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REVIEW

Kenaf Fibre–Based Composites as Sustainable Materials for Marine Applications: A Short Review

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ABSTRACT: Kenaf fibre has attracted increasing attention as a sustainable reinforcement material for polymer composites, particularly for applications in marine environments where lightweight structures, corrosion resistance, and environmental compatibility are essential. This review critically examines the current state of research on kenaf fibre–reinforced composites for marine applications, focusing on their mechanical performance, environmental durability, processing methods, and sustainability potential. Existing studies consistently indicate that kenaf fibres offer favourable strength-to-weight ratios, low density, and renewable characteristics, making them promising alternatives to conventional synthetic reinforcements. Surface modification techniques, including alkaline and silane treatments, have been widely reported to enhance fibre–matrix interfacial bonding, thereby improving tensile strength and reducing moisture absorption in composite systems. In addition, hybridisation strategies and the use of bio-based polymer matrices, such as polylactic acid (PLA), have demonstrated potential for improving both mechanical performance and environmental sustainability. However, despite these advantages, several challenges remain unresolved, particularly concerning long-term durability under marine exposure, moisture-induced degradation, and biofouling susceptibility. Current literature also highlights the need for further investigation into lifecycle performance, large-scale manufacturing feasibility, and optimisation of fibre treatment methods. Overall, the collective evidence suggests that kenaf fibre composites represent a promising class of environmentally responsible materials for selected marine applications, especially in non-load-bearing and semi-structural components, although further research is required to address durability and performance limitations before broader industrial implementation can be achieved.

KEYWORDS: Kenaf fibre; eco-friendly material; biocomposite; marine applications

1 Introduction

The increasing demand for sustainable and environmentally responsible materials has become a central concern within the marine engineering sector. Growing awareness of environmental degradation, coupled with stricter international regulations on emissions and marine pollution, has intensified the need for innovative material solutions that minimise ecological impact while maintaining structural performance [1].

In this context, material selection plays a pivotal role in the development of marine structures, as it directly influences mechanical reliability, service life, and environmental sustainability [2].

Among the various material alternatives being explored, kenaf fibre–based composites have attracted considerable attention for marine applications owing to their favourable balance between mechanical performance and environmental compatibility. To be suitable for marine environments, such composites must fulfil stringent requirements, including high mechanical strength, resistance to moisture-induced degradation, long-term durability, and chemical stability under harsh operating conditions [3,4]. In environmentally friendly, kenaf (*Hibiscus cannabinus* L.) fibre does not pose a significant threat to the marine ecosystem. Unlike conventional synthetic materials, kenaf fibre is biodegradable and can be naturally decomposed by marine microorganisms, thereby minimising long-term accumulation and reducing the risk of persistent marine debris. This characteristic makes kenaf fibre-based composites a more sustainable alternative for applications where environmental impact is a critical consideration. These composites that demonstrate favourable mechanical performance, particularly in terms of impact resistance, offer considerable potential as substitutes for metals, for instance in the fabrication of ship bearings [5]. Their inherent resistance to friction and corrosion further enhances their suitability as protective coatings for marine components [6], Islam et al. [7] reported that the integration of composites in ship propellers is feasible, particularly when optimised for improved impact strength. Moreover, research has shown that composites are widely employed in the construction of yachts, racing boats, high-speed ferries, naval and coast guard patrol vessels, fishing vessels, work-boats, and offshore oil and gas platforms [8]. In general, composite materials demonstrate broad applicability across numerous marine structural elements. For example, El Hawary et al. [9] highlighted that components such as hulls, decks, and sail masts in sea vessels can be effectively manufactured using composite technologies.

Despite these advantages, the increasing use of polymer-based composites in marine environments has raised concerns regarding their long-term environmental footprint. The accumulation of plastic debris and microplastics generated from the degradation of synthetic materials presents a significant ecological threat to marine ecosystems [10,11]. Studies have reported that microplastic contamination in marine environments is escalating at an alarming rate, with projections indicating substantial increases in oceanic pollution levels in the coming decades [12]. For instance, Everaert et al. [13] estimates that in 2010, about 0.17% of global sea level (depth 0–5 m) is at risk of microplastic contamination, with projected increases to 0.52% by 2050 and 1.62% by 2100. In particular, the Mediterranean Sea and the Yellow Sea have been identified as hotspots of microplastic pollution risk.

In response to these challenges, natural fibre-reinforced composites have emerged as a promising class of materials for marine applications. Their inherent advantages including low density, renewability, biodegradability, and creep resistance reduced carbon footprint, make them attractive substitutes for conventional synthetic composites [14,15]. In particular, kenaf fibre has gained recognition for its favourable mechanical properties, cost-effectiveness, and environmental compatibility, positioning it as a viable reinforcement material for marine structures [16]. The integration of kenaf fibres into composite systems not only contributes to weight reduction and improved energy efficiency but also supports broader sustainability objectives by lowering greenhouse gas emissions and dependence on non-renewable resources [17].

Against this backdrop, the present review focuses on the potential of kenaf fibre–based composites for marine applications, with particular emphasis on their mechanical performance, durability, and environmental advantages. By synthesising current research findings, this work aims to highlight the suitability of kenaf-based composites as sustainable alternatives to conventional marine materials and to identify key challenges and future research directions necessary for their wider industrial adoption.

2 Kenaf Fibre and Its Properties

2.1 Brief History and Cultivation of Kenaf

Kenaf is a bast fibre plant native to central and eastern Africa and has been cultivated for more than six millennia, initially for rope production and animal feed [18] Belonging to the *Malvaceae* family, kenaf is now extensively cultivated across tropical and subtropical regions, including Asia, Africa, and parts of the Americas. Major producing countries include India, China, Bangladesh, Thailand, Indonesia, Malaysia, and the United States, reflecting its adaptability to diverse agro-climatic conditions [19].

Kenaf thrives in warm, humid climates, typically requiring temperatures between 20°C and 40°C and annual rainfall ranging from 500 to 1200 mm [20]. The kenaf plant is characterised by filaments composed of discrete fibres measuring 2–5 mm in length [21,22]. Structurally, the kenaf stem consists of two distinct regions: the outer bast and the inner core. The bast region, accounting for approximately 30%–40% of the stem mass, contains long, strong fibres with high cellulose content, while the woody core comprises the remaining 60%–70% and is characterised by lower density and strength [23,24].

2.2 Chemical Compositions of Kenaf Fibres

Kenaf is widely recognised as one of the most promising lignocellulosic fibres for composite applications due to its favourable chemical composition and sustainability profile [25]. The primary constituents of kenaf fibre include cellulose, hemicellulose, lignin, and minor amounts of extractives, each of which plays a crucial role in determining the fibre's mechanical, thermal, and interfacial behaviour [26].

Numerous studies have reported variability in the chemical composition of kenaf fibres depending on plant maturity, cultivation conditions, and processing techniques. For instance, cellulose content typically ranges from 56 to 64 wt%, hemicellulose from 21 to 35 wt%, and lignin from 8 to 14 wt% [27,28]. Table 1 summarises the compositional variations reported under different treatment conditions. Chemical treatments, particularly alkaline and pressure-assisted processes, have been shown to significantly increase cellulose content, with values reaching up to 73.89% in optimised systems. The value of the chemical composition depends on the chemical, mechanical and enzymatic treatment carried out. From Table 1, it can be known that chemical treatment can increase the concentration of cellulose kenaf up to 92%.

Table 1: Chemical composition of kenaf fibre.

No.	Treatment	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)	Pectin (%)	Refs.
Untreated							
1	Untreated	56.4	26.2	13.4	–	–	[24]
2	Untreated	66.24	16.28	14.67		0.57	[29]
3	Untreated	54.1	32.2	20.35	1.38	–	[30]
Chemical Treatment							
4	NaOH, 15% + 0.1% of anthraquinone (AQ)	81.5	12.7	2.5	0.9	–	[31]
5	Alkaline-Hydrogen peroxide treatment Alkaline Stage: 15% + 0.1% of anthraquinone (AQ) Bleaching Stage 1:	92.0	5.2	0.5	0.5	-	[31]
6	Acid hydrolysis (H_2SO_4, 4%)	56.81	13.59	18.27	7.87	–	[32]
7	Alkaline treatment (NaOH, 5%)	65.24	10.42	15.93	6.56	–	[32]

(Continued)

Table 1 (continued)

No.	Treatment	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)	Pectin (%)	Refs.
8	Alkaline-Potassium permanganate treatment (NaOH, 4% + $KMnO_4$, 0.02%)	68.77	8.94	15.18	5.16	–	[32]
9	Alkaline-Potassium dichromate treatment (NaOH, 4% + $K2Cr_2O_7$, 0.02%)	67.78	10.18	14.64	5.30	–	[32]
10	Alkaline-Hydrogen peroxide treatment (NaOH, 4% + H_2O_2, 10.8 mL)	79.30	9.69	7.22	5.59	–	[32]
11	Alkaline-Sodium chlorite treatment (NaOH, 4% + $NaClO_2$:water = 1:25)	75.92	9.03	8.03	6.95	–	[32]
12	NaOH, 5%	73.89	3.17	14.55	–	–	[33]
13	NaOH, 6%	62.73	20.2	17.07	0	–	[34]
Enzymatic Treatment							
14	Freshwater and enzymes	58.72	15.66	16.07	–	–	[35]

Chemical modification techniques, including alkaline, silane, acetylation, permanganate, peroxide, benzoylation, acrylonitrile grafting, maleic anhydride grafting, and isocyanate treatments, have been shown to alter cellulose concentrations and improve fibre performance [17]. These treatments primarily function by altering the chemical composition and surface characteristics of the fibres, thereby improving fibre–matrix interfacial bonding. Cellulose, the principal structural component of kenaf fibre, contributes significantly to tensile strength and stiffness owing to its highly crystalline structure. Hemicellulose, in contrast, plays an important role in fibre–matrix interaction through its amorphous nature, facilitating stress transfer within composite systems. Lignin, particularly in the form of Klason lignin, acts as a natural binder that imparts rigidity and dimensional stability; however, its hydrophobic character can adversely affect interfacial adhesion with polymer matrices. Extractives, although present in smaller quantities, influence surface energy, moisture affinity, and biological resistance, thereby affecting the overall durability of the fibres.

Materials used in marine applications experience swelling due to water absorption, natural fibres, especially kenaf, have amorphous surface areas derived from hemicellulose and lignin which have easy properties to absorb water and crystalline comes from cellulose with the characteristics of good mechanical properties and low water absorption. The crystalline regions of the kenaf are levelled using chemical treatments such as alkalizing, bleaching and acid hydrolysis. Research conducted by Fiore et al. showed that a 10% sodium bicarbonate solution affects the mechanical properties and aging of natural composite fibres in the marine environment [36]. However, research on the effect of natural fibre chemical treatment on water absorption and prevention of antifouling of composites in the marine environment has not been widely carried out, including kenaf fibre biocomposites. This is supported by a review conducted by Fragassa et al. that studies of natural fibre composites (NFC) using chemically treated fibres generally discuss improved mechanical performance because the interface bond between the matrix and the fibres is better after chemical treatment [37]. These findings have the potential for future research development related to the influence of chemical treatments such as alkali, silane, acetylation, sodium bicarbonate and enzymatic treatment on water absorption and antifouling in marine applications.

The chemical composition of kenaf fibres is commonly determined using gravimetric analytical techniques in accordance with standardised protocols such as those established by TAPPI and the National Renewable Energy Laboratory (NREL), ensuring reliable and reproducible quantification of constituent components [32,38]. Numerous studies have demonstrated that chemical treatments, including alkalisation, silane coupling, and maleic anhydride modification which effectively enhance fibre–matrix interfacial bonding, resulting in improved tensile strength, impact resistance, and reduced moisture absorption in kenaf-reinforced composites [39]. Collectively, these modifications play a critical role in optimising the performance of kenaf fibres for advanced composite applications, particularly in demanding structural and environmental conditions.

2.3 Mechanical Properties of Kenaf Fibre

Kenaf fibres are increasingly utilised as reinforcement in polymer composites due to their favourable strength-to-weight ratio and compatibility with both thermoset and thermoplastic matrices. Numerous studies have demonstrated that kenaf-reinforced composites exhibit competitive mechanical performance, particularly when combined with suitable matrices such as epoxy, polyester, and biodegradable polymers.

The tensile strength of kenaf fibres typically ranges from 427 to 930 MPa, depending on fibre source, extraction technique, and surface treatment [40]. The Young's modulus generally lies between 2.09 and 2.31 GPa, reflecting adequate stiffness for load-bearing applications. Although the elongation at break of kenaf fibres (approximately 1.6%) is lower than that of many synthetic fibres, it remains comparable to other natural fibres such as jute and hemp. Several studies report that kenaf composites exhibit fatigue properties of 18,630 cycles at 60% ultimate tensile strength and fracture energy (261.3 kJ/m^2), indicating potential for medium-load structural applications [41]. Other studies revealed that kenaf composites have a fairly good balance between static strength and fatigue strength with low fatigue sensitivity in a bidirectional plane [40]. These properties collectively render kenaf fibres suitable for semi-structural applications which could influence the resistance toward wave oscillation in marine environment. Table 2 summarises the tensile properties of various kenaf-based composite systems, highlighting the influence of fibre architecture, chemical treatment, matrix selection, and hybridisation strategies. The table shows that the value of tensile strength is in the range of 4.22–190.92 MPa. This difference in tensile strength value is significantly influenced by the type of matrix used, the content of kenaf fibre in the composite and the chemical treatment. This review shows that natural matrix-based biocomposites such as PLA with a combination of chemical treatments have the potential to become construction materials, especially in marine applications due to their tensile strength capabilities and better impact on the environment than composites based on synthetic polymers such as polypropylene and epoxy.

Table 2: Mechanical properties of kenaf fibre.

Matrix	Kenaf Fibre Content	Treatment	Tensile Strength (MPa)	Refs.
Thermoplastic-based polymer	40%	Untreated	160	[42]
Polypropylene	10%	Untreated	21.612	[43]
Polypropylene	10%	6% NaOH	21.618	[43]
Polypropylene	40%	Untreated	24.686	[43]
Polypropylene	40%	6% NaOH	25.186	[43]
PLA	25%	5% NaOH	8.45	[44]
PLA	40%	Untreated	61	[45]
PLA	50%	Untreated	190.92	[46]
PLA	15% kenaf + 15% aloevera fibre	6% NaOH	53.88	[34]

(Continued)

Table 2 (continued)

Matrix	Kenaf Fibre Content	Treatment	Tensile Strength (MPa)	Refs.
PLA	2.5%	6% NaOH + 0.5% Silane	54.01	[47]
PLA	2.5%	6% NaOH + 1% Silane	57.85	[47]
PLA	2.5%	6% NaOH + 2% Silane	56.99	[47]
PLA	–	20% sodium acetate	68.8	[48]
Corn starch	6%	Untreated	17.74	[49]
Corn starch	8%	Untreated	17.01	[49]
Polypropylene granules	30%	Untreated	15.83	[50]
Polypropylene granules	30%	1% NaOH	16.29	[50]
Polypropylene granules	30%	3% NaOH	17.11	[50]
Polypropylene granules	30%	5% NaOH	18.26	[50]
Polypropylene granules	30%	7% NaOH	14.57	[50]
Polypropylene granules	30%	1% Silane	16.37	[50]
Polypropylene granules	30%	2% Silane	17.82	[50]
Polypropylene granules	30%	3% Silane	18.73	[50]
Polypropylene granules	30%	4% Silane	18.42	[50]
Polypropylene granules	30%	5% Silane	16.99	[50]
Epoxy resin	30% of woven kenaf	Untreated	70.96	[51]
Epoxy resin	40% of woven kenaf	Untreated	76.67	[51]
Epoxy resin	50% of woven kenaf	Untreated	50.54	[51]
Epoxy resin	Kenaf fibre + glass fibre (0° orientation)	Untreated	49.27	[52]
Epoxy resin	22.5% kenaf + 7.5% palm leaf	5% NaOH	4.22	[53]
Epoxy resin	5%	Untreated	27.1	[54]

In term of marine applications, the mechanical properties refer to the capability of kenaf fibres to enhance the structural performance of composite materials, particularly in relation to the requirements for marine products. For instance, Fu et al. [55] marine structural materials are generally required to exhibit mechanical strength in the range of 355–690 MPa. As shown in Table 2, kenaf-based composites demonstrate mechanical properties that approach these requirements, indicating their potential suitability for marine applications.

Several strategies have been reported to further enhance the mechanical performance of kenaf composites. For instance, hybridisation with other natural fibres has been shown to improve strength and stiffness, where the combination of kenaf and oil palm fibres resulted in notable enhancements in tensile properties [56], Similarly, Verma et al. [57] reported that the incorporation of 5 wt% of NaOH-treated kenaf fibres together with glass fibre reinforcement significantly improved tensile strength, flexural behaviour, and impact resistance. In addition, the use of geopolymer-modified matrices has been identified as a promising approach for improving the mechanical performance of composite materials intended for marine environments [58].

Beyond material selection and hybridisation, optimization techniques such as Response Surface Methodology (RSM) and the Taguchi method have been effectively employed to further enhance the mechanical performance of kenaf-based biocomposites. These approaches enable the systematic optimisation of processing parameters, leading to substantial improvements in material performance. For instance, optimisation using RSM has been reported to achieve increases of up to 100%, 174%, and 100% in compressive, tensile, and flexural strengths, respectively, compared with untreated control sample [59,60]. Collectively, these findings reinforce the suitability of kenaf-based composites for marine structural applications when appropriately engineered and optimised.

2.4 Other Properties of Kenaf Fibre

Beyond mechanical performance, the physical characteristics of kenaf fibres play a decisive role in determining their suitability for composite applications. Density, moisture absorption, thermal stability, and surface morphology are particularly critical parameters. Kenaf fibres exhibit relatively low density, typically ranging from 0.53 to 1.00 g/cm^3, which contributes to the high specific strength of kenaf-based composites. However, increasing fibre content can raise composite density, as observed in bio-epoxy systems reaching values up to 1.26 g/cm^3.

Moisture absorption remains a key challenge due to the hydrophilic nature of kenaf fibres. Water uptake can reach 10%–20%, leading to swelling, interfacial debonding, and degradation of mechanical properties [61]. Similar behaviour has been reported in hybrid systems such as kenaf–bamboo composites, where moisture absorption and thickness swelling increase proportionally with fibre content [62]. Similar behaviour has been reported in hybrid systems such as kenaf–bamboo composites, where moisture absorption and thickness swelling increase proportionally with fibre content [63]. Yusuff et al. [51] further demonstrated that water absorption increases linearly with fibre content until saturation is reached, confirming the strong dependence of moisture uptake on fibre volume fraction.

Despite these limitations, the physical characteristics of kenaf fibres remain attractive for environmentally sustainable applications. The equilibrium moisture content of kenaf fibres typically ranges from 8%–12%, depending on climatic conditions and storage environment. Although such hygroscopic behaviour may induce dimensional instability, it can be effectively mitigated through chemical treatments such as alkalisation and acetylation, which reduce hydroxyl group availability and improve fibre–matrix interfacial bonding [64]. These modifications significantly enhance dimensional stability and broaden the applicability of kenaf-based composites in moisture-prone environments.

From a thermal perspective, kenaf fibres exhibit initial thermal degradation temperatures in the range of 200°C–250°C, as determined by thermogravimetric analysis. Exceeding this threshold results in the decomposition of cellulose and lignin constituents, thereby compromising structural integrity. Consequently, careful control of processing temperatures is essential, particularly for thermoplastic composite manufacturing. Morphologically, kenaf fibres display rough and porous surfaces, especially following chemical or mechanical treatments. Scanning electron microscopy reveals surface irregularities and micro voids that promote mechanical interlocking and improve interfacial adhesion with polymer matrices.

The degree of crystallinity of kenaf fibres, typically ranging from 40% to 70%, also plays a significant role in governing mechanical performance. Higher crystallinity contributes to increased stiffness and strength, although excessive crystallinity may reduce flexibility. Therefore, controlled modification strategies, including thermal, chemical, and enzymatic treatments, are often employed to balance stiffness and toughness according to application requirements. In parallel, recent studies have highlighted the importance of interfacial strengthening mechanisms, such as load transfer efficiency, thermal mismatch mitigation, and microstructural refinement in enhancing the performance of bio-based composites. For instance, Notably, advanced approaches involving improved interfacial bonding and thermal management have demonstrated potential for reducing thermal degradation in hybrid biocomposites by up to 492°C [65].

Collectively, the physical and thermal characteristics of kenaf fibres underscore their suitability as sustainable reinforcement materials. When combined with appropriate surface modification techniques and optimised composite design strategies, kenaf-based fibres offer a promising, environmentally responsible alternative for advanced engineering and marine applications.

3 Processing and Treatment of Kenaf Fibre

3.1 Fibre Extraction Methods

Following harvesting, kenaf stems undergo fibre extraction through a process commonly referred to as retting. This process facilitates the separation of fibre bundles from the surrounding non-fibrous tissues by exploiting biological, chemical, or mechanical actions. Fig. 1 illustrates the structural components of the kenaf stem, while Fig. 2 depicts the fibres obtained after separation. Retting relies primarily on the degradation of pectic substances within the middle lamella, which bind adjacent fibre cells together, thereby enabling the release of individual fibres.

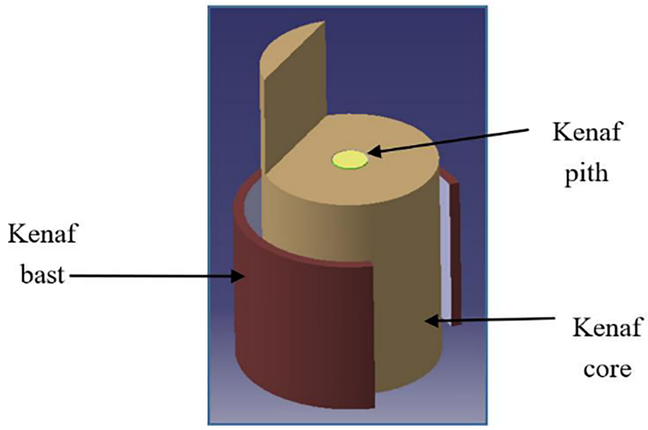

Figure 1: Schematic diagram of kenaf stem components [62]. Creative common CC BY license.

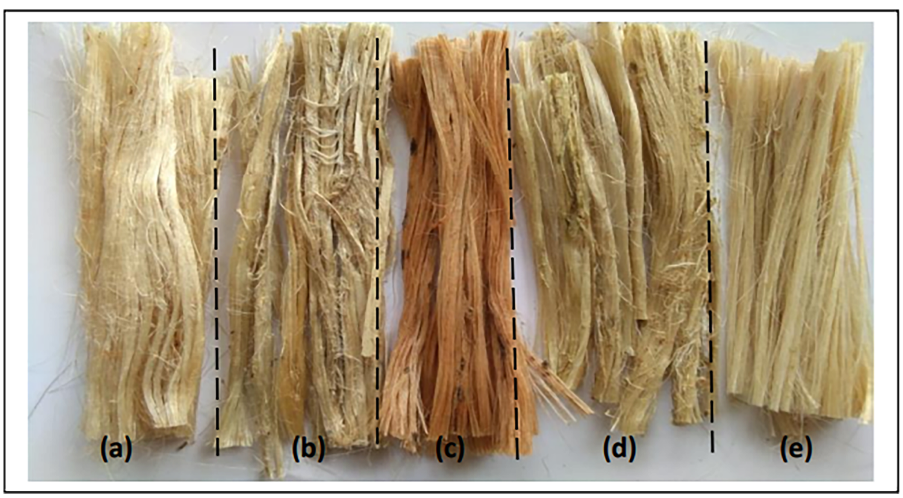

Figure 2: Kenaf fibres after mechanical separation: (**a**) clean water; (**b**) pond immersion for 10 days; (**c**) combined pond–ditch immersion for 8 days; (**d**) pond connected to a small river stream for 10 days; (**e**) rain and bore water immersion for 14 days, followed by washing with clean water [21]. Creative Common CC BY license.

Several retting techniques have been developed, including dew retting, water retting, enzymatic retting, chemical retting, and mechanical retting, each offering distinct advantages and limitations [66]. Scanning electron microscopy (SEM) observations indicate that properly retted kenaf fibres exhibit relatively smooth and well-defined surfaces with minimal fibrillation or fibre pull-out as shown in Fig. 3 [21]. In particular, water-retted fibres display clean surfaces with limited structural damage, as the controlled microbial action effectively removes non-cellulosic materials without excessive fibre degradation [67]. In contrast, mechanically retted fibres often exhibit surface irregularities and microstructural defects due to the aggressive nature of the separation process.

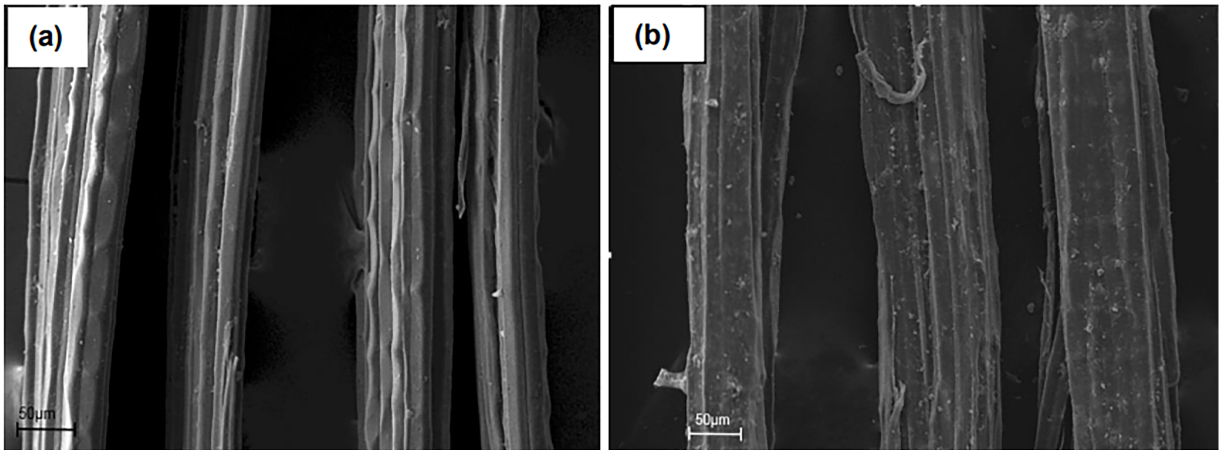

Figure 3: SEM of kenaf fibre resulting from retting treatment (**a**) untreated fibres exhibiting relatively smooth surfaces with longitudinal grooves and minimal surface irregularities; (**b**) treated fibres showing increased surface roughness, the presence of surface deposits, and micro-scale irregularities [21]. Creative Common CC BY license.

Chemical retting techniques, employing agents such as sodium hydroxide, hydrogen peroxide, or sodium benzoate, are widely used to accelerate fibre separation and enhance surface cleanliness. These methods efficiently remove hemicellulose, lignin, and other amorphous constituents, yielding fibres with improved uniformity and surface quality compared with untreated or mechanically processed fibres [68]. However, the use of aggressive chemical treatments requires careful optimisation to prevent excessive fibre damage.

Water retting, on the other hand, is known for producing fibres with good uniformity and relatively high quality, although the process requires longer treatment periods and careful control to prevent excessive fibre degradation. Dew retting offers the advantage of facilitating the natural breakdown of pectic substances through microbial activity, allowing for easier fibre separation under favourable environmental conditions. Enzymatic retting represents a more controlled and environmentally friendly alternative, as specific enzymes can be selected to target particular fibre components. This method allows the tailoring of fibre properties by adjusting enzyme type and treatment duration, resulting in fibres suited for specific end-use applications. In contrast, mechanical retting is characterised by its ability to rapidly produce large quantities of short fibres, making it suitable for high-throughput industrial processing, although it may result in greater fibre damage.

Beyond fibre separation, the retting process also influences the internal structure of the fibres. Studies have shown that retting can significantly increase the crystallinity index of kenaf fibres, which is closely associated with improved mechanical performance. For instance, chemically treated fibres have demonstrated a higher crystallinity index (approximately 71.93%) compared with untreated fibres (57.39%) and enzyme-treated fibres (66.70%) [69]. This increase in crystallinity contributes to enhanced stiffness and strength, further supporting the suitability of chemically treated kenaf fibres for composite applications.

3.2 *Surface Treatment Techniques*

Despite their favourable intrinsic properties, kenaf fibres exhibit limited interfacial compatibility with polymer matrices due to the presence of non-cellulosic components such as lignin, hemicellulose, pectin, and surface waxes. These constituents hinder effective stress transfer at the fibre–matrix interface, thereby reducing composite performance [66]. To address this limitation, a variety of surface modification techniques have been developed to enhance fibre–matrix adhesion and overall composite behaviour.

Chemical surface treatments remain the most widely adopted approach and include alkalisation, silane treatment, acetylation, peroxide treatment, and other coupling-agent-based modifications, as summarised in Table 3. Among these, alkalisation is particularly effective and widely employed as shown in Fig. 4. As reported by Guo et al. [32], alkali treatments using reagents such as sodium hydroxide, potassium permanganate, potassium dichromate, hydrogen peroxide, and sodium chlorite promote the removal of surface impurities and expose reactive hydroxyl groups on the fibre surface. This enhances interfacial bonding and facilitates stronger chemical interactions with polymer matrices [70].

Table 3: Comparison of chemical treatments for kenaf fibre.

Treatments	Chemical Agents	Processing Conditions	Findings	Refs.
Acetylation treatment	Sodium acetate	Concentrations of 10%, 15%, and 20%; treatment durations of 24, 48, and 72 h at room temperature	Effective removal of non-cellulosic constituents, leading to improved fibre surface characteristicsfibre	[71]
Ethanolamine deep eutectic solvent	Choline chloride and ethanolamine	Molar ratios of 1:2, 1:4, 1:6, and 1:10; treatment at 70°C	Environmentally benign treatment enhancing fibre purity and surface modification	[72]
Alkaline-Sodium chlorite treatment	Sodium chlorite	77.5%–82.5% purity, treatment at 70°C for 2 h; pH ≈ 11.1	Effective removal of lignin and non-cellulosic components	[32]
Alkalization	Sodium hydroxide (NaOH)	6% NaOH solution; immersion time of 3 h	Improved tensile and flexural properties of hybrid composites	[73]
Esterification	Propionic anhydride and succinic anhydride	Reaction in N,N-dimethylformamide with sodium formate catalyst at 100°C for 180 min	Enhanced tensile, flexural, and impact properties of treated composites	[74]

(Continued)

Table 3 (continued)

Treatments	Chemical Agents	Processing Conditions	Findings	Refs.
Multi-step surface modification (acetylation, permanganate, maleation)	Acetic acid, potassium permanganate, maleic anhydride	10% acetic acid for 1 h; 20% maleic anhydride solution; 0.5% $KMnO_4$ treatment	Improved tensile strength, hardness, and reduced water uptake at 10% fibre loading	[75]
Hydrogen peroxide bleaching	Hydrogen peroxide	Concentration not specified	Improved mechanical performance of PLA–kenaf composites	[76]
Alkali–silane hybrid treatment	Sodium hydroxide and 3-aminopropyltriethoxysilane	2%–6% NaOH followed by 5% silane treatment	Enhanced fibre–matrix interfacial bonding and improved composite strength.	[77]

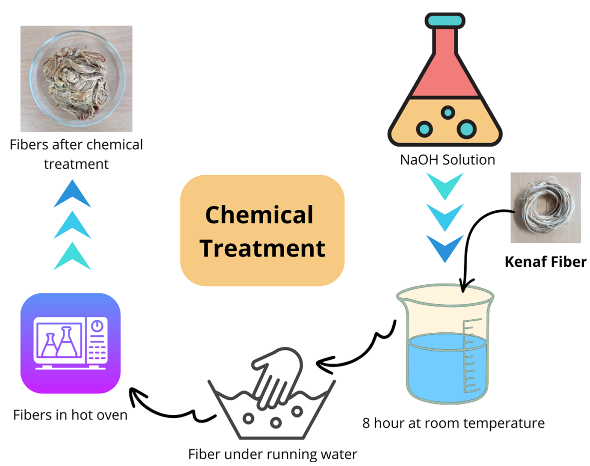

Figure 4: Schematic representation of the chemical treatment process.

Surface modification not only improves interfacial adhesion but also enhances the thermal stability of kenaf fibres. Nursheila Wan Jusoh et al. [78] demonstrated that surface treatments can also improve the thermal stability of kenaf fibres. In their study, fibres treated with ammonium polyphosphate (APP), 6% NaOH, and a combination of both treatments exhibited enhanced heat resistance. Thermogravimetric analysis (TGA) revealed that fibres treated with APP achieved the highest degradation resistance, with a minimum weight loss of approximately 66%, outperforming both untreated and other treated fibres. These findings confirm that appropriate chemical surface modifications (Fig. 5) not only strengthen fibre–matrix interfacial bonding but also enhance the thermal durability of kenaf-reinforced composites.

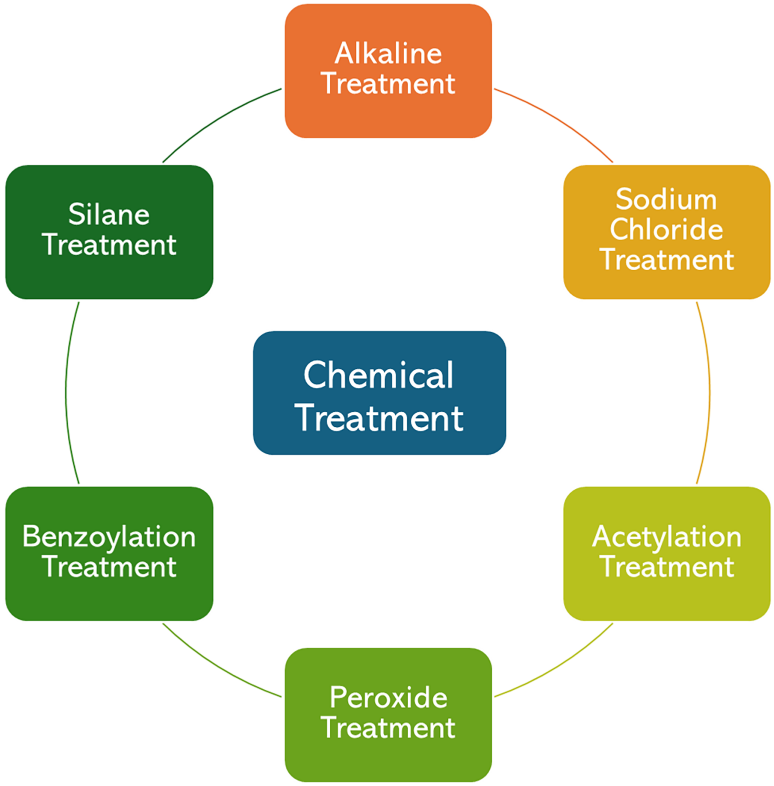

Figure 5: Types of chemical treatments for kenaf fibres.

While processes such as alkalisation, silane treatment, acetylation, and peroxide modification are effective in enhancing interfacial bonding, moisture resistance, and mechanical properties, they may also introduce additional chemical consumption, energy use, and waste generation. This raises valid questions regarding the sustainability of such treatments when applied to NFCs. However, it should be emphasised that these treatments do not remove the environmental benefits of kenaf fibres; rather, they highlight the need for carefully optimised processing strategies. Hence, the use of chemical treatments in kenaf fibre composites should not be viewed as contradictory to sustainability goals. Instead, when applied judiciously and at controlled levels, such treatments enable the development of composites that meet engineering performance requirements while still offering a reduced environmental footprint compared to conventional synthetic fibre systems.

4 Marine Composite Materials: Performance Requirements and Durability Challenges

Marine structures impose stringent performance requirements on composite materials due to the aggressive nature of the ocean environment. Materials used in marine applications must provide high strength, stiffness, and fatigue resistance to withstand dynamic loads generated by waves, currents, and operational forces. At the same time, they must resist environmental degradation caused by prolonged exposure to seawater, salt spray, ultraviolet (UV) radiation, thermal cycling, and biological activity [9,79]. In service conditions, marine components are frequently subjected to saltwater immersion, hydrostatic pressure, solar radiation, and biofouling organisms, all of which can progressively deteriorate material performance. Fibre-reinforced polymer (FRP) composites are widely adopted in marine structures because they do not undergo electrochemical corrosion in seawater, unlike conventional metallic materials such as steel or aluminium. Nevertheless, corrosion resistance alone does not guarantee long-term durability, and marine composites must still be carefully engineered to withstand the combined mechanical and environmental stresses encountered in ocean conditions.

Despite their advantages, traditional synthetic composites reinforced with glass or carbon fibres can still experience ageing and degradation in marine environments. Moisture diffusion into the composite laminate gradually plasticises the polymer matrix and causes swelling of the reinforcing fibres, which weakens the fibre–matrix interface. This process often leads to microcracking, void formation, and eventual delamination within the laminate structure, thereby reducing stiffness, strength, and fatigue resistance over time. Ultraviolet radiation further accelerates degradation through photo-oxidative reactions, which induce surface cracking, embrittlement, and roughening of the composite surface. In addition, continuous cyclic loading generated by wave action and operational stresses promote fatigue damage and crack propagation within the composite structure [40]. Marine biofouling organisms such as algae, barnacles, and microorganisms also contribute to material deterioration by increasing structural weight, altering surface roughness, and increasing hydrodynamic drag. Consequently, the combined effects of moisture ingress, UV exposure, mechanical fatigue, and biological activity can significantly compromise the long-term integrity of composite materials unless appropriate protective measures and design strategies are implemented [80].

Natural fibre-reinforced composites have recently attracted attention as environmentally sustainable alternatives to conventional FRP systems. Polymer reinforced with plant fibres such as kenaf offer several advantages, including low density, renewability, and reduced environmental impact. In addition, natural fibres are electrically non-conductive and therefore do not promote galvanic corrosion when used in hybrid structural systems. However, the hydrophilic nature of lignocellulosic fibres introduces challenges related to moisture absorption. Natural fibres readily absorb water into their microstructure, which leads to fibre swelling, interfacial debonding, and deterioration of the fibre–matrix bonding. As a result, mechanical load transfer between the reinforcement and matrix becomes less effective, ultimately reducing the structural performance of the composite. Experimental studies have demonstrated that moisture-induced degradation in NFCs primarily occurs within the fibre phase and at the fibre–matrix interface rather than within the polymer matrix itself [81]. For instance, kenaf fibre composites exhibited mass losses of 15.56% and 27.56% after 100 days of soil burial under controlled conditions, demonstrating the enhanced degradability of PLA-based systems compared with conventional polymers [59].

To overcome these limitations, several material engineering strategies have been developed to improve the moisture resistance and durability of NFCs. Chemical surface treatments, including alkali and silane treatments, are widely applied to modify the fibre surface by reducing hydrophilic hydroxyl groups and improving interfacial adhesion with the polymer matrix. Fibre hybridisation, optimised laminate stacking sequences, and improved matrix selection can also reduce water diffusion and enhance structural performance [82]. These approaches strengthen the fibre–matrix interface and significantly reduce moisture uptake within the composite laminate. When such treatments and design strategies are implemented, NFCs such as kenaf-reinforced laminates have demonstrated the ability to retain a substantial proportion of their mechanical properties even after prolonged exposure to marine environments.

Beyond performance considerations, sustainability has become an increasingly important factor in the development of marine composite materials. Conventional FRP systems rely heavily on petroleum-based resins and energy-intensive reinforcing fibres such as carbon and glass, which contribute to high embodied energy and limited recyclability. Carbon fibre composites, in particular, are associated with significant carbon emissions during production and present substantial challenges in end-of-life recycling due to the thermoset matrix. In contrast, bio-based resins and natural fibres offer a more sustainable alternative by reducing life-cycle environmental impacts. Plant fibres such as kenaf, flax, and bamboo not only require lower energy inputs during processing but also act as carbon sinks during growth, thereby contributing to reduced greenhouse gas emissions.

However, the successful implementation of sustainable composites in marine structures requires careful integration of environmental durability and structural performance. Marine materials must be designed to withstand simultaneous exposure to seawater, ultraviolet radiation, cyclic mechanical loading, and biological fouling while maintaining long-term structural stability. Recent studies have demonstrated that the incorporation of advanced material technologies, including silane-based fibre treatments, nanocellulose reinforcements, and hybrid fibre architectures, can significantly enhance the durability and moisture resistance of NFCs. In addition, protective surface coatings and antifouling treatments further improve long-term performance in marine environments. Through the combination of advanced resin systems, tailored fibre treatments, and protective design strategies, modern composite materials can meet both performance and sustainability requirements, enabling the development of durable and environmentally responsible marine structures.

5 Kenaf Fibre as Key Components in Composite Materials

5.1 Matrix Compatibility with Kenaf Fibre

Kenaf fibres exhibit favourable compatibility with a wide range of polymer matrices, particularly when appropriate surface treatments are applied to enhance interfacial bonding. Both chemical and physical modification techniques have been shown to improve the adhesion between kenaf fibres and polymer matrices, thereby enhancing the mechanical performance of the resulting composites [66]. Thermoplastic polymers such as polyamide, polypropylene, polyethylene terephthalate (PET), and polybutylene terephthalate (PBT) are increasingly employed in marine-related applications due to their good processability, recyclability, and resistance to environmental degradation.

Among these matrices, polylactic acid (PLA) has attracted significant attention as a bio-based alternative to conventional petroleum-derived polymers. Although PLA exhibits higher susceptibility to hydrolytic degradation, particularly under prolonged exposure to moisture and elevated temperatures, its selection in composite systems is driven by sustainability considerations rather than universal structural suitability. The use of PLA is therefore most appropriate in applications where environmental performance and reduced carbon footprint are prioritised over long-term structural endurance. The performance limitations of PLA-based composites can be effectively mitigated through material engineering strategies. Fibre surface modification, polymer blending, and the incorporation of nanofillers have been shown to improve interfacial adhesion, reduce moisture sensitivity, and enhance overall durability. When reinforced with kenaf fibres, PLA-based composites demonstrate a favourable balance between mechanical strength and environmental sustainability. Studies have reported that appropriate fibre–matrix combinations can significantly improve tensile and flexural properties, while simultaneously reducing environmental impact. In particular, a PLA–kenaf composite with a fibre-to-matrix ratio of 50:50 has been shown to achieve increases of 224% and 239% in tensile and flexural strength, respectively [59].

Hence, the findings highlight the potential of such systems for use in non-load-bearing and semi-structural marine components, including interior panels and secondary structural elements. Although bio-based composites remain less widely adopted than conventional materials, their capacity to reduce toxic emissions, enhance recyclability, and support circular material flows positions them as promising candidates for sustainable marine applications [83].

5.2 Fabrication Techniques and Performance Implications

The fabrication of kenaf fibre composites is governed by application requirements, material characteristics, and economic considerations [84]. A range of manufacturing techniques has been developed to optimise mechanical performance and structural integrity. Among these, Resin Transfer Moulding (RTM) is widely employed for producing high-quality composite components with complex geometries. RTM enables efficient resin impregnation of fibre preforms and offers good control over fibre volume fraction, resulting in enhanced mechanical performance. Trofimov et al. [85] reported that RTM-fabricated composites reinforced with three-dimensional woven fibres exhibited high structural efficiency, making them suitable for demanding applications in the marine sectors. An optimal fibre loading of approximately 40% has been shown to produce tensile strengths of up to 55 MPa [86].

Vacuum-Assisted Resin Infusion (VARI) represents another widely adopted technique, offering improved resin distribution and reduced void content compared with conventional methods. The enhanced impregnation achieved through VARI contributes to superior tensile and flexural properties, particularly in large or complex composite structures [87]. In addition to these advanced processes, conventional fabrication techniques such as compression moulding and hand lay-up continue to be utilised, especially in cost-sensitive or low-volume production scenarios [14,88], While these methods may offer lower processing precision, they remain attractive due to their simplicity, flexibility, and economic viability, particularly for prototyping and small-scale manufacturing.

Collectively, the selection of an appropriate fabrication method plays a critical role in determining the mechanical performance, structural reliability, and economic feasibility of kenaf fibre composites, and must therefore be carefully aligned with the intended application and performance requirements.

6 Performance of Kenaf Fibre Composites in Marine Environments

Natural fibre–reinforced composites, particularly those incorporating kenaf fibres, have attracted increasing interest for marine applications due to their favourable environmental profile and mechanical potential. Several studies have demonstrated that kenaf fibre–reinforced cementitious and polymer composites can exhibit improved resistance to seawater penetration compared with unreinforced systems.

For instance, Hashim et al. [89] reported that the incorporation of kenaf fibres enhanced the sealing of surface pores in cementitious matrices, thereby reducing seawater ingress and improving overall durability. Additionally, several studies on kenaf fibre–reinforced PLA composites revealed that prolonged exposure to seawater resulted in fibre swelling, matrix plasticisation, and progressive interfacial debonding, ultimately leading to mechanical degradation [90]. Similar trends have been observed in composites containing hydroxyapatite (HA), where exposure to different seawater temperatures induced further reductions in mechanical performance, suggesting that filler–matrix interactions play a significant role in governing durability under marine conditions [91].

Apart from that, one of the principal challenges associated with the use of biocomposites in marine environments is their inherent tendency to absorb moisture, even under routine service conditions such as cleaning or exposure to humid atmospheres. Water uptake leads to plasticisation and swelling of the polymer matrix, which in turn weakens fibre–matrix interfacial bonding and accelerates mechanical degradation [37]. Prolonged exposure to seawater further exacerbates this process, promoting structural deterioration and facilitating biofouling, defined as the accumulation of biological organisms on material surfaces [92]. In this context, NFCs, including those reinforced with kenaf fibres, present a complex behaviour. On one hand, several studies suggest that lignocellulosic fibres may inherently limit microbial adhesion due to their surface chemistry, potentially reducing biofouling under certain conditions [93]. On the other hand, their hydrophilic nature enables significant water absorption, which can increase biological activity within the material and accelerate interfacial degradation. This dual behaviour indicates that natural fibres may act not only as passive reinforcements but also as active contributors to moisture transport and microbial interaction within the composite system.

Experimental evidence supports these concerns, as kenaf fibres have been shown to absorb greater amounts of water when immersed in seawater compared with distilled or acidic environments. Extended exposure results in measurable reductions in tensile strength, reflecting progressive fibre degradation and loss of structural integrity [94]. These findings highlight the complex and sometimes competing roles of natural fibres in marine composites, where their environmental advantages and potential resistance to surface biofouling must be carefully balanced against their susceptibility to moisture-induced degradation. Consequently, effective material design strategies, including fibre surface modification, matrix optimisation, and protective coatings, are essential to mitigate these effects and enhance long-term performance in marine applications.

7 Environmental Impact and Sustainability

7.1 Kenaf Fibre as an Environmentally Sustainable Resource

The rapid expansion of industrial activity and global population growth has intensified environmental degradation, prompting an urgent search for sustainable material alternatives. In this context, bast fibres such as kenaf have gained increasing attention due to their favourable environmental profile and multifunctional potential [95]. Bast fibre plants demonstrate significant phytoremediation potential, as their rapid growth rates and well-developed root systems enable the uptake of heavy metals and other contaminants from soil and water environments as shown in Table 4. This characteristic allows such plants to contribute to the rehabilitation of polluted sites while simultaneously improving soil structure and fertility. However, this beneficial trait also raises an important consideration for composite applications. As highlighted by the reviewer, there is a potential risk that heavy metals absorbed during phytoremediation may be retained within the plant biomass and subsequently transferred into composite materials if the fibres are used without appropriate control measures.

Table 4: Heavy metals absorbed by kenaf plant.

Heavy Metal	Concentration/Content of Heavy Metal in Different Plant Parts	Experimental Setup	Reference
Cd	2.67 mg/kg in root, 2.05 mg/kg in xylem, 3.87 mg/kg in phloem	Field study	[96]
Cu	95.1 mg/kg in root, 21.3 mg/kg in leaf, 11.6 mg/kg in stem	Pot study	[97]
Sb	0.8 mg/kg in plant	Pot study	[98]
Cd	355 mg/kg in plant		
Pb	606 mg/kg in plant		
Ni	488 mg/kg in plant		
As	1.612 mg/kg in root, 5.229 mg/kg in shoot	Pot study	[99]
Pb	422.7 mg/pot in shoot	Pot study	[100]

(Continued)

Table 4 (continued)

Heavy Metal	Concentration/Content of Heavy Metal in Different Plant Parts	Experimental Setup	Reference
Cd	2.49 mg/kg in shoot	Plant grown in Lysimeter	[101]
Zn	82.5 mg/kg in shoot		
Fe	47.0 mg/kg in root, 2.37 mg/kg in stem	Plant grown in plastic bags	[102]
Zn	1.50 mg/kg in root, 1.64 mg/kg in stem		
Pb	51.14 mg/kg in stem	Pot Study	[103]
Cd	0.87 mg/kg in roots, 0.36 mg/kg in shoots	Field study	[104]

In the context of kenaf fibre, this issue is particularly relevant, as the plant is widely recognised for its high uptake efficiency of certain heavy metals. Therefore, careful material selection and feedstock management are essential to minimise the risk of contamination. This includes ensuring that kenaf fibres intended for composite reinforcement are sourced from controlled cultivation environments rather than from soils with known heavy metal contamination. In addition, monitoring soil quality and implementing appropriate agricultural management practices can further reduce the likelihood of metal uptake.

Despite this consideration, the utilisation of kenaf fibres remains highly attractive due to their considerable economic and environmental value. Harvested fibres are widely applied in textiles, bio-composites, and construction materials, linking environmental remediation with value-added industrial applications [95,105]. When appropriate sourcing and quality control measures are implemented, kenaf fibres can be safely and effectively integrated into composite systems, enabling the development of sustainable materials while mitigating potential risks associated with heavy metal accumulation. Additionally, kenaf fibre is particularly promising due to its combination of favourable properties, including high mechanical strength, ease of processing, and inherent biodegradability [20]. These attributes position kenaf not only as a sustainable raw material for composite applications but also as a strategic eco-friendly alternative to conventional synthetic fibres in support of global sustainability goals.

7.2 Life Cycle Assessment of Kenaf Fibre Composites

Life Cycle Assessment (LCA) provides a comprehensive framework for evaluating the environmental impacts associated with materials throughout their entire life cycle, from raw material extraction to end-of-life disposal. In the context of kenaf fibre composites, LCA has been instrumental in quantifying energy consumption, greenhouse gas emissions, and overall environmental burden relative to conventional composite systems [106].

Studies have demonstrated that kenaf-based composites generally exhibit lower embodied energy and reduced carbon footprints compared with glass fibre-reinforced counterparts. For example, life cycle assessments of kenaf-based structural components have shown substantial reductions in non-renewable energy use and greenhouse gas emissions. Batouli and Zhu [107] reported that kenaf-based structural insulated panels performed favourably in several environmental impact categories, although certain trade-offs were observed, highlighting the importance of optimised material design and processing conditions. Further investigations have shown that replacing conventional glass fibres with kenaf fibres can lead to energy savings of up to 22–23 MJ per component during manufacturing. Such reductions contribute significantly to the sustainability of composite materials, particularly in applications where large volumes of material are required.

Collectively, these findings underscore the potential of kenaf fibre composites to support circular economy principles by reducing resource consumption, minimising environmental impact, and enhancing material sustainability across their life cycle.

8 Applications of NFCs from Kenaf in Marine Industry

The use of FRP composites in marine applications dates back to the late 1940s, when such materials were first introduced for boat hull construction [10]. Since then, composite technologies have become firmly established within the maritime sector. Conventional marine structures predominantly rely on glass fibre–reinforced polymer composites [8] and, while more advanced applications employ carbon or aramid fibre composites combined with epoxy or vinyl ester matrices to meet demanding mechanical and durability requirements. These materials are widely favoured for their high strength-to-weight ratio, corrosion resistance, and design flexibility.

In contemporary practice, composite materials are extensively used in shipbuilding and repair, particularly for hull repairs, deck structures, and secondary load-bearing components. Glass fibre composites remain the most common choice, while carbon fibre systems are increasingly adopted for high-performance and weight-sensitive applications. In parallel with these developments, growing environmental awareness has driven interest in sustainable and bio-based alternatives, leading to increased research into natural fibre–reinforced composites for marine use [12].

Among these, kenaf fibre–based composites have attracted attention due to their low density, renewability, and favourable mechanical properties. Their resistance to corrosion and suitability for pultruded components such as walkways, gratings, and structural panels make them attractive candidates for certain marine applications. Commercial initiatives, including eco-boat hulls and marine components developed by companies such as Sustainable Composites and Movevirgo, demonstrate the practical potential of NFCs in low- to moderate-load marine environments [108].

However, despite these promising attributes, it is important to recognise that kenaf-based composites are not yet suitable for safety-critical or primary load-bearing marine structures, such as ship hulls, deep-sea mooring systems, or offshore load-bearing components. Exposure to seawater, cyclic loading, and long-term environmental ageing can significantly affect their mechanical integrity. Current evidence indicates that, while kenaf composites perform well under moderate service conditions, their long-term durability under extreme marine environments remains limited when compared with conventional fibre-reinforced systems.

Nevertheless, this limitation does not preclude their broader application. Rather, it highlights the need for targeted material development strategies. The integration of kenaf fibres with advanced polymer matrices such as bio-based epoxies and PLA, along with hybridisation approaches combining natural and synthetic fibres, offers a promising pathway to improve mechanical performance and durability. Such strategies allow kenaf-based composites to be effectively utilised in non-load-bearing or semi-structural marine components, including interior panels, decking, protective covers, and secondary structural elements.

In this context, the future of kenaf fibre composites lies not in replacing high-performance synthetic composites entirely, but in complementing them within a sustainable materials framework. Through continued optimisation of fibre treatment, matrix selection, and composite architecture, kenaf-based systems can contribute meaningfully to reducing the environmental footprint of marine structures while maintaining acceptable levels of safety and performance [10].

9 Conclusion

This review has synthesised current research on kenaf fibre–reinforced composites with particular emphasis on their potential for marine engineering applications. The literature consistently demonstrates that kenaf fibres provide several advantages over conventional synthetic reinforcements, including low density, renewability, biodegradability, and reduced environmental impact. When combined with suitable polymer matrices and appropriate surface modification techniques, kenaf-based composites can achieve mechanical properties that are suitable for a range of semi-structural marine applications. In particular, studies have shown that chemical surface treatments, hybrid fibre architectures, and optimisation of processing parameters can significantly improve fibre–matrix interfacial bonding and enhance composite performance. Despite these promising developments, several key challenges remain unresolved. The hydrophilic nature of lignocellulosic fibres results in moisture absorption, which can lead to fibre swelling, interfacial debonding, and progressive mechanical degradation under prolonged marine exposure. In addition, long-term resistance to biofouling, ultraviolet radiation, and cyclic mechanical loading remains insufficiently understood. These limitations indicate that further research is required to improve the durability and reliability of kenaf fibre composites in harsh marine environments.

Future research should therefore focus on several critical directions. First, more comprehensive investigations into long-term environmental ageing and seawater exposure are needed to better understand degradation mechanisms. Second, the development of advanced fibre treatment methods and hybrid composite architectures may further enhance durability and mechanical stability. Third, lifecycle assessment and large-scale manufacturing studies are required to evaluate the practical feasibility and environmental benefits of these materials in real marine applications. Overall, the current body of literature suggests that kenaf fibre composites have significant potential as sustainable alternatives to conventional materials in marine engineering. While they may not yet fully replace high-performance synthetic composites in primary load-bearing structures, their application in secondary and non-structural marine components offers a promising pathway towards more environmentally responsible marine material systems.

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