Research Article

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Investigation on mechanical properties of the green synthesis bamboo fiber/eggshell/coconut shell powder-based hybrid biocomposites under NaOH conditions

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Abstract: This research delves into the effects of different alkalization treatment approaches on the mechanical characteristics of epoxy matrix composites that are reinforced with natural bamboo fibers and enriched with egg and coconut shell powders as fillers. Various weight ratios of fibers and fillers were investigated, specifically at 5%, 10%, 15%, 20%, 25%, and 30%. The study assessed mechanical properties such as tensile strength, flexural behavior, microhardness, and impact resilience. Findings indicate that composites with alkali-treated fibers demonstrate superior mechanical performance (49.28 MPa of tensile, 57.33 MPa of flexural 89 HV of hardness, and 1.3 kJ·m^{-2} of impact) compared to untreated counterparts. Particularly noteworthy is the significant improvement in fracture toughness observed with the inclusion of 20% hybrid laminates, surpassing the performance of existing biomaterial-based composites. This heightened toughness is attributed to the optimized composition of fibers and enhanced water absorption capabilities. Conversely, the incorporation of 25% and 30% hybrid composites led to a decrease in mechanical strength (38.65 MPa of tensile, 46.7 MPa of flexural, 72 HV of hardness, and 1.19 kJ·m^{-2} of impact) due to the formation of additional interfacial contacts, pores, and voids within the polymeric matrix.

Keywords: mechanical properties, bamboo fiber, eggshell, sustainability, coconut shell powder, hybrid composites, green synthesis, alkaline treatment

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1 Introduction

Due to environmental concerns, the exhaustion of petroleum fuels, and global warming, there is now a significant focus on replacing synthetic materials in composite materials with naturally derived strands like cotton, coco fiber, flaxseed, wheat, rattan, and agave. Plant-origin fibers are used because of their light weight, excellent thermal insulating and structural qualities, low cost, sturdiness, friendliness, and renewability [1,2]. Plant natural fibers offer high cost, environmental, and economic advantages as substitutes for synthetic materials such as polyamides and glass fibers. They are thus gaining popularity in the automotive, aerospace, and critical structural industries. Although natural fabrics are not as strong as synthetic materials, they are less expensive, environmentally benign, and recyclable [3,4]. Because of the persistent need for natural fibers, the already worldwide need for timber, and significant ecological issues, among many other factors, scientists are striving to produce an environmentally friendly substance appropriate for various uses. Bamboo fiber is without a doubt the most significant natural fiber species because of its high rate of growth as well as its versatility [5,6]. Bamboo fiber is a genus of permanent deciduous grasses of the family Fabaceae, subsection Bambusoideae, and family groups. And over 1,500 reed varieties belonging to 80 families may be discovered in habitats ranging from icy highlands to hot tropical areas. China is renowned as the "Empire of Bamboo fiber" because it has over 450 types of bamboo fiber flourishing under its control [7]. China boasts the world's highest bamboo fiber companies in variety, quantity, and productivity. Bamboo fiber plantings in China totaled nearly 13 ha in 2019, with just an average expansion of 2.5 million acres. Bamboo fiber has traditionally been used in building and the paper and pulp manufacturing industries [8,9].

Among the various options, agricultural leftovers (such as coconut husks, corn husks, textile stalks, millet stalks, and other debris) are gaining popularity. Agricultural residues are effective and adaptable replacements for wood and certain textile materials. Their advantageous properties are preferred over recycled construction [10,11]. Among the various benefits of agro-residues are their copious and ample accessibility, recyclability, eco-friendliness, simplicity of production, and lower carbon emissions. Bamboo fiber, coconut shell, and eggshell (ES) were employed as reinforcements in this study due to their plentiful accessibility locally and potential use depending on their features [12]. Despite numerous beneficial efforts in the literature on crop wastes and fibers in biodegradable polymers, only a minuscule portion of research on agricultural residues as well as homogenization of agribusiness has been conducted, which needs to be inspired to enhance the commercialization of such innovative materials and will create quality financial returns to growers [13]. ES accounts for roughly 13% of overall egg mass and is thus accessible as waste material from food manufacturing and incubation businesses in massive numbers. Only food manufacturing companies produce approximately 1 million metric tonnes of ES powder debris annually, with an estimated utilization value of 1 million euros. ES comprises approximately 95% calcium phosphate (calcite), containing 8% inorganic 73 elements such as oligosaccharides, elastin, and other peptides [14–16]. Because of its great mechanical and mechanical resilience and relatively simple recycling route, ES is seen as a viable and sustainable alternative to conventional goods. The ES wastes might be an excellent choice for an eco-friendly filler metal in strengthened composite materials, enhancing their mechanical characteristics, including heat resistance. In a recent project 73, the production of thermochromic retardant coverings with chicken ES wastes as 74 additives were investigated [17].

The biological and mechanical characteristics of coconut shell esters were examined by Velmurugan et al. Coconut shell particle hybrids have a 50% maximum rupture modulus and fracture toughness. The toughness of the samples decreased as the shell content increased. Moisture content rises with particle diameter, and a similar pattern was noticed in the water uptake experiment [18]. Taylor et al. [19] studied the dynamic and anaerobic decomposition behaviors of wheat fiber using different natural padding hybrids and determined that the physical qualities of padding hybrids outperformed biocomposites because of their higher screen resolution. The green building is being created via a propane injection molding process using agricultural residues and mixed polyethylene. This results in less monomer, greater husk contents, and reduced waste by Agunsoye et al. [20]. Kumar et al. [21] studied the creation of coir pith-nylon-cloth polymer composite laminates. The coir epoxy composites were made by compressing an epoxy/coir pith/two- or three-layer nylon textile combination. In this work, NaOH-treated coco fiber pulp and multiple nylon textile resins outperformed other hybrids in physical toughness and hardness. This study showed that distinct grinding methods significantly affected the proportion of damaged starch and particle size distribution [22].

A potential direction for investigation is the mechanical characteristics of green-synthesized bamboo fiber/ES/coconut shell powder-based hybrid biocomposites under NaOH conditions; nevertheless, a significant research gap must be filled. Although the proposed study aims to examine the mechanical properties of the hybrid biocomposites, little previous research has particularly addressed how NaOH treatment affects these materials [23]. Optimizing the parameters of the composite requires understanding how NaOH conditions affect mechanical performance, including tensile strength, flexural behavior, microhardness, and impact resilience. Furthermore, few thorough investigations have examined the synergistic effects of ES, coconut shell powder, and bamboo fibers in green synthesis, especially under alkaline settings. The lack of research highlights the necessity of conducting a concentrated study on the mechanical behavior of these hybrid biocomposites after being treated with NaOH, which will provide important information for creating high-performing and sustainable materials. This research discovered that different crushing processes substantially influenced the amount of broken starch and the particle size distribution. The primary goal of this study is to examine the mechanical parameters of alkali-treated bamboo fiber and coconut/ES-based hybrid-reinforced materials, like tension, bending, hardness, and impact properties. The scanning electron microscope was used to investigate the morphological characteristics of a mixture.

2 Materials and methods

2.1 Materials

This research used bamboo fiber with 20 mm length, coconut shell powder with 20 nm, and ES powder with 50 nm size as reinforcing materials. The reinforcement material and fillers were procured from Deekshi Fiber and Chemicals Industry, Madurai, Tamil Nadu, India. The matrix fabric is constructed from a readily accessible epoxy resin (Standard Araldite AW 105 type of epoxy and HV 953 in hardener). Figure 1 shows the real-time images of bamboo fiber and filler materials.

2.2 Preparation of materials

First, gather or purchase bamboo stalks to produce 20 mm bamboo fibers from a larger length. The bamboo stems should be cleaned and cleared of leaves or other debris. Next, chop the bamboo stalks into at least 20 mm long pieces, depending on how long you want them to be. Next, carefully break the bamboo parts into narrower strips using a cutting tool, like a bamboo splitter or a sharp knife. Proceed with the splitting procedure until you obtain individual bamboo fibers of around 20 mm in length. Preserving the fibers' equal thickness throughout this process is imperative for consistent outcomes. The 20 mm bamboo fibers can then be processed further or used for various purposes, including handicraft and the reinforcement of composite materials.

This study used two agricultural residue particles: egg and coconut shell powders. Bamboo fiber, coconut, and ESs are made of lignocellulosic materials in tropical locations like India. Bamboo fiber, ESs, and coconut husks form fibrous waste products, activated carbon trash frequently deposited on unoccupied land and exploited because of its energy value. Finally, agriculture granules were cleaned with acetone and dehydrated in direct sunlight for about 2 days to absorb humidity from the substance. Afterward, particulate and unwanted particles were eliminated by manual ordering and kept at 180°C for 1.5 h in the vacuum oven. A mean particle size of 30 microns was validated using particle sieve spectrum analysers [24].

2.3 Alkaline treatment

At 28°C, bamboo fiber fibers and agricultural wastes were steeped in a 5% NaOH solution. For up to 24 h, the fibers were submerged in an alkali solution. The modified reinforcements were then thoroughly rinsed out with distilled water. Any leftover residues of NaOH on the fiber surface were subsequently neutralized with 2% hydrochloric acid for 10 min. The fibers were rinsed again with deionized water to maintain a pH of 7. The fibers were then cured for 5 h at 65°C [25].

2.4 Composite fabrication

By reinforcing bamboo fiber, ES, and coconut husk, hybrid particle compounds of varying configurations are created

Figure 1: Photographic images of (a) raw bamboo fiber; (b) NaOH treated fiber; (c) eggshell powder; and (d) coconut shell powder.

in an epoxy substrate. Previous research [26,27] on bio-filled particle composites has shown that composites with a 20% particle concentration exhibit improved mechanical behavior. As a result, the grid to reinforce proportion throughout this study is 80:20 by composition. To guarantee system homogeneity, particles of varying weights are mixed with epoxy resin using a mechanical blender. The slurry mixture is placed into a steel mold on a compression-molding machine and compacted at 70°C and 2.5 MPa. After manufacturing, hybrid composites are treated for 90 h at room temperature and trimmed to the requisite shapes in conformity with the ASTM specifications for physical and structural assessment. Table 1 displays the mixtures of bamboo fiber and filler grains.

2.5 Materials characterizations

Tensile testing is often done on fat specimens. The tests followed ASTM D 638 specifications using a computerized (TFUC-100 servo model with 10 kN load capacity, Germany) universal testing machine (UTM) with a 250 kN load and a stay period of 20 s. All samples have been subjected to short beam shear examinations at ambient temperature to explore flexural strength following ASTM D 790 with the same UTM. The impact toughness of the specimens was tested using the IT-30 (AIT-300 model, with 50 Hz) manufacturing impact test machine [28]. The sample was cut to the ASTM D 256-10 specification. Vickers is among numerous measurements of a substance's microhardness. The hardenability of fiber composites is measured using Vickers' toughness testing equipment (VM-50 model, Germany) following ASTM E 384 criteria, with a 70-g weight and a retention duration of 10 s. To examine Vickers fracture toughness, these samples were sliced by 10 mm in length and 5 mm in width. For each mechanical test, five samples were tested, and the mean values were reported [29].

3 Results and discussion

3.1 Mechanical properties

3.1.1 Tensile behavior

Tensile properties of treated bamboo fiber, ES, and coconut shell with a particle content of 20% were improved by 31.20%. That enhancement level achieves the greatest percentage gain compared to the total weight percentage. The 5% particulate load caused the boost. The proportion of improvements in mechanical properties error bars for bio-composites is depicted in Figure 2, with variations ranging from 15% to 20% (38.1–52.2%). Its tensile modulus in a composite tends to diminish as the fraction of particles increases [30,31]. The proportion of tensile properties drops at a 25 wt% doping concentration. Figure 2 reveals the tensile behavior of the hybrid composites. Figure 3, stress vs strain diagram, also supports the findings.

The aggregation of particulates into a thermoplastic result in insufficient colloidal particles because of an increased inter-particle hydroxyl group that binds the particles collectively and does not allow for colloidal particles inside the matrices. Inadequate reinforcing and matrix binding will prevent significant tensile enhancement [32,33]. As a result, as the weight percent of doping concentration in the resin increases proportionally due to colloidal particles and agglomeration, the resin cannot thoroughly moisten those granules. As a result, no bonding occurs between the reinforcing and the matrix particles. That causes the tensile qualities of the composites to disintegrate. Therefore, in bamboo fiber, ES, and coco shell-reinforced materials, greater wt% particulate loading was restricted [34].

3.1.2 Flexural behavior

Figure 4 depicts the influence of agricultural particle content on elastic modulus with just an error margin,

Table 1: Compositions of hybrid composites

Sl. no.	Symbols	Compositions
1	A	5 wt% of bamboo fiber + 5 wt% coir shell + 5 wt% of ES
2	B	10 wt% of bamboo fiber + 10 wt% coir shell + 10 wt% of ES
3	C	15 wt% of bamboo fiber + 15 wt% coir shell + 15 wt% of ES
4	D	20 wt% of bamboo fiber + 20 wt% coir shell + 20 wt% of ES
5	E	25 wt% of bamboo fiber + 25 wt% coir shell + 25 wt% of ES
6	F	30 wt% of bamboo fiber + 30 wt% coir shell + 30 wt% of ES

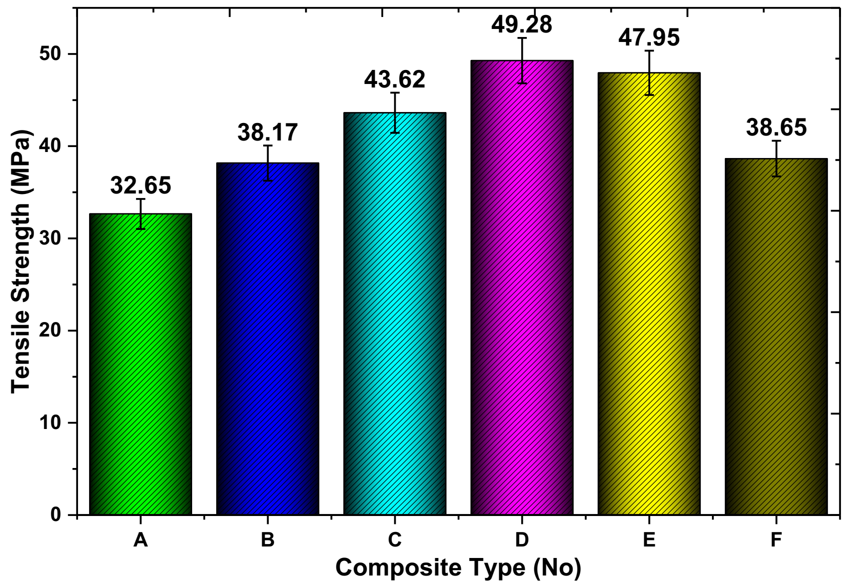

Figure 2: Tensile behavior of bamboo fiber and filler-based hybrid composites.

indicating that increasing overall particle content significantly increases the bending properties of the material. Overall, the greatest flexural strength of a material generated with pre-treated reinforcing was 57.33 MPa at a 20 wt% particle concentration. The bending quality of the composite improved more when it was treated with 5% NaOH. Tannins and lignocellulose on surfaces would be effectively removed with reinforcements and additives [35]. Those polymers with a doping concentration of 20% by weight were 39%. It perfectly demonstrates that increasing the particle content significantly increases the bending quality of the composites. It is related to NaOH processing, which removes contaminants from agro-residue surfaces [36]. Figure 5 explains and supports the stress–strain diagram of bending strength.

3.1.3 Microhardness

All specimens are microhardness tested using a Shimadzu fracture toughness analyzer. Every test has been performed multiple times in three distinct places using

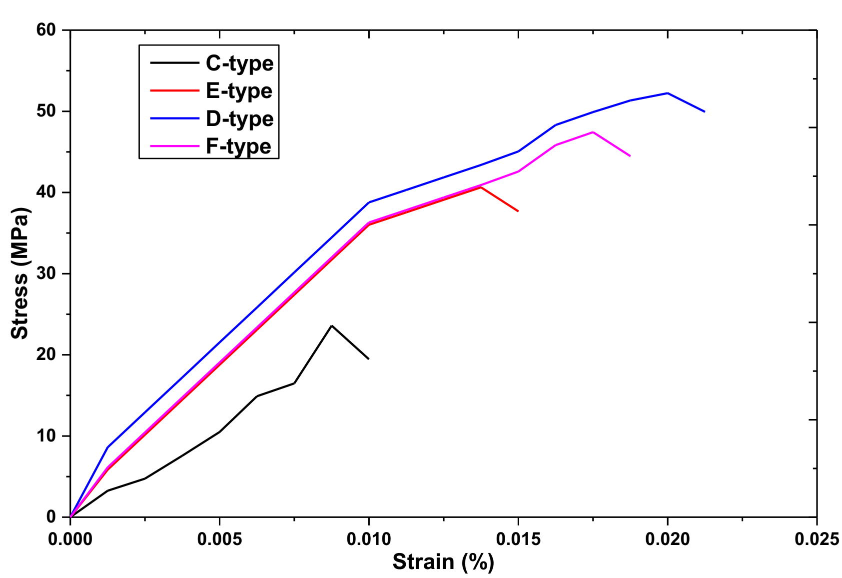

Figure 3: Tensile stress–strain diagram of bamboo fiber and filler-based hybrid composites.

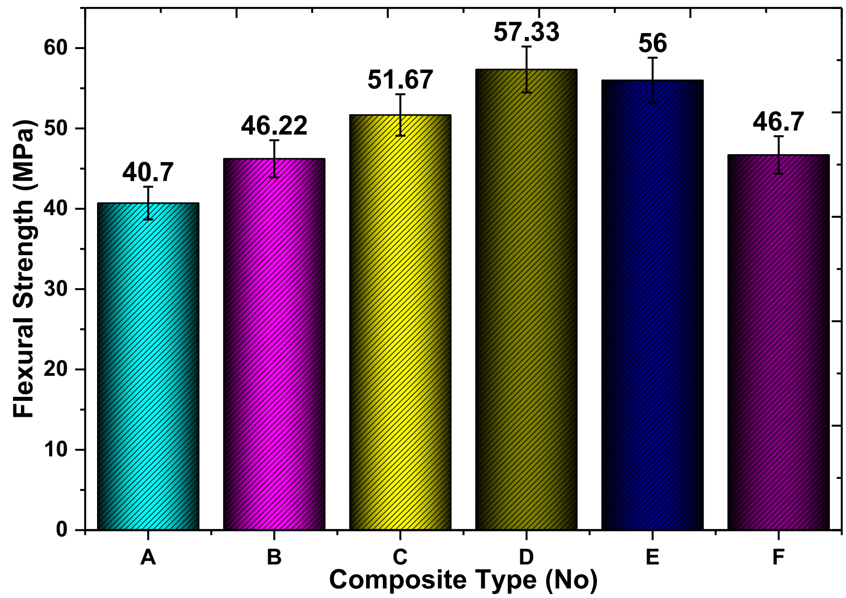

Figure 4: Bending behavior of bamboo fiber and filler-based hybrid composites.

confidence intervals, and the mean data are displayed in Figure 6. The addition of reinforcing particles enhances the microhardness of a matrix. The weight ratio of bamboo fiber and ESs, as well as the coco-shell combination, increased toughness. The robust reinforcing particles support the load, limiting composite displacement and toughness [37,38]. Earlier research has shown that increasing the weight percent of agricultural waste results in similar incidents as filler particles. The fracture toughness of 5% bamboo fiber, ES, and coconut husk is 38 HV when treated with epoxy. This increased toughness at 89 HV was attained due to a 20% improvement in epoxy compared to prior experiments. Therefore, enhanced toughness combined with a shortened response time helps further refine the finely ground morphology [39].

3.1.4 Impact strength

As indicated in Figure 7, boosting overall NaOH processing throughout the mixture enhances the impact strength. The

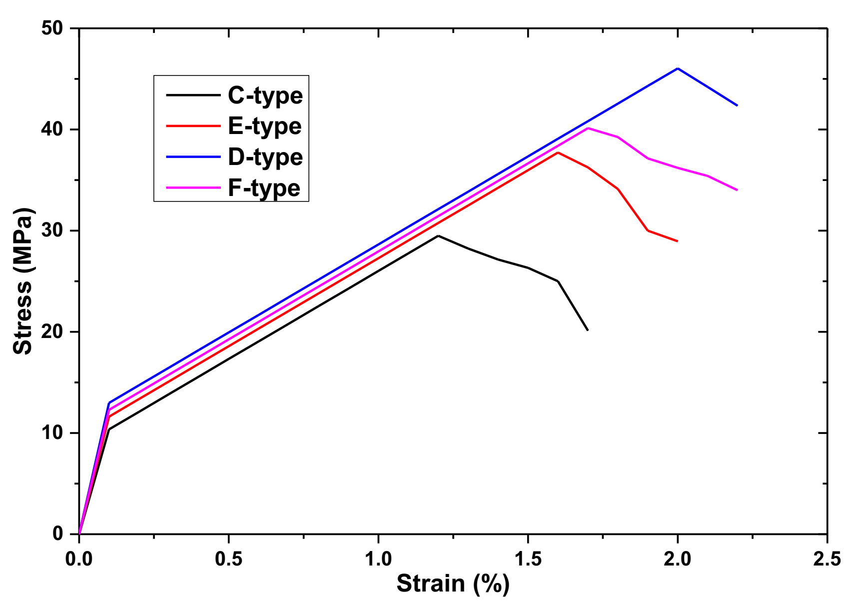

Figure 5: Flexural stress–strain diagram of bamboo fiber and filler-based hybrid composites.

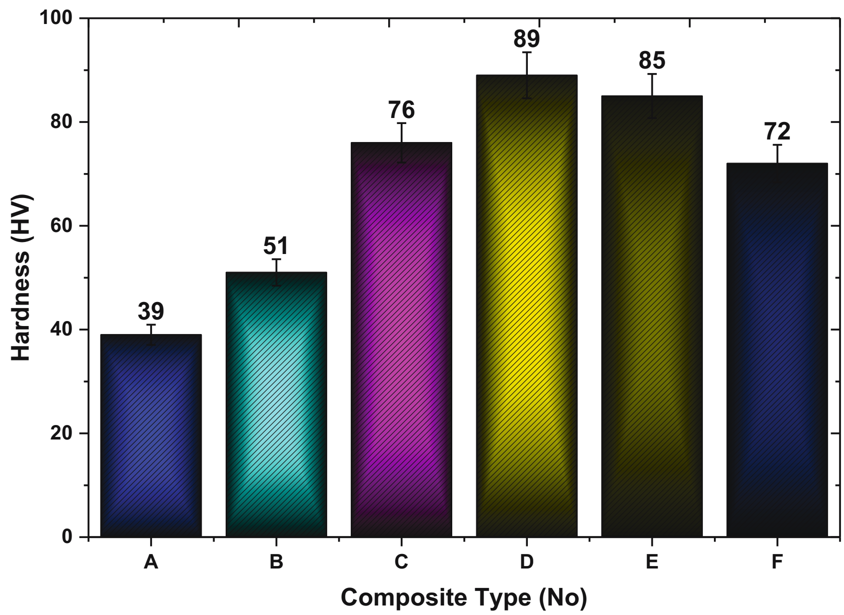

Figure 6: Hardness behavior of bamboo fiber and filler-based hybrid composites.

greatest impact strength values were found at 20% of a doping concentration. Further than this weight percentage, the impact strength decreases, as shown by the error margins. The improved impact toughness of a composite is related to eliminating contaminants from the agro-residues, which improves the overall mechanical characteristics of granules. As a consequence, its structural coupling among the reinforcing as well as the matrix connections is enhanced [40]. For bamboo fiber fiber-reinforced materials, the optimum combinations of biomechanical qualities like bending and tensile strength are within the range of 10–20 wt% of doping concentration, while the impact energy is at its greatest at 20 wt%.

Bamboo fiber, ESs, and coconut husks were investigated and evolved with epoxy resins to improve their mechanical qualities. This essential requirement for experimentation is the search for an acceptable rooting medium in a closed development environment. Agro-residues were gaining appeal as good organic biofuel in India and Europe. Agro-residues like bamboo fiber, ESs, and coconut shell contributed to a composite's superior properties and increased performance between the fiber and the matrix. That sort of granule increases the substance's hardness and structural qualities.

3.2 Microstructural analysis

3.2.1 Scanning electron microscopy (SEM) analysis

Figure 8(a) depicts the chemically processed fiber matrix interaction. Most cross-sections of the fibers were round. In a new analysis, NaOH treatment largely eliminated its pectin during the synthetic modification process, and the shape of hydroxide-processed bamboo fiber differed from that of organic bamboo fiber, as seen in Figure 8(b). The fibers are longitudinally oriented toward the fractures in Figure 8(a). The tension-pulled out fibers of a matrix are visible in the fiber and matrix contact high magnification microscope. Their presence of fiber clusters inside the matrices resulted in areas saturated by filaments and regions with excess elastomer, lowering mechanical behavior [41].

Figure 8(c) depicts the bamboo fiber with 20% padding matrices' interaction. It demonstrates homogeneous filler distribution, which aids in increasing the adhesion properties of bamboo fiber hybrids. Figure 8(d) depicts the assortments of filler particles in the matrices, as opposed to Figure 8(c). That sort of material does not adequately transmit stress distribution. It has the potential to diminish the quality of the materials. Creating clusters in a substance is undesirable since it reduces mechanical properties [42].

3.2.2 XRD analysis

We can see from the intensity vs 2θ values scattering graph that agro-residue particulates were predominantly naturally amorphous. Figure 9(a)–(c) depicts the X-ray scattering of composite materials. A low average crystallite size, as indicated by a graph, indicates the presence of

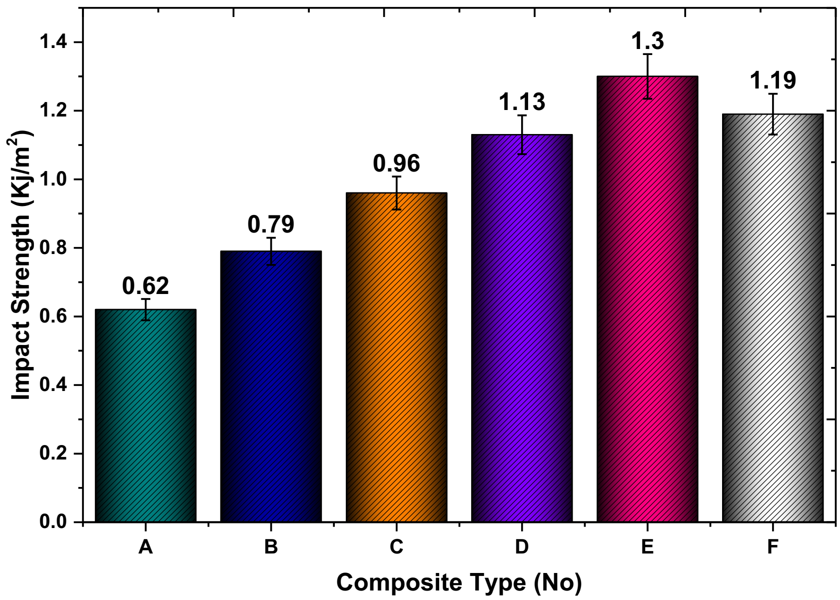

Figure 7: Impact behavior of bamboo fiber and filler-based hybrid composites.

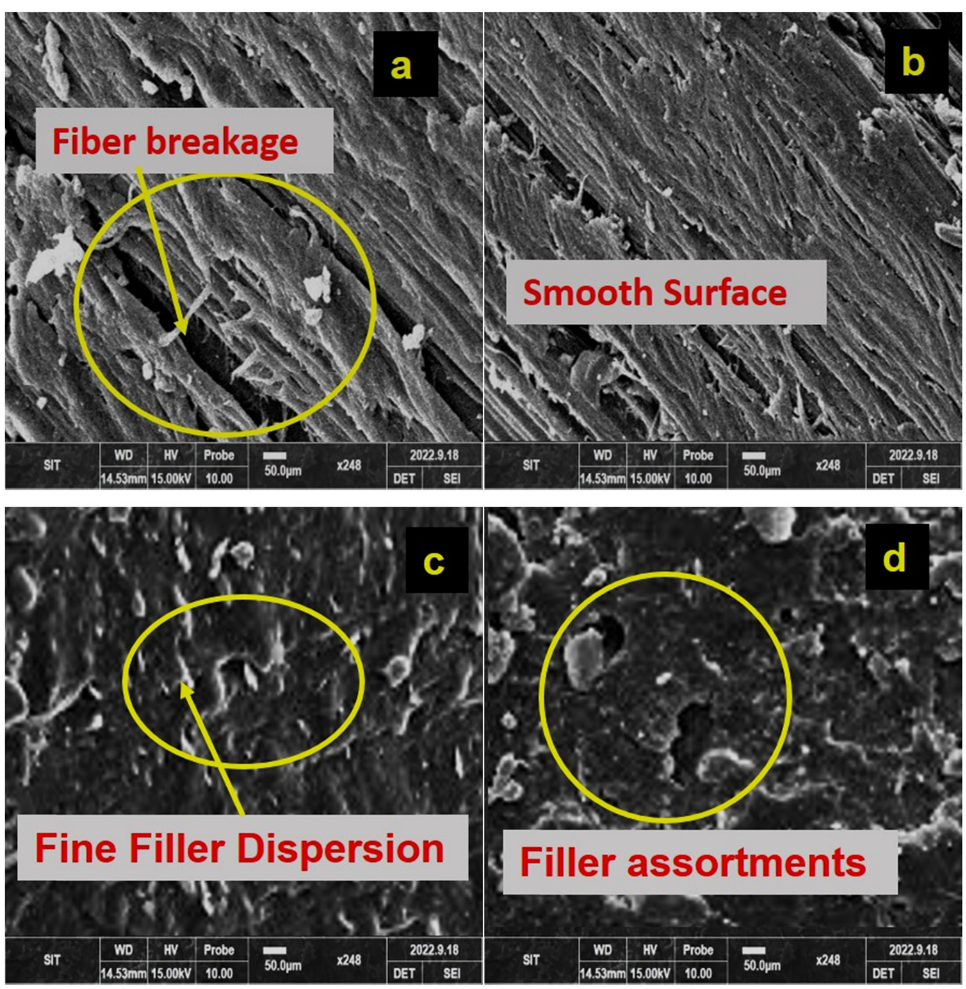

Figure 8: Microstructural images of (a) untreated fiber; (b) NaOH treated fiber; (c) 20 wt% filler inclusion; and (d) 30 wt% filler inclusion.

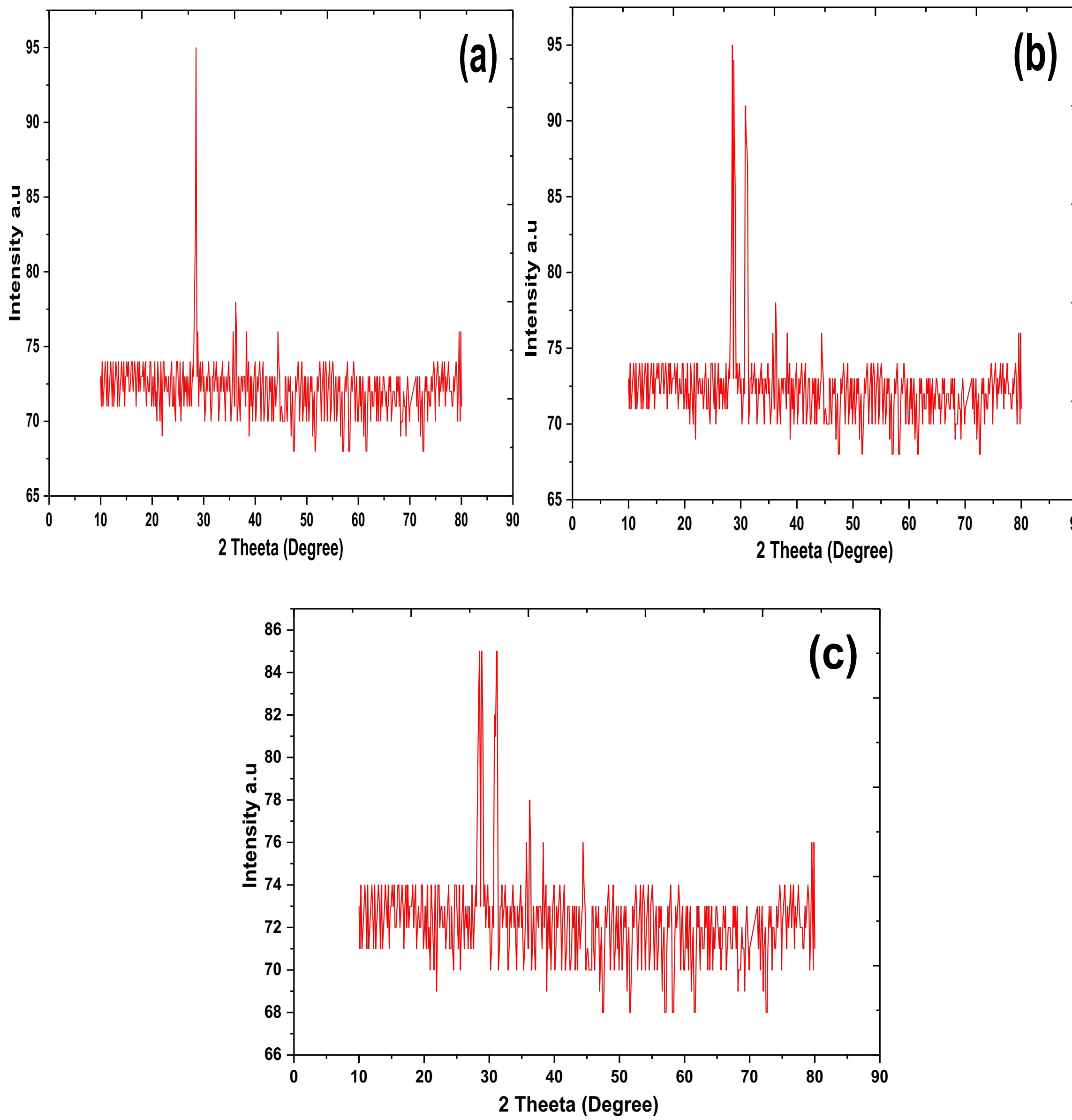

Figure 9: XRD analysis of (a) 10 wt% of fiber and fillers; (b) 20 wt% of fiber and fillers; and (c) 30 wt% of fiber and fillers.

alkali-treated agricultural residual particulates. Figure 9(a) depicts incorporating bamboo fiber, ES, or coconut shell into the epoxy polymer. The inclusion of 10% bamboo fiber, 10% ES, and 10% coconut shell particulates produces low spikes that approximately correlate with JCPDS card No. 89-4032 at 11°, 18°, and 21°. Both Si and Ca stages were augmented by 20% particle reinforcement by epoxy at 26°, 28°, and 32°, as illustrated in Figure 9(b). Following subsequent increases of 30% in particle reinforcement using epoxy resin, morphological peak shift, and stages are a disadvantage owing to non-uniform dispersion and poor water sorption, as seen in Figure 9(c) [43].

4 Conclusion

The advancement of novel materials to address emerging challenges in both therapeutic and technological sectors has become increasingly crucial. One such innovation, a unique “biohybrid composite,” has been meticulously engineered to meet the industry’s specific requirements. Compared to traditional polymer composites reinforced with ES, bamboo fiber, or coconut shell, this biohybrid composite offers significantly improved tensile and bending performances, with up to 44% enhancements.

This material's exceptional mechanical properties can be largely attributed to a higher concentration of fibers, which contributes to its superior tensile strength. Additionally, the biohybrid composite shows remarkable fracture toughness, outperforming other biocomposite combinations by a substantial margin when 20% hybrid laminate is incorporated. The composite's refined fiber content and optimal water absorption characteristics enhance its hardenability. However, it is essential to note that the mechanical performance can decline by introducing 25% or higher hybrid composites, likely due to increased inter-molecular interactions and the creation of microvoids in the matrix.

SEM analysis supports these observations and reveals a densely packed, pore-free exterior in a hybrid epoxy/20% filler reinforcement laminate. Furthermore, X-ray diffraction studies corroborate the inclusion of silicon and calcium components, exhibited at distinct 20° and 40° peak intensities.

In conclusion, this biohybrid composite material's development and thorough analysis offer promising avenues for multiple applications across different sectors. Its superior mechanical properties and material characteristics pave the way for a new generation of lightweight, high-strength materials that could revolutionize various industries, from healthcare to aerospace engineering.

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