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Review Article

A Review on the Effect of Various Chemical Treatments on the Mechanical Properties of Renewable Fiber-Reinforced Composites

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Increased environmental concerns and global warming have diverted effort all over the world to focus on renewable and sustainable resources for the next generation of composite products due to their recyclability, renewability, cost effectiveness, and satisfactory mechanical performance. Bio/natural fibers which are environment friendly materials employed as reinforcement have led to developing a biocomposite for reduction in greenhouse emission and carbon footprints. However, biofibers are also having some limitations that need to be addressed including poor compatibility between the reinforcing fiber matrices, high moisture absorption, swelling, poor chemical and fire resistance, and high dispersion of mechanical properties. A lot of research has been performed on physical and mechanical properties of natural fiber composite. Properties of such novel composite mainly depend on adhesion between fiber and matrices. Consequently, poor adhesion, high moisture absorption, and swelling lead to formation of crack in both the matrix and fiber. Therefore, numerous techniques have been tried till date to modify both fiber surfaces to enhance their adhesion and reduce their water absorption. This review article provides comprehensive information about effect of various surface modification techniques that include alkaline, silane, acetylation, permanganate, peroxide, benzoylation, acrylonitrile grafting, maleic anhydride grafted, acrylation, and isocyanate. In addition, the effects of cellulose, hemicellulose, lignin, and pectin of biofibers are also reported. This review concluded that chemical treatment of biofibers with 5% NaOH concentration improves the physical, mechanical, and thermal properties of the resulting composites compared to untreated fiber composites.

1. Introduction

Presently, the automotive industries do face many challenges, such as the shortage of supply of fossil fuels, new technological innovations, and environmental sustainability to fight global warming. The above listed factors increase the pressure in the current materials design and manufacturing technologies in automotive industries [1, 2]. A lightweight material was a necessity for the structural components for lower energy consumption of vehicles. The research community has shifted the focus towards effective utilization of the biofibers extracted from renewable sources. The natural fibers are being employed for application components such as interior dashboard trims for automobiles and household applications [3, 4]. The utilization of lightweight and low-cost biofibers such as abaca, banana, bamboo, coir, flax, ramie, tea leaf, pineapple, sisal, kenaf, and jute was already tried as reinforcements in the polymer matrix for composite materials used for manufacturing automobile components [5–7]. The biodegradability of biofibers is associated with physical, chemical, mechanical, thermal, and moisture conditions which have increased their scope of use in numerous applications [8, 9]. Based on the usage and utilization, usually biofibers are classified as primary and secondary fibers. Primary fibers include jute, sisal, kenaf, and hemp fibers, where these fibers are grown for their fiber contents. Secondary fibers include agroresidues, coir fibers, and pineapple fibers, which are fibers obtained from plant by-products. These fibers can be further classified into six types: bast fibers (flax, jute, etc.), leaf fibers (sisal, pineapple leaf fiber), seed fibers (cotton, coir), core fibers (hemp, kenaf), grass and reed fibers (wheat, corn, and rice), and all other types (wood and roots). The structure and chemical constituents of biofiber depend on several factors like extraction process, location of plant growth, climate, plant age, and plant nature [10–13]. When compared to synthetic glass fibers, natural fibers have better specific modulus. The cost saving on the material owing to the use of plant based fibers and nonabrasive nature of the materials during mixing and moulding makes the natural fibers a promising reinforcement for polymer composites [14]. These advantages make the biofiber be employed in any application like automobile, domestic utilities, and distinction [15, 16]. The biofiber composites were used in many places because of the following merits: eco-friendly nature, easy availability, low weight, good strength, low cost, and ease of manufacturing process [17–19]. The foremost disadvantages of the biofibers are that they absorb more moisture. The moisture absorption of biofibers has several unfavourable effects on their properties and thus affects the long-term performance of the composites [20]. The mechanical and thermal performances of bio/natural fibers reinforced composites (NFRC) were influenced by weight/volume fraction of fiber, fiber orientation, selection of chemical treatment method, and physical characteristics of the natural fiber [21–23]. However, the water absorption and thermal stability of the composite laminate were noticed to reduce with increase in weight fraction of fiber [24–28]. The natural fibrils are constituted of cellulose, hemicellulose, and lignin in varying percentages. In addition, the natural fibers do have other substances like pectin, wax, and other water soluble compositions. The cellulose is enclosed in soft lignin, while hemicellulose forms the ancillary layer of the fiber material [29]. Ishak et al. [30] studied the tensile strength of bagasse fiber obtained from plants of different heights. The tensile properties were specifically high for the fibers extracted from bottom of tree due to their chemical composition, particularly cellulose, hemicellulose, and lignin. Moisture absorption of the natural composites was increased when fiber content increased because of its higher cellulose content amount. George et al. [31] stated that the biofibers have high amount of hydrophilic property which leads to poor adhesion properties between the hydrophilic fiber and hydrophobic matrix. Hydrophilicity is the stronger affinity of the fibers towards moisture. The major disadvantages of natural fiber are poor adhesion between fiber and matrix, presence of cellulose content, moisture absorption, and voids at interface between fiber and matrix which results in dimensional inaccuracy, thus affecting the mechanical properties [32–35]. In addition to that, presence of high moisture content in fiber leads to swelling of fiber and matrix within composites resulting in dimensional instability. This disadvantage and limitation can be overcome by chemical treatments. The chemical treatments are carried out to reduce the hydrophilic nature of fiber but the surface treatments not only modify the fiber surface but also increase the fiber strength leading to the improvement of adhesion between fiber and matrix [36–38]. The most common chemical treatment and surface treatment methods are silane, alkaline, acetylene, maleated coupling, anhydride, and benzolytation. Optimization of fiber and matrix is aimed to improve the adhesion, surface tension, interfacial strength, and wettability that offer good surface roughness leading to good bond [39]. These could be done by adding suitable compatibilizer/coupling agent and chemically treating the fiber. Recent literature survey showed that several works have been published on different natural fibers extracted from renewable sources which are used as reinforcement with polymer matrix over a wide dimension of applications. This survey depicts various surface treatments done to enhance the properties of the fibers and for enrichment in mechanical properties of the composites in contrast with untreated fiber-reinforced polymer composites. Therefore we summarized the major findings on different types of chemical treatments and surface treatments.

2. Constitution of Biofiber

2.1. Cellulose. In plant based fibers, cellulose is the primary structural constituent and the cellulose portion influences the mechanical properties of the lignocellulose fibers. The cellulose is the fundamental constituent which is liable for the strength of the plant fibers and variance in strength may be due to growth conditions of the plant and soil nature. Cellulose is a lined, semicrystalline polysaccharide build-up of polymer links compromising the recurring modules of anhydroglucose grouped via 1,4-β-D-glucosidase. The recurring modules of the monomers are termed as degree of polymerization. The monomers of glucose in the chain of cellulose result in formation of the hydrogen bonds among the link forming fibers as well as associated chains. The binding of intramolecular and intermolecular hydrogen regions results in development of linear crystalline structure called cellulose.

2.2. Hemicellulose. Hemicellulose is a multidiverged polysaccharide made up of many distinctive glucose monomers, while cellulose is composed of only single 4-βD-glucopyranose repeating units. When compared to cellulose, the constituent of hemicellulose varies from one plant to other. The amorphous nature of the hemicellulose is confirmed by its high degree of chain grouping.

2.3. Lignin. Lignin is an intricate hydrocarbon polymer composed of aliphatic and aromatic elements. In addition to the cellulose, lignin is another important constituent in the lignocellulose fibril. The lignin binds the fibers together to make the fiber surface be stiffer enough by giving compression strength to the plant. The chemical composition of lignin is made of phenylpropane elements obtained from an enzyme-initiated dehydrogenate polymerization of three distinct constituents which are trans-p-coumaryl, trans-coniferyl, and trans-sinapyl.

2.4. Pectin. Pectin is an element of acidic polysaccharides with complex structure. The main constituents of pectin are homopolymeric acid and partial residues of methylated poly-α-(1-4)-D-galacturonic acid. When treated with alkali or ammonium hydroxide, pectin will become a water soluble polymer. The role of pectin is to function as cementing element among the plant fibrils which binds with other constituents to form stacks. Higher amount of pectin is present in the primary cell wall and the middle lamella of lignocellulosic fibril. During the process of retting, most of the pectin contents get removed from the natural fiber. Only after the removal of pectin does the natural fiber get qualified to be employed as reinforcement material with polymer matrices. Pectin is another component which makes the cellulose fibers get attached to all other constituents of the fiber. When compared to cellulose, lignin and pectin are the weaker amorphous polymers [40].

3. Effect of Various Chemical Treatments on the Mechanical Properties of Composites

Kobayashi et al. [41] discussed the mechanical properties of the hemp fiber-reinforced composite fabrication, and the hemp fiber was chemically treated to improve compatibility between fiber and the matrix. The authors found that the physical and mechanical properties of the natural and synthetic fibers were influenced by climate/natural/environmental changes. Hence, the surface of the hemp fiber was treated by chemical treatment process like acetyl, alkali, and silane. Alam et al. [42] explored the tensile strength of a new composites, combined with untreated kenaf, treated kenaf, jute fiber, and jute rope. They observed that the tensile strengths of kenaf and jute fiber are higher than that of jute rope. Similarly the water absorption properties of treated fiber were higher than those of untreated fibers. The stress transfer capacity of the fiber gets improved as a result of micro void exclusion and the fiber surfaces turn more uniform. The diameter of the fiber is also improved owing to the axial splitting of the fibrils [43]. Wang et al. [44] studied the feasibility of using coffee hull as reinforcement member with high density polyethylene matrix. Improvement in mechanical characteristics of the coffee hull polyethylene composites was compared against various chemical modifications done on the coffee hull powder. It was found that coffee hull powder subjected to calcium hydroxide treatment resulted in maximum strength of the composites. The fiber loading was found to increase up to 10 wt% above which the tensile strength decreases, whereas the flexural strength was found to be prominent for coffee hull treated with maleic anhydride grafted polypropylene. The moisture absorption property was found to be significant for the composite subjected to calcium hydroxide treatment. Therefore it was concluded that coffee hull powder could be a possible alternate for synthetic fiber. Rout et al. [45] conducted morphology analysis of palm tree leaf stalk fibers, where the SEM images confirmed the removal of wax, oil, and hemicellulose content from treated fibers. The cleaner surfaces besides pores were noticed in treated fibers compared to untreated fibers. The natural plant fibers have many advantages; there are also a few limitations which have to be studied. The major limitation of natural plant fibers is their hydrophilic nature which restricts the use of the fibers as reinforcement in PMC. The inappropriateness between the hydrophilic fibers and hydrophobic matrix results in swelling due to moisture absorption and it shows the poor interfacial bonding between matrix and the fibers [46–48]. Improvement was found in the interfacial bonding between the fiber and matrix due to the chemical treatments of fibers which also reduce the hydrophilicity, fiber surface cleanness, the moisture absorption, and improvement in the surface roughness [49]. Various natural fiber surface treatments like alkaline, silane, acetylation, and preimpregnation with polyethylene solution resulted in the enhancement of strength due to increase of interfacial bonding between fiber and matrix [50]. Venkatesha Gupta et al. [51] developed a new composite material which had the highest strength to weight ratio in comparison to existing composite materials. Sisal and hemp fibers were reinforced with epoxy matrix prepared using compression moulding method according to ASTM standard. For alkali treatment, NaOH (sodium hydroxide) was used and the amount of reinforcement was changed from 10% to 50% by weight. After the specimen was prepared, various mechanical properties were investigated and it was proved that the prepared specimen was better in terms of mechanical properties. Athipathi and Hegde Sowmitha Vijay [52] discussed the experimental evaluation based mechanical properties of coir and *Roystonea regia*-epoxy laminate with various fiber contents ratios. Orientation of the fiber was maintained as 0°, 45°, and 90°. From the results, three different points were observed. The untreated matrix-material based composite exhibits high tensile strength, high flexural strength, and high impact strength. The fibers were subjected to 30% NaOH solution treatment for 1 h. The mechanical and electrical properties of composites with treated fibers were compared with those of untreated fiber composites. The modification of plant based lignocellulose fibrils by sodium hydroxide is the most widely adopted technique to alter the cellulose molecular portion of the natural fiber. The coir/epoxy composites were used in the seat cushions, mirror casing, storage tank, post boxes, helmet casing, brushes, ropes, bags, brooms, door shutters, and building panels. The alkali treatment results in formation of amorphous region from the densely packed crystalline cellulose structure. The alkali-sensitive hydroxyl units existing in the natural fibers were removed, which further react with the water molecules. Thereby the moisture resistance property of the fiber improved. The alkali treatment also removes some portions of hemicellulose, lignin, pectin, wax, and other surface related impurities present in the natural fiber [53, 54]. Thereby the effective bonding between the fiber and the matrix is also enriched and the mechanical and thermal properties of the composites are improved. When the percentage of alkali treatment is increased, excess delignification of the natural fiber occurs, which leads to damage of fibers, and the mechanical properties of the fibers get reduced [55]. Alkalized lignocellulose fibers have reduced lignin content, partial removal of wax and oil covering substances happens, and disintegration of crystalline cellulose occurs.

More research articles have been published on the influence of mercerization on the mechanical and thermal properties of lignocellulose fiber-reinforced polymer matrix composites [56, 57]. Sathish et al. [53] explored the influence of mercerization of date palm fibers on the mechanical, thermal, and morphological properties. It was reported that 5% of NaOH concentration enhanced mechanical and thermal behaviour of the composites. When the percentage of sodium hydroxide was increased to 10%, deterioration on the properties was observed owing to the damage of fibers at increased concentration. The thermal resistance of the fiber was also improved due to the pulling out of waxy layers and various surface impurities present in the date palm fibers. Chen et al. [58] investigated the wettability and thermal stability of bamboo fibers exposed to alkali treatment. The percentage of alkali treatment was varied; it was found that surface roughness of the bamboo fiber was increased and found to be optimum at 15% of NaOH treatment. The thermal stability and wettability were also found to be promising for the similar alkali concentration. Reddy et al. [59] investigated the tensile and structural properties of borassus fruit fine fibers subjected to 5% of alkali treatment under different treatment time. The crystallinity of the fibers was analysed by X-ray diffraction technique. The removal of amorphous hemicellulose substance was witnessed by FTIR analysis. The concentration time of 8 hours resulted in optimum fiber properties. It was also found that the borassus fibers will be a suitable reinforcement for the manufacturing of green composites. Balaji and Nagarajan [60] investigated the tensile and chemical behaviour of cellulose fibers extracted from saharan *Aloe vera* cactus leaves exposed to mercerization treatment. The fibers exposed to mercerization resulted in removal of hemicellulose, lignin, wax, and other surface related impurities present in the fibers. It was also found that the hydrophobic nature of the lignocellulose fibrils is lowered and interfacial adherence among the fibrils and the matrix enhanced. Increase in thermal stability of the fibrils was witnessed by TG analysis. The SEM analysis also confirmed the removal of hemicellulose, lignin, wax, and other layers present in the fibers. Finally, it was found that natural fiber extracted from saharan *Aloe vera* cactus leaves was found to be a suitable alternate to synthetic fibers for reinforcement with polymer matrix. Dawit et al. [61] explored the property of *Acacia tortilis* fibrils extracted from the barks of *Acacia tortilis* tree. The extraction of fiber was based on natural water based retting. The extracted fibers were subjected to mercerization treatment with 10% and 20% of NaOH solution. The alkalization of the fiber resulted in removal of hemicellulose, lignin, wax, and other surface related impurities present in the fiber. As the percentage of alkali treatment is increased to 20%, decrease in tensile strength of the fibrils was noted. This phenomenon could be explained as follows: when the concentration of alkali solution exceeds the limit, the diameter of the fiber gets reduced even further, which results in reduced tensile strength. It was also concluded that *Acacia tortilis* fiber could be a viable alternate for manmade fiber in polymer composite applications. Narayanasamy et al. [62] explored the possibility of lignocellulose fibril extracted from *Calotropis gigantea* fruit bunch as a possible alternate for artificial fiber-reinforced polymer composites. The fibers were extracted from the fruits of *Calotropis gigantea* fruit bunch through retting process. Then the extracted fibers were mercerized with 5% of NaOH. XRD and FTIR analysis revealed the removal of hemicellulose, lignin, wax, and other surface related impurities existing in the fibers. The thermal stability of the fibrils was also enriched by the influence of alkali treatment, which is inferred by TG analysis. Finally SEM analysis revealed that the surface of fibers was rougher due to alkali treatment. Negawo et al. [63] researched the effect of alkali modification on the *Ensete* stem fibrils obtained from the Ethiopian *Ensete ventricosum* plant. The fibers were subjected to 2.5%, 5%, and 7.5% of mercerization. The mercerization resulted in removal of lignin, wax, and hemicellulose existing in the fibrils. The 5% mercerized fibers exhibited better properties when compared with untreated fibrous composites owing to the enhanced interfacial adherence between the fiber and the matrix. The 5% alkalized fibers exhibited better mechanical properties under static and dynamic conditions. From the experimentation, it was also concluded that *Ensete* stem fiber could be a possible alternate to synthetic fiber-reinforced polymer composites for wide assortment of applications. Reddy et al. [64] studied the influence of NaOH and KOH fiber surface modifications on the mechanical properties of Tapsi fiber-reinforced epoxy composites manufactured by hand layup technique. Initially the fibrils were pretreated with 5% of concentrations for two hours. Composites were manufactured by varying the fiber weight fraction. Tensile and flexural test performed on the composite samples revealed that composites with 15% of fibers exhibited higher properties for NaOH-treated fibers when compared to KOH-treated fibers. FTIR analysis revealed the removal of functional groups present in the fibers and XRD analysis revealed the improvement of crystallinity index and size for NaOH-treated fiber-reinforced composite samples when compared to KOH-treated sample. SEM analysis revealed fiber pull-out as a result of improper fibril wetting, which resulted in poor adherence between the interfaces of fiber and matrix in the composites. Senthilkuamr et al. [65] reviewed the mechanical properties of sisal fiber-reinforced polymer composites. The sisal fibers have been extracted by the process of decortication and the extracted sisal fibers were exposed to chemical treatment like alkalization and coupling agents. The pretreated sisal fiber showed improvement in mechanical, hydrophilic tendency resulting in effective bonding between the interfaces of fiber and polymer matrix. The mechanical properties of the developed composites depend on different characteristics like fiber length, fiber orientation, fiber volume fraction, and several other parameters. Appreciable enhancement in mechanical properties was found owing to the chemical modifications on the surface of sisal fibers. Overall, it was concluded that the enrichment in properties of the sisal fiber-reinforced composites depends on surface treatment concentration type and time; beyond the concentration level, deterioration in properties of the fibers was noticed. It was also concluded that impact strength of the sisal fiber composites decreased as a result of chemical modifications done on the sisal fibers. Balaji et al. [66] explored the influence of fiber content on the mechanical properties of the alkali-treated bagasse fiber reinforced with cashew nut shell liquid. Initially the fibers were chopped to 10 and 20 mm and the composites were prepared by compression moulding technique by varying the fiber volume fraction as 0, 5, 10, 15, and 20 wt%. The tensile and flexural test revealed that maximum strength was attained for 15 wt% of fiber-reinforced composites. FTIR analysis revealed the removal of functional groups present in the fibers owing to the alkali treatment of sugarcane bagasse fiber. The thermal stability of the fibers was also enhanced due to the mercerization and SEM analysis revealed the enhanced interfacial adherence between the fiber and the matrix which resulted in the homogeneous nature of composite. Komal et al. [67] investigated the prominence of alkalization done on the surface of banana fibers. The surface modified banana fibers were reinforced with polypropylene and then the tensile, flexural, and impact strength and degradation behaviour were studied for untreated and surface modified banana fiber-reinforced polypropylene composites. Thermogravimetric analysis revealed removal of hemicellulose, lignin, pectin, wax, and other surface related impurities present in the banana fiber as a result of mercerization. Significant enhancement in tensile and flexural strength was found between untreated and pretreated banana fiber-reinforced polypropylene composites. Improvement of impact strength by 11.5% was observed for untreated and mercerized banana fiber-reinforced polypropylene composites. The tested composite samples were subjected to morphology analysis by scanning electron microscope to study the fracture behaviour of the composite samples. Fiber pull-outs were observed in untreated banana fiber-reinforced polypropylene composite; as a result, tensile and flexural strength of the composites decreased in contrast with alkali-treated and untreated banana fiber-reinforced polypropylene composite. Marginal reduction in weight loss of the samples was also observed. Alkali-treated banana fiber-reinforced polypropylene composites absorbed less water as the hydrophilic tendency of the fiber was altered by alkali treatment, whereas the untreated banana fiber-reinforced polypropylene composites absorbed water due to higher hydrophilic tendency. Ameer et al. [68] explored the mechanical and moisture characteristics of hydrophilic modified jute fiber-reinforced unsaturated polyester composites. The extracted jute fiber was exposed to mercerization treatment to improve the hydrophilic tendency. Better interlocking in the middle of fiber and matrix was attained by the removal of amorphous substances present in the jute fibers. The mercerization treatment resulted in significant reduction in hydrophobic nature of the jute fiber. The mercerized jute composites showed improved mechanical properties in contrast with untreated jute composites. Chin et al. [69] investigated the mechanical and thermal characteristics of bamboo fiber-reinforced composites, where the bamboo fibers were exposed to mercerization with different concentrations over varying time. The effect of alkali treatment was inferred with FTIR and XRD analysis. Enhancement in crystal size and crystallinity index was observed by XRD analysis and removal of lignin, cellulose, and other surface related impurities was observed by FTIR analysis. The thermal stability of the composites was also enhanced, which was evident from the thermogravimetric analysis. The composites with 40 wt% contributed to maximized tensile and flexural properties of the composites. Balaji et al. [66] explored the mechanical properties of sugarcane bagasse fiber-reinforced cardanol composite. Mercerization of fiber resulted in removal of amorphous substances and improved interlocking between the bagasse fiber and cardanol matrix. The composites with 15 wt% of fiber exhibited better properties. Senthamaraikannan et al. [70] explored the possibility of using *Acacia planifrons* fibers as possible reinforcement material with polymer matrices. The fibers were extracted by the process of retting. The extracted fibers were subjected to mercerization with varying percentage of sodium hydroxide. It was found that the mercerization leads to improvement of crystallinity index and thermal stability and removal of amorphous substances present in the fibers. The optimal alkali treatment is found to be 5%. Tables 1–10 present the effects of various chemical treatments of biofibers.

Mouhoubi et al. [174] reported the SEM images of alfa fiber with alkali treatment (5% NaOH) at different time intervals (2 h, 4 h, 6 h, and 24 h). Figures 1(a)–1(e) represent the alfa fiber. Figure 1(b) shows the fiber treated with 5% NaOH at 2 h. During this time period, the waxy substances in the fiber were removed. Figures 1(c)–1(e) show that the fiber resulted in low moisture absorption, removal of extractives, and increase in crystallinity and stiffness.

Table 1: Effect of alkaline treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Kenaf	Alkaline treatment	At 6% concentration of NaOH it has good effect on kenaf fiber resulting in removal of all impurities from the surface.	[71]
2	Bamboo, kenaf, hemp, sisal, jute, and kapok	Alkaline treatment	The treatment removed the noncellulose constituent in fibers such as lignin, wax, and oils, promoted ionization of hydroxyl group of cellulose to alkoxide, and reduced the hydroxyl group content. The treatment improved the surface roughness and hydrophobicity resulting in good adhesion.	[72]
3	Pineapple leaf	Alkaline and acetic	Improvements in tensile strength, impact strength, and flexural strength.	[73]
4	Abaca	Alkaline and silane treatment	The silane-treated fiber has higher thermal transfer coefficient.	[73]
5	Bamboo	Alkaline treatment	An enhancement in tensile strength by adding 30% treated bamboo which is slightly higher than silane-treated composite.	[74]
6	Sisal	Alkaline treatment	Improvement in interfacial shear strength.	[75]
7	Sisal/hemp	Alkaline treatment	At 10% concentration of NaOH, enhanced the flexural strength by adding 40 wt% sisal and hemp.	[75]
8	Curaua	Alkaline treatment	An increase in NaOH concentration and decrease of fiber diameter, fiber density, and fiber weight.	[76]
9	Ramie	Alkaline treatment	Alkali treatment possesses better tensile strength than silane-treated fiber composite.	[76]
10	Hemp	Alkaline treatment	The treated fiber has high crystallinity resulting in improvement in tensile strength and Young's modulus.	[76]
11	Jute	Alkaline treatment	The treatment removed hemicellulose, pectin, and lignin resulting in decreased fiber diameter.	[76]
12	Basalt	Alkaline treatment	The NaOH-treated fiber has superior properties compared to glass fiber.	[76]
13	Banana	Alkaline treatment	5% NaOH-treated fiber has better properties.	[77]
14	Luffa/coir	Alkaline treatment	Improvement in tensile and flexural strength and hardness.	[78]
15	Luffa/groundnut fiber	Alkaline treatment	An increment in mechanical properties by removal of hemicellulose, wax, lignin, and impurities from the fibers, thus increasing the adhesive characteristics of composite.	[79]
16	Abaca	Alkaline treatment	Improvement in moisture resistance.	[80]
17	Alfa	Alkaline treatment	At 10% of NaOH content, increases in flexural strength and flexural modulus by 60% and 62%, respectively, and fiber becomes stiffer and brittle.	[81]
18	Drumstick (*Moringa oleifera*)	Alkaline treatment	The addition of glass fiber increased impact strength and frictional coefficient.	[82]
19	Ladies finger	Alkaline treatment	Double-stage chemical treatment possessed better properties than single-stage treatment, while an increase in span length decreased the tensile strength and increased Young's modulus.	[83]
20	Tamarind	Alkaline treatment	Chemically treated 2 cm fiber length was optimum to achieve better hardness, impact, and frictional coefficient.	[84]
21	Vetiveria zizanioides/jute	Alkaline treatment	The treated fibers improved tensile strength, flexural strength, and impact strength by 26.8%, 30.44%, and 59.1%, respectively.	[85]
22	Borassus	Alkaline treatment	At 5% of NaOH content, significantly increased tensile properties.	[86]
23	Palm wood	Alkaline treatment	The optimum residual mass at 0% to 0.75% NaOH. With further 1% NaOH it decreased.	[87]
24	Palmyra palm leaf stalk fiber (PPLSF)/jute	Alkaline treatment	The alkali-treated PPLSF has maximum tensile and flexural properties by the addition of alkali-treated jute fiber.	[88]
25	*Roystonea regia*	Alkaline treatment	Improvement in tensile and flexural properties.	[88]
26	*Borassus flabellifer* (Asian palmyra)	Alkaline treatment	Improvement in tensile strength.	[88]
27	Buriti and ramie	Alkaline treatment	At 2% NaOH treatment of ramie fiber, increased flexural strength by 70%. However, alkali treatment was only favorable for buriti fibers.	[89]

Table 1: Continued.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
28	Rice husk	Alkaline treatment	An increase in cellulose content, resulting in increased crystallinity index. Therefore diameter decreased from 170 to 7 mm, as well as further diameter value from 10 to 15 nm by performing acid hydrolysis treatment.	[90]
29	Rice husk	Alkaline treatment	Improvement in adhesion characteristics.	[90]
30	Jute	Alkaline treatment	An increase in flexural strength, modulus, and interlaminar shear strength.	[91]
31	Coir	Alkaline treatment	At 5% alkali treatment increases in impact and flexural strength for 72 h by 40%.	[92]
32	Jute	Alkaline treatment	At 5% alkali treatment increases in flexural strength for 4 h by 20%.	[93]
33	Banana	Alkaline treatment	At 1% alkali treatment enhanced flexural strength, flexural modulus, tensile strength, and tensile modulus by 20, 12, 132, and 131%, respectively.	[94]
34	Ramie	Alkaline treatment	At 9% alkali treatment enhanced tensile strength for 1 h by 23%.	[95]
35	Jute	Alkaline treatment	An increase in flexural strength, flexural modulus, and interlaminar shear strength by 35%, 23%, and 19%, respectively.	[93]
36	Abaca/roselle	Alkaline treatment	The treatment increased fiber/matrix adhesion property due to removal of hemicellulose, waxes, lignin, and impurities from the fibers.	[96]
37	Jute	Alkaline treatment	The treatment removed the hemicellulose and promoted the interlocking points in the fiber for better adhesion and stress transfer across the interface resulting in increased tensile strength, flexural strength, flexural modulus, and interlaminar shear strength.	[97]
38	Jute	Alkaline treatment	The treatment increased the cellulose content after removal of pectin, lignin, and other impurities. An increase in cellulose content leads to better interfacial adhesion.	[98]
39	Sisal	Alkaline treatment	The treatment had better mechanical properties due to good adhesion between fiber and matrix.	[99]
40	Oil palm	Alkaline treatment	A bigger increase in flexural strength by performing 24-hour NaOH treatments compared to other chemical treatments.	[100]
41	Jute	Alkaline treatment	At 25% fiber loading and 10% NaOH treatment showed increase in tensile strength due to decrease in fiber diameter and density.	[101]
42	Jute	Alkaline treatment	At 20% fiber loading and 10% NaOH treatment showed increase in tensile strength due to decrease in fiber diameter and density.	[102]
43	Napier grass	Alkaline treatment	The 12 h soaking time of treated fiber had least fiber diameter and mass. The 6 h soaking time exhibited highest tensile strength. An increase in surface roughness with the increase in soaking time beyond 18 h. However, 24 h-treated fiber had damage on its surface.	[103]
44	Henequen	Alkaline treatment	The treated fiber had higher adsorption rate at 100 h to attain adsorption equilibrium.	[50]
45	Sisal	Alkaline treatment	The 45 min of treatment yielded more level of crystallinity with more cell wall structure. Tensile and shear strength were increased by 12.04% and 173%, respectively.	[104]
46	Sisal	Alkaline treatment	An increase in crystallinity decreased the absorption rate. Optimum fiber length 5.8–9 cm displays better performance in tensile strength with increase in fiber loading.	[105]
47	Ladies finger	Alkaline treatment	Removal of hydrophilic hemicellulose led to enhanced surface roughness.	[83]
48	Kenaf	Alkaline treatment	Chemically treated 6% NaOH sample was optimum to achieve better tensile strength and modulus of elasticity.	[106]

Table 1: Continued.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
49	Kenaf	Alkaline treatment	At 9% NaOH alkali treatment displayed cleanest surface although tensile strength decreased. However, 6% NaOH alkali treatment with higher temperature was optimum in cleaning fiber.	[49]
50	Banana	Alkaline treatment	An enhancement in tensile modulus and impact and tensile strength by adding 3 wt% of fiber.	[107]
51	Banana	Alkaline treatment	At 10% of NaOH content, significantly increased thermal conductivity.	[108]
52	Banana	Alkaline treatment	At 4% concentration of NaOH, enhanced the tensile strength, tensile modulus, and flexural strength.	[109]
53	Banana	Alkaline treatment	Alkali treatment possesses better tensile strength and flexural strength when compared with benzoylation and PSMA treatment.	[110]
54	Banana	Alkaline treatment	The treatment decreased modulus of rigidity, tensile strength, and strain due to degradation of cellulose.	[111]
55	Pineapple leaf	Alkaline treatment	An increase in fiber density, cellulose, and crystallinity led to enhanced tensile strength, thermal stability, and water retention with increasing the NaOH up to 7% concentration.	[112]
56	Pineapple leaf	Alkaline treatment	The treated fiber significantly improved the flexural strength, impact strength, storage modulus, and thermal resistance by 79%. Heat deflection temperature (171.3°C) which is close to the melting temperature of neat polymer. Reduction in crystallization by 14°C.	[113]
57	Pineapple leaf	Alkaline treatment	An enhancement in Young's modulus by 30% compared to untreated fiber.	[114]
58	WSF	Alkaline treatment	An enhancement in thermal stability by adding 3% NaOH.	[115]
59	Banana	Alkaline treatment	At 1% NaOH treatment possess better properties.	[94]
60	Hemp	5% NaOH, 0.5% silane	The combined NaOH and silane treatment increased the tensile and flexural strength by 100% and 45%, respectively. But fracture toughness decreased.	[116]
61	Jute	Alkaline treatment	At 4% NaOH treatment increased tensile strength up to 30%.	[117]
62	Agave	Alkaline treatment	Increased the fiber matrix adhesion and fracture strain.	[118]
63	Palm leaf stalk/jute	Alkaline treatment	An increase in storage modulus and loss modulus by addition of jute fiber.	[88]
64	Coir	Alkaline treatment	Enhancement in mechanical properties, moisture resistance, and adhesion properties.	[119]
65	Flax	Benzoylation, peroxide, mercerization, silane treatment.	The treatment exhibited improved mechanical and physical properties.	[120]
66	Hemp/jute	Alkaline treatment	Increase in crystallinity can enhance the fiber strength.	[121–123]
67	Hemp	Alkaline treatment	An increase in crystallinity of PLA matrix due to crystalline cellulose in the alkaline-treated hemp fibers, which acts nucleating sites resulting in increase in fiber strength.	[124]
68	Kenaf/hemp	Alkaline treatment	The treated fiber found to have better mechanical properties, thermal stability, and moisture resistance.	[125, 126]
69	Sisal	Combined NaOH + actylation	Increase in mechanical properties due to better adhesion between fiber and matrix.	[104]
70	*Tridax procumbens*	Alkaline treatment	At 5% concentration of NaOH, enhanced the wettability and crystallinity and reduced amorphous region and fiber diameter.	[127]

Figure 2 represents the SEM images of untreated and treated *Prosopis juliflora* fiber-reinforced epoxy composites at different concentrations (5%, 10%, and 15%). Figure 2(a) shows the untreated fiber surface which consists of impurities and fiber pull-outs on the surface. This was due to the waxy substances present on the surface of the fiber and the existence of hydroxyl groups, which leads to water absorption, weakening interfacial strength with the matrix. Figures 2(b)–2(d) represent the treated *Prosopis juliflora* fiber-reinforced epoxy composites at concentrations of 5%, 10%, and 15%, and increase in alkali treatment beyond 5% damaged the fiber surface and reduced the cellulose content in the fiber, which in turn resulted in lower strength and stiffness [175].

Liu et al. [176] researched the supremacy of silane coupling agent treatment done on the surface of corn stalk

Table 2: Effect of silane treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Kenaf	Silane treatment	The presence of lignin and hemicellulose was removed by performing silane treatment. Removal of lignin and hemicellulose led to enhanced interfacial bonding.	[71]
2	Pineapple leaf	Silane treatment	The treated fiber has fewer voids on the interface which makes strong interfacial bonding and results in better mechanical properties.	[71]
3	Abaca	Mercerization and silane treatment	The silane-treated fiber has higher thermal transfer coefficient.	[73]
4	Bamboo	Silane treatment	An enhancement in tensile strength by incorporation of 30% treated bamboo, while flexural strength is higher than that of NaOH-treated fiber.	[74]
5	Sisal	Silane treatment	The treatment enhances the mechanical properties and moisture resistance.	[75]
6	Hemp/ kenaf	Silane treatment	The treatment possesses higher flexural modulus in comparison with alkali-treated composite and similar to glass fiber composite.	[128]
7	Hemp	Silane treatment	Flexural and tensile strength were increased by 2% and 4%, respectively.	[129]
8	Kenaf	Silane treatment	An enhancement in storage modulus and viscoelasticity by 45% and 25%, respectively.	[130]
9	Oil palm	Silane treatment	Reduced the mechanical properties due to poor adhesion between fiber and matrix.	[131]
10	Henequen	Silane treatment	An enhancement in tensile strength from 21 MPa to 27 MPa by performing combination of silane and NaOH.	[50]
11	Sisal	Silane treatment	The treated fiber had higher impact strength compared to alkali-treated fibers.	[132]
12	Banana	Silane treatment	An increase in flexural strength about 160% and considerable increase in tensile and toughness.	[133]
13	Banana	Silane treatment	An enhancement in impact and tensile strength by 30.84% and 19.43%, respectively, and slight increase in tensile modulus.	[134]
14	Jute	Silane treatment	An increase in strength and modulus about 12% and 7% by alkali treatment followed by silane treatment.	[135]
15	Jute	Silane treatment	At 0.3%, silane-treated composites enhanced the tensile, flexural, and interlaminar shear strength by 40%, 30%, and 55%, respectively.	[113]
16	Pineapple leaf	Silane treatment	Improvement in flexural modulus and storage modulus by 47% as compared to alkali treatment.	[114]
17	Pineapple leaf	Silane treatment	The resulting composite has less Young's modulus than alkali-treated composites.	[136]
18	Pineapple leaf	Silane treatment	Reduction of hydrophilic tendency of the fibers leads to increase in tensile strength and crystallinity size but % crystallinity decreases.	[72]
19	Hemp	Silane treatment	Found maximum mechanical properties compared to other chemical treatments.	[137–139]

Table 3: Effect of acetylation treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Coir/oil palm	Acetylation treatment	A bigger increase in tensile strength, flexural strength, Young's modulus, and impact strength by performing acetylation treatment compared to silane treatment.	[140]
2	Flax	Acetylation treatment	An enhancement in tensile and flexural strength by 35%.	[141]
3	Abaca	Acetylation treatment	The treatment possessed higher tensile strength, Young's modulus, and impact strength by 81, 70, and 8%, respectively.	[133]
4	Oil palm	Acetylation treatment	The treatment has high strain value which resulted in enhanced elastic and impact property.	[100]
5	Green flax	Acetylation treatment	At 65% of relative humidity, decrease in the moisture absorption. An increase in thermal stability with increase in degree of acetylation. About 25% improvement in strength properties was observed compared to untreated composites.	[139]
6	Flax	Acetylation treatment	At 18% of acetylation, concentration of flax fiber exhibited better tensile strength and thermal stability by 25% and 50%, respectively. However, the addition of maleic anhydride resulted in increase in mechanical properties by 20–35%.	[139]

Table 3: Continued.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
7	Sisal	Acetylation treatment	Improvement in tensile strength and shear strength by 14.08% and 435%, respectively. The acetic acid treatment followed by ethyl acetate with H_2SO_4 resulted in high levels of cellulose swelling or loosened cell wall structure.	[104]
8	Sisal	Acetylation treatment	A decrease in dielectric constant with increasing frequency.	[105]
9	Banana	Acetylation treatment	The treated fiber has high fibrillation and is more rougher resulting in better tensile properties than mercerization treatment.	[109]
10	*Grewia serrulata* bast	Acetylation treatment	The treated fiber has better dimensional stability and more moisture resistance. However, high degree of ultraviolent energy can degrade the composite.	[142]
11	Phosphate bonded composite	Acetylation treatment	The treated fiber reduces water absorption and hence improves dimensional stability, tensile strength, and stiffness. However, this treatment reduces the impact strength as compared to other chemical treatments.	[143]

Table 4: Effect of permanganate ($KMnO_4$) treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Sisal	Permanganate treatment	Improvement in tensile strength.	[75]
2	Oil palm	Permanganate treatment	The treated fiber has highly fibrillated structure and hence very good fiber matrix adhesion. As a result, better tensile strength and modulus were observed	[100]
3	Sisal	Permanganate treatment	At 1% concentration of $KMnO_4$ polar groups between fiber and matrix are formed leading to degradation of cellulose. The hydrophilic tendency of fiber decreases as the $KMnO_4$ concentration increases up to an optimum.	[105]
4	Sisal	Permanganate treatment	At 1% concentration, higher degradation of cellulose occurred due to formation of polar group. Optimum properties were found to be better at 0.055% concentration. Tensile properties were observed between alkali and peroxide.	[144]
5	Sisal	Permanganate treatment	Improvement in interlaminar shear strength, tensile strength, and flexural properties compared to silane. But impact properties were lower than those of untreated fiber.	[145]
6	Banana	Permanganate treatment	An increase in thermal diffusivity, tensile strength, and tensile modulus by 16%, 6.4%, and 7.5%, respectively. However, flexural strength and modulus were found to have increases of 6% and 10%, respectively, which were lower compared to alkali and silane treatment.	[108]
7	Flax	Permanganate treatment	Improvement in tensile and moisture resistance as compared to alkali and silane-treated fibers.	[108]
8	Banana	Permanganate treatment	An increase in tensile strength and flexural strength by 5% and 10%, respectively. Increases in polarity and roughness of fiber were also observed.	[146]

Table 5: Effect of peroxide treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Sisal	Peroxide treatment	Enhancement in tensile properties.	[72]
2	Sisal	Peroxide treatment	Crystallinity index and decomposition rate were found to be better at soaking time of 30 min.	[146]
3	Kenaf	Peroxide treatment	At 30% fiber loading exhibited higher tensile and flexural strength, whereas modulus was high at 40% fiber loading.	[146]
4	Oil palm	Peroxide treatment	Improvement in flexural modulus as compared to other chemical treatments.	[147]
5	Sisal	Peroxide treatment	50% higher tensile strength of treated fiber compared to untreated fiber composites.	[105]
6	Jute	Peroxide treatment	The treatment exhibited better tensile and flexural properties than alkali and permanganate treatment, but not as superior as silane treatment, whereas the thermal stability was reduced.	[105]
7	Pineapple leaf	Peroxide treatment	Better in tensile strength, tensile modulus, and abrasion resistance as compared to untreated composites. But there was a reduction in elongation breaks.	[148]
8	Wheat straw	Peroxide treatment	The treated composites were found to have increase in ash content. Removal of lignin was around 50%.	[149]

Table 6: Effect of benzoylation treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Sisal	Benzoylation treatment	Improvement in tensile strength by 91%.	[75]
2	Jute	Benzoylation treatment	Improvement in storage modulus and thermal stability.	[150]
3	Flax	Benzoylation treatment	The treated composites were found to have highest tensile and impact strength for LDPE and highest impact strength for HDPE. Resulted in less water absorption as compared to silane and peroxide. Smooth fiber surface was observed.	[43]
4	Sisal	Benzoylation treatment	At 6% of benzoyl peroxide showed better mechanical properties.	[83]
5	Banana	Benzoylation treatment	The treatment significantly improved thermal conductivity and was found to have increase in tensile strength and modulus by 13% and 5%, respectively, although not as good as alkali and silane-treated fiber.	[109]
6	Sisal	Benzoylation treatment	The treatment increased the activation energy for glass transition temperature (Tg). Maximum activation energy was observed.	[151]

Table 7: Effect of acrylation treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Bagasse	Acrylation treatment	Acrylation treatment offers superior tensile and flexural strength compared to alkali treatment.	[152]
2	Oil palm	Acrylation treatment	The treatment yielded higher extension and impact resistance. At 40% of fiber with 50°C exhibited moderate level of moisture absorption compared to other treatments.	[102, 155]
3	Flax	Acrylation treatment	The treated fiber exhibited higher tensile strength and moisture resistance than those treated with silane, permanganate, and sodium chloride treatment. Higher smooth fiber surface was observed.	[131]
4	Flax	Acrylation treatment	At higher concentration, grafting was increased due to higher availability of monomer molecules in cellulose radicals as well as polymerization medium.	[154]
5	Jute	Acrylation treatment	An increase in tensile strength and flexural strength by 42.2% and 13.9%, respectively.	[155]

Table 8: Effect of acrylonitrile grafting treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Pineapple leaf	Acrylonitrile grafting	Improvement in tensile strength by adding AN (acrylonitrile grafting). It has major effect on tensile strength.	[75, 102]
2	Oil palm	Acrylonitrile grafting	The treatment showed high strain rate and elastic modulus. But slight improvement in stiffness was absorbed. However at 40 wt% of fiber with 50°C exhibited higher moisture resistance compared to other treatments.	[153]
3	Agave Americana fibers	Acrylonitrile grafting	An increase in percentage of graft and decrease in the moisture resistance, in addition to improvement in thermal stability of fiber.	[156]
4	Sisal	Acrylonitrile grafting	The treatment showed enhanced tensile and flexural strength as compared to other treatments. Least degradability of fibers was observed.	[157]
5	Pineapple leaf	Acrylonitrile grafting	The treatment possesses lower grafting yield than unmodified fibers.	[158]
6	Cellulose polymer	Graft copolymerization	Improvement in physical, chemical, and thermal resistance.	[159]

fibers extracted from the waste of corn stalk. Initially the fibers were modified with different percentages of silane concentration such as 1%, 5%, 9%, and 13%. The effect of silane treatment on corn stalk fibers was investigated by FTIR and XRD analysis. Results showed improvement in the crystalline size for 5% silane-treated fiber and also removal of hemicellulose, lignin, and other impurities present in the fibers was found by FTIR analysis. The impact behaviour of the composites was also found to be superior for 5% silane-treated corn stalk fiber-reinforced composites. Finally SEM analysis revealed that the surface of fibers was rough in contrast with untreated fiber owing to the effect of silane treatment. Liu et al. [177] investigated the effect of silane coupling agent on the mechanical, tribological, and morphological characteristics of corn stalk fiber-reinforced polymer composites. The extracted corn stalk fibers were

Table 9: Effect of isocyanate treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Oil palm	Isocyanate treatment	At 40% fiber loading exhibited higher moisture absorption (280%) compared to other treatments.	[153]
2	Sisal	Isocyanate treatment	The treatment exhibited superior tensile properties than alkaline and untreated fibers but with decrease in dielectric constant.	[107, 146]
3	Pineapple leaf	Isocyanate treatment	The treatment reduced hydrophilic tendency of the fiber compared to silane-treated composites. Reduction in % of crystallinity leads to increase in tensile strength.	[136]
4	Jute/hemp/flax	Isocyanate treatment	The treatment increased stiffness and reduction in impact by 17%.	[31]
5	Fibrous cellulose	Isocyanate treatment	The treatment shows enhanced tensile, elongation, and interfacial adhesion.	[160]
6	Kenaf	Isocyanate treatment	The presence of isocyanate hydrolysis to urea, reacting with hydroxyl group of fiber, decreases the moisture absorption and increases the mechanical properties.	[72]
7	Sisal	Isocyanate treatment	Improvement in tensile strength	[161]

Table 10: Effect of maleic anhydride grafted treatment on various biofibers.

S. no.	Fibers used	Type of chemical treatment	Effects	Ref.
1	Jute	Maleic anhydride grafted	Coupling agent has greater effect on Young's modulus and dynamic storage modulus.	[162]
2	Flax and hemp	Maleic anhydride grafted	The treatment improved dynamic and mechanical properties.	[163]
3	WSF	Maleic anhydride grafted	The treatment significantly reduced crystallinity and thermal stability is higher than that in acetylation treatment.	[164]
4	Wood flour	Maleic anhydride grafted	An enhancement in tensile strength and modulus properties became twice as compared with untreated fibers.	[165]
5	Sisal	Maleic anhydride grafted	Improvement in tensile, flexural, and impact strength by 50%, 30%, and 58%, respectively. Reduction in water absorption by 61%. Higher level of crystallinity was also observed.	[166]
6	Banana/hemp/sisal	Maleic anhydride grafted	Reduction in moisture resistance compared to untreated fiber. At 50% fiber loading, increases in tensile, flexural, and impact strength. Flexural modulus values were higher than those of untreated fiber.	[167]
7	*Hildegardia*	Maleic anhydride grafted	An increase in tensile properties with addition of compatibilizers.	[168]
8	Pineapple leaf	Maleic anhydride grafted	The treated fiber exhibited increased aspect ratio and matrix resulting in increased tensile strength, impact strength, and flexural strength by 9%, 30%, and 3%, respectively, compared to untreated fibers	[169]
9	Jute/sisal	Maleic anhydride grafted maleated HDPE	At 1% concentration of coupling agent increased the dynamic (storage modulus and loss modulus) and static (tensile, flexural, and impact) mechanical properties.	[170, 171]
10	Wood flour	Maleated polypropylene	An increase in dimensional stability and strengthening by MAPP addition.	[172]
11	Natural fibers	Maleated coupling agents	An increase in interfacial adhesion between fiber and matrix due to removal of hydroxyl group by addition of coupling agent.	[173]

exposed to surface modifications with silane coupling agents. Results showed an enhancement in water absorption and porosity of the silane-treated corn stalk fiber-reinforced composite specimens. Improvement in wear behaviour was noticed between the untreated and silane-treated corn stalk fiber-reinforced polymer composites. SEM analysis revealed the formation of secondary plateaus on the composite specimens which leads to the reduced wear rate on the composite samples. Jappes and Siva [178] researched the influence of silane modification done after the mercerization treatment on coconut sheath fiber to improvise the mechanical properties of the composites. The fabricated coconut sheath polyester composites were taken for testing of tensile, flexural, and impact strength, and the properties were compared with fabricated glass fiber-reinforced polyester composites. The coconut sheath fiber-reinforced composites showed better mechanical properties against glass fiber-reinforced polyester composites. The alkali and silane modification done on the surface of coconut sheath improved the hydrophilic nature of the fiber which ensured enhanced adhesion between the coconut sheath fibril and the matrix. SEM analysis was done to study the result of alkalization on the coconut sheath fiber; dismissal of waxy layers and other surface related impurities to make the fiber

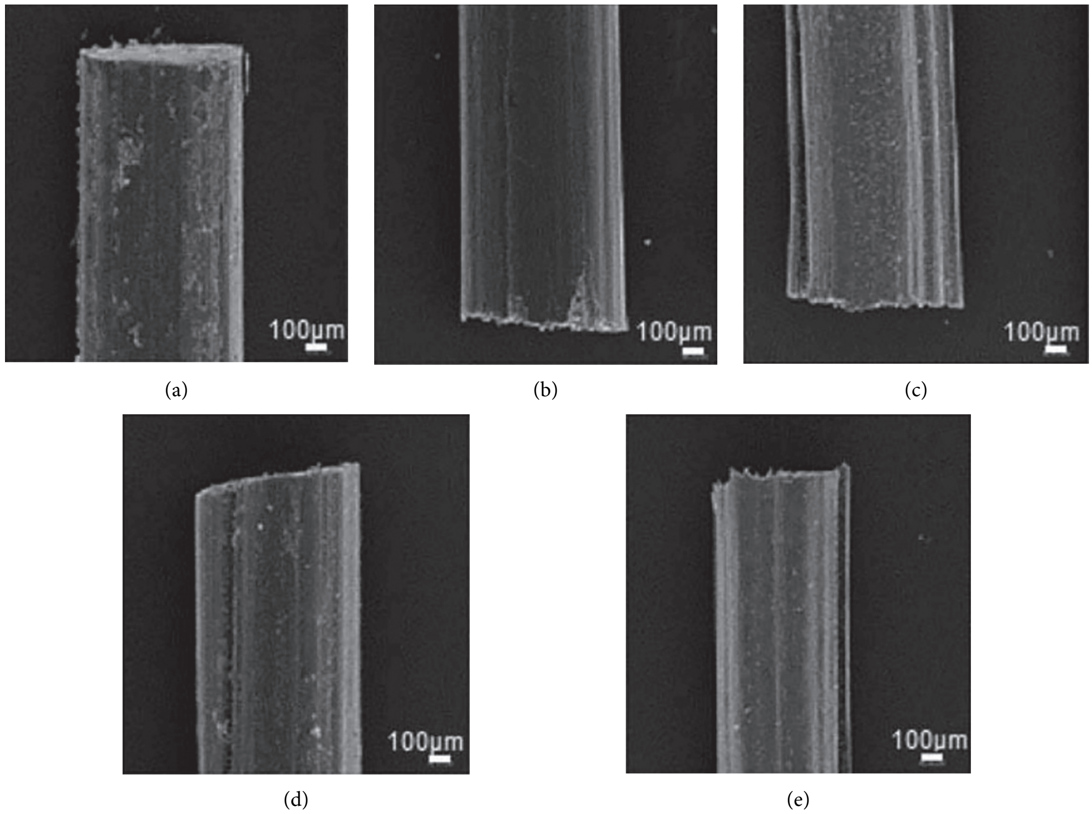

Figure 1: 5% NaOH-treated alfa fiber at different time intervals: (a) raw fiber, (b) 2 h, (c) 4 h, (d) 6 h, and (e) 24 h [174].

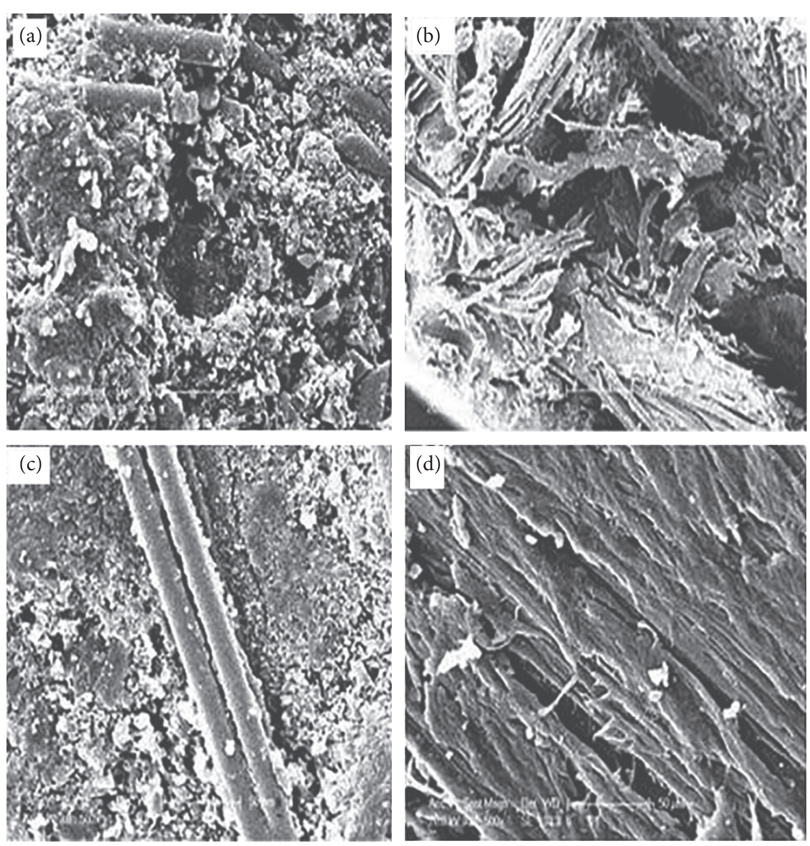

Figure 2: SEM images. (a) Untreated *Prosopis juliflora* fiber. (b) 15% NaOH-treated fiber. (c) 10% NaOH-treated fiber. (d) 5% NaOH-treated fiber [175].

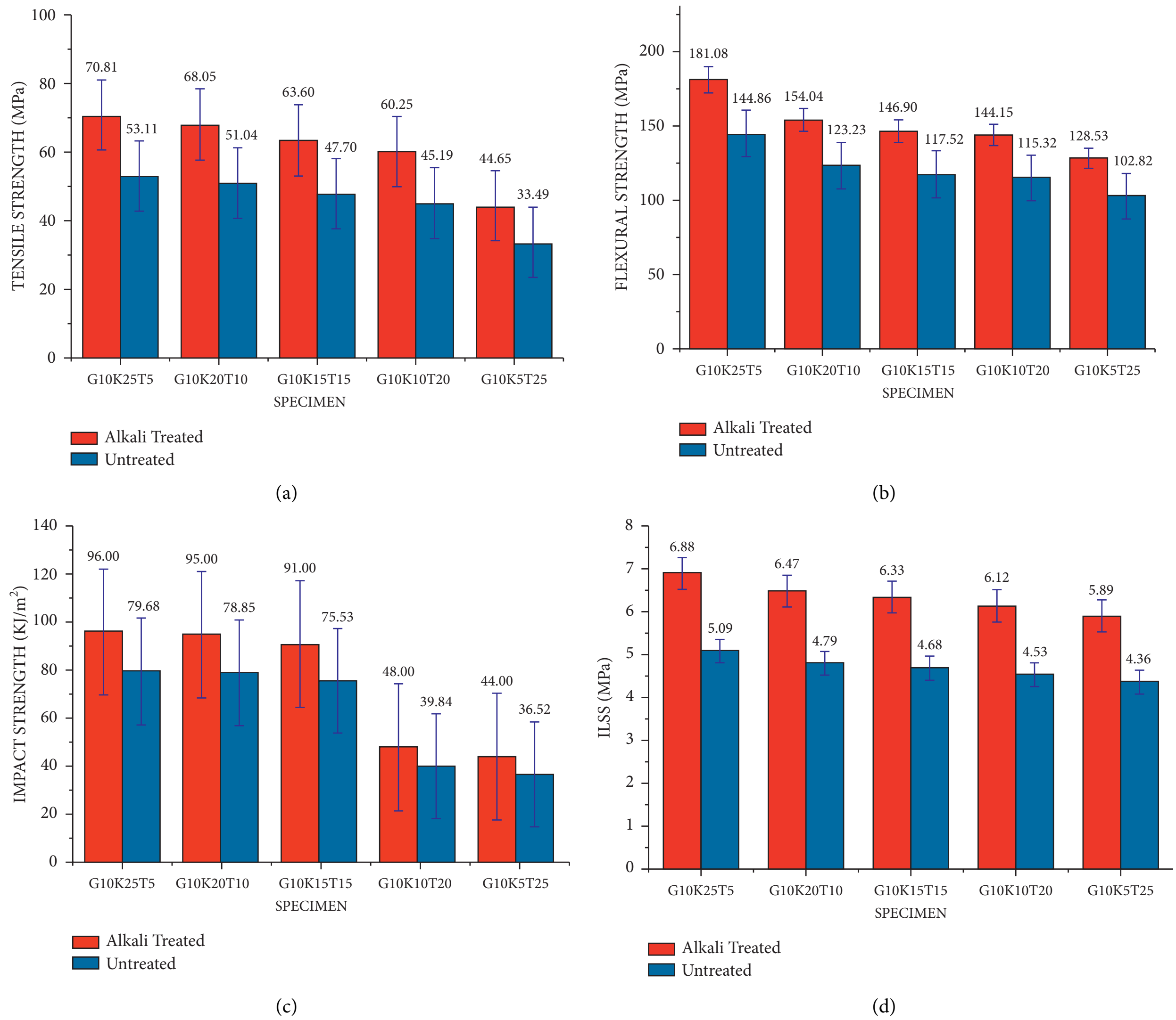

FIGURE 3: Tensile, flexural, impact, and interlaminar shear strength of glass/kenaf/tea leaf fiber-reinforced hybrid composites: effect of 5% NaOH alkaline treatment [12].

surface be rough enough has happened. Overall it was concluded that coconut sheath fiber-reinforced polyester composites could be a vital replacement for glass fiber-reinforced polymer composites. Kim et al. [179] studied the influence of bamboo fibers extracted by subjecting the fibers to steam explosion, alkalization, and chemical extraction. The conversion rate from raw source to extracted fiber was found to be significant for alkali extraction method. Then the extracted fibers were subjected to alkali, silane, and combined treatment with different proportion to study the optimal and suitable pretreatment type for bamboo fiber. The tensile strength and modulus of mercerized bamboo fibers were found to be superior when compared to silane and alkali/silane modified bamboo fibers. But the mechanical property of composites was found to be higher for alkali/silane-treated bamboo fiber-reinforced composites. Finally the water intake characteristics of alkali and alkali/silane-treated bamboo fiber-reinforced vinyl ester composites were better when compared to bamboo fiber-reinforced vinyl ester composites. Liu et al. [177] explored the silane coupling agent's influence on the tribological behaviour of corn stalk fiber-reinforced polymer composites. The silane treatment of fibril resulted in enhanced wear resistance; however, friction performance was not effective. The examination of worn surface morphology revealed the emergence of secondary plateau on the composite surface which enhanced the tribological characteristics of the composites. Lai et al. [180] investigated the possibility of fabricating fiber-reinforced polymer composites using coconut coir fiber as reinforcement material. The coconut coir fibers were exposed to mercerization followed by permanganate and stearic acid modifications to improve the effective adherence between the fiber and matrix. The fibrils were sized to 0.3 mm and 0.5 mm during the fabrication of the composites. Tensile and flexural strength results revealed that when the percentage of fiber loading increased, the strength values decreased. This was due to the inability of the fiber to support the stress shifting from the polypropylene

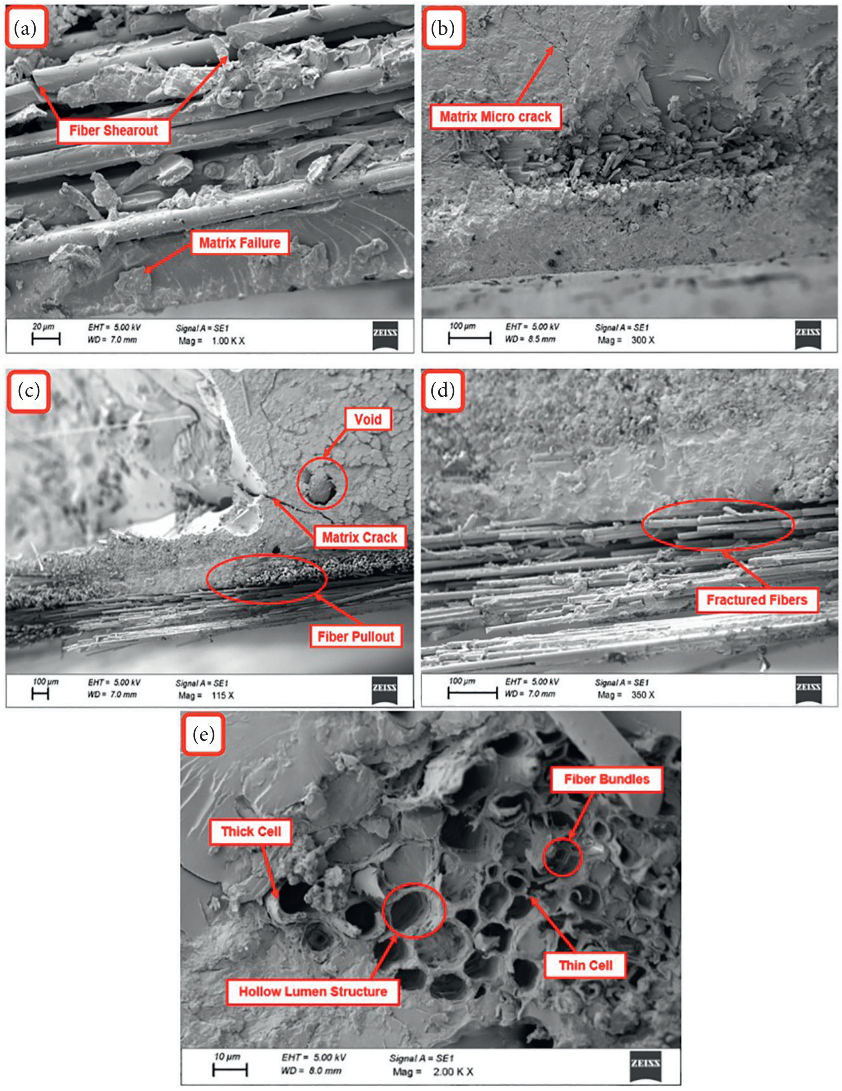

Figure 4: SEM micrographs of (a) tensile test of 5% NaOH-treated composites, (b) matrix microcrack, (c) fiber pull-out and void formation in the impact test specimen, (d) fractured surface of impact test specimen, and (e) hollow structure of natural hybrid fiber composites [12].

matrix and due to poor reinforcement property. Tensile and flexural modulus increased with increase in fiber loading, which was because of the higher fiber size, and this can also be inferred based on the aspect ratio of the fibrils. Zaman and Beg [119] evaluated the mechanical characteristics of banana fiber-strands-reinforced low density polyethylene matrix. The banana fiber strands were pretreated with methylacrylate (MA) solution combined with methanol and benzyl peroxide. The mechanical properties improved as a result of better adherence between the interface of banana fiber strand and polyethylene matrix. The banana fiber strands modified with starch solution showed improvement in composite properties against methylacrylate-treated fiber. Joseph et al. [161] studied the effects of benzoyl chloride treatment on sisal fiber and found maximum thermal stability compared to raw fiber composites. The treatment removes the hemicellulose and fatty substance in fiber surfaces for better mechanical and thermal properties. The sisal/glass/filler/epoxy reinforced composites were used in the frames, toys, and electronic panels. Sampathkumar et al. [181] analysed the influence of surface treatment on water absorption nature of *Areca* fiber. Due to the presence of hydroxide and other constituents in chemicals, the water absorption nature was higher and this leads to poor wettability. The results of their work concluded that there was a reduction in water absorption during acetylation of *Areca* fiber and increase in water absorption in treatment with alkali. Alfa fibers were kept under the various fiber surface treatments involving acetylating and it was confirmed that the treatment enhanced the resistance of fiber to moisture [182, 183]. Bisanda [184] reported that alkali-treated sisal fiber-reinforced polylactic acid composites removed lignin and waxy substances which led to better mechanical interlocking. The tensile, flexural, impact, and interlaminar shear strength (ILSS) of 5% NaOH-treated kenaf and tea leaf fibers-reinforced composites improved by 33.32%, 25%, 20.48%, and 35.16%, respectively, when compared with untreated composites due to removal of hemicellulose,

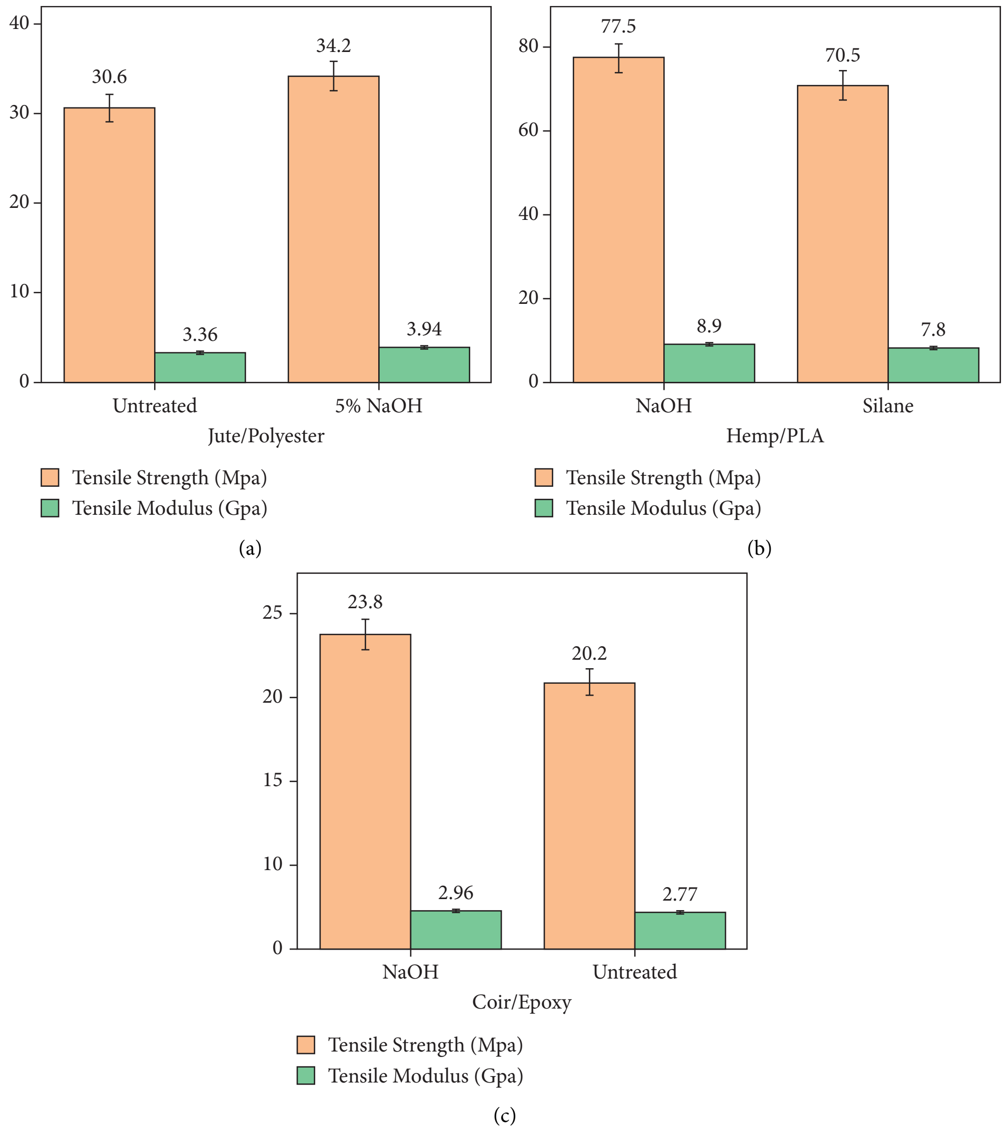

Figure 5: Tensile properties of 5% NaOH-treated jute/polyester and hemp/PLA composites [190].

lignin, pectin, and waxy elements which resulted in better interactions between hydrophilic fiber and hydrophobic matrix [12]. Figure 3 presents the mechanical properties of glass/kenaf/tea leaf fiber-reinforced hybrid composites.

The SEM analysis (Figure 4) shows that mechanical properties of untreated fiber composites were decreased by the problems such as fiber breakage, fiber pull-out, formation of micro voids, and nonuniform distribution of fiber and matrix. The 5% NaOH-treated kenaf and tea leaf fiber improved the adhesion between the fiber and matrix which resulted in better mechanical properties [12].

The biodegradability of chemically modified cellulosic fibers is associated with physical, chemical, mechanical, and thermal properties [5, 185, 186]. The agricultural waste fiber-reinforced composites are used in automobile, aerospace, construction materials, packaging applications, and medical applications. Sharma and Kumar [187] studied the tensile properties of sugar palm fiber obtained from different height of the palm plant. The tensile properties enhanced in the bottom part of the tree fiber due to their chemical composition, particularly cellulose, hemicellulose, and lignin [188, 189].

The tensile strength and tensile modulus of 5% NaOH-treated jute fiber-reinforced polyester composites improved by 5.2% and 17.2%, respectively, when compared with untreated composites due to better interaction between fiber and matrix (Figure 5). It was also revealed that 5% NaOH-treated hemp fiber-reinforced PLA composites exhibited outstanding results compared to silane-treated hemp fiber-reinforced PLA composites [190]. The tensile strength and tensile modulus of 5% NaOH-treated hemp fiber-reinforced PLA composites improved by 9.9% and 14.1%, respectively, when compared with silane-treated composites owing to better removal of unwanted substances such as hemicellulose and waxy elements. Likewise, 5% NaOH-treated coir fiber-reinforced epoxy composites exhibited superior tensile properties such as tensile strength (17.8%) and tensile modulus (6.8%) compared to untreated fiber composites. Based on various chemical treatments, alkaline treatment (5% NaOH) is the most economical and effective treatment in promoting better communications between fiber and matrix by removal of hemicellulose, lignin, and waxy elements due to disruption of hydrogen bonding in the fiber structure, thus resulting in better mechanical and thermal properties.

4. Conclusions

In this detailed review, the effects of various chemical treatments on different biofiber-reinforced composites were summarized. Furthermore, the effect of constitution of biofibers was also reported. The physical, mechanical, and thermal properties of various biofibers-reinforced composites were improved up on modification of fiber surfaces, while fiber swelling effect and water absorption rate were decreased by various chemical treatments like alkaline, silane, acetylation, permanganate, peroxide, benzoylation, acrylonitrile grafting, maleic anhydride grafted, acrylation, and isocyanate. Based on various chemical treatments, alkaline treatment (5% NaOH) is the most economical and effective treatment in promoting better communications between fiber and matrix by removal of hemicellulose, lignin, and waxy elements due to disruption of hydrogen bonding in the fiber structure, thus resulting in better mechanical and thermal properties. It was concluded that alkaline treatment of fibers with 5 wt% NaOH made the fibers more resistant to deformation and heat. The alkaline treatment has been one of the successful methods used to treat the natural fibers in order to achieve better results.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

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