ_{th} indicates the theoretical density, and ρ_{ex} indicates the experimental density.

2.4 Mechanical (Tensile) characterisation

A standardised testing instrument known as a UTM is used for the evaluation (Model: KIC-2–1000-C). The maximum allowable force is 100 kN. The dimensions are measured in accordance with the D638 norm (254 × 25.4 × 3 mm^3). The deflections caused by applying a weight while firmly holding the specimen are measured. After a specimen fails

Table 2 Laminates density

Laminates	Stacking sequence	Theoretical density (g/cm^3)	Experimental density (g/cm^3)	Void fraction (%) V_f
L1	L1 is epoxy + LAF	0.2958	0.2882	2.56
L2	L2 is epoxy + HCl-treated LAF	0.2866	0.2756	3.83
L3	L3 is epoxy + NaOH-treated LAF	0.3129	0.3027	3.25

Table 3 Laminates weight and volume fraction

Laminates	Weight in (g)		Weight fraction (%)		Volume fraction (%)
	w_f	w_m	w_f	w_m	V_f
L1	75 ± 2	295 ± 10	20.27	79.72	34.3
L2	77 ± 2	305 ± 10	20.15	79.85	34.1
L3	74 ± 2	276 ± 10	21.24	78.76	34.1

under a predetermined force, its ultimate tensile strength is recorded until the load is removed [33]. Documentation of tensile stress and strain is made, as well as graphs showing how load and length relate to each other. Figure 2 shows the specimen after the tensile test.

2.5 Flexural test

The flexural test is carried out using a three-point flexural setup in accordance with the standard ASTM D790. The specimen deforms and cracks under a centrally applied stress [34]. The UTM takes the breaking load and plots it against the length of the test specimen, which is then used for further analysis. Figure 3 showcases the specimen after the flexural test.

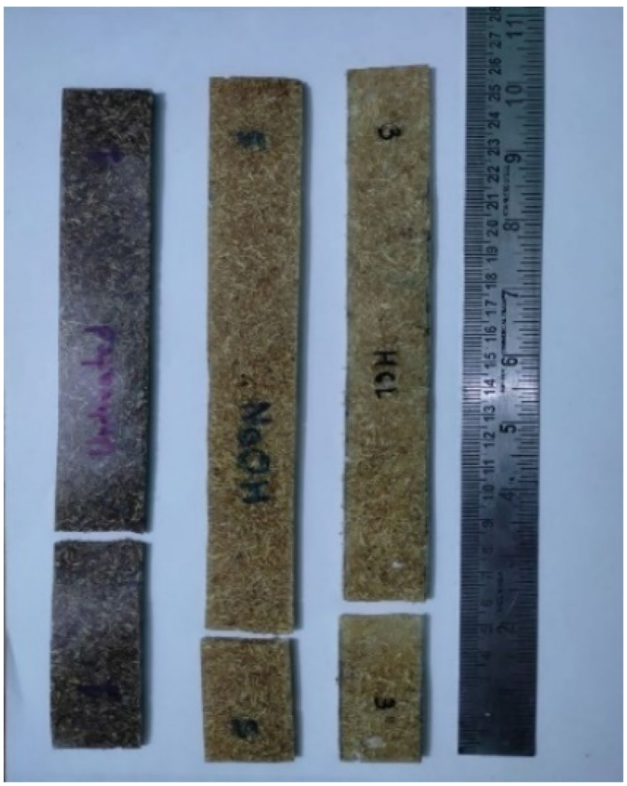

Fig. 2 Tensile tested specimen

2.6 Interlaminar shear strength (ILSS) test

UTM conducts the ILSS analysis in accordance with the requirements of ASTM: D2344. It is used as a measure of quality assurance for laminated advanced composites. In layered materials, it represents the highest shear stress possible between the individual layers. Figure 4 shows the specimen after ILSS test.

2.7 Impact test

The impact test is carried out using a Charpy impact setup in accordance with the standard set forth by ASTM: D256. The sample (Fig. 5) needs to be put into the testing equipment, and the pendulum needs to swing back and forth until the sample breaks or cracks. When performing the impact test, the amount of energy that is required to fracture the material is recorded. This energy is then utilised to determine the material's toughness as well as its yield strength. It is determined how much influence the rate of strain has on the material's brittleness and ductility.

2.8 Water absorption study

A comparative examination of the water absorption properties of treated and untreated fibre-reinforced composites was carried out as per the ASTM D 1037–99 standard. The

Fig. 3 Flexural tested specimen

Fig. 4 ILSS tested specimen

Fig. 5 Impact tested specimen

samples were put in water at room temperature for different amounts of time to find out how quickly they absorbed water [35–37]. After being submerged for 24 h, the specimens were removed from the water bath and blotted with a clean, dry cloth to remove excess water. This process was repeated several times. After that, they were instantly reweighed, and their dimensions were impulsively observed. In a similar manner, each and every specimen was subjected to consistent weighing at 1, 4, 8, 18, and 28 days of exposure until the weight of the samples achieved a level of consistency.

The composite structure's capacity to absorb moisture was determined (Eq. 4) by comparing its initial and final weights.

$$W(\%) = (W_o - W_i)/(W_i) \tag{4}$$

where, W_i is the weight of the initial weight of the specimen, and W_o is the weight of the specimen after immersion.

2.9 Scanning electron microscopy (SEM)

The broken surfaces of the tensile specimens were analysed using a Hitachi SU 3500 SEM. The ends of the broken specimens were trimmed down to less than $10 \times 10 \times 3$ mm^3, and a homogeneous coating of carbon and gold was applied to their surfaces. The voids, fibre pull-out, fabric-matrix interface, consistent mixing of filler materials, and adhesive property behaviour between the reinforcement and matrix phases were all identified through morphological testing [38–41].

3 Results and discussion

3.1 Tensile properties

The tensile characteristics of the composite L1, L2, and L3 specimens are evaluated using the UTM, and the results are displayed in Figs. 6, 7, 8. The improved tensile strength observed for laminates L2 and L3 compared to L1 can be attributed to the chemical treatment of the luffa fibres. The alkali treatment (NaOH) for L3 and acid treatment (HCl) for L2 are known to modify the fibre surface and enhance the fibre-matrix interfacial adhesion, leading to better stress transfer and improved mechanical properties.The superior tensile strength of L3 (16.47 N/mm^2) over L2 (15.42 N/mm^2) can be explained by the more effective removal of hemicellulose and lignin from the fibres by the NaOH treatment, resulting in better exposure of the high-strength cellulose fibrils. This finding is consistent with previous studies on alkali-treated natural fibres, which showed improved tensile properties due to the increased crystallinity and degree of polymerisation of the cellulose. However, the observation of decreased tensile strength with prolonged or higher-dose chemical treatment is in line with other reports, where excessive delignification and fibre damage can occur, leading to a reduction in mechanical properties. This highlights the importance of optimising the treatment conditions to achieve the desired fibre modification without compromising the fibre integrity. The exceptional tensile properties of

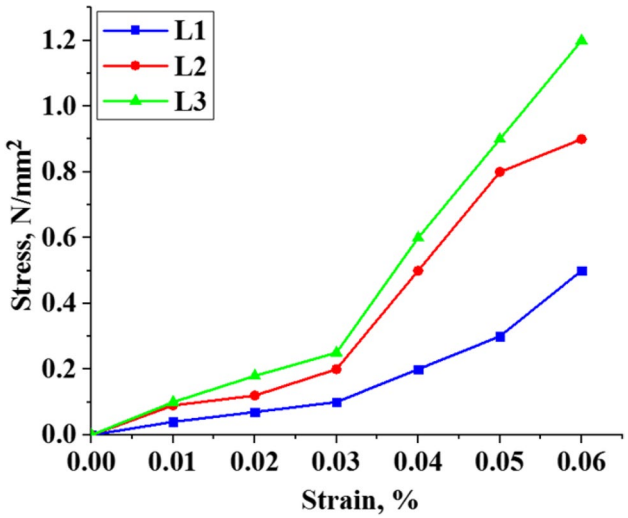

Fig. 6 Stress vs strain

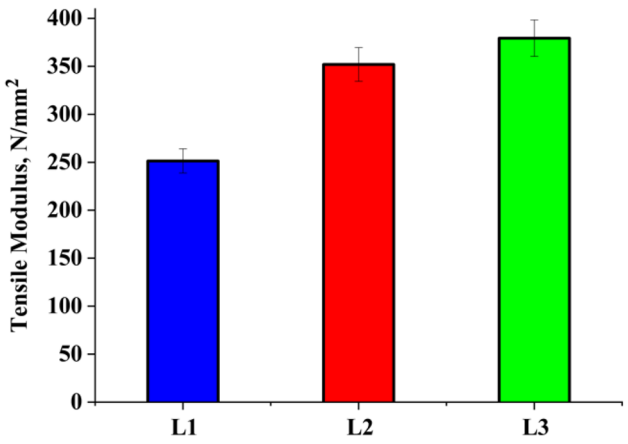

Fig. 7 Tensile Modulus vs laminates

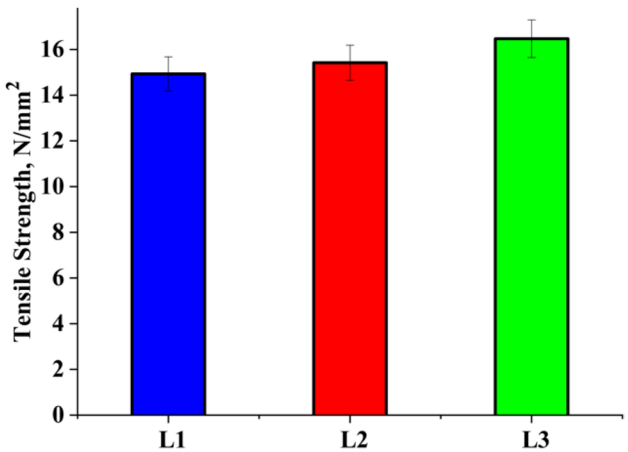

Fig. 8 Tensile strength vs laminates

the luffa fibre-reinforced composites can be attributed to the unique microstructure and composition of luffa fibres. Previous studies have shown that the luffa fibres possess a highly porous and aligned vascular bundle structure, contributing to their high specific strength and stiffness. Additionally, the high cellulose content and low microfibrillar angle of luffa fibres enhance their mechanical performance as reinforcements. The comparison of the energy absorption, tensile strength, and stiffness of luffa sponge gourd material with foam and metallic cellular materials is supported by earlier investigations. These studies highlighted the potential of luffa as a sustainable and cost-effective alternative to conventional materials in various applications, such as energy-absorbing structures and lightweight composites [42–44].

3.2 Flexural properties

Natural fibre-reinforced composites that have undergone the recommended procedures have shown significant increases in flexural strength. This seems to be essential for improving the mechanical characteristics of the composite by strengthening the interfacial connection between the fibre and the matrix. Consequently, it is important to find an appropriate pharmaceutical dose and the length of time spent in treatment. On the other hand, if the chemical concentration and timing are optimised, the interfacial reactivity between the fibre and cement matrix is enhanced, leading to better flexural performance. There is no discernible difference in flexural strength between using longer and shorter luffa fibres as reinforcement in a composite. Figures 9, 10, 11, 12 depict the flexural characteristics of composites L1, L2, and L3 including their flexural modulus and ultimate flexural strength (UFS). The flexural strength of the laminate L3 is measured at 11.205 N/mm^2, which is significantly higher than that of the laminate L1, which measures only 3.843 N/mm^2. The laminate L2, which is composed of LAF that has been treated with NaOH, measures 10.752 N/mm^2 in flexural strength. Likewise, similar to tensile strength, the chemically treated fibre laminates L2 and L3 demonstrate superior performance when compared to L1 [45–47].

3.3 Interlaminar shear strength (ILSS)

The results of the ILSS calculations for the various composite combinations are shown in Figs. 13 and 14. The higher interlaminar shear strength (ILSS) observed for laminate L3 (4.105 N/mm^2) compared to L2 (value not provided) and L1 (1.72 N/mm^2) can be attributed to the improved fibre-matrix interfacial adhesion facilitated by the alkali (NaOH) treatment of the luffa fibres in L3. Alkali treatment is known to enhance the surface roughness and wettability of natural fibres, leading to better mechanical interlocking and increased compatibility with the matrix material. This

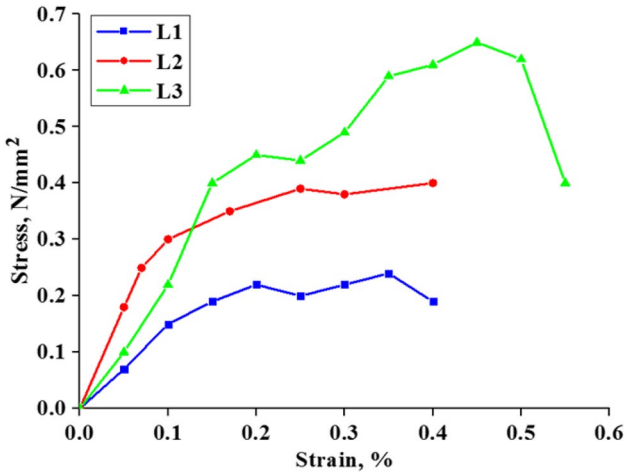

Fig. 9 Stress vs strain

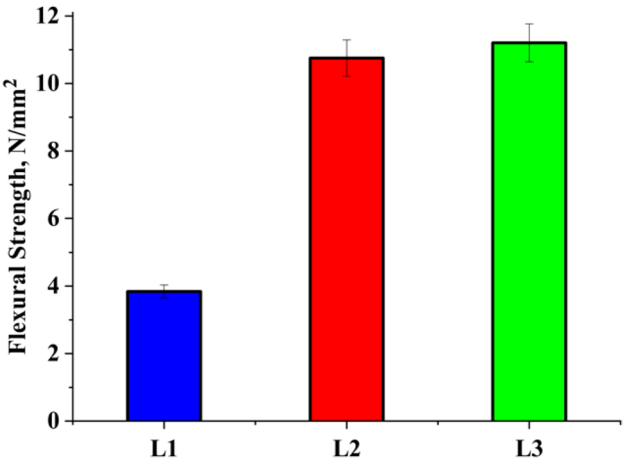

Fig. 12 Flexural strength vs laminates

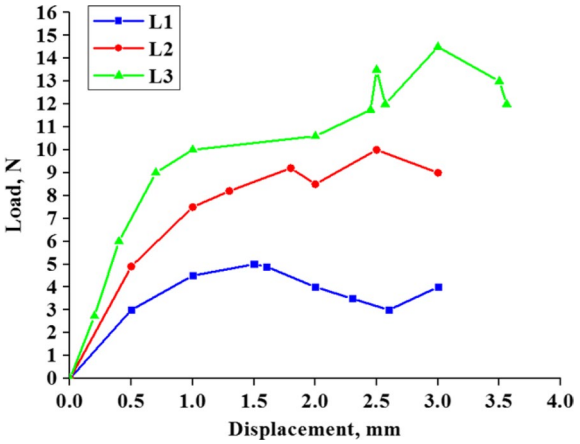

Fig. 10 Load vs displacement

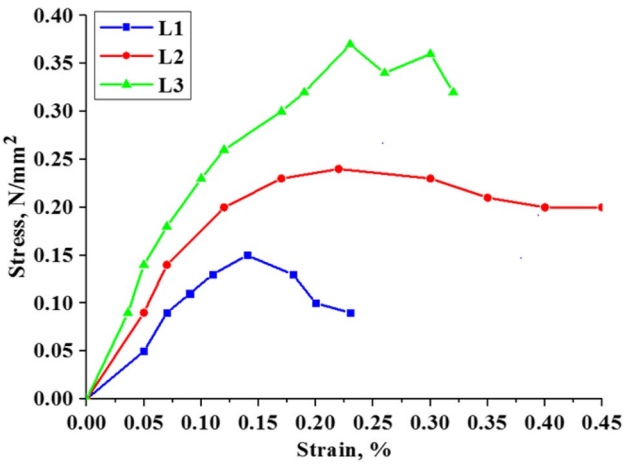

Fig. 13 Stress vs strain

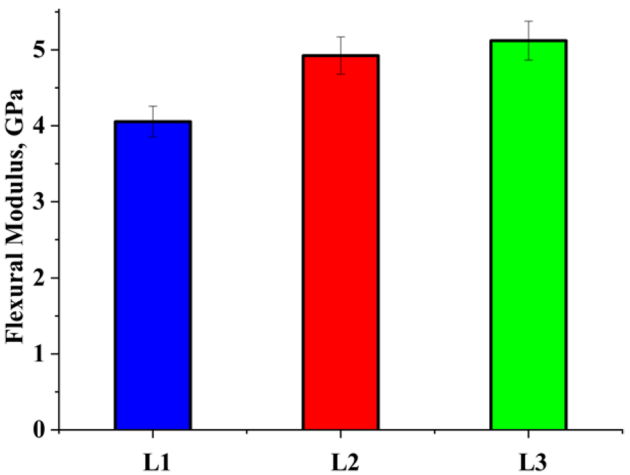

Fig. 11 Flexural modulus vs laminates

improved interfacial bonding allows for more efficient stress transfer from the matrix to the fibres, resulting in higher ILSS values, as observed in the case of L3. The superior ILSS of L3 over L2 (assuming L2 has a lower ILSS than L3) can be attributed to the more effective removal of hemicellulose and lignin from the fibres by the NaOH treatment compared to the acid (HCl) treatment in L2. This finding is consistent with previous studies that have reported higher ILSS values for alkali-treated natural fibre composites compared to untreated or acid-treated counterparts.The relatively low ILSS value of L1 (1.72 N/mm^2) can be attributed to the poor interfacial adhesion between the untreated luffa fibres and the matrix material. This is a common issue observed in natural fibre-reinforced composites, where the hydrophilic nature of the fibres and the lack of compatibility with the hydrophobic polymer matrices lead to poor stress transfer and reduced mechanical properties [6, 7]. Previous research

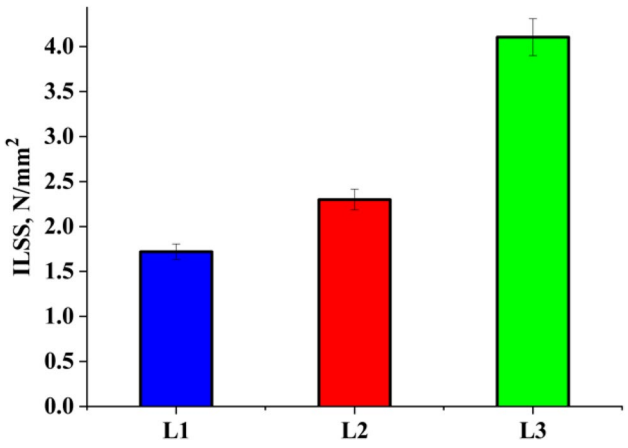

Fig. 14 ILSS vs laminates

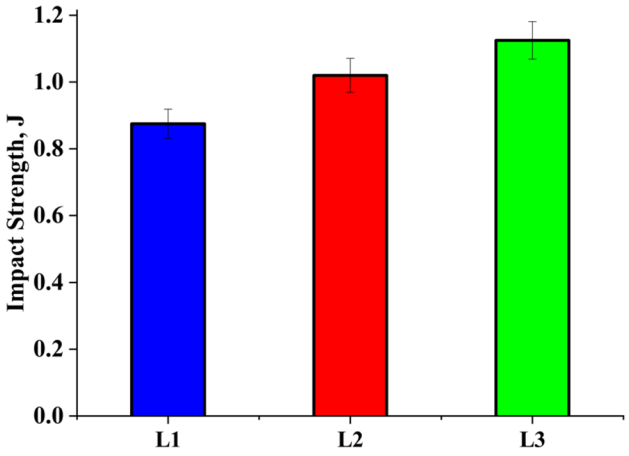

Fig. 15 Impact strength vs laminates

has shown that the ILSS of natural fibre composites is highly dependent on the fibre-matrix interfacial bonding, which can be improved through various surface treatments, such as alkali treatment, silane treatment, or the use of coupling agents. These treatments not only enhance the fibre-matrix adhesion but also promote better dispersion and wetting of the fibres, further contributing to the improvement in ILSS. It is worth noting that the ILSS values reported in this study are comparable to or even higher than those reported for other natural fibre-reinforced composites, highlighting the potential of luffa fibres as an effective reinforcement material [48–52].

3.4 Impact test

The loss of energy during impact is the energy absorbed by the specimen during impact. Figure 15 shows a comparison between energy absorbed by the different combination of composites. The higher impact energy absorption observed for laminate L3 compared to L1 and L2 can be attributed to the improved fibre-matrix interfacial adhesion and enhanced toughness of the alkali-treated luffa fibres. Alkali treatment is known to increase the surface roughness and wettability of natural fibres, promoting better mechanical interlocking and adhesion with the matrix material. This improved interfacial bonding allows for more efficient stress transfer and energy dissipation during impact loading, resulting in higher impact strength, as observed in the case of L3.The superior impact strength of L3 over L2 (assuming the values are provided) can be explained by the more effective removal of hemicellulose and lignin from the fibres by the NaOH treatment compared to the acid (HCl) treatment in L2. This modification in the fibre composition and structure can enhance the toughness and energy absorption capability of the treated fibres, contributing to the improved impact performance of L3.The relatively low impact strength of L1 (0.875 J) can be attributed to the poor interfacial adhesion between the untreated luffa fibres and the matrix material, as well as the inherent brittleness of the untreated fibres. This finding is consistent with previous studies that have reported lower impact properties for untreated natural fibre composites compared to their treated counterparts. It is noteworthy that the impact strength values observed in this study are comparable to or even higher than those reported for other natural fibre-reinforced composites, particularly those reinforced with treated fibres. This highlights the potential of luffa fibres as an effective reinforcement material for applications requiring high impact resistance. Previous research has shown that the impact performance of natural fibre composites can be improved through various strategies, such as fibre treatment, hybridisation with synthetic fibres, and optimisation of fibre loading and orientation. These approaches aim to enhance the energy dissipation mechanisms, such as fibre-matrix debonding, fibre pull-out, and fibre fracture, which contribute to the overall impact resistance of the composite [53–55].

3.5 Water absorption analysis

The investigation of water absorption was carried out to foresee the durability of the manufactured composite laminates in this study [56–58]. The test to see how much water it could hold was done over the course of 28 days. During that time, it was exposed to distilled, salt, and regular water. Because the water molecules were able to be absorbed by the specimens while they were submerged, the weight of the submerged specimens rose. It is evident that the hydrophilicity of the specimens practically increases with the immersion period (7 to 8 days) beginning, but as the time continues, the absorption capacity decreases down. The biggest increase in weight percentage, somewhere between 24 and 25%, was seen in L1 laminated fibre composites when compared to

Table 4 Water absorption test results

Laminates	Type of water specimens' immersion	Weight of the specimens before immersion (g)	Percentage increase in weights				
			Day 1	Day 4	Day 8	Day 18	Day 28
L1	Normal water	4.189	2.68	4.51	7.85	8.33	8.45
	Salt water	4.182	2.71	4.83	7.6	7.77	7.84
	Distilled water	4.008	2.95	5.21	8.95	9.95	10.01
L2	Normal water	4.325	2.08	3.53	6.28	6.77	7.18
	Salt water	3.845	2.26	4.31	7.33	7.56	6.95
	Distilled water	4.132	2.14	3.84	6.67	6.73	7.67
L3	Normal water	3.624	1.97	3.07	6.17	6.28	6.37
	Salt water	3.534	2.11	3.76	5.97	6.19	6.26
	Distilled water	3.546	2.71	4.76	6.28	6.69	6.73

L3. The percentage of weight gain between the beginning of immersion and the end of immersion is noted in Table 4. Since it was untreated and has a more hydrophilic character, the L1 specimen was shown to have a higher water absorption percentage than the other specimens. It was discovered that specimen L3 had the lowest water absorption [59, 60].

3.6 Morphological analysis

When performing mechanical testing on fibre-reinforced materials, a SEM (Fig. 16) can provide important information about the material's underlying structure through microstructural analysis. The SEM analysis of untreated fibres,

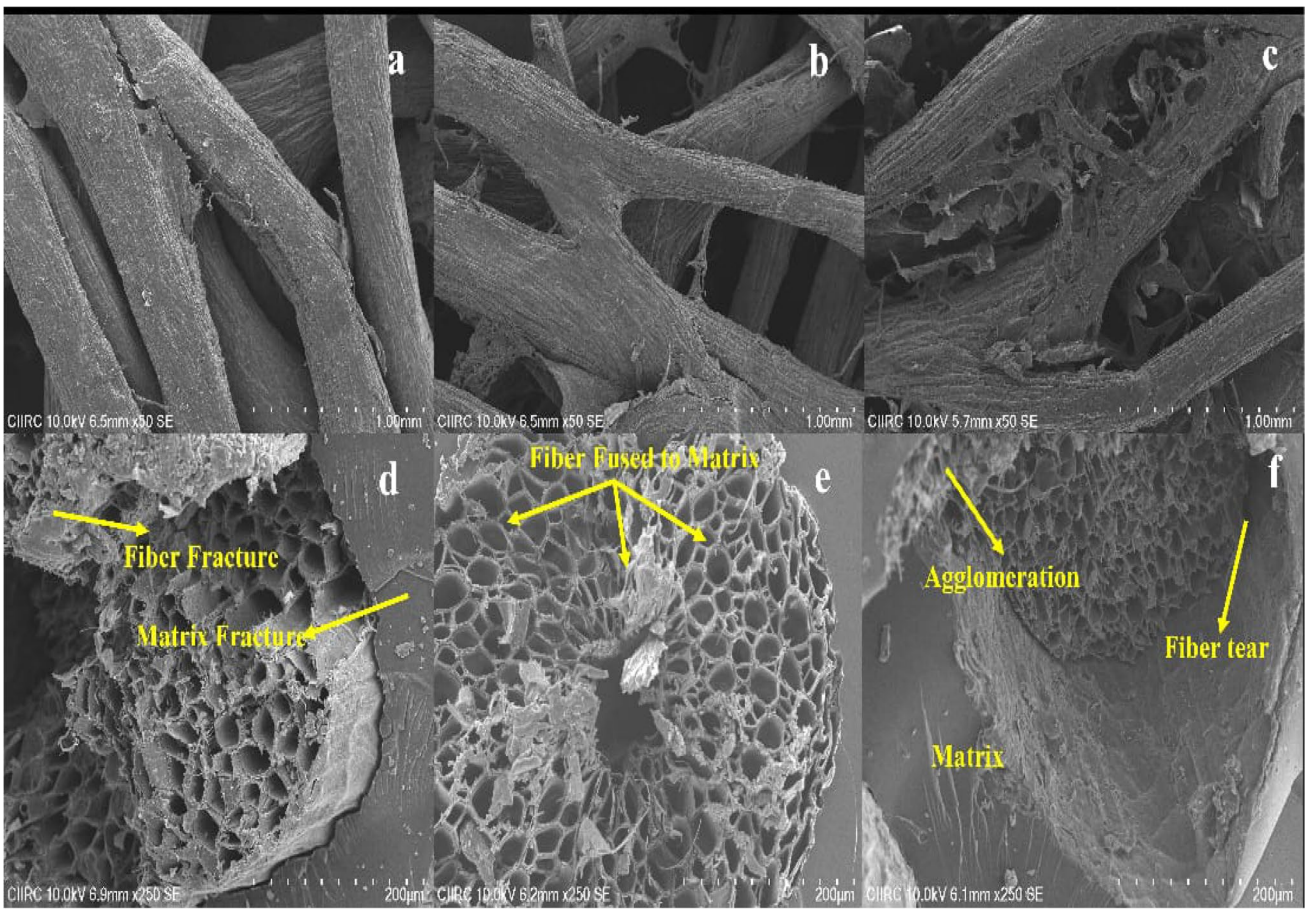

Fig. 16 **a–c** SEM micrographs of fibres that have been treated with NaOH and HCl, and the untreated fibre, **d–f** tensile test samples of fibre untreated/NaOH-based epoxy resin reinforced composite

fibres that have been treated with NaOH and HCl, and fibres that have not been treated at all is displayed in Fig. 16a–c, respectively. Chemically treated fibres are superior to untreated fibres, which still have some impurities present, as the former have had all of their impurities removed and have excellent surface modification. Figure 16d demonstrates that the luffa composite that has been treated with NaOH fails brittlely due to fibre breakage, fibre tear, and a greater modulus of the LAF in the matrix. Because of the strong fusion that took place between the matrix and the fibre, the LAF were unable to peel away, which resulted in an increased capacity for the matrix to transfer stress. It can be seen rather plainly from Fig. 16 that the fibre breaking and pull-out occurred under a tensile loading condition with total abduction fibre bundles. This can be deduced from the fact that the fibre bundles were completely confiscated. From the micrographs, it was also seen that, to a lesser extent, interfacial voids were generated, which is something that might have happened during the fabrication process. The luffa epoxy-based composite laminates display significantly poorer interfacial adhesive behaviour and a more debonding nature than epoxy-based laminates, and this could be the explanation for their inferior mechanical performance. Figure 16f is a SEM image that depicts an untreated luffa composite. This composite exhibits brittle failure as a result of fibre breakage, fibre tear, and the increased modulus of the LAF in the matrix. Failure in the sample happened as a result of fibre pulling out and fibre tearing. It can be inferred that the existence of fewer voids, improved adhesion between the fibres and matrix material, and improved fibre breaking and pull-out behaviour in composite laminates are all factors that contribute to the acquisition of desirable mechanical properties.

4 Conclusions

The study describes the hand layup process for fabricating out of LAF that has been both chemically treated and left raw, utilising a reinforced epoxy composite and a hand layup technique. The following inferences can be made from the results of the tests:

- When compared to composite L3, which is made up of LAF that has been treated with NaOH, the results for composite L1, which is made up of untreated LAF composition, are quite low.
- There is a clear improvement in performance from composite L1 to the chemically treated LAF composites L2 and L3, which use HCl and NaOH-treated fiber compositions, respectively.
- The NaOH-treated luffa fiber-reinforced composite has a tensile strength of 16.47 MPa, the highest of any of the tested laminates. This value is greater than those obtained with the L1 and L2 stacking sequences. Stacking sequence L3 has a stronger flexural strength than both L2 and L3 laminates, at 11.205 MPa. Among all the other laminates, the laminate with the highest ILSS value is L3, which measures 4.105 MPa. In comparison to all of the other laminates, the impact resistance of laminate L3 is the highest, measuring 1.125 J.
- SEM images revealed that the failure of the composite was primarily attributable to the pull out of the fibres. Since it was untreated and has a more hydrophilic character, specimen L1 was shown to have a higher water absorption percentage than the other specimens.

When the attributes of the developed laminates are compared, it is discovered that the laminate that has been subjected to chemical treatment achieves the best results in terms of tensile strength, flexural strength, impact strength, and ILSS. Chemically treated LAF composites improve mechanical qualities, which in turn leads to an increase in the exploitation of natural fibres in a variety of applications.

Author contribution All the authors equally contributed to conceptualisation, methodology, writing, reviewing, and editing.

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Data availability Not applicable.

Declarations

Ethical approval The authors hereby state that the present work is in compliance with the ethical standards.

Competing interests The authors declare no competing interests.

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