Review Article

Effects of fibre treatment on mechanical properties of kenaf fibre reinforced composites: a review

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\textbf{A B S T R A C T}

There have been review on kenaf fibre (KF) production and mechanical properties but lacks review on the treatment and surface modification on kenaf fibre. Therefore, this study is to show the type of treatment that have been done by previous researcher. A lot of methods have been investigated to find the optimum method to obtain better condition and properties for kenaf fibre. The present review describes those applied to kenaf fibre. The most widely used chemical treatment is the alkaline treatment using a sodium hydroxide (NaOH) solution, followed by a silane treatment. Variety of chemical concentration for NaOH solution and silane solution are investigated and a few combined treatments such as alkaline-silane, alkaline-steam, alkaline-radiation and alkaline-bleaching are also discussed. Thus, this paper presents an overview of investigated treatment methods with application to kenaf fibre and what are the effects of chemical treatment to the surface of kenaf fibre and the mechanical properties of the composites developed based on treated kenaf fibre.

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Fig. 1 – Classification of natural fibres (from Akil et al. [16]).

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Density (g/cm³)</th>
<th>Elongation (%)</th>
<th>Tensile strength (MPa)</th>
<th>Young's modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kenaf</td>
<td>1.50</td>
<td>1.6</td>
<td>930</td>
<td>53</td>
</tr>
<tr>
<td>Ramie</td>
<td>1.5</td>
<td>2.0–3.8</td>
<td>220–938</td>
<td>44–128</td>
</tr>
<tr>
<td>Flax</td>
<td>1.4–1.5</td>
<td>1.2–3.2</td>
<td>345–1500</td>
<td>27.6–80</td>
</tr>
<tr>
<td>Hemp</td>
<td>1.48</td>
<td>1.6</td>
<td>550–900</td>
<td>70</td>
</tr>
<tr>
<td>Jute</td>
<td>1.3–1.46</td>
<td>1.5–1.8</td>
<td>393–800</td>
<td>10–30</td>
</tr>
<tr>
<td>Sisal</td>
<td>1.33–1.5</td>
<td>2.0–14</td>
<td>400–700</td>
<td>9.0–38.0</td>
</tr>
<tr>
<td>Coir</td>
<td>1.2</td>
<td>15.0–30.0</td>
<td>175–220</td>
<td>4.0–6.0</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.5–1.6</td>
<td>3.0–10.0</td>
<td>287–597</td>
<td>5.5–12.6</td>
</tr>
<tr>
<td>Softwood kraft</td>
<td>1.5</td>
<td>–</td>
<td>1000</td>
<td>40.0</td>
</tr>
<tr>
<td>E-glass</td>
<td>2.5</td>
<td>2.5–3.0</td>
<td>2000–3500</td>
<td>70.0</td>
</tr>
<tr>
<td>S-glass</td>
<td>2.5</td>
<td>2.8</td>
<td>4570</td>
<td>86.0</td>
</tr>
</tbody>
</table>

Table 2 – composition for natural fibres.

<table>
<thead>
<tr>
<th>Type of fibre</th>
<th>Cellulose (%)</th>
<th>Lignin (%)</th>
<th>Hemicellulose (or Pentosan) (%)</th>
<th>Pectin (%)</th>
<th>Ash (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bast fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenaf</td>
<td>31–57</td>
<td>15–19</td>
<td>21.5–23</td>
<td>–</td>
<td>2–5</td>
</tr>
<tr>
<td>Seed flax</td>
<td>43–47</td>
<td>21–23</td>
<td>24–26</td>
<td>–</td>
<td>5</td>
</tr>
<tr>
<td>Fibre flax</td>
<td>71</td>
<td>2.2</td>
<td>18.6–20.6</td>
<td>2.3</td>
<td>–</td>
</tr>
<tr>
<td>Jute</td>
<td>45–71.5</td>
<td>12–26</td>
<td>13.6–21</td>
<td>0.2</td>
<td>0.5–2</td>
</tr>
<tr>
<td>Hemp</td>
<td>57–77</td>
<td>3.7–13</td>
<td>14–22.4</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Ramie</td>
<td>68.6–91</td>
<td>0.6–0.7</td>
<td>5–16.7</td>
<td>1.9</td>
<td>–</td>
</tr>
<tr>
<td>2. Core fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenaf</td>
<td>37–49</td>
<td>15–21</td>
<td>18–24</td>
<td>–</td>
<td>2–4</td>
</tr>
<tr>
<td>Jute</td>
<td>41–48</td>
<td>21–24</td>
<td>18–22</td>
<td>–</td>
<td>0.8</td>
</tr>
<tr>
<td>3. Leaf fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abaca</td>
<td>56–63</td>
<td>7–9</td>
<td>15–17</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>Sisal</td>
<td>47–78</td>
<td>7–11</td>
<td>10–24</td>
<td>10</td>
<td>0.6–1</td>
</tr>
<tr>
<td>Henequen</td>
<td>77.6</td>
<td>13.1</td>
<td>4–8</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

United Kingdom. He is also the Honourable Secretary of Malaysian Society of Structural Health Monitoring (MSSHM) based in UPM Serdang, Selangor, Malaysia. Currently, he is also attached to the Institution of Engineers Malaysia (IEM) as the Chairman in the Engineering Education Technical Division (E2TD). He also appointed as Panel Evaluator for Engineering Accreditation Council Malaysia (EAC) and Engineering Technology Accreditation Council (ETAC).
1. **Introduction**

Natural fibres have been used by humans from very early times. In recent years, the usage of natural fibres in composites has received significantly increasing attention [1-15]. Fibre-reinforced composites are based on a fibre used as reinforcement and a polymer as matrix. Natural fibres can be basically divided into animal fibres, vegetable fibres and mineral fibres as shown in Fig. 1.

There is a wide variety of plant fibres that have been investigated for the use as reinforcement in composites. The production of natural fibres has been steadily increasing, besides they are easy to handle and present great advantages in terms of eco-friendliness [17]. The mechanical properties of natural fibres are shown in Table 1.

Another important aspect for using natural fibres in various applications is their chemical composition. The composition of some investigated natural fibres is shown in Table 2 [18,19].

The constituents of natural fibres include hemicelluloses, cellulose, pectin, lignin, waxes and water-soluble substances. The chemical composition of fibres may vary even within the same plant species, as a function of the growth conditions of the plant, geographical factors and the method of fibre extraction. Most chemical treatments of fibres pertain surface modifications as described by [2,7,20-23].

Currently, there is still quite a great discrepancy between the strength of natural fibres and that of conventional reinforcing fibres, such as glass fibres. The difference in strength is one of the main reasons why natural fibres cannot fully replace the glass fibres. Thus, researchers started investigating the hybridization of composites by combining two or more types of fibres to produce a new material with improved characteristics compared to those of the original materials. Laminates composite structures consist of woven plies of reinforcing fibre, and a matrix that bonds the plies together and gives stiffness to the whole assembly. Their properties differ from those of metallic alloys since each of the materials in a composite still maintains its original chemical, physical and mechanical properties. The interfacial bonding between the fibre surface and the polymer matrix is one of the major factors that determine the mechanical properties of composites. Example of mechanical properties that can be examine on a composites structure are by conducting tensile test [24], thermal buckling analysis [25], post buckling analysis [26,27], flexure analysis [28] and bending analysis [29,30]. After testing have been done the structure can be further observe to determine the structure that undergo tensile and thermal testing have been totally damaged or still useable for certain period of time as studied by Mustapha et al. [31].

Recently, composites have become widely employed in the aerospace industry. Basically, there are two types of fibre reinforced materials that have been used in the aerospace industry, namely, carbon/epoxy and glass/phenolic composites. Carbon/epoxy composites are mostly applied to major-load bearing structures, while glass/phenolic ones are intended for cabin furnishings. The composites started to be applied in aircraft structures in the late 1960s, but at first, they were used for manufacturing only military aircraft, as the military has the privilege of funding for research on composite materials [32]. Over time, the use of composite materials has been extended and they steadily replaced older structures in aircraft, which were mainly made from aluminium until then. Currently, most parts of the aircraft are manufactured from composite materials, as shown in Fig. 2.

1.1. **Kenaf plant**

Kenaf (Hibiscus cannabinus L., Malvaceae) is an annual crop that grows during the warm season and is almost similar to the okra (Abelmoschus esculentus L., Malvaceae) and cotton (Gossypium hirsutum L., Malvaceae) [33]. Kenaf originated from Africa, but more than 75 percent of the worldwide kenaf production is from India and China, which makes kenaf the major bast fibre source in these countries. Intensive research on kenaf started in the United States in 1957 [34]. An interesting fact about kenaf is that up to 40% of the stalk obtained is usable fibre, almost double that of jute, hemp or flax. This yield percentage makes the fibre more economical compared to that of other plants. In addition, the growth of kenaf plant from seeds to heights of 3.6 m–4.3 m (12 ft–14 ft) only takes five to six months [35].

![Fig. 2 - Materials in commercial aircraft [32.](image)]
1.2. Kenaf fibre

Kenaf fibre (KF) is extracted from the bast of the plant and has been extensively used as a jute-like material in the past. In Asia, kenaf is cultivated predominantly for the fibre, the extraction process involves soaking the stalks (the retting process) and manual removal of the fibres. This method has been found to give superior reinforcement quality. On the other hand, the U. S. kenaf producers, for example, the Greene Natural Fibres (Snow Hill, N. C.) and Kenaf Industries of South Texas (Raymondville, Texas) use the method of field retting and mechanical separation. The use of kenaf core materials as absorbents and animal bedding are more ready markets [36]. Nishino et al. [37] stated that the shape, size and strength of natural fibres mostly depend on the cultivation environment. Example of research that been done using kenaf fibre involving different type of chemical treatment and different matrix for composite structure [38-41]. These characteristics will influence the mechanical properties of the fibre reinforced composites produced. Table 3 shows range of values for kenaf fibre. (Table 3)

1.3. Kenaf fibre application

Kenaf is produced for various applications, including paper products, absorbents, building materials, and livestock feed, which is diverging from its historical role as a cordage crop (twine, rope and sackcloth). The variety of kenaf end products will continue to extend, involving issues ranging from the choice of general agricultural production methods to marketing of kenaf products [33]. Studies on combining kenaf with synthetic fibre as E-glass Kenaf is a versatile industrial crop and has been proven as a good natural fibre for textiles and a variety of other industrial applications [42]. Vision Paper, a company based in New Mexico, has managed to produce kenaf-based papers. Ibrahim et al. [43] have carried out research on the development of a new method to produce rayon grade dissolving pulp from Malaysian kenaf stalk. Enhanced production of kenaf for dissolving pulp, which will be subsequently used to produce rayon, is expected to help the batik industry and kenaf planters on the east coast. Other than that, the investigation done by Ali et al. [44] have concluded that the combination of kenaf core and bast fibre to reinforce composite materials, including other fillers as well, to manufacture automotive components will contribute to reducing the pressure on the environment by storing more carbon in the auto body. Also, this will give a superior industrial product through the lifetime of the automobile, when the percentage of fibre in the manufactured components is increased.

2. Chemical treatments for kenaf fibre

2.1. Alkaline treatment

Alkaline treatment is commonly used for chemical modification of natural fibres. An important improvement achieved by the alkaline treatment consists in altering or breaking down the hydrogen bonding that holds together the entire system structure, and in this way the surface roughness is increased. The alkali treatment of KF has been thoroughly researched [45-59]. Alkaline treatment also partially removes the lignin, oils and wax covering the outer part of the fibre cell wall. The treatment depolymerizes the cellulose in fibre and thus opens up the short length crystallites [19]. Referring to Eq. (1) below, the presence of aqueous sodium hydroxide (NaOH) helps promoting the process of ionization of the hydroxyl group into an alkoxide [60]:

\[
\text{Fibre-OH} + \text{NaOH} \rightarrow \text{Fibre-O-Na} + \text{H}_2\text{O}
\] (1)

Therefore, the alkaline treatment directly affects the cellulose fibrils, the extraction of lignin and hemicellulosic compounds, as well as the level of polymerization [61]. A simple method of performing fibre treatment is by immersing the fibre in a certain concentration of NaOH solution for a certain period of time. Most research has focused on the effect of NaOH concentration percentage and treatment time on the strength of the treated fibre, while there are also a few studies that investigated the effect of the temperature used during fibre treatment on mechanical properties. Table 4 is an overview of the research that has been previously done on the alkaline treatment of kenaf fibre.
Through to further investigation, the room of concentration strength.

Alavudeen et al. [62] used 5%, 10% and 15% concentration of NaOH solution for 2 h, 4 h, 6 h and 8 h on two types of woven KF at room temperature. Their study shows that 10% NaOH treatment for 8 h gives the best effect on the mechanical properties of KF. Smaller concentrations of NaOH, namely, 3%, 6% and 9%, have been used by Edeerozy et al. to treat kenaf fibre for 3 h at room temperature [22]. They found that 6% NaOH gives the best result in terms of mechanical properties, and performed a further experiment treating the KF using 6% NaOH at different temperature (room temperature and 50 °C). The researchers found out that KF treated with 6% NaOH at 95 °C presents better mechanical properties than that treated with 6% NaOH at room temperature.

Another research applied 3%, 6% and 9% concentrations of the NaOH solution for 12 h and 24 h on long bast KF at room temperature [9]. The authors reported that KF treated with 6% NaOH for 12 h exhibits better mechanical properties. Fiore et al. [63] carried out alkaline treatment of KF, varying the duration of the treatment (48 h and 144 h), while maintaining the concentration at 6% NaOH. Their research shows that KF treated for 48 h presents better properties and all the impurities have been removed. Meanwhile, the KF treated for 144 h exhibits crack propagation, which indicates that the fibre has been heavily damaged, resulting in lower tensile strength.

In research done by Ikhwann Ibrahim et al. [64] which investigate the effect of 2%, 4%, 6% and 8% concentrations of the NaOH solution on a single kenaf fibre found out that 6% NaOH concentration give improvement of the young modulus, tensile strength and percentage fracture strain compared to untreated single kenaf fibre as shown in Table 5.

To observed the effect of untreated and 2%, 4%, 6% and 8% concentration of NaOH solution is shown by Arbanah et al. [65] Through scanning electron microscopy (SEM) as shown in figure 3.

Overall, the alkaline treatment has been reported as mainly involving the use of NaOH solution, and such a treatment has a few major effects on the fibre. First, it changes the fibre structure, which increases surface roughness. Better mechanical interlocking between fibre and matrix can be achieved when the surface roughness or surface area is increased. Then, the exposure of the cellulose on the fibre surface caused by the alkaline treatment increases the number of possible reaction sites [66]. Higher percentage of alkali concentration can cause excess delignification of the natural fibre, which damages the fibre or makes it weaker. Enhancing the NaOH concentration beyond a certain percentage, the tensile strength of the composite produced has been also found to drastically decrease.

### 2.2. Silane treatment

The chemical compound with the chemical formula of SiH₄ is known as silane. Silanes are applied as coupling agents to glass fibres in order to ensure that they effectively adhere to a polymer matrix, which stabilizes the composite material. There is still little research on using solely silane treatment on KF [2,67,68]. As shown in Eq. (2), hydrolyzable alkoxy groups will form the silanols, which will react with the hydroxyl groups of the fibre under moisture conditions. Stable covalent bonds at the cell wall are formed during the reaction and silanols are chemically adsorbed onto the fibre surface [60]. Thus, the hydrocarbon chains available by applying the silane will prevent the swelling of fibre, as illustrated by Equation 3. Covalent bonding between the matrix and the fibre is the one that enables the crosslinked network to occur. The chemical reaction is given as follows [60]:

\[
\begin{align*}
\text{CH}_{2} \text{CHSi(OH)}{\text{CH}_{3}} & \rightarrow \text{H}_{2} \text{OCH}_{2} \text{CHSi(OH)}{\text{CH}_{3}} + 3\text{C}_{2}\text{H}_{5}\text{OH} \\
\text{CH}_{2} \text{CHSi(OH)}{\text{CH}_{3}} + \text{Fibre} \rightarrow \text{CH}_{2} \text{CHSi(OH)}{\text{CH}_{3}} + \text{Fibre} + \text{H}_{2}\text{O} 
\end{align*}
\]
Some researchers applied silane treatment to the KF to improve the bonding between the fibre and the matrix by increasing the degree of cross-linking in the interface region. The silane treatment also contributes to stronger bonding between the fibre and the matrix by increasing the fibre surface area \([2,67,68]\). The research by Cho et al. \([67]\) investigated the effect of 3-methacryloxypropyltrimethoxysilane (MPS), 3-glycidoxypropyltrimethoxysilane (GPS), and 3-aminopropyltriethoxysilane (APS), which are three totally different silane coupling agents, on the properties of the treated fibre. They found out that the treatment with 0.5 wt% GPS was the most effective in improving the mechanical properties of KF. Furthermore, thermosetting unsaturated polyester (UPE) and Thermoplastic polypropylene (PP) were used as matrix and combined with chopped KF to develop composites. By the compression moulding technique, composites were produced with untreated KF or with treated one at different GPS concentrations, ranging from 0.1 wt% to 5 wt%. The properties for the two kenaf/UPE and kenaf/PP composites were found to be highly dependable on the GPS treatments based on the results of the interfacial, flexural and tensile tests, as well as those of the dynamic mechanical analysis (DMA). The most significant improvement in the properties of both thermosetting UPE and thermoplastic PP polymer composites was found when using 0.5% silane treatment of the fibre.

Table 6 presents an overview of the silane treatments investigated by three researchers. The silane coupling agents were concluded as effective in improving the natural fibre–polymer matrix interface, thus increasing the interfacial strength. Stronger bonding in composites in the presence of silane treated fibre, leading to higher tensile strength of the composite material, compared to that comprising alkaline-treated fibre, confirmed positive effect of the interaction between the silane coupling agent and the fibre \([69]\).

### 3. Treatment combinations

#### 3.1. Alkaline – silane treatment

Tensile and flexural tests were conducted by Asumani et al. in order to study the effect of different treatments performed on kenaf fibre \([70]\). The chemical treatment being conducted is shown in Table 7. It has been found that both tensile and flexural properties were significantly improved when KF was subjected to an alkali-silane treatment. The research shows promising results, namely, 4% lower specific tensile and 11% lower flexural strengths for 30% fibre mass fraction of alkali-silane treated kenaf composites, compared to the corresponding values of the composites made with glass fibre. The improvement in the tensile and flexural properties was supported by the observation via Scanning electron microscopy (SEM), which confirmed better bonding between the fibres and the matrix.

The effectiveness of the treatment was compared in terms of tensile, morphological, and structural properties, between pineapple leaf fibres (PALF) and KF. The objective of the research was to investigate techniques to improve natural fibre compatibility with polymer matrices.

The removal of impurities from the fibre surfaces using fibre treatment as in Table 8 for PALF and KF was observed by using SEM and Fourier Transform Infrared spectrometry (FTIR). The silane treated fibres were found to have fewer impurities and less lignin and hemicelluloses removed than those subjected to the other chemical treatments, as observed.
in the SEM morphological study of treated PALF and KF. Furthermore, the silane-treated PALF and KF display better tensile strength, compared to the untreated, alkaline and NaOH-silane treated fibres. Droplet tests showed that the silane treated fibres display the highest Interfacial Stress Strength (IFSS), those modified with the combined alkali and silane treatment come second in terms of IFSS. Based on the result, it can be concluded that fibre treatments have great potential in developing high-performance KF and PALF reinforced polymer composites, which are suitable for industrial applications (Table 8).

Table 8 – chemical treatment by Asim et al.

<table>
<thead>
<tr>
<th>Type</th>
<th>Chemical treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silane</td>
</tr>
<tr>
<td>2</td>
<td>Alkali</td>
</tr>
<tr>
<td>3</td>
<td>Silane + alkali</td>
</tr>
</tbody>
</table>

Five variants of surface treatments have been performed on three different fibres, namely, Kenaf, oil palm and abaca, as shown in table 9 [72] table Untreated fibres were compared with treated fibres to evaluate the difference in the mechanical strength of the fibres. The best strength was recorded for the fibres treated with NaOH, followed by those subjected to the mixed treatments, and then by the fibres treated with silane.

Additionally, microdroplet pull-out tests were done to evaluate the bonding strength between the fibres and unsaturated polyester resin. In this case, the best results were achieved for the silane treatment, followed by the combined silane and NaOH one. Also, with regard to the mixed treatments, it was noted that the lowest treatment period of 6h gave the best IFSS results. This is probably explained by the alkali nature of NaOH degrading the fibres in the presence of silane, which as a consequence leads to dropping the ability of the fibre to properly bond with the resin. The fibres treated with NaOH were found to present a decreased diameter, due to the elimination of impurities and lignin, as observed by the analysis of surface morphology by SEM. At the same time, as the silane coats the fibre surface, the diameter of the fibre increases and the aspect ratio decreases.

The study conducted by Huda et al. [68] was carried out with the objective to investigate the thermal and mechanical properties of composites. Alkalinization and silane treatments were done to improve the characteristics of KF. Superior mechanical properties were found for the silane-treated fibres (FIBSI) reinforced composite and alkali-treated fibre (FIBNA) reinforced composite, as compared to the untreated fibre (FIB) reinforced composite. Also, the composite reinforced with fibre subjected to the combined alkali-silane-treatment (FIBNASI) exhibited substantially advanced mechanical properties. DMA was conducted to observe the effect of treatment temperature on the viscoelastic properties of composites. Furthermore, higher adhesion between the fibre and the matrix was confirmed by morphological studies by means of scanning electron microscopy (SEM). The studies highlighted the fact that common PLA resins make remarkable mixtures for manufacturing KF reinforced laminated biocomposites with excellent engineering properties.

3.2. Alkaline – steam/heat treatment

Surface modifications of kenaf bast fibres have been achieved with steam, alkali and a combination of the steam-alkali treatments [73]. To understand their effects, the tensile strength, surface morphology and crystallinity of the treated fibres has been evaluated and compared with those of the raw fibres. The tensile strength of the fibres that underwent the steam-alkali treatment was much improved in comparison with that of the raw fibre. The tensile strength of the fibres was enhanced after the steam treatment, and a quite similar effect was noted after the alkali treatment, while it slightly decreased for the fibre modified through steam treatment accompanied by alkalinization. Increasing the concentration of alkali is usually intended to improve the tensile strength. The variations in the tensile strength of treated fibres are explained by modifications in surface morphology and crystallinity. Deeper understanding of these relationships may trigger a step forward towards manufacturing natural fibre reinforced composites with higher overall performance. Fig. 4 show the SEM on the natural fibre surface [73].

Gao et al. [74] stated that efficiently taking advantage of available kenaf sources would help to fulfill the increasing demand of natural fibre. The steam explosion (STEX) pretreatment, followed by alkali-oxygen treatment, was studied as a suitable method to achieve the degumming of different fibre materials. The characteristics of kenaf were studied as a function of the duration of the STEX treatment and the most advantageous degumming method was established. By analyzing the STEX pretreatment, it is observed that it successfully eliminates pectin and a certain percentage of the hemicelluloses. The amount of carbohydrates (hemicelluloses and cellulose) can diminish through excessive pressure treatment. After the alkali-oxygen treatment, it can be ensured that there is sufficient content of residual gum and the fineness of the KF is satisfying for fabric manufacturing. High pressure was proven as the main reason that makes this degumming method unacceptable.

Meanwhile, conducting STEX at low pressure (0.5 MPa) with the addition of alkali-oxygen treatment was demonstrated as a green approach for degumming KF.

Ways to improve the mechanical properties of natural fibre, specifically KF, when subjected to heat and alkali treatments, were studied by Cao et al. [41]. Analysis of the impact of various heat treatment temperatures revealed that the tensile strength of KF exhibited the most significant change at 140 °C, which might be attributed to the growth of the crystallinity index of the fibres after the heat treatment. The results of the tests confirmed enhanced fracture strain of the alkali treated fibres. The alkali treatment brought about the removal of hemicelluloses and, partially, of impurities, which led to a

Table 9 – Chemical treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaOH</td>
<td>24</td>
</tr>
<tr>
<td>Glycidoxypropyltrimethoxy-silane</td>
<td>24</td>
</tr>
<tr>
<td>NaOH + silane</td>
<td>24 (each treatment)</td>
</tr>
<tr>
<td>NaOH + silane</td>
<td>12 (each treatment)</td>
</tr>
<tr>
<td>NaOH + silane</td>
<td>6 (each treatment)</td>
</tr>
</tbody>
</table>
loose structure of the fibre, which resulted in better elongation at break of the treated fibre.

3.3. Alkaline – bleaching treatment

Alkali treatment, hydrogen peroxide bleaching and alkali-bleaching techniques were applied to raw kenaf and hemp bast fibres done by Wang et al. [75] in order to investigate the effects of the treatments and dye affinities towards treated fibres. Both kenaf and hemp fibres had proper substantivity for basic and direct dyes. Reactive dyes exhibited quite small exhaustion and k/S values. Dyeing properties were associated with the cellulose, lignin, and hemicellulose content of the fibres. As hemp fibres are chemically very similar to cotton fibres, the dye exhaustion was quite comparable between the two, however, hemp fibres showed deeper colouration totally based on k/S values. The outcome of dyeing kenaf was considerably better than those of cotton. On average, kenaf had higher k/S values for the dye classes evaluated than those of hemp fibres. Such variations may be attributed to the optical differences of bast fibres.

Andreu et al. [76] reported on the primary utility of laccase-mediator systems (LMS) to kenaf pulp. The mediator used comprised five natural phenolic compounds (acetosyringone, syringaldehyde, p-coumaric acid, vanillin and acetovanillone) that were mixed with laccase. The combination was performed (L level), so as to elucidate the impact of the developed systems on delignification. Pulp samples were subjected to two alkaline treatments (E or P level) after LMS treatment. The results acquired were compared with the ones obtained using the laccase-1-hydroxybenzotriazole (HBT) system. Based on the observation, the use of natural mediators led to elevated kappa numbers, reduced brightness and additionally modified optical properties of the pulp at the L level. Such changes indicate that natural mediators have a tendency to bond to fibres at some point of the laccase-mediator treatment. The best bleaching and delignification outcomes at the P level were determined for the use of syringaldehyde and acetosyringone, which proved to be very efficient in delignifying kenaf.

A combined treatment consisting in the use of 4% sodium hydroxide solution followed by bleaching with sodium chlorite with the addition of an acidic buffer, was used for kenaf core fibre [77]. The ensuing white, bleached kenaf core was hydrolyzed in 64 wt% sulfuric acid (H2SO4) to acquire NCC. The ensuing NCC suspension was characterized by various techniques, such as X-ray diffraction (XRD), differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), FTIR spectroscopy and scanning transmission electron microscopy (STEM). Hydrolysis with highly concentrated H2SO4 similarly improved the crystallinity of bleached kenaf core cellulose and decreased the size of cellulose crystals to the nanoscale. As confirmed by the FTIR analysis, with every subsequent treatment, some amounts of hemicellulose and lignin had been eliminated, while the chemical functionalities of cellulose were maintained after the acid hydrolysis treatment.

A three-step treatment involving alkali treatment, bleaching, and sulfuric acid hydrolysis was conducted by Zarina et al. on KF [78]. The study was intended to extract cellulose nanocrystals (CNCs) from KF in order to use them as reinforcement in biocomposites primarily based on κ-carrageenan. FTIR analysis revealed that the alkali treatment accompanied by bleaching completely eliminated lignin and hemicelluloses from the kenaf fibre. The optimum content of CNCs of 4% to reinforce the κ-carrageenan biocomposite films demonstrated excellent dispersion and endowed the films with advanced mechanical properties and improved thermal stability.

3.4. Alkaline – electron beam irradiation treatment

Different concentrations of sodium chlorite solution were applied to KF to make the fibre suitable for being used as a trunk polymer [79]. Treated KF was subjected to electron beam irradiation via an electron grafting reaction in a GMA/water emulsion machine. Grafting was investigated as a function of response time, response temperature, absorbed dose and concentration of monomer. The results confirmed that the content of lignin in the material was reduced from 14.3% to about 3% with increasing sodium chlorite concentration. The changes found were also demonstrated with the help of SEM images, which displayed a much smoother surface of the treated KF compared to that of the untreated one. In addition, XRD analysis showed that when the degree of grafting was increased, the degree of crystallinity of the graft copolymers decreased.

Another research was conducted by Han et al. with the objective to compare the impacts of natural fibre treatment by electron beam irradiation (EBI) and alkaliization as shown in (Table 10)[38]. The researchers examined the thermal and DMA properties of the kenaf fibre reinforced polypropylene (PP) composites produced. Also, they investigated the alpha cellulose contents, the surface functional groups and the thermal stability of the untreated and treated KF. KF/polypropylene (PP) biocomposites were fabricated using chopped KF by the compression moulding technique.

Thermogravimetric analysis, DMA and fractographic observation were performed to investigate the thermal stability, the dynamic mechanical and the interfacial properties of the untreated and treated kenaf/PP biocomposites. EBI was found to have a positive impact on the KF and the resulting biocomposites.

### Table 10 – chemical treatment by Han et al. [38]

<table>
<thead>
<tr>
<th>Type</th>
<th>Chemical treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 kGy + (2, 5, 10 wt% NaOH)</td>
</tr>
<tr>
<td>2</td>
<td>200 kGy + (2, 5, 10 wt% NaOH)</td>
</tr>
<tr>
<td>3</td>
<td>500 kGy + (2, 5, 10 wt% NaOH)</td>
</tr>
</tbody>
</table>

4. Conclusion

KF is considered to have a huge potential to replace partially or fully man-made fibres in the field of composite materials. Natural fibre, and specifically KF, has considerable advantages over man-made fibres, for example, kenaf fibre is cheap due to its low production cost. Other than that, KF has low density, which makes the fibre lighter in weight. Despite its good properties, KF is not totally flawless. The researchers have
put forward different methods to overcome its shortcomings, for example by using surface treatments. The modifications yielded great results in terms of better properties when KF was integrated in composites, but the economic aspect should be always kept in mind. Chemical treatments have been found to increase the interface adhesion between the fibre and the matrix. At the same time, such treatments lead to a reduction of water absorption by the fibres. A few methods are already known to promote adhesion within composites. For example, this can be achieved by chemically bonding the adhesive to the material, by applying sodium hydroxide, silane or combined treatments, such as alkaline-silane, alkaline-heat, alkaline-beam irradiation, alkaline–bleaching treatments etc. There is a variety of treatments for KF, but the choice will depend on the form of the KF. Further studies are necessary to compare the combinations of treatment sequences as a function of the form of KF. Overall, it can be said that each of the treatments investigated is successful in improving the mechanical properties of kenaf fibre reinforced composites. However, the fibre modification methods that have been discussed are different in terms of their efficacy with regard to improving the adhesion between the matrix and the fibre. Overall, all the treatments show great potential in increasing fibre strength, fibre suitability and fibre–matrix adhesion, but further research should be done to compare the effects of the treatments related to the fibre type of interest, in order to find out the optimum treatment for each fibre type. Other method such as fibre prestressed [80,81] while testing method such as impact test [82,83] and compression after impact [84] is an available studies that not yet been extensively investigate involving kenaf fibre.

**Conflicts of interest**

The authors declare no conflicts of interest.

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**References**


