ENHANCING THE PHYSICO-MECHANICAL PERFORMANCE OF BAMBOO, JUTE, AND COIR REINFORCED GREEN HYBRID COMPOSITES THROUGH CHEMICAL TREATMENT

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Abstract: *In addition to their traditional uses, bamboo, jute, and coir have important non-traditional uses in the aerospace, construction, furniture, biomedical, and auto industries. For unconventional applications, these natural fibers must be converted into reinforced composite materials. These composite materials are strong for their weight, have a high ratio of strength to weight, are renewable, and are safe for the earth. Epoxy composites reinforced with bamboo, jute, and coir were developed and characterized in this work. The composites were fabricated with fixed 50 wt. % of epoxy resin as binder material with varying other fiber fillers by press formation. Coir fiber wt. % was fixed at 10% and bamboo and jute fiber wt. % were varied to evaluate the consequences. Bamboo fiber wt. % varied to 30%, 25%, 20%, 15% respectively. Jute fiber wt. % varied to 10%, 15%, 20%, 25% respectively. The result showed that mechanical strength and water absorption increased, and the density decreased as the jute fiber wt.% increased. It was additionally determined that the composites that were treated with sodium hydroxide had better physical and mechanical characteristics than the composites that were not treated with sodium hydroxide.*

Keywords: Natural Fiber Composites, Bio-Composites, Fiber Reinforcement, Eco-Friendly Materials, Green Composites.

POBOLJŠANJE FIZIČKO-MEHANIČKIH SVOJSTAVA ZELENIH HIBRIDNIH KOMPOZITA OJAČANIH BAMBUSOM, JUTOM I KOKOSOVIM VLAKNIMA PRIMENOM HEMIJSKOG TRETMANA

Apstrakt: *Pored tradicionalne upotrebe, bambus, juta i kokos imaju važnu netradicionalnu upotrebu u vazduhoplovnoj, građevinskoj, industriji nameštaja, biomedicinskoj i automobilskoj industriji. Za nekonvencionalne primene, ova prirodna vlakna moraju se pretvoriti u ojačane kompozitne materijale. Ovi kompozitni materijali* *su jaki za svoju težinu, imaju visok odnos čvrstoće i težine, obnovljivi su i bezbedni za Zemlju. Epoksidni kompoziti ojačani bambusom, jutom i kokosom su razvijeni i okarakterisani u ovom radu. Kompoziti su napravljeni sa fiksnih 50 težinskih procenata epoksidne smole kao vezivnog materijala sa različitim drugim punilima od vlakana presovanjem. Težinski procenat težinskih kokosovih vlakana je fiksiran na 10%, a težinski procenat bambusovih i jutinih vlakana su varirani kako bi se procenile posledice. Težinski procenat bambusovih vlakana varirao je na 30%, 25%, 20%, 15% respektivno. Težinski procenat jutinih vlakana varirao je na 10%, 15%, 20%, 25% respektivno. Rezultat je pokazao da su se mehanička čvrstoća i apsorpcija vode povećavale, a gustina smanjivala sa povećanjem težinskih procenata jutinih vlakana. Dodatno je utvrđeno da kompoziti tretirani natrijum hidroksidom imaju bolje fizičke i mehaničke karakteristike od kompozita koji nisu tretirani natrijum hidroksidom.*

Ključne reči: Kompoziti od prirodnih vlakana, Bio-kompoziti, Armatura vlaknima, Ekološki prihvatljivi materijali, Zeleni kompoziti.

1. INTRODUCTION

Fiber-reinforced composite materials are made up of at least two different substances that have very different chemical or physical qualities, which, when amalgamated, yield a material exhibiting characteristics divergent from those of separate components. The rise in environmental awareness, the introduction of new ecological regulations, and the detrimental usage of petroleum prompt consideration of environmentally sustainable materials. Natural fiber is regarded as an environmentally sustainable material, possessing remarkable qualities in comparison to synthetic fiber. The world market for natural fiber reinforced polymer composites (NFPCs) is expected to grow by 10% [1].

Fibers that are neither synthetic nor artificial are referred to as natural fibers. They could be from zoological or botanical sources [2]. Many people are interested in composite materials made from natural fibers derived from both renewable and nonrenewable sources, including jute, oil palm, sisal, flax, and coir. Plants that generate cellulose fibers are categorized into various sorts: superior fibers (e.g., ramie, jute, flax, hemp), seed fibers (e.g., coir, cotton, kapok), leaf fibers (e.g., abaca, sisal, pineapple,), grass fibers (e.g., wheat, rice, corn,), core fibers (e.g., kenaf, hemp, jute), and other types (e.g., wood and roots) [3]. Natural fibers' appealing qualities, such as their high impact strength, low cost, low energy requirements, abundance, enhanced surface finishing, and environmental friendliness, develop composites made from natural fibers and polymers that are useful for many various purposes [4]. Improved mechanical strength and dimensional stability of natural fiber reinforced polymer composites are achieved by reducing hydroxyl groups by a variety of chemical treatments, which diminish the hydrophilic qualities of the fibers [5]. A wide variety of industries rely heavily on NFPCs. These include biomedical, construction, aerospace, furniture, and automotive industries. Lightweight, dimensionally stable materials have been manufactured for use in aerospace and automotive applications, leading to innovative components in the automotive sector [6,7].

The nature of natural fibers, which includes cellulose, lignin, hemicellulose, pectin, and waxy compounds, allows them to absorb moisture from their environment. As a result, the interfacial characteristics between the matrix of polymer and the reinforcement of fiber are diminished. The interactions between the matrix and fibers made from nature are a matter of debate because of their dissimilar chemical structures. So, a stress transition that wasn't very effective happened while making NFPCs [8]. In order to solve this problem, it is crucial to chemically modify either the matrix or the reinforcement. The literature makes it a given that adding reinforcements chemically improves the composite's mechanical qualities [9]. Also, because binder is so expensive, raising the matrix percentage to enhance the mechanical characteristics of NFPCs becomes prohibitively expensive and unattractive.

Khan et al. studied using jute fibers as reinforcement in composite constructions [10]. The mechanical characteristics of the composites were shown to be improved with longer soaking times and higher NaOH concentrations when treating jute fibers. However, after 60 minutes of soaking in a 20% NaOH solution, the mechanical qualities began to decline [11]. Hai et al. discovered that after being treated with 2% alkali for 24 hours, jute fibers showed a 40% increase in tensile strength and a 9% increase in modulus. Conversely, coir fibers treated with a 6% concentration for the same amount of time showed a 17% increase in modulus and a 62% improvement in tensile strength [12]. At a 2% concentration of alkali treatments, the elongation of coir composites reached 13% and jute composites 8%. Composites made from treated fibers reduced moisture absorption by 60% and 50% in the case of jute, respectively, when compared to untreated fibers. Polyurethane composites with coconut fiber reinforcements were the subject of mechanical property investigations by Mulinari et al [13]. Their analysis of the untreated fibers revealed a lot of dust stuck to the fiber bundles' surface because of the non-cellulosic substance they were coated in. Li et al. also noted how coconut fibers behaved [14]. Following the treatment of coconut fibers, it was noted that the fiber surface became smooth, and its characteristics transitioned from hydrophilic to hydrophobic. The removal of the surface layer (parenchyma cells) was confirmed to enhance the contact area. There was a noticeable increase in fiber roughness, which might have improved the fibers' adherence to the matrix.

Ram Krishna Adhikari et al. investigated the mechanical characteristics of a banana-jute polyester composite. They demonstrated that tensile strength rises as much as fifteen percent as the fraction of fiber volume increases. At fifteen percent fiber loading, the maximum tensile strength for specimens measuring three millimeters and five millimeters in thickness was 25.21 MPa and 32.38 MPa, respectively. Tensile strength decreases as fiber loading increases further. Because fiber has a higher load-bearing capacity than the matrix, strength can be increased by up to fifteen percent with fiber loading. The loss in tensile strength with greater loading is caused by inadequate bonding between the fibers and matrix, as well as increased micro space creation inside the composite. Because the fibers and matrix adhere better to one another, specimens that are thicker have greater strength. According to the findings, flexural strength has a similar trend to tensile strength, rising up to 15% with the volume percentage of banana or jute fibers before declining with further increases in fiber loading. This is caused by the matrix's inability to support and transfer the bending load that the fibers exert. At 15% fiber loading, the maximum flexural strengths of specimens with thicknesses of three millimeters and five millimeters were 182.34 MPa and 184.37 MPa, respectively. percentage of jute/banana fibers up to fifteen percent, after which there is a decrease with further fiber loading increases [15].

Jute ranks second in global fiber output volume, following cotton, and is primarily produced for its fiber. Notwithstanding the drawbacks of jute fiber, including its significant brittleness and comparatively lower tensile strength, it possesses a wide array of applications owing to its fine texture and heat resistance [16] . Bamboo fibers are derived from bamboo plants. Bamboo fibers have exceptional mechanical strength, rigidity, low density, and elevated modulus of elasticity. As a result, coir fiber is among the top three natural plant fibers by volume. Most of the coir fiber produced is exported as raw fiber. Coir pith, a byproduct of coconut husk processing, is progressively acquiring economic significance as a horticulture substrate.

Previously, it was found that Tensile strength ranged from 12.48 (18% weight of jute epoxy composite) to 22 (50% weight of coir polypropylene composite) MPa when jute or coir were the only materials utilized. However, the tensile strength rose to 392 MPa for treated fiber and 216 MPa (52% weight of bamboo epoxy composite) for untreated fiber if solely bamboo was utilized in the composite. Compared to coir or jute, the bio-composite made of bamboo demonstrated a high tensile strength. However, bamboo is expensive and challenging to process [17]. For this reason, it is necessary to produce a combined reinforcement effect by bamboo, jute, and coir fiber where baboo and jute can improve strength, and coir can ameliorate the impregnation.

The primary objective of the research is to determine the effects of the material's functional group (NaOH) on the fiber reinforcements of green hybrid NFPCs with the aim of improving their mechanical properties. By adjusting the fiver volume fraction of the three natural fibers (coir, jute, and bamboo), we may get the optimal fiber volume fraction percentage for combining these three unique natural fiber reinforcements. Making lightweight composites utilizing press molds and reducing the amount of epoxy binder can make them more affordable. This study compared previous findings with those of other studies that examined the physical and mechanical properties of epoxy composites reinforced with bamboo, jute, and coir.

2. MATERIALS AND METHODS

2.1 Materials

Bamboo, jute, and coir are renewable and biodegradable plant-based fibers that were the primary raw materials used in this study. These fibers came straight from Bangladeshi marketplaces. Different types of fiber have different strengths and characteristics; for example, bamboo fiber is very strong and stiff, jute fiber has a high cellulose content and excellent inter-fiber bonding, and coir fiber is very resistant to moisture because of its high lignin concentration. All fibers were manually extracted and processed to the desired size for composite fabrication.

Following the manufacturer's instructions, a 1:1 weight ratio of epoxy resin (AW-106) and hardener (HY-951) was utilized as the matrix material. Epoxy was chosen for fiber reinforcing applications because of its outstanding mechanical qualities, low shrinkage, and strong adherence. In order to enhance mechanical performance and reinforce fiber-matrix contact, a few fiber samples were chemically treated with a 5% sodium hydroxide (NaOH) solution. By removing lignin, hemicellulose, and surface impurities, the alkali treatment improved surface roughness and reduced hydrophilicity, ultimately increasing fiber compatibility with the epoxy matrix. The final composite samples were prepared by mixing 50 wt.% epoxy resin with 50 wt.% total fiber content, where coir fiber was kept constant at 10 wt.%, and bamboo and jute fibers were varied in different ratios to evaluate their impact on physio-mechanical properties.

2.2 Methods

The fabrication of green hybrid composites using bamboo, jute, and coir fibers followed a systematic and structured process designed to ensure optimal material performance. Thorough chemical treatment to enhance fiber-matrix adhesion, regulated mixing of resin and hardener, molding employing compression techniques, and finally, fiber-matrix adhesion improvement were all essential processes in this procedure. Finally, the cured composites were cut to standard dimensions and tested for physical and mechanical properties. The detailed flow chart is provided below in Figure 1.

2.2.1 Fabrication of Mold

The material mix is filled into the die part of the mold and the pressure is given by the presser part. The pressure is transferred from the material mix to the wall surface. To get accurate shape of the specimen, the wall surface of the specimen must not bend. For this reason, cast iron die part is used. The bending strength of the cast iron is more than 300 MPa. Where the compacting pressure was 140 MPa. For making the process cost effective wooden block was used as presser part. Specimen size was collected from ASTM standards. The die and presser part of the mold is shown in Figure 2 and Figure 3 where the size of the pressure is 9-10 inches. A 0.05-inch clearance is given between the die and presser part of the mold. The die part was made by welding of four pieces of cast iron bar. And they were smoothened by the grinding process. For the presser part, mahogany wood was used.

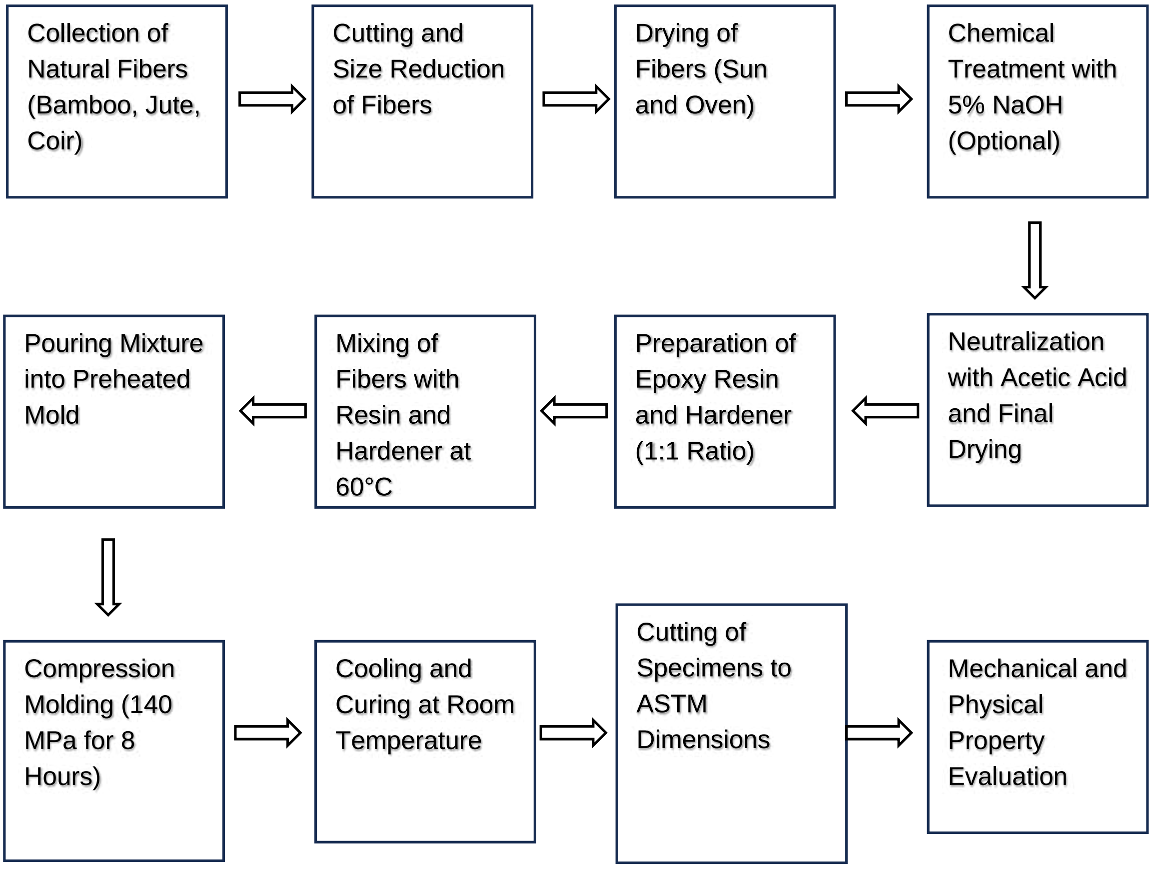

Figure 1: Composite Fabrication Flow Chart

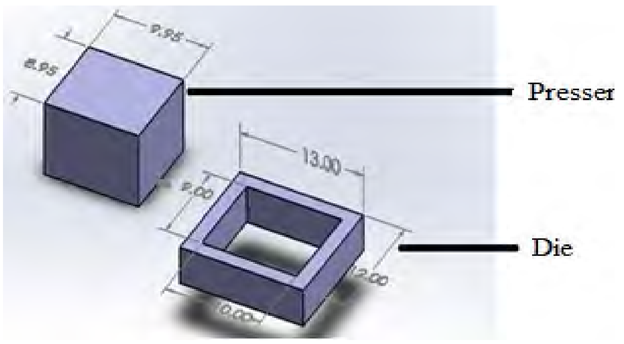

Figure 2: Die and presser part of the mold

Figure 3: Die and presser part combination

2.2.2 General Methodology for Fabrication of Composite

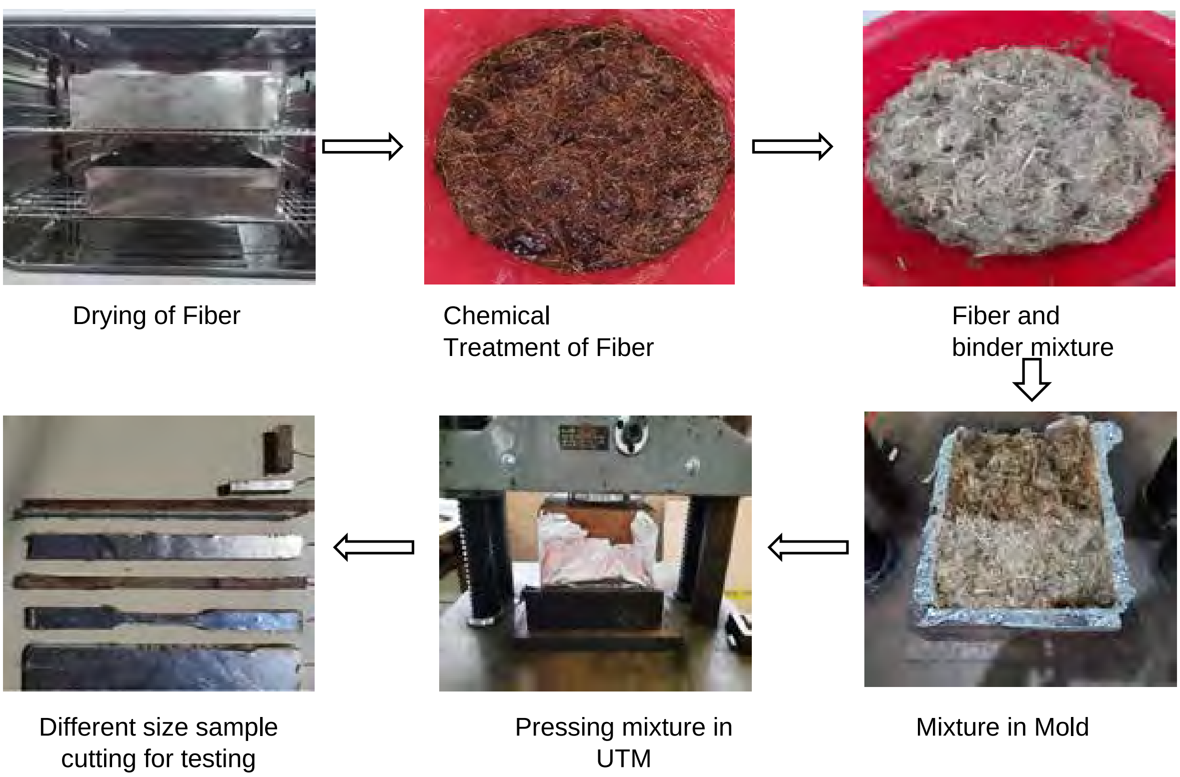

Figure 4: Flow chart Methodology for Fabrication of Composite

Composite materials are developed by integrating two or more different components, resulting in a hybrid that surpasses the performance of each individual element; when at least one component is derived from a biological source, ASTM D7075-04 categorizes the material as a bio-composite. Figure 4 illustrates the full workflow.

Initially, to guarantee even dispersion and minimize tangling, locally procured bamboo, jute, and coir fibers were hand-selected and precisely cut. Bamboo strips were cut to between 0.5 and 1.5 mm in length and between 2 and 3 mm in breadth, while jute and coir bundles were broken up into 1-2 mm pieces. These sized fibers were then subjected to a two-stage moisture-removal regime-sun drying followed by hot-air oven drying at 50–120 °C - until a constant mass was achieved, thus preventing void formation during molding.

An enhanced fiber-matrix interaction was achieved by immersing the dried fibers in a 5-weight percent NaOH solution for four hours. By removing hemicellulose, lignin, and surface contaminants, this alkali treatment roughened the fiber's surface and revealed more hydroxyl sitesAfter rinsing with distilled water, the fibers were treated with 5% acetic acid to neutralize them. Another rinse brought the pH level down to 7, and finally, they were redried till they reached equilibrium mass.

Meanwhile, epoxy resin (AW-106) and hardener (HY-951) were pre-heated to 110 °C for fifteen minutes, cooled to 60 °C and blended in a 1:1 (wt/wt) ratio. Pre-heated fibres (≈ 50 °C) were then gradually introduced, maintaining a fixed formulation of 50 wt % epoxy and 50 wt % total fibre, with coir held constant at 10 wt % while bamboo and jute were varied systematically. The four untreated reference formulations are mentioned in Table 1.

Table 1: Different components composition table (without treatment)

Sample no	Epoxy resin wt.%	Coir wt.%	Bamboo wt.%	Jute wt.%
01 (B30J10)	50	10	30	10
02 (B25J15)	50	10	25	15
03 (B20J20)	50	10	20	20
04 (B15J25)	50	10	15	25

3. RESULT AND DISCUSSION

3.1 Physical Properties

3.1.1 Density

Here fiber and epoxy density are different from each other. Epoxy resin density was 1.176 gm/cm^3 which was declared by manufacturer. In Figure 5 shows density of different prepared composite.

Density decreased as jute fiber increased, and bamboo fiber decreased, i.e. cellulose increased. Because cellulose has low molecular weight per volume as compared to hemi-cellulose and lignin. Density decreased as jute wt.% increased because compact jute had less void area than bamboo. Besides, bamboo fiber is harder, and its diameter is greater than jute. So, when compact in press mold, bamboo fiber itself did not mesh with itself properly. But jute properly meshed with itself for the reason of thinner diameter.

B15J25 without chemical treatment of fiber composite showed the lowest density which is 0.59gm/cc.

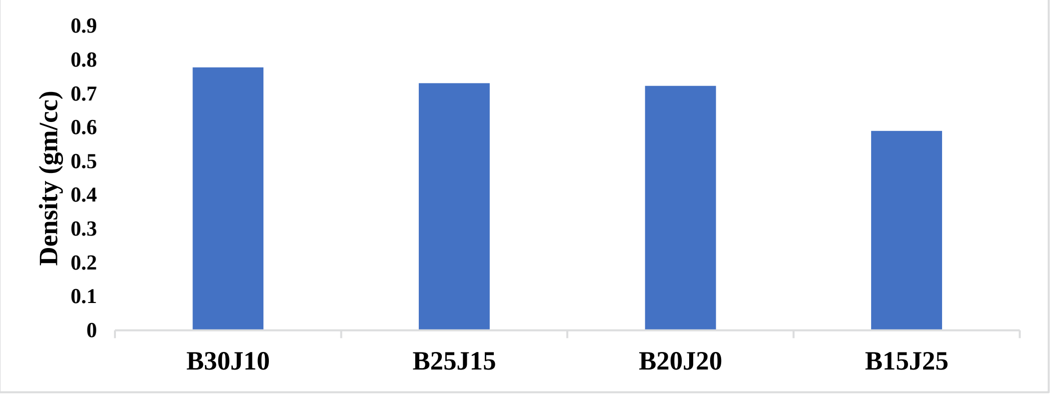

Figure 5: Density of different sample

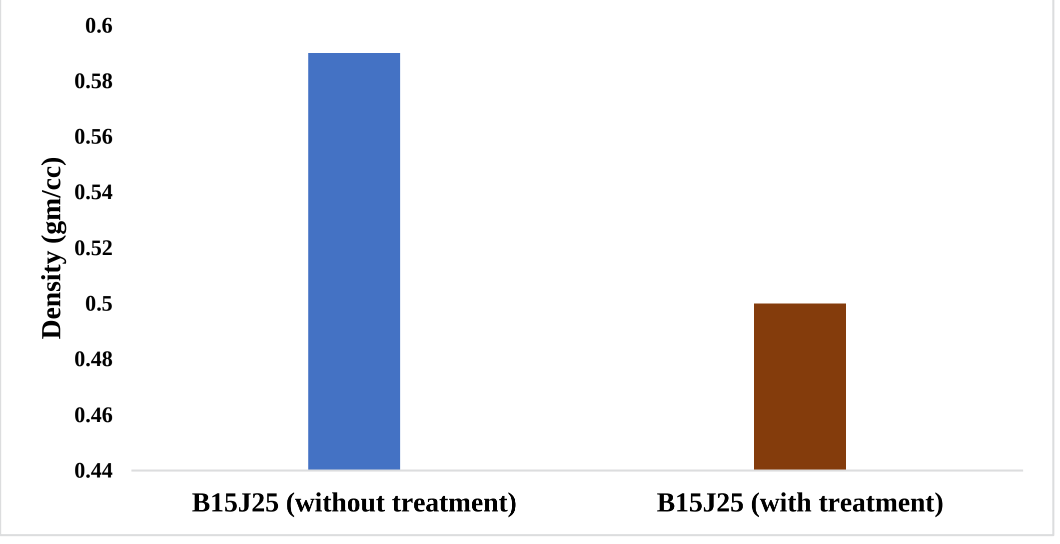

Figure 6: Density comparison without treatment vs with treatment of fiber

Same composition of B15J25 with treatment of fiber density was 0.50gm/cc which is 18% lower than without treatment. B15J25 with and without treatment comparison is shown in Figure 6. The density decreased for the same composition for chemical treatment because hydrophilic – OH group reduction which made the fiber thinner i.e. better mixing with each other.

3.1.2 Water Absorption

Figure 7 illustrates the temporal evolution of water absorption (wt.%) for four untreated hybrid composite samples-B30J10, B25J15, B20J20, and B15J25-where coir content is fixed at 10 wt.% and bamboo and jute contents are systematically varied. The results depict a pronounced initial uptake of moisture during the first hour across all samples, Afterwards, there is a noticeable slowdown in the water absorption rate, which approaches saturation by the third hour

Among the compositions, B15J25 exhibited the highest water absorption (~15.1 wt%) at the 1-hour mark, while B30J10 absorbed the least (~12.2 wt%). The rise in jute fiber content and the corresponding decline in bamboo fiber content is directly correlated with this trend. Jute, being rich in cellulose and inherently more hydrophilic due to its abundant hydroxyl groups, contributes to higher moisture affinity compared to bamboo, which is relatively less hygroscopic. Consequently, as the jute proportion increased, the overall composite's susceptibility to water uptake also increased. Notably, after the first hour, the rate of water absorption sharply decreased for all samples. This rapid saturation behavior can be attributed to the filling of readily accessible voids and micro-capillaries within the fiber-matrix interface. Beyond this point, diffusion becomes limited to more tortuous or less accessible pathways, leading to a plateau in absorption rates after six hours.

B15J25 with chemical treatment, water absorption result is shown in Figure 8. Here the highest water absorption wt.% was 9% after 1 hour. After 1 hour the previously described phenomena had happened. The data clearly shows that B15J25 absorbed the most water throughout the 1-hour period. Jute outperformed

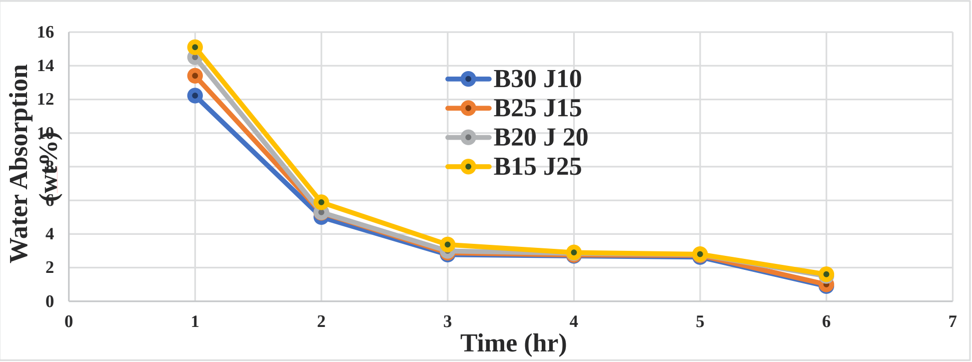

Figure 7: Water absorption result for different sample

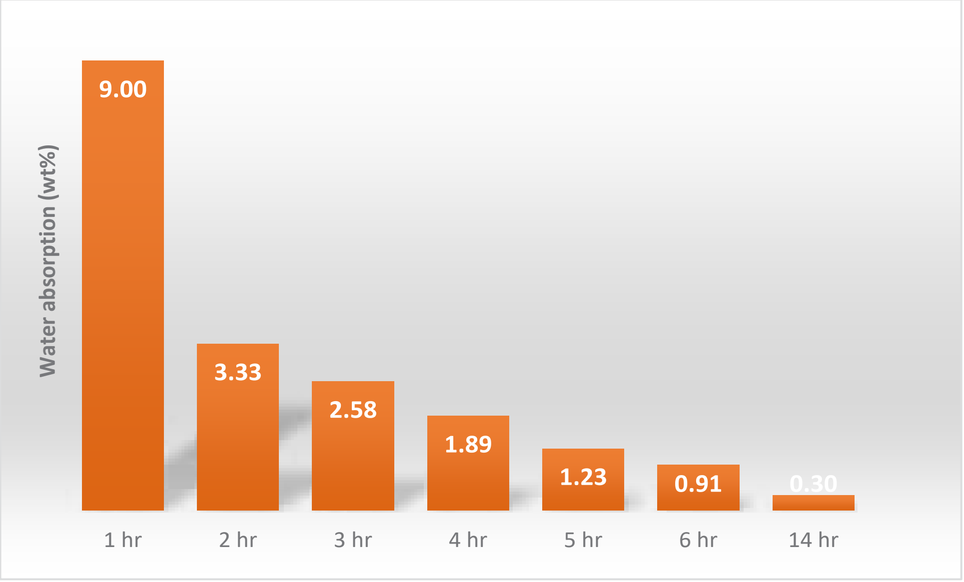

Figure 8: B15J25 (with treatment water absorption result)

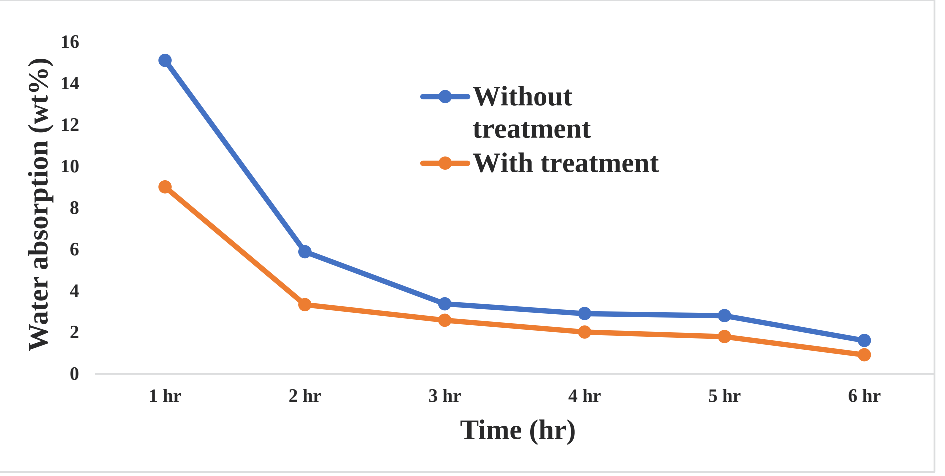

Figure 9: B15J25 without treatment vs with treatment water absorption result

bamboo and coir in terms of hydrophilicity. So, as the jute wt. % increased water absorption increase.

Same fiber wt.% composition for B15J25 with treatment showed less water absorption than without treatment by 67.77%. Chemical treatment reduced the –OH group and made the fiber less hydrophilic. So hydrophobic property of the fiber increased, and water absorption decreased. It is shown in Figure 9.

Water absorption or diffusion in polymer composites is controlled by a number of processes, one of which is the diffusion of water molecules into the gaps between resin molecular chains [18]. Water molecules diffuse into the fiber structure, where they form hydrogen bonds with the hydroxyl groups of cellulose molecules. They then migrate into gaps and flaws at the fiber/matrix interface because of capillary action. Finally, as a result of fiber swelling, they transfer into microcracks in the matrix [19].

It was found that incorporating more jute fiber into the composites caused them to expand and absorb more water. The observed volume swellings for the epoxy matrices were 19% at a 40% fiber percentage. The epoxy composites had the highest water absorption values, 17.5%, among composites with 40% fibers. All treated cellulose hybrid composites had substantially reduced water absorption compared to untreated hybrid fiber composites [20].

The hydrophilicity of untreated fibers was caused by the abundance of hydroxyl groups (-OH). Reduced moisture resistance is frequently seen in fibers with a higher percentage of -OH groups. As a result, the fiber and matrix had insufficient interfacial adhesion and dimensional disparities [21]. Additionally, this caused voids and microcracks to form, which trap and absorb a higher amount of water. Capillarity and the transport of water molecules via the microcracks were initiated when the microcracks widened.

3.2 Mechanical Properties

3.2.1 Tensile Properties

Figure 10 shows that tensile strength increased by increasing jute fiber weight percentage and re-

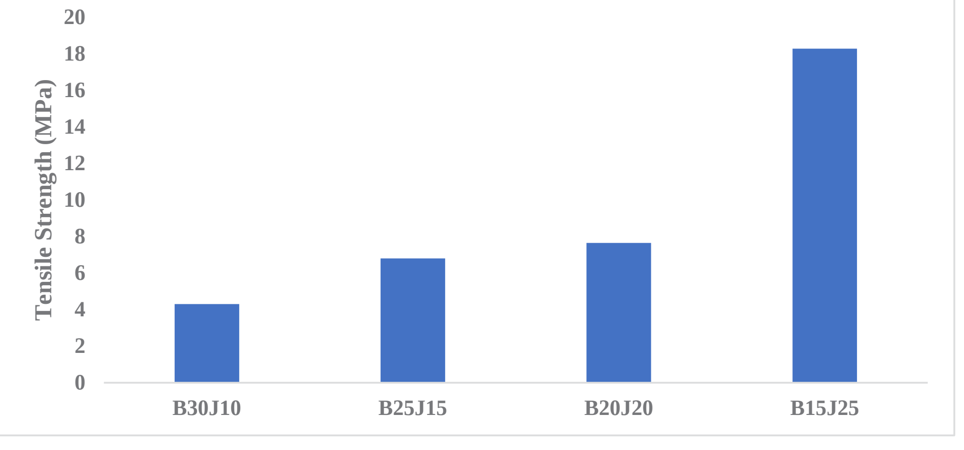

Figure 10: Tensile strength of different sample

duced bamboo fiber weight percentage. Jute fiber contains a greater percentage of cellulose than coir and bamboo. Cellulose glucose units have several hydroxyl groups that firmly connect adjacent or neighboring chains by forming hydrogen bonds with oxygen atoms. Thus, jute's tensile strength is greater than that of coir and bamboo. B15J25 (untreated) demonstrated the greatest tensile strength of 18.27 MPa.

Figure 11 shows tensile strength of B15J25 with vs without treatment. Tensile strength increased 16.03% for treatment. For chemical treatment the void spaces inside the composite are reduced. So, the composite became more compact than without treatment and tensile strength increased.

3.2.2 Flexural Properties

Figure 12 shows the flexural strength of different composites. As the jute wt.% increased flexural property increased. Reasons were the same because there is no transverse or longitudinal dimension of the composite because fiber was randomly mixed with each other.

Figure 13 shows the flexural strength of B15J25 with and without treatment results. Here treatment increased flexural strength by 25.44%. For chemical treatment, the void spaces inside the composite are reduced. So, the composite became more compact than without treatment and flexural strength increased.

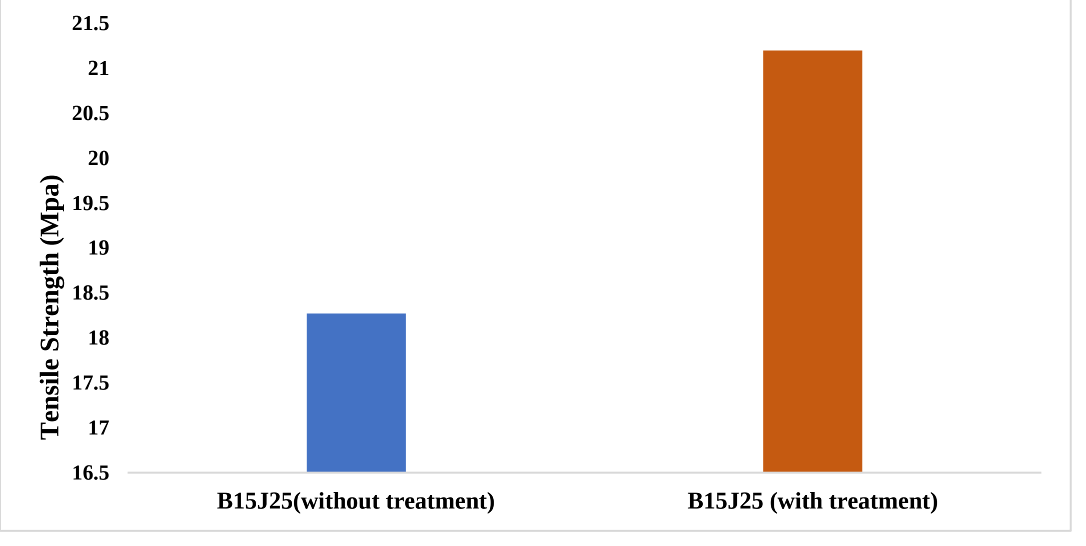

Figure 11: B15J25 tensile strength with vs without treatment

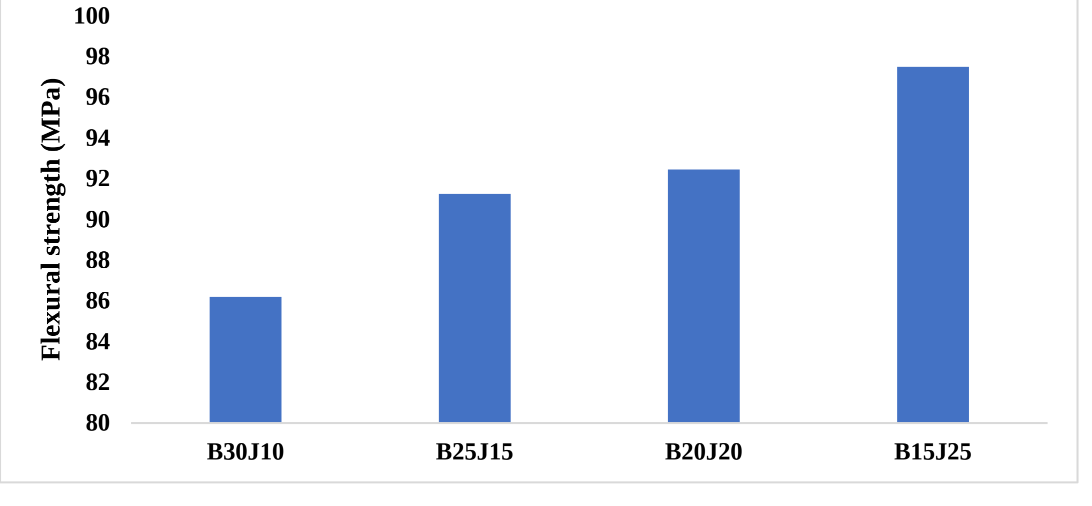

Figure 12: Flexural strength of different sample

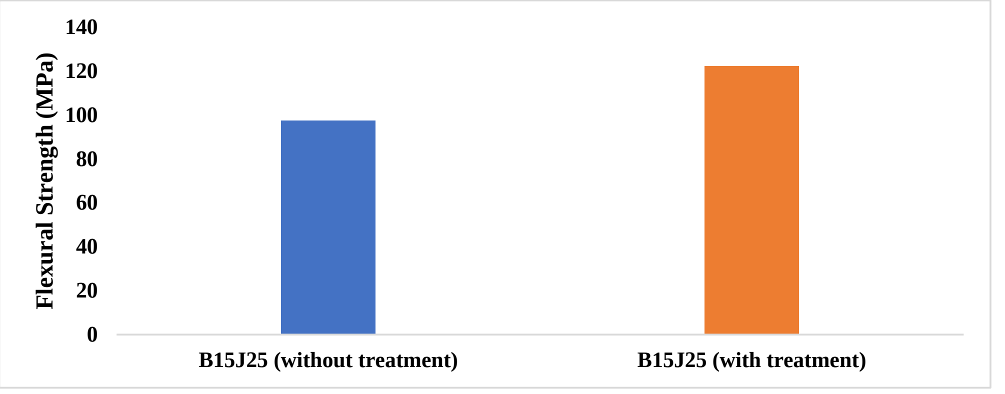

Figure 13: Flexural strength of B15J25 with vs without treatment

3.2.3 Compressive Properties

Various samples' compressive strengths are displayed in Figure 14. The benchmark for compressive strength is 10.67 MPa, achieved by B15J25. Compressive strength rose in tandem with the amount of jute fiber. Because jute has a narrower diameter than bamboo due to a reduced vacancy content in its internal structure, the composite grew more compact as the jute fiber content rose. In addition, bamboo fiber has a larger diameter than jute and is tougher. Therefore, the bamboo fiber itself did not mesh with itself properly when compacted in a press mold. However, because of its smaller diameter, jute meshes with itself properly

Figure 15 Shows B15J25 with vs without treatment result. Here chemical treatment increased compressive strength by 24.64% and made the fiber thin-

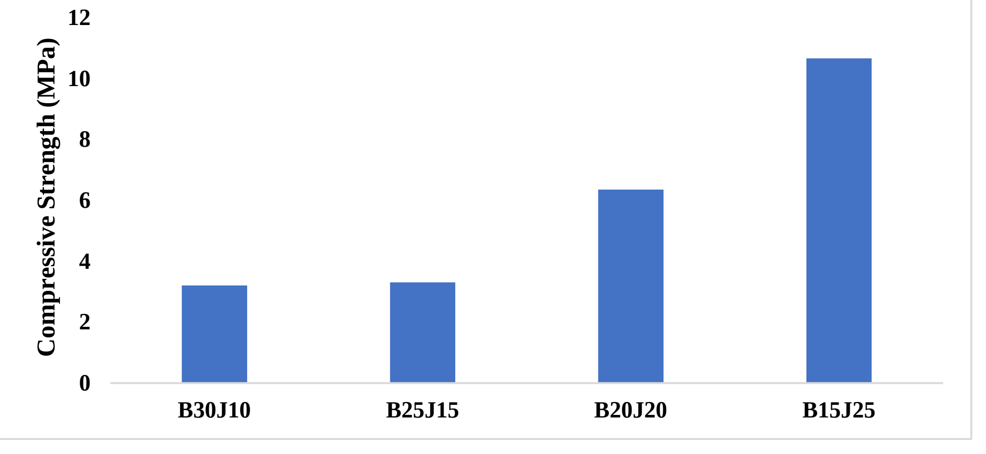

Figure 14: Compressive strength of different sample

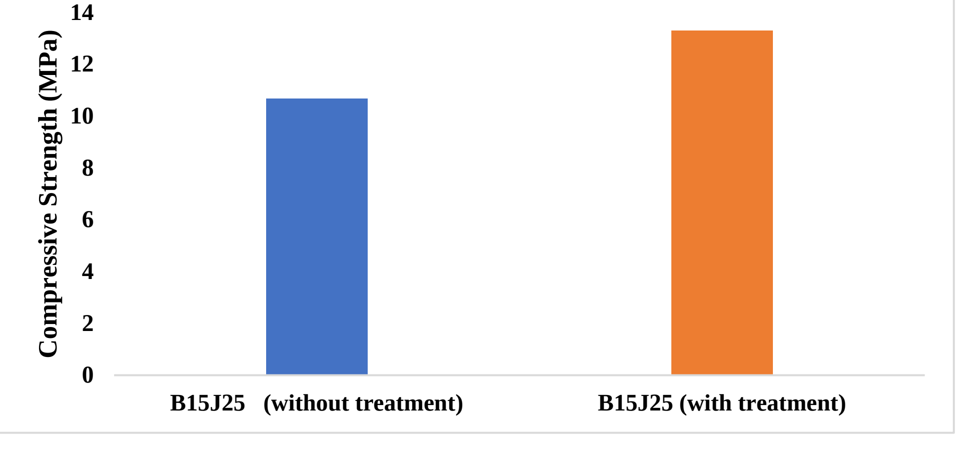

Figure 15: Compressive strength of B15J25 with vs without treatment

ner than without treatment by reducing – OH group. So, after compacting void spaces reduced and composite became more compact.

3.3 Chemical treatment impact on mechanical properties

Compared with the literature review, it is observed that only bamboo or jute-based composites showed high tensile strength. But bamboo processing is costly, and jute is hydrophilic. Additionally, in literature review composites, the binder accounted for almost 80%. Binder increased all kinds of mechanical properties rapidly, but it is costly. A 30% Binder reduction results in a significant cost reduction, albeit at the expense of reduced mechanical properties. Chemical treatment can be a sustainable alternative. Chemical treatment comparison is shown in Figures 16 and 17. Chemical treatment increased the same composition composite tensile property by 16.03%, flexural property by 25.44%, and compressive property by 24.64%.

4. CONCLUSION

This study scientifically investigated the physio-mechanical properties of green hybrid epoxy composites that were chemically treated with or without 5% NaOH, and which were reinforced with varying weight fractions of coir, jute, and bamboo fibers. Experimental results showed that a 25% increase in jute fiber content and a 30% decrease in bamboo fiber percentage greatly enhanced mechanical characteristics. The flexural strength improved by almost 25%, the compressive strength peaked at 10.67 MPa, and the tensile strength increased from 12.5 MPa to 18.27 MPa. The tighter fiber-matrix interaction and composite compactness that jute achieves are directly attrib-

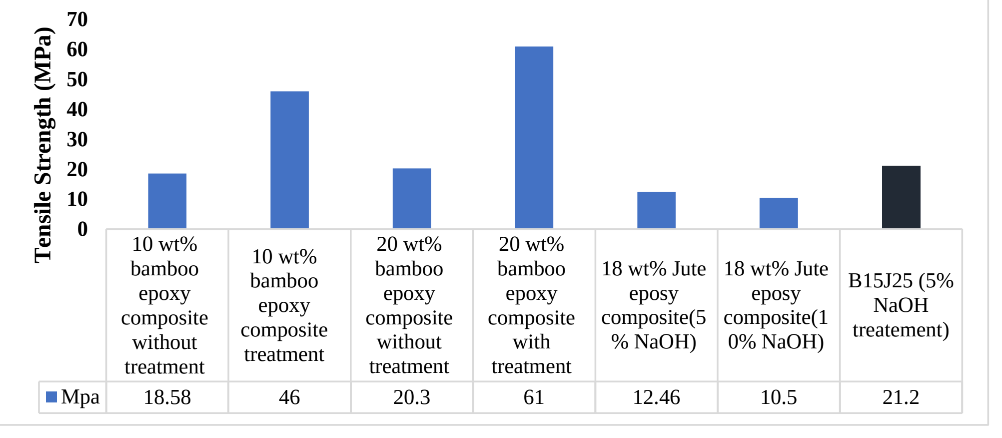

Figure 16: Chemical treatment comparison for tensile strength with literature review

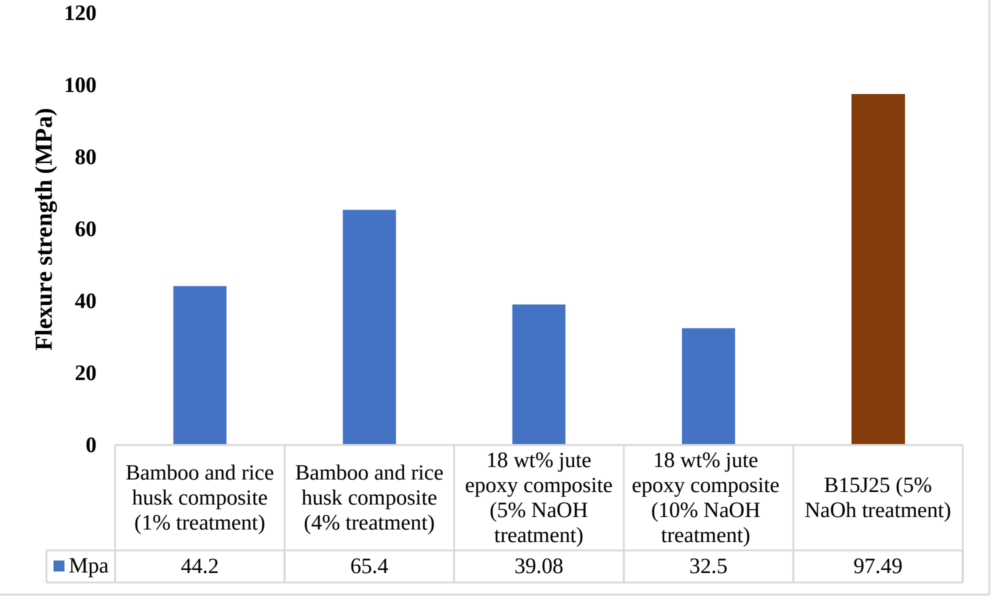

Figure 17: Chemical treatment comparison for flexural strength with literature review

utable to its higher cellulose content and smaller fiber diameter.

By chemically treating the material with 5% NaOH, the hydrophilic -OH groups were successfully reduced, resulting in thinner fibers with improved interfacial bonding and reduced spaces between them. Therefore, treated composites demonstrated a 16% increase in tensile strength, a 25% increase in flexural strength, and a 24% increase in compressive strength when contrasted with their untreated equivalents. In addition, the treated composites exhibited a remarkable 67.7 percent reduction in water absorption rates, indicating enhanced resistance to moisture and dimensional stability.

Because of improved fiber packing and decreased void volume, composites with a higher jute content showed lower density, according to density measurements. Chemical treatment further decreased density by 18%. With only 50 weight percent epoxy binder-much less than the usual 80 weight percent used in literature-the hybridization of bamboo, jute, and coir fibers along with chemical modification thus offers an efficient and economical method for creating lightweight, mechanically strong, and moisture-resistant green composites.

Overall, the results support the possibility of chemically treated, optimized natural fiber hybrid composites as environmentally benign substitutes for high-strength, cost-effective materials used in construction, automotive, and aerospace applications.

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