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Research Article

Water Retention Behaviour and Fracture Toughness of Coir/Pineapple Leaf Fibre with Addition of Al_2O_3 Hybrid Composites under Ambient Conditions

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Due to their high mechanical and physical properties, natural fibre-based composite materials have been important in many fields of application for four to five years. The chief intention of the current study is to determine the mechanical and water retention features of composite materials under ambient conditions. Coir and pineapple leaf fibre were used as a reinforcement, aluminium oxide as additives, and polyester as a matrix. The hybrid resources were laminated by the manual hand lay-up method. The mechanical characteristics like tensile, flexural, and fracture toughness properties were tested as per the ASTM standard. Nanoparticle weight ratio and its size variation significantly impact mechanical qualities. The hybrid composite's water retention behaviour was tested for two types of water levels: ordinary tab water and nanofluid. The moisture uptake of the composites rose as the fibre volume increased, and after 640 hours, all of the composites had reached equilibrium. According to the results, the following combinations have the maximum mechanical strength: 15% wt.% coir, 15% wt.% pineapple, 10% wt.% nanofiller, and 60% wt.% polyester resin. The combinations mentioned above withstand the most load during the tests. Compared to 20% filler, 10% Al_2O_3 filler produces good interfacial adhesion in the current study. The fractured specimens were analyzed using scanning electron microscopic (SEM) pictures to recognize better the failure process of composites during mechanical testing.

1. Introduction

Due to their higher strength, precise toughness, and low carbon emissions, fibre-reinforced polymer composites play an important role in various industries. Natural fibre reinforcements like jute fibre, rice husk, bamboo, flex, cotton, pineapple, and others have appeared to be a viable alternative to conventional fibre-reinforced composites in numerous applications since the 1990s. Plant fibres provide several technological and environmental advantages over typical glass fibres, including recyclability, degradability, low toxicity, and reduced abrasion on raw material management equipment [1]. Scientists are inspired by the growing awareness of environmental problems, which contributes to the emergence of more ecological constituents [2]. Natural fibres were once utilized to make a wide range of items, including anything from roofing to clothing. On the other hand, natural fibres have emerged as a viable alternative to traditional glass and carbon fibres in the recent fabrication of composite materials. Natural fibre-reinforced polymer composites (NFCs) are nonconductive and have good corrosion and damage tolerance [3]. NFCs are significant since their mechanical qualities have significantly improved, making them potentially helpful in practical applications [4]. Fibre-matrix adhesion, fibre length, fibre content (loading), fibre treatment, and fibre dispersion in the matrix are all elements that affect composite quality. Researchers look at various composites' mechanical qualities, including tensile, flexural, and impact strength. Natural fibres replace cementitious materials, lumber, glass fibre, steel, and other materials in the automotive, construction, aerospace, medical, and electronic sectors. Organic fabric usage has dramatically augmented due to its high fatigue, resistance to corroding, higher hardness, low mass, and environmentally friendly nature [5].

Coir would be a tough, rigid, compostable cellulosic fibre derived from the fibrous rhizome of coconut fruits, which accounts for around 35% of the nuts. Coconut (Cocos nucifera) is widely grown in tropical nations, including Malaysia, Thailand, and India. Coir fibres may be chemically manipulated and are resilient, weatherproof, and somewhat impenetrable due to their higher lignin concentration [6]. The fibres have significant flexibility and can be stretched over their elastic region without breaking. Research has been conducted to improve the quality of coir fibre composites with other fibres such as jute, wood, agricultural residues, and fibreglass. Many researchers have provided an overview of the manufacturing method and mechanical characteristics of various fibre composites, such as coir, because there has been less emphasis on coir composite materials. For coir fibre-reinforced polymerizable polymers, Nam et al. [7] found an interface shear capacity of 3.01 MPa. The inconsistency of the fibre and the matrix and contaminants on the fibre surface were blamed for the low shear strength. Coir fibres show better interface toughness in polyvinylidene and maleic anhydride-grafted propylene than in polyethylene, according to Tran et al. [8, 9]. Natural fibre alterations or treatment processes employing different chemicals like siloxane, sodium chloride, amides, peroxidase, and inorganic compounds can increase the interface strength of composite materials. Surface morphology reduces the absorption of moisture and the fibres' hydrophilic character, allowing for improved substrate attachment. Hybridization of fibres and any/combination of treatment procedures can improve the material possessions of biomaterials [10, 11].

Pineapple leaf fibres are the most significant among organic fibres since tons of pineapple fibres are generated yearly. However, only a tiny percentage is employed in feed and power generation. The increased use of biomaterials in the industry has increased the potential for reducing the waste of recycled resources [12]. It encourages agriculture to expand into nonfood markets. It is a white, silky, clear, and shiny fibre with a medium height and good tension behaviour. It consumes a smoother texture than other organic materials, engrosses, and holds colour well. PALF, on the other hand, has a strong specific strength while being hydrophilic owing to its large cellulose content. Fibres are found in around 3% to 4% of leaves. The arterial network in the form of bundles in PALF fibre cells is acquired following the complete removal of the whole top layer following harvest [13]. PALF is made up of a variety of chemical constituents. It is a multilayer cellulosic fibre rich in carbohydrates, lignin, and other mining compounds such as fat, waxes, gelatin, sarcastic acidity, iodide, pectin, coloured pigments, and inorganic matter. Fibre is a thread-like aggregation of very thin and microscopic heterogeneous fibres [14]. With the aid of tannin, those particles are bound together securely. PALF is primarily cellulosic (75–88%) and has the same fibre configuration as silk (81.8%). Pineapple plant fabrics are the sample's most suitable organic fibre source and have an excellent chemical structure [15]. PALF has a good tensile strength when used to make fine yarn compared to cotton. PALF's cellulose molecule models have a solid construction similar to the fabric's crystallographic area. Amorphous areas are expected to interact with the rest of the molecule. Pineapple leaf fibre (PALF) is an important natural fibre that, like kenaf fibre, has excellent mechanical properties, stiffness, and bending and twisting stiffness. Because of its unique features, PALF can be an interesting substitute raw material for strengthening composite structures [16, 17].

Natural fibres were treated using alkali, terephthalate bonding chemicals, siloxane, and benzoylation to enhance their thermo-mechanical characteristics. Filler in the matrix phase will improve mechanical qualities to a greater extent. Nanoparticles such as silicon, graphene, nanotube tubes, zeolite, titanium oxide, coco shell powders, and bagasse ash are often utilized as fillers [18]. Adding nanocoir powders (10 to 150 nm) to jute nanohybrid composites improves mechanical and thermal characteristics. The ideal degree of filler addition in terms of increasing characteristics is 4% nanoparticle inclusion. Including 2 wt.% nanographite in the bagase/polypropylene biocomposites showed more stability than other nanopowder weight ratios. Because of its physical, thermodynamic, and tribological uses, graphite is in high demand in the market [19]. Aluminium, bronze, and organic fibre matrix hybrids are all employed as a reinforcement. Natural composites' tensile, thermodynamic, and geometric durability was improved by incorporating 0.1% nanoaluminium oxide. The limit oxygenation index and surplus weight percentage were at their highest levels. The glass transition of polyester-based polymers is improved by adding nanoparticles [20, 21].

Previous studies looked at how fibre direction, content, and processing affected composite samples' mechanical performance. Because these three components affect the mechanical properties in actual manufacturing circumstances, it is important to identify factors that have a more substantial influence on the material possessions of the materials and acquire proposals for the ideal possible combination. The current investigations resolved to examine the effectiveness of process variables on the bending strength and durability of the composite material. The influence of nano-Al_2O_3 concentration on the tension, flexural, and fracturing possessions of a coir/pineapple/polyester nanocomposite is investigated in this work. By adding nanoaluminium oxides into coir/pineapple/polyester composites, we expect considerable improvements in flexural characteristics and toughness. Understanding the varied fracture characteristics of nanomaterials under constant and transient stresses takes a lot of time and effort. The shattered surface of the hybrid composites was studied using a scanning electron microscope.

2. Investigational Resources and Methods

2.1. Resources. The woven coir and pineapple fibre companions were donated by the Rithu natural fibre factory in Madurai, Tamil Nadu, India. Both fibre mates were carefully washed with sparkling water and sundried for 48 h to eliminate the moisture. Nanoaluminium oxide and a polyester resin were utilized in the present investigation. Rithu Chemicals Industries, India, provided the matrix and nanoadditives. Figure 1 demonstrates the matrix, filler, and reinforcement materials. Table 1 demonstrates the common properties of reinforcement employed in the current research.

2.2. NaOH Processing. Natural surface treatment is among the most commonly used procedures on natural materials, especially lightweight materials. A chemical process improves surface properties by disturbing hydrogen just on the interfacial framework. Sodium hypochlorite's hydroxyl group is ionized into particles and transformed into an alkene. The amount of phenol, a waxy substance that covers the bulk of the fibre's outer surface, is drastically reduced. It also helps with cellulosic protein denaturation and exposes the smaller crystalline nature.

Mercerization is a type of alkali treatment. It is commonly used in the garment sector. The ASTM D1965 concept of recrystallization presents a vegetable fibre in combination with a reasonably saturated solution of a good platform, resulting in considerable expansion and alterations in fine structure, size, morphological, and mechanical behaviour. Natural fibre alkali treatment is a chemical deposition procedure that alters the chemical component behaviour in natural fibre. The impact of alkaline on lignocellulosic biomass is a stretching response wherein the cellulose's native crystal lattice breaks. Native cellulose has a hexagonal crystal solid structure of lignocellulosic biomass that may be transformed into several pleomorphic forms by chemicals or temperature processing. The introduction of sodium hypochlorite (NaOH) to natural fibre enhances hydroxyl ionization to an aldehyde group. NaOH can complete the lattice transition of lignocellulosic biomass I to lignocellulosic II. As a consequence of alkali treatment, the corresponding reactions take place.

$$\text{Vegetable Fiber} - \text{OH} + \text{NaOH} \longrightarrow \text{Fiber} - \text{O} - \text{Na} + \text{H}_2\text{O} \quad (1)$$

For such dichlorination, new coco fibre and pineapple fibres are collected and meticulously washed. According to the publication, a 5% aqueous layer of ultimate strength was created, and both threads were then immersed in it for four hours. After that, the transformed natural materials were diluted using caustic soda until the pH approached 7, measured by fluorescent dye. The calibrated formulations were washed thoroughly to remove any excess chemicals. The alkaline procedure would have been put on hold [10].

2.3. Fabrication of Nanocomposites. The nanoaluminium oxide employed in the current research was of the marketable score, with an excellence assessment of 92%. To make the modified nanocomposite, to vary the filler like Al_2O_3 weight concentration, the ultrasonication procedure was utilized to scatter the aluminium oxide and natural fibres in polyester. The multirolled mixing technique was utilized to scatter the aluminium oxide and coir/pineapple fibres, and the mixture was constantly mixed. The matrix and other additive combinations were purred into a $150\,\text{mm} \times 150\,\text{mm} \times 3\,\text{mm}$ steel mould to make laminates. Based on the constraint levels, Table 2 demonstrates the parameters used in composite manufacturing.

2.4. Characterizations. The manufactured specimens were sliced and concentrated as per the ASTM specification of D 638-03 imitations with a size of $150 \times 25 \times 3$ mm for tensile testing. The biobased nanocomposites were cut to ASTM D-790 dimensions for bending. To increase the electrical conductivity of the composites, the sample was cleaned, dried, and coated with electrical conductance materials. At a microscopic level, SEM was employed to analyze damaged composite materials.

2.5. Fractured Toughness. The ASTM D 5045–2007 standard measured fracture toughness in mode-I stress intensity factor utilizing a three-point single-edge notch bend arrangement. The total dimensions of the fracture toughness sample were 44 mm in length, 10 mm in breadth, and 5 mm thick. A fingernail clipper razor was used to create a natural fracture ahead of the machining notch. The overall length of the crack, which is the sum of the lengths of a machining groove and a spontaneous fracture, was kept between 4.7 and 5.7 mm. Longitudinal testing setup "Tinius Olsen" fitted of 200 N load was used to measure toughness. The deflection rate was kept consistent throughout toughness measurement at 10 mm/min. At least 5-10 samples were evaluated for every weight % and kind of aluminium oxide nanoparticulate.

2.6. Hygroscopic Behaviour. To make rectangular samples measuring $39\,\text{mm} \times 10\,\text{mm} \times 3\,\text{mm}$, composite materials were mixed according to ASTM D570. The water retention test is performed with tierce dissimilar liquid medium: blow water, deionized water-based aluminium oxide nanofluid, and distilled water-based aluminium oxide nanoliquid. These 2 samples were gathered in each fluid for 640 hours. The nanofluid is made from deionized water and is prepared in two phases. 1% weightiness of filler is submerged in aquatic and thoroughly assorted for 24 hours using a mechanical stirrer. In addition, the combined mixture is placed in an ultrasonicator for 300 minutes to guarantee homogeneous fraternization of fillers in aquatic. The weight variation of the samples is measured before they are immersed in fluid. Every fifteen days, the weight of each specimen is measured to examine weight variations induced by hygroscopic. The time it takes to remove specimens from liquid and weigh them is quite short. Before a weight measurement, observed watery on

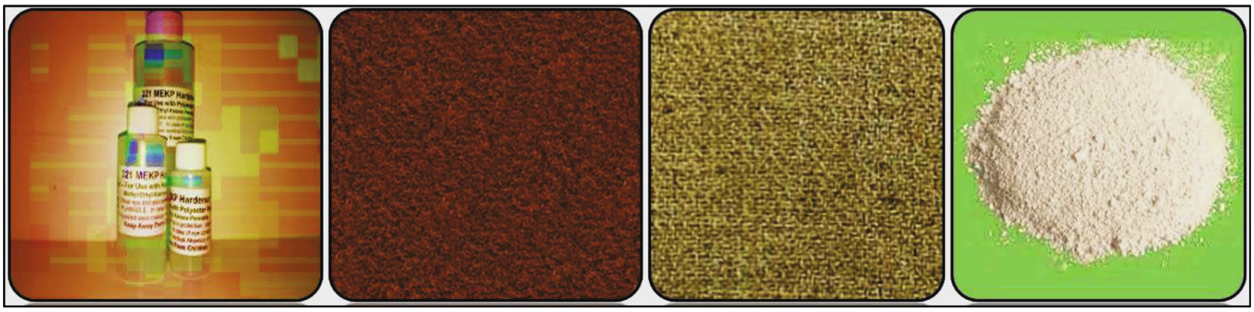


Figure 1: Photographic images of matrix, coir fibre, pineapple fibres, and nano-Al_2O_3.

Table 1: Mechanical possessions of coir and pineapple leaf fibre.

Sl. no	Properties	Coir	Pineapple
1	Cellulose (%)	33-44	71-84
2	Hemicellulose (%)	0.16-0.28	18.92
3	Lignin (%)	41-46	5.5-13.2
4	Density (g/cm^3)	1.3	0.99
5	Tensile strength (MPa)	132-230	414-1631
6	Young's modulus (GPa)	4.2-6.1	35.3-38.6
7	Elongation (%)	16-41	1.7

Table 2: Parameters and their constraints of nanocomposites.

Sample no	Coir fibre (wt.%)	Pineapple fibre (wt.%)	Al_2O_3 (wt.%)	Polyester matrix (wt.%)
1	40	0	0	60
2	0	40	0	60
3	20	20	0	60
4	20	0	20	60
5	0	20	20	60
6	15	15	10	60

complexes is smeared off with new yarn. The proportions of water uptake were estimated using the equation below [22].

$$\text{Moisture absorption} = \frac{W_2 - W_1}{W_1} \times 100 \quad (2)$$

W_2 is the model's weight after immersion and W_1 is the model's weight before immersion. Five tests were conducted on each sample type, with the average findings presented.

3. Result and Discussion

3.1. Tensile Strength. Figures 2 demonstrates several nanocomposites' tension characteristics, tensile strength, and modulus. The tensile strength and tensile modulus of the pineapple and polyester composite and the coir and polyester composite were almost equal, as indicated in Figure 2. It might be because the cellulose content of coir and pineapple fibres is similar [22]. Pineapple fibre is more hydrophilic than coir fibre due to its higher hemicellulose content, but polypropylene is naturally hydrophobic. As a result, the hydrophilic pineapple/coir

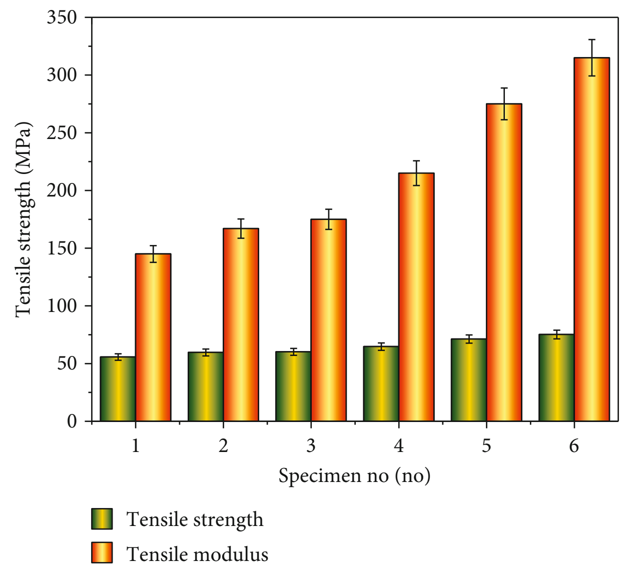


Figure 2: Tensile properties of coir/pineapple/Al_2O_3/polyester-based nanocomposites.

and hydrophobic polyester failed to attach correctly, decreasing tension and its modulus. In terms of tensile strength and modulus, hybrid composites outperformed coir/polyester and pineapple/polyester composites when pineapple fibre was combined with wood fibre in polyester, and nano-Al_2O_3 was added. Because of fibre/matrix bonding, composite materials containing pineapple or coir are expected to have stronger tensile qualities than other compositions, resulting in an even and efficient stress distribution across fibres. The hybrid composites exhibited maximum tensile strength and modulus when nano-Al_2O_3 was introduced. By improving interfacial contact and adherence among reinforcement and the polymer resin, the nano-Al_2O_3 improved the mechanical properties of the materials. Similar findings were found in a previous investigation [23].

3.2. Flexural Strength. Flexural loading, which includes stretching a square sample to fracture or employing a multiple-point flexural assessment approach, appears to be the most prevalent application rate of the deformation technique. Flexural strength reflects the maximum strain inside the material at its yielding point. Figure 3 depicts the bending strength of particle biocomposites. The pineapple/polyester

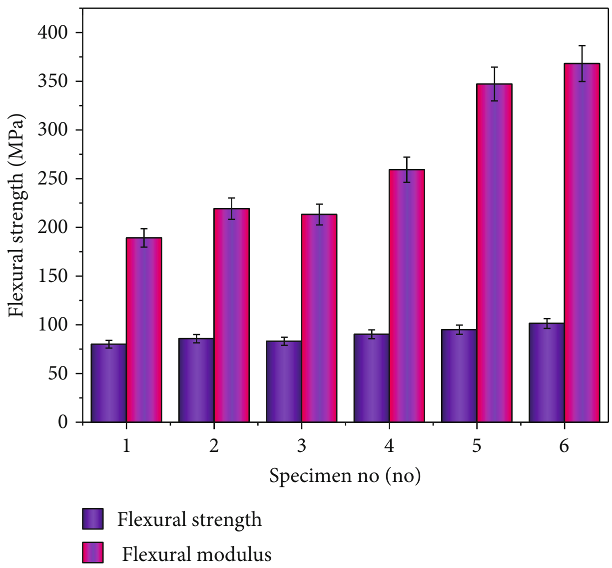


Figure 3: Flexural properties of coir/pineapple/Al_2O_3/polyester-based nanocomposites.

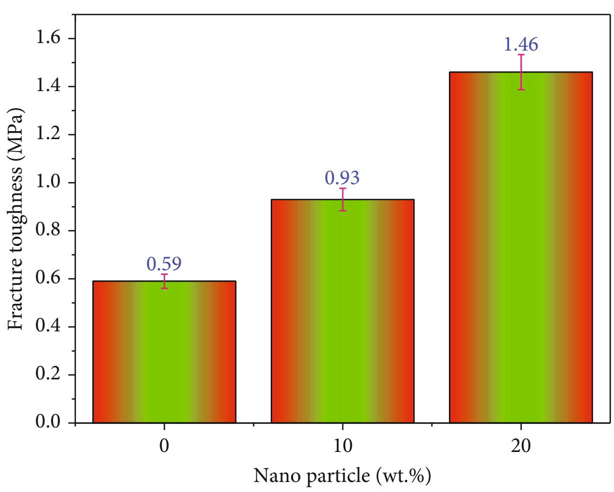


Figure 4: Fracture toughness of coir/pineapple/Al_2O_3/polyester-based nanocomposites.

composites had the highest flexural strength compared to coir/polyester composites. When compared to coir, this finding indicates that pineapple fibre adheres well. The addition of nano-Al_2O_3 to polyester composites enhanced their three-point bending strength. Including nanofiller improved the composite material's strength qualities, with a mixture of coir/pineapple/nanofiller/polyester having the highest bending strength. The increased surface area displayed by the tiny filler particles enhances the dispersion between the filler and the matrix. It improves the interfacial connection, as seen in the bending strength of the composite [24, 25]. The above trends are visible in the SEM picture. Polyester has excellent adhesion to many substrates and may be strengthened by adding fibres and particles. Compared to other combinations, the results demonstrate that hybrid nano-Al_2O_3 and coir/

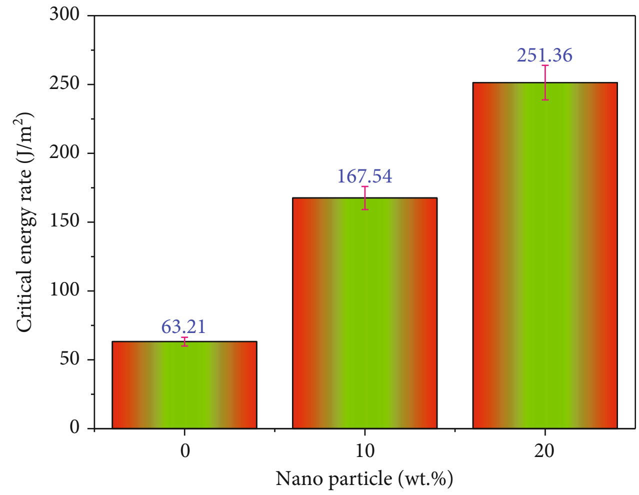
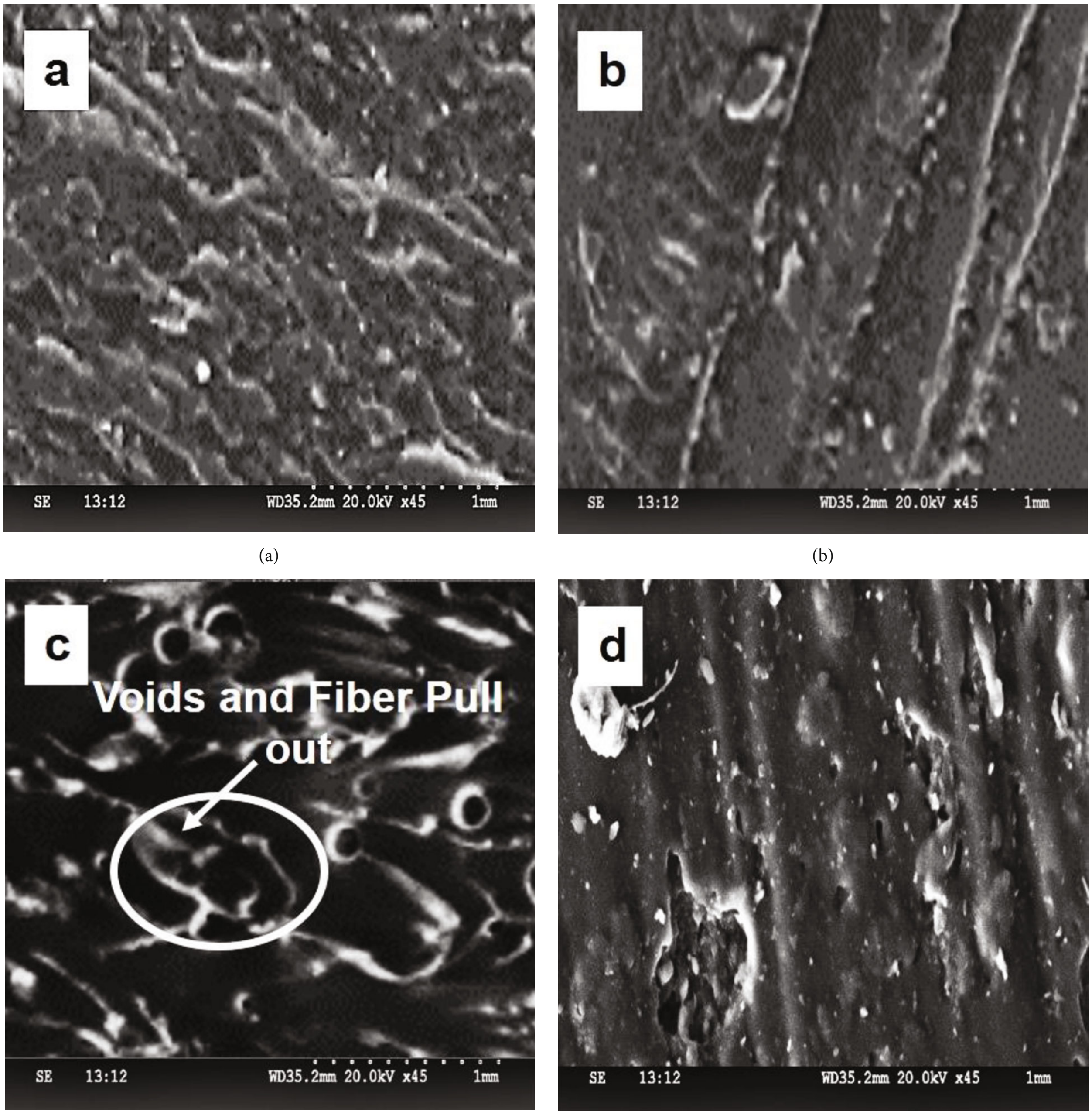


Figure 5: Critical energy of coir/pineapple/Al_2O_3/polyester-based nanocomposites.

pineapple/polyester composites produce the best results in both the tensile and bending instances.

3.3. Fracture Toughness. Figure 4 shows the fracture toughness of coir/pineapple/polyester composites with several Al_2O_3 nanoparticles at different weight %. All of the composites' fracture toughness is improved by adding Al_2O_3 nanoflakes. The fracture toughness rises linearly as the weight % of Al_2O_3 nanoparticles increases. The fracture toughness increases more when 20 weight % Al_2O_3 nanoparticles are used than when 10 weight % Al_2O_3 nanoparticles are used. Compared to empty polyester composites, composite materials contain 10 and 20 wt.% Al_2O_3 nanograins increased toughness by 29 and 44%, respectively. The drop in toughness at greater concentrations of nanospheres (over 20%) could be due to a nanoparticle aggregation and poorer susceptibility to fracture propagation. The resin seems unable to permeate between filler grains owing to aggregation, resulting in weak adhesive binding [26, 27]. Whenever the spreading fracture meets with the agglomerates, the weakly connected particle opens up, generating holes and separating the particles from the matrices completely. Fracture development via agglomerates requires little energy and provides no resistance to crack growth. When there is little or no friction to the spreading fracture, the fracture thrust force and energy at the crack growth increase. This rising fracture moves quickly through the substance, requiring a shorter time elapsed for fracturing, lowering the composite's toughness [28, 29]. As a result of the stress concentration and simpler crack initiation caused by aggregation, the composite's toughness is reduced. The energy required to advance the split at the split front is equal to the total of the energy expended in forming new interfaces at the crack tip and the energy released by the other energetic viscous dissipation processes like permanent deformation and fracture tip dulling [30, 31].

Figure 5 shows the variance in the critical energy extraction yield of nanocomposite for various weight % of all Al_2O_3 nanoparticles [32]. For any weight % of Al_2O_3



(a) (b) (c) (d)

Figure 6: Microstructural images of coir/pineapple/Al_2O_3/polyester-based nanocomposites.

nanoparticles, the critical energy release rate of the composite will behave similarly to fracture toughness [33] compared to unfilled epoxy; the 10 and 20 wt.% Al_2O_3-filled coir/pineapple composites produce 34 and 56% binding energy, respectively [34]. The material's increased failure strain indicates increased flexibility and capacity to withstand higher deformations before fracture [35]. As a result, the plastic zone ahead of the fracture tip is greater at 20 wt.% Al_2O_3 nanoparticle-filled composites than in 10 wt.% Al_2O_3 nanoparticle-filled composites [36].

After fracture toughness testing on empty polyester and polyester Al_2O_3 composites, scanning electron fractography was obtained from the fracture surface of the specimen shown in Figure 6. Figures 6(a)and 6(b) show that the fracture surface of unfilled polyester was smooth and featureless. Still, the fracture surface of composites filled with Al_2O_3 nanoparticles was relatively rough [37]. The increasing smoothness of the cracked surface implies that the nanoparticles provided more resistance to the spreading crack and that crack defect increased crack length [38]. Fracture divergence and crack crossing waste more energy at the crack front, slowing crack extension and improving the composite's fracture toughness [39]. The fibre pulled out of the coir/pineapple/polyester and coir/pineapple/polyester composites are shown in Figures 6(c) and 6(d). When integrating the nanofiller, this picture shows strong interfacial bonding [40].

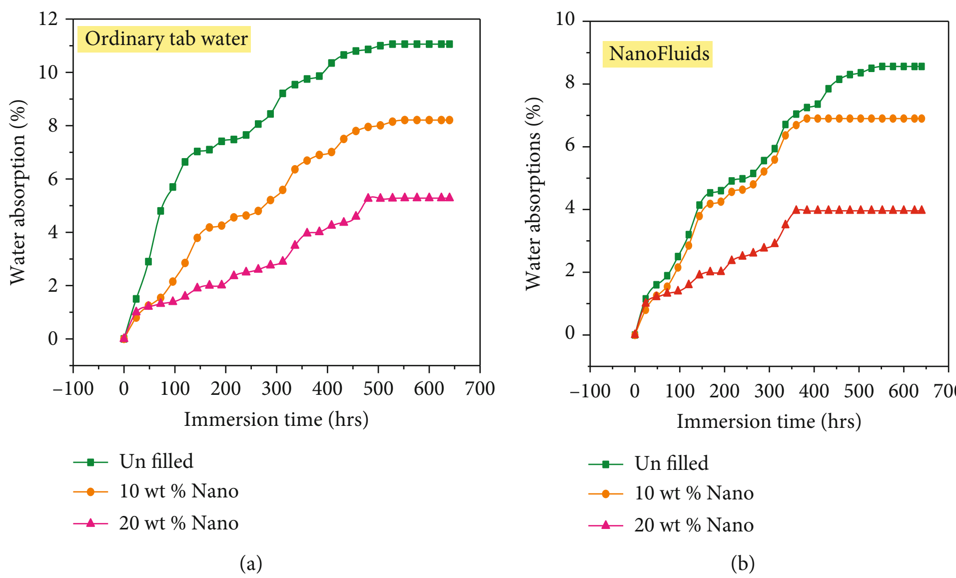


Figure 7: Hygroscopic behaviour of nanocomposites: (a) ordinary tab water; (b) nanofluids.

3.4. Hygroscopic Characteristics. Natural fibre-reinforced composites with lignocellulosic fibres have low moisture resilience and, as a result, have detrimental effects on structural stability and mechanical characteristics when subjected to moisture in the atmosphere [41]. The moisture-absorbing characteristics of natural fibre composites must be studied to comprehend the composites' endurance dependent on the field of application [42]. Water particles infiltrate organic fibre composites by three different mechanisms: water diffusion inside the microgaps between polymers, capillary transportation through microgaps, and flaws at the interface between reinforcement as well as the matrices [43]. Hydroxyl groups primarily capture water at the interface between the fibre and the matrix, as well as by the fibre itself. However, introducing nanoparticles into natural fibres alleviated the foregoing issues. The current study studied the water retention properties of nanocomposites using two types of solutions (ordinary tap water and nanofluid). The composite system has greater retention properties than regular water in a nanofluid environment [44]. When nanocomposites are submerged in nanofluid, the interface attraction between reinforcements, fillers, and matrix increases dramatically. It might be due to the improved hydrophilicity of the hybrid nanocomposite following fibre mixing and nano-Al_2O_3 inclusion. The pineapple/polyester composite exhibited the highest water retention ratings compared to the other composites. It is due to the large number of OH groups discovered on the pineapple and coir fibre contacts. The number of hydroxyl groups and microvoids in the pineapple composites increased, resulting in a considerable rise in moisture fascination.

On the other hand, the hybrid of coir and pineapple absorbed the least amount of water. The inclusion of hydrophobic nano-Al_2O_3 into the hybrid composite, on the other hand, resulted in more hygroscopic behaviour than the hybrid nanostructure alone. Figure 7 clearly demonstrates the above findings.

4. Conclusion

The mechanical and water retention characterization of several combinations of coir, pineapple, nanoaluminium oxide, and polyester-based nanocomposites were discovered, and the following findings were drawn.

(i) Compared to coir/polyester, pineapple/polyester, and coir/pineapple/polyester composites, coir/pineapple/nano-Al_2O_3/polyester hybrid composites had the highest tensile and flexural strength. It may clearly show how well the polymer matrix and fibres interact

(ii) The nanofiller significantly improves the mechanical strength of hybrid composites by improving adhesive bonding strength. In SEM analysis, this is readily evident

(iii) The coir/pineapple/nano-Al_2O_3/polyester combination has the best water retention compared to other combinations. The nanocomposites exhibit better properties as nanofluids compared to ordinary tap water

(iv) According to the results, the following combinations have the maximum mechanical strength: 15% wt.% coir, 15% wt.% pineapple, 10% wt.% nanofiller, and 60% wt.% polyester resin. These combinations withstand the most load during the tests. Compared to 20% filler, 10% Al_2O_3 filler produces good interfacial adhesion in the current study

(v) The 20 wt.% inclusion of Al_2O_3 reveals the highest values of fracture toughness. This combination needs more energy to break the bonding between the fibres and matrix

(vi) The research comprised an experimental investigation effort to determine the properties of coir/pineapple/nano-Al_2O_3. Furthermore, it is accepted that the production of nanocomposites with a large filler loading is complex and impacts the materials' quality and properties. Selecting a dependable production technique to make lightweight structures with a high amount of filler integration remains difficult for manufacturers

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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