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Kenaf Fiber-Reinforced Biocomposites: A Review of Mechanical Performance, Treatments and Challenges

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Abstract: The increasing demand for sustainable materials has positioned kenaf fiber-reinforced composites as promising alternatives to conventional synthetic composites. This review paper synthesizes recent research on kenaf fiber biocomposites, focusing on the impact of fiber content, length, and surface treatments on their mechanical, thermal, and environmental properties. Studies highlight the potential for significant mechanical improvements, particularly in impact strength, through optimized fiber loading and the incorporation of nano-reinforcements. Surface modification techniques, notably alkali treatment, are crucial for enhancing fiber-matrix interfacial bonding and overall composite performance. Furthermore, the critical challenge of moisture sensitivity in natural fiber composites is addressed, with evidence suggesting that chemical treatments effectively reduce water absorption and improve long-term durability. Scanning electron microscopy (SEM) analysis of untreated kenaf fiber/epoxy biocomposites reveals interfacial failure and fiber pull-out, suggesting that surface treatments would lead to altered fracture mechanisms characterized by enhanced adhesion and potentially fiber breakage. This review underscores the multifaceted potential of kenaf fiber biocomposites in sustainable materials science, emphasizing the necessity of continued research into advanced processing and surface modification strategies to overcome existing limitations and expand their industrial applicability.

1. Introduction

The growing worldwide demand for sustainable and environmentally friendly materials has prompted extensive research into the development of natural fiber-reinforced composites. These materials provide a promising alternative to traditional synthetic fiber-reinforced composites, which are generally linked with environmental issues like non-biodegradability, toxic emissions during processing, and dependence on non-renewable petroleum-based resources (Meziane *et al.*, 2024; Puttegowda, 2025; Syduzzaman *et al.*, 2020). Of the many natural fibers investigated, kenaf (Hibiscus cannabinus) fibers are one of the most promising reinforcements based on their good mechanical properties, high biomass production, low cost, and sustainability (Millogo *et al.*, 2015; Silva *et al.*, 2021). Kenaf is an annual herbaceous plant with a rapid growth rate, reaching a height of 3–5 meters in 4–5 months, providing a quick source of lignocellulosic biomass (Ad *et al.*, 2016).

Bast fibers obtained from kenaf stems are especially prized due to their high cellulose content (70.4 wt%), moderate hemicellulose content (18.9 wt%), and low lignin content (3 wt%), which endow them with good mechanical performance and biocompatibility with polymer matrices (Millogo *et al.*, 2015). These fibers have remarkable tensile characteristics with a tensile strength of 1 ± 0.25 GPa and Young's modulus of 136 ± 25 GPa, which place them on par with some synthetic fibers in their ability to be used as structural and semi-structural materials (Silva *et al.*, 2021). Some of the principal physical and mechanical characteristics of kenaf fibers are listed in Table 1 as fiber diameter, 0.13 mm; specific weight, 1.04 g/cm³; water absorption capacity, 307% - factors to be kept in mind when evaluating their behavior in composite matrices.

Table 1. Physical and Mechanical Properties of Kenaf Fiber

Properties	Results
Diameter (mm)	0.13
Natural humidity: H (%)	6.1
Water absorption: W (%)	307
Specific weight: γ (g/cm^3)	1.04
Elasticity modulus (MPa)	136 ± 25
Tensile strength: σ (GPa)	1 ± 0.25

The value of kenaf lies not just in mechanical applications. Its growth rate and photosynthetic yield qualify it as a good crop for sequestering carbon. Research indicates that kenaf fixes two times as much CO_2 as a tree in a tropical rainforest in high-density plantings (Azam *et al.*, 2023). Such a characteristic qualifies kenaf as a dual-use crop with material utility as well as the capability to mitigate the climate. Nonetheless, this argument is not uncontested; some researchers have criticized the scalability of such carbon sequestration volumes and the environmental consequences of large-scale kenaf production (Korol *et al.*, 2020). On the applications front, kenaf fiber-reinforced biocomposites have been increasingly studied for use in automobile parts, packaging, construction materials, and consumer goods, where lightweight and biodegradable material is much sought after.

Within the automotive industry, for example, kenaf composites can be used to save weight and fuel consumption, while complying with regulatory requirements for recyclability and emissions. Research like (Andilolo *et al.*, 2017) has analyzed the mechanical characteristics of ABS composites reinforced with short kenaf fibers, showing that optimized processing of kenaf fibers (soaking, drying and milling) impacts considerably on mechanical performance. Their findings indicated that higher fiber loading enhanced impact strength but at the expense of decreased tensile strength, primarily as a result of void formation and poor interfacial adhesion between the fibers and matrix. In order to overcome these shortcomings, new developments have investigated hybridization methods, such as using nano-reinforcements like multi-walled carbon nanotubes (MWCNTs). (Yaghoobi and Fereidoon, 2017) investigated polypropylene (PP)/kenaf/PP-g-MA composites and concluded that MWCNTs significantly improved mechanical and thermal characteristics with tremendous improvements in tensile strength, modulus, and resistance against thermal degradation at optimal loading. These improvements highlight the potential of multiscale reinforcement methods to overcome the performance shortcomings of biocomposites.

In addition, the contribution of fiber length and dispersion to composite performance has been a focus of interest. (Suherman *et al.*, 2021) proved that the mechanical properties of shorter kenaf fibers are better due to enhanced dispersion in the matrix and the minimization of void formation. Their result supports the significance of fiber morphology and processing in the tailoring of composite behavior.

Furthermore, chemical surface treatments like acetylation have been found to increase fiber-matrix adhesion, enhancing the integrity of composites. (Datta *et al.*, 2015) confirmed that acetylated kenaf fibers showed better compatibility with thermoplastic polyurethane (TPU) and thus demonstrated improved mechanical behavior and thermal stability.

Notwithstanding these developments, moisture sensitivity continues to be the most significant issue with natural fiber composites. The hydrophilic character of lignocellulosic fibers causes them to absorb water, leading to swelling, plasticization, and deterioration of mechanical properties. In this regard, methods involving the application of nanoclays and graphene-based fillers have been shown to be very promising. (Mahalingam *et al.*, 2025; Sapuan *et al.*, 2025) have reported that such treatments can effectively minimize water absorption, thus maintaining mechanical strength and dimensional stability in humid environments.

Bibliometric analysis

To highlight this review, a bibliometric analysis for mapping the scientific performance of authors, institutions, countries, … can be conducted. This method identifies the most published authors and the possible collaborations forming clusters of scientists in the world, as well as the most cited papers and the countries investigating around projects towards the development of scientific areas (Skute *et al.*, 2019; You *et al.*, 2024; Laita *et al.*, 2024; Kachbou *et al.*, 2025). In this way, more than 14,500 articles were collected from Scopus using “bio-composite OR biocomposite” from 1983 (one article) to >1,900 articles in 2024 as shown in **Figure 1**. This finding proves the importance of biocomposites and their uses in different area (synthesis to engineering…) (**Figure 2**).

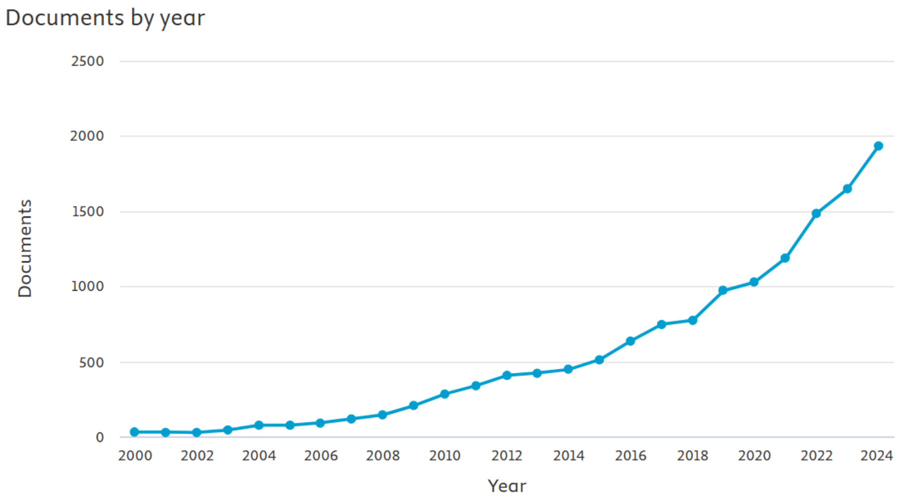

Figure 1. Increase of the scientific production on biocomposite from 2000 to 2024

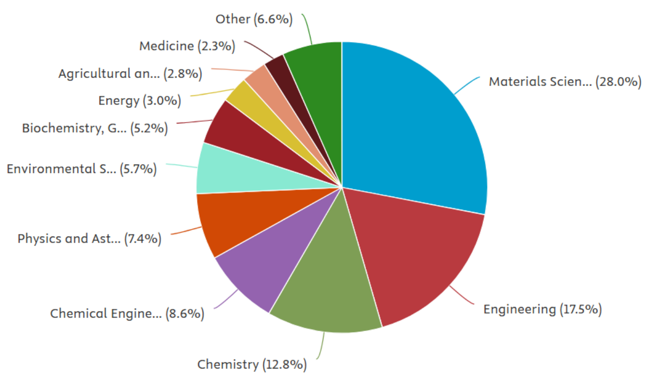

Figure 2. Percentage of articles per area for biocomposite from 2000 to 2024

During 25 years (2000 to 2024), among the 13,672 articles, three authors have around 100 articles (**Figure 3**). Misra, Sapuan and Mohanty published 108, 106 and 98 papers, respectively. **Figures 4 and 5** presented the Network and Overlay visualization obtained by VOS viewer of the authors. Misra is shown by the orange node, and Sapuan by the red node in **Figure 4**. The Canadian Misra and Mohanty belongs to the same cluster as indicated in **Figures 6** (left), also, the Malaysian Sapuan forms the other cluster (right). We can also remark that there is no collaboration between the Canadian and Malaysian researchers (You *et al*., 2024; Salim *et al*., 2022; Martins *et al*., 2024).

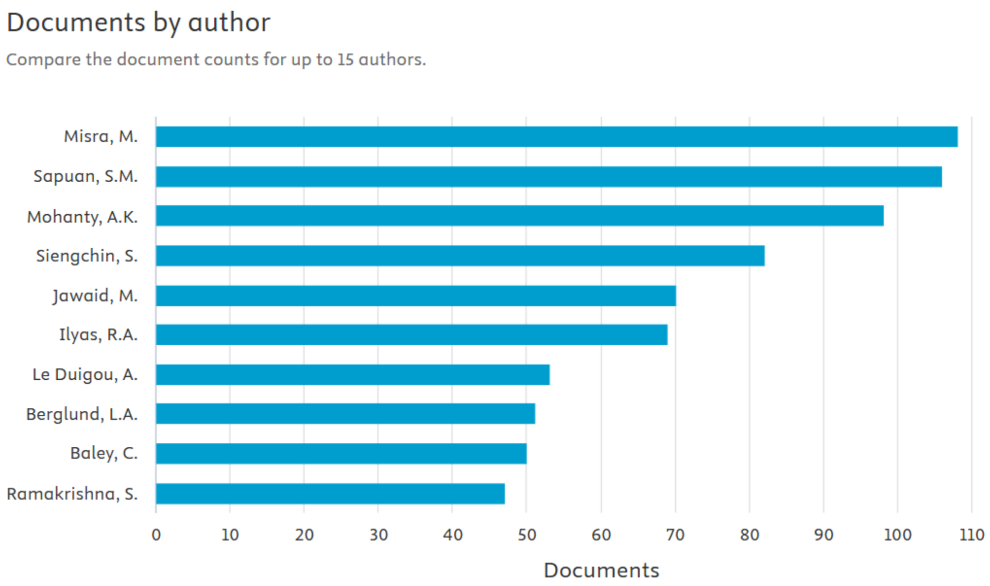

Figure 3. The ten most published authors during 25 years (2000-2024)

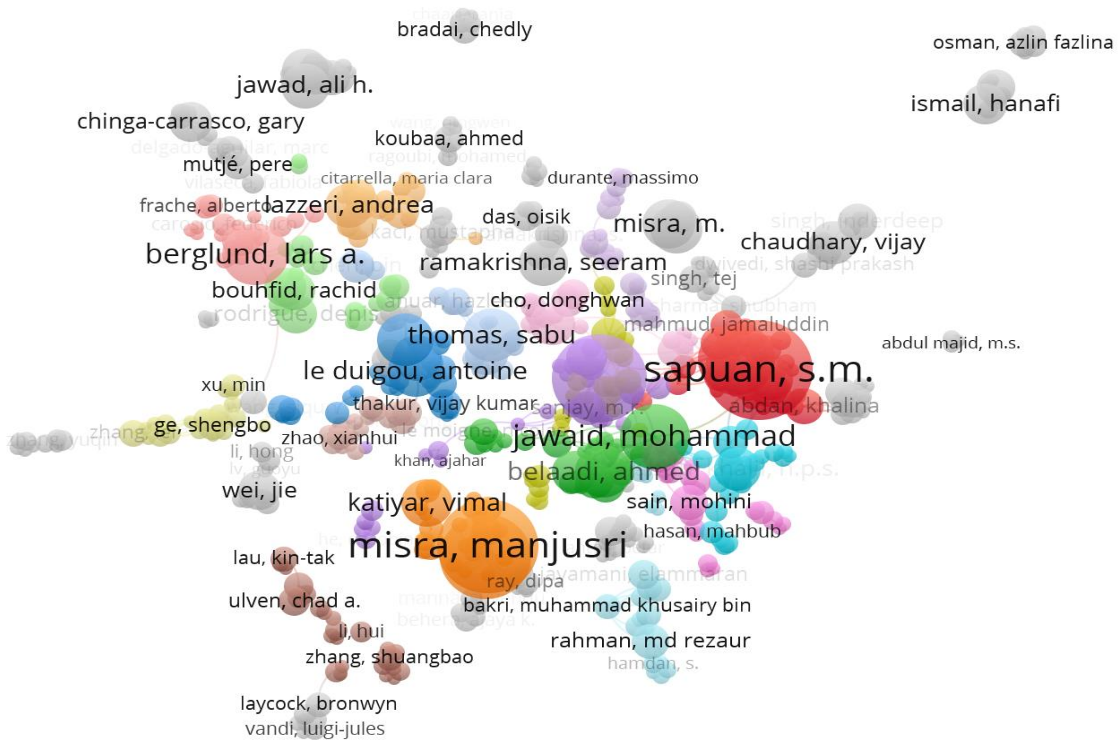

Figure 4. Network visualization of the authors during 25 years

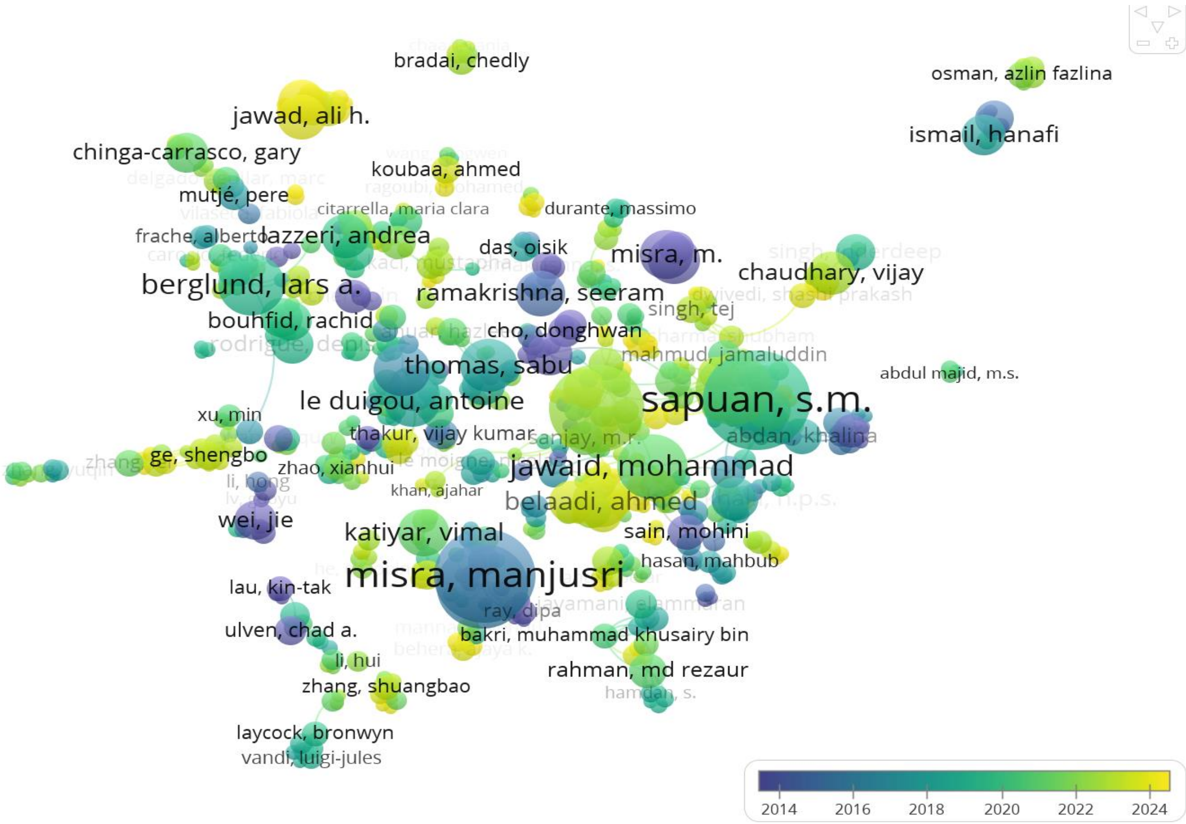

Figure 5. Overlay visualization of the authors during 25 years

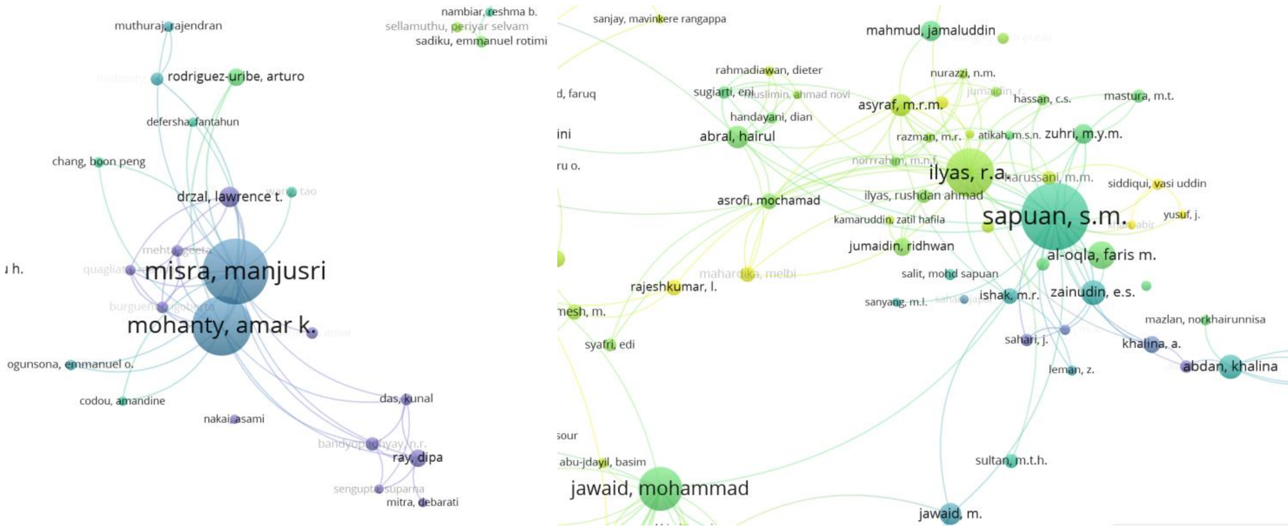

Figure 6. Scanning

The bibliometric analysis indicated that a concurrence between developed countries. India and China are the most produced of papers on Biocomposites reaching over 2250 and 1800 articles, respectively (**Figure 7**). Since 2018, China became more productive than the US in various area. The US published around 1200 papers in the studied period. Malaysia occupied the fourth position with over 1200 articles. The interest of biocomposites as the materials resulted from a natural and renewable source is largely discussed in literature (Thyavihalli Girijappa *et al*., 2019; Ahmad *et al*., 2022; Akartasse *et al*., 2022; Azzaoui *et al*., 2024; Simona Bălțatu *et al*., 2025). VOS viewer mapping offered more visibility for the most published countries by indicating India with the largest mustard color node followed by

China (purple node), the US (purple node), and Malaysia (green node). The lines refer to the various collaborations between authors, institutions and countries (**Figure 8**).

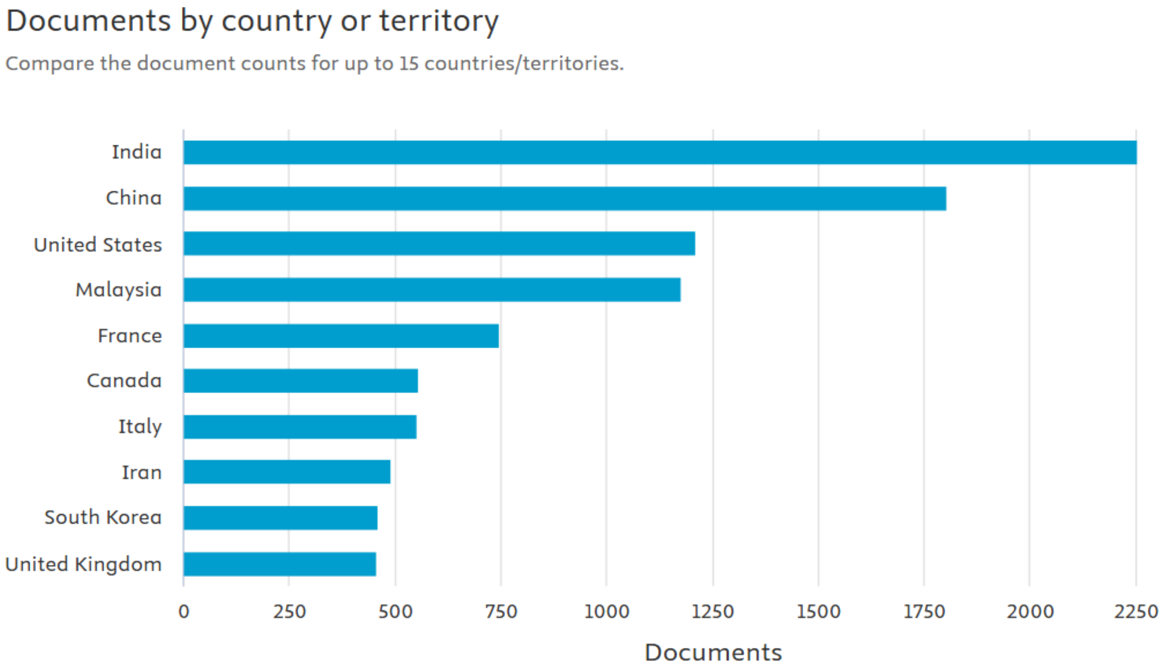

Figure 7. Ten most countries concerned by biocomposites

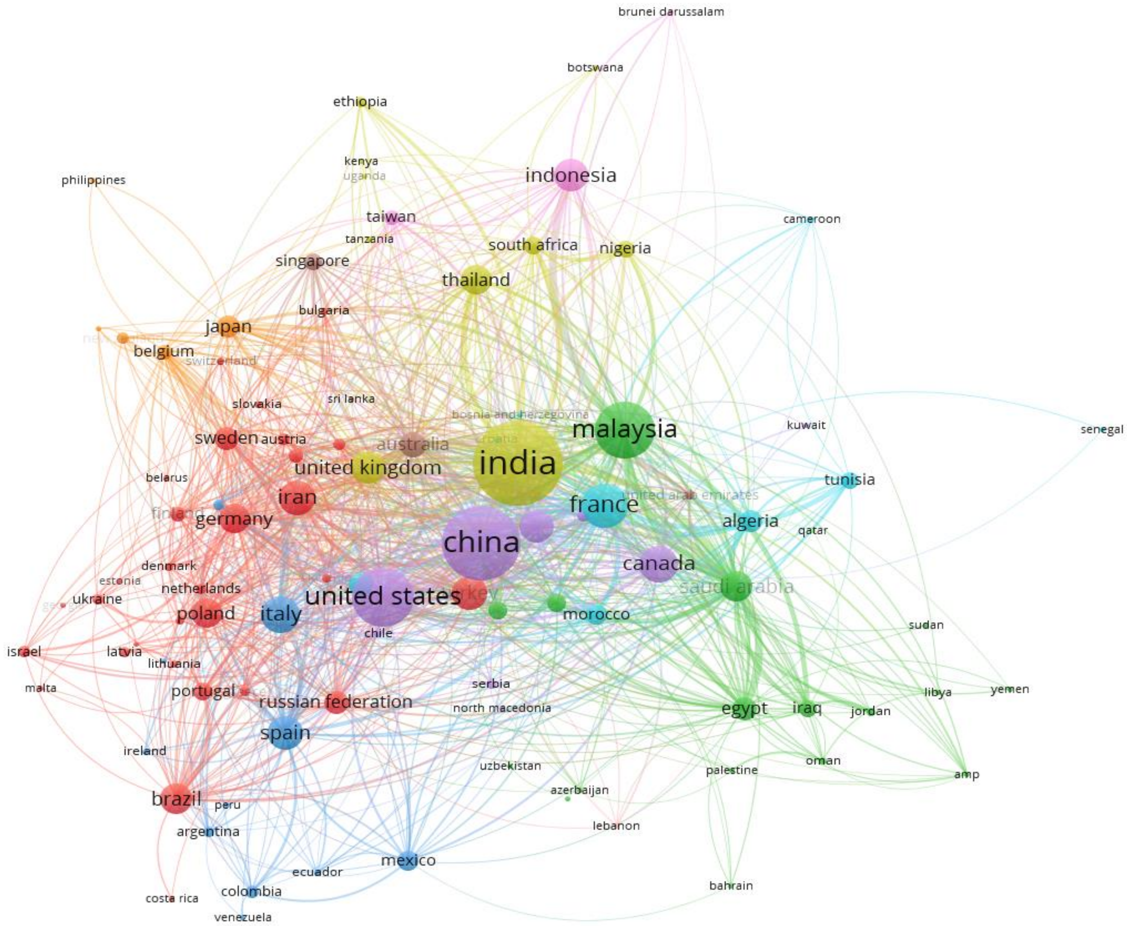

Figure 8. Clustering via VOS viewer of the Ten most countries concerned by biocomposites

Overall, kenaf fiber-reinforced biocomposites are a multi-faceted answer to the increasing need for sustainable, high-performance materials. Their built-in advantages—such as mechanical strength, renewability, biodegradability, and environmental advantages—spotlight their potential in a diverse range of applications. Nevertheless, issues regarding water absorbency, fiber dispersion, and interfacial adhesion require ongoing research into advanced processing, hybridization, and chemical modification methods. The objective of this review is to unify the recent scientific findings regarding mechanical, thermal, and environmental kenaf fiber composites' properties, along with the determination of major challenges and future research aspects essential to creating next-generation biocomposite products. With insights into these drivers, we may further support innovation in green, high-performance products for multiple purposes.

2. Methodology

2.1 Methods Used by Different Researchers

Investigation of kenaf fiber-reinforced biocomposites has utilized a wide range of methods, including fiber preparation, mechanical and thermal analyses, chemical treatments, and statistical modeling. Such diverse methods make the investigation thoroughly holistic with respect to understanding what affects the properties of kenaf composites (Hamidon *et al.,* 2019).

The most significant part of the study is preparing and processing the kenaf fibers. For example, (Andilolo *et al.,* 2017) followed a multi-stage preparation procedure involving soaking, drying, milling, and sieving to obtain homogenous fiber sizes. They followed TAPPI standards to find the chemical composition of the fibers, specifically cellulose content, which has a direct influence on mechanical behavior. Similarly, (Lee *et al.,* 2016) incorporated magnesium hydroxide as filler within biocomposites, with controlled mixing ratios to achieve effective fiber dispersion and thus improve matrix compatibility.

Mechanical testing continues to be the core in composite performance assessment. (Yaghoobi and Fereidoon, 2017), according to ASTM standards, measured properties like tensile strength, Young's modulus, flexural strength, and impact resistance. Their research progressively changed the proportion of multi-walled carbon nanotube (MWCNT) while holding concentrations of kenaf fiber and compatibilizers constant to facilitate focused evaluation of reinforcement. Similarly, (Mutasher *et al.,* 2011) adopted a hand layup fabrication technique and performed tensile tests in order to study the stress-strain behavior and gained important insight into the impact of fiber treatment on mechanical behavior.

To enhance fiber-matrix bonding, chemical treatment and surface modification procedures have been widely utilized. Alkali treatment, for example, has been found to improve the interfacial bonding by deboning hemicellulose and surface contaminants (Kamaruddin *et al.,* 2022). Datta *et al.,* 2015, assessed various chemical treatments, such as acetylation and maleic anhydride grafting, to examine their impact on mechanical performance and fiber morphology in thermoplastic polyurethane composites. Analytical equipment like Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM) were employed for the characterization of surface chemistry as well as induced structural changes resulting from these treatments.

(Saravanan *et al.,* 2024) further refined the composite design by using a Design of Experiments (DoE) approach to optimize hybrid composites composed of jute, kenaf, and glass fibers. Their study systematically varied treatment methods, fiber orientations, and filler loadings to identify the best combinations for enhanced mechanical response.

Thermal and structural stability tests have also been instrumental. (Yaghoobi and Fereidoon 2018) conducted Thermogravimetric Analysis (TGA) to assess the effect of MWCNT addition on the degradation temperatures of composites. In tandem, (Salim *et al.*, 2023) studied water absorption behavior, specifically targeting the effect of alkali-treated fibers on moisture resistance in polypropylene-based composites.

Lastly, sophisticated data modeling and analysis methods have been used to maximize composite properties. (Saravanan *et al.*, 2024) used Central Composite Design (CCD) to model the effect of factors such as stacking sequence and filler fraction on the mechanical properties. Likewise, (Mutasher *et al.*, 2011) performed statistical tests contrasting mechanical results of treated and untreated fiber composites with the main focus on interfacial bonding and uniformity of treatment. Together, these methodological strategies offer a solid basis to comprehend and enhance the mechanical, thermal, and environmental performance of kenaf fiber-reinforced biocomposites towards their suitability in sustainable engineering applications.

2.2 Literature Review

The increasing demand for sustainable materials has spurred broad research into natural fiber-reinforced composites, with considerable interest in the use of kenaf fibers owing to their balanced mechanical performance, renewability, and minimal environmental footprint (Rajendran *et al.*, 2025). In this section, the authors summaries major insights from recent publications on mechanical behavior, treatment process, and field applications of kenaf fiber-reinforced biocomposites.

a. Mechanical Properties of Kenaf Fiber-Reinforced Biocomposites

kenaf fiber-reinforced Acrylonitrile Butadiene Styrene (ABS) composites and reported that adding kenaf fibers with cellulose content of 66.47% greatly enhanced impact strength and hardness (Andilolo et al., 2017). Yet, a compromise was evidenced—increased fiber loading led to decreased tensile strength due to the presence of voids and poor matrix wetting. These results emphasize the need for optimizing fiber processing and dispersion to achieve the full mechanical potential of natural fibers.

In a different study, (Yaghoobi and Fereidoon, 2017) investigated the effect of adding multi-walled carbon nanotubes (MWCNTs) to polypropylene/kenaf fiber composites and found that the addition of 1 wt.% MWCNT resulted in the greatest improvement in tensile strength and flexural modulus. This research highlighted the capability of hybrid composites to overcome the intrinsic limitations of natural fibers and improve thermal stability.

The influence of fiber length and alkali treatment in kenaf fiber-reinforced unsaturated polyester composites (*Arjmandi e t al.*, 2012). Their findings indicated that 5 mm long fibers performed better than shorter fibers under tensile and flexural testing, while alkali treatment was found to enhance fiber-matrix adhesion greatly and lower water absorption. This emphasizes the need for both physical size and chemical alteration to define composite performance.

b) Chemical Treatments and Surface Modifications

Chemical treatments, especially alkali treatment, have been used extensively to enhance fiber-matrix compatibility. the reinforcement of polyester composites using ZnO NPs with different loadings of kenaf fibers. Their findings revealed that ZnO treatments increased interfacial adhesion and flexural strength to facilitate better stress transfer within the composite (Mohammed *et al.*, 2023). (Mutasher *et al.*, 2011) also found significant enhancements in mechanical properties—between 5% and 10%—in alkali-treated fiber composites. They did find, however, that overloading of the fibers may result in reduced tensile strength, with possible reasons being agglomeration and insufficient matrix penetration.

A novel and environmentally friendly surface modification method by utilizing rice-washed water that enhanced fiber surface reactivity through the exposure of cellulose chains. This process improved both mechanical strength and interfacial adhesion and is a cost-effective and sustainable fiber enhancement method (Park *et al.,* 2015).

c) Thermal Stability and Moisture Resistance

Thermal and water resistance characteristics are imperative for biocomposite durability in practice. Hydrolytic degradation was highlighted as one of the challenges based on the observation that poor resin coverage and moisture invasion detrimentally impacted strength retention. Their research underscored the importance of strong matrix encapsulation towards sustained performance (Lee *et al.,* 2016). Corroborating these results, alkali-treated kenaf fibers have lower water absorption and consequently higher mechanical strength in humid environments (Salim *et al.,* 2023). The enhanced performance was attributed to the elimination of hemicellulose, which eliminated the hydrophilicity of the fibers.

Collectively, the literature forms a developing consensus regarding the mechanical and thermal benefits of kenaf fiber-reinforced composites and highlights the pivotal role of fiber treatment, dispersion, and hybridization. Much has been achieved, but more work is required to standardize treatment regimes, enhance water resistance, and investigate new combinations of fibers or nano-reinforcements. Kenaf fibers offer a promising route towards sustainable, high-performance biocomposites. Additional research into processing parameters, chemical modification, and environmentally friendly reinforcement methods is expected to open up wider industrial uses and extend the limits of what natural fiber composites can accomplish.

2.3 Product characterisation

The recovered products (biomass biochar and hybrid biochar) were characterised to determine some of their properties using Scanning Electron Microscope with energy Dispersive X-ray Spectroscopy (SEM-EDS), Fourier Transform Infra-Red Spectroscopy (FTIR) and Brunauer-Emmet-Teller (BET) analysis. Scanning Electron Microscopy (SEM, Phenom proX, Phenom-World BV, Netherlands) was employed to examine the surface morphology of particles of the biochar. Double adhesive was applied on a sample stub. The sample was deposited on the sample stub and then taken to a sputter coater (quorum-Q150R Plus E) and coated with 5 nm of gold. The sample was put on a charge reduction sample holder and was introduced into the column of the SEM machine. It was first observed using a NavCam prior to being forwarded to SEM mode. The microscope acceleration voltage was set at 15 kV and magnification of 1000 – 1500×. FTIR (Shimadzu, FTIR-8400S, Japan) was employed to analyze the functional groups and complexes of both the biochar samples. Surface area, pore volume and pore size of the chars were analyzed. The surface characteristics of the char samples were investigated by a Multipoint BET surface area and DR (Dubinin–Radushkevic) method for the pore volume and breadth (diameter). Adsorbate was added to provide the lowest wished-for relative pressure, and then measured the volume adsorbed.

3. Results and Discussion

3.1 Mechanical Improvements

Recent developments in sustainable materials studies have focused on the production of natural fiber-based composites, of which the kenaf fiber has been specific interest due to its balance between mechanical performance, biodegradability, and renewability. researchers have tried to find out if kenaf fibers, being added to thermoplastic and thermoset matrices, will improve mechanical, thermal, and environmental properties of composites. This research stems from the current need for environmental-friendly, high-performance substitutes of synthetic fiber-reinforced plastics.

A number of studies have examined altering the fiber composition, length, and surface treatment has on the mechanical properties of such biocomposites. For instance, short kenaf fiber-reinforced Acrylonitrile Butadiene Styrene (ABS) composites and noticed a significant improvement in impact strength and hardness (Andilolo *et al.,* 2017). Nevertheless, as fiber composition was raised to 10% and 15% by weight, tensile strength reduced, possibly as a result of void generation and poor wetting of the matrix. Notwithstanding this, overall strength was enhanced (Table 1), demonstrating that optimal fiber composition should be well-balanced in order to avoid mechanical degradation. For impact performance, the same research had documented 15% kenaf fiber loading attaining greater impact strength and energy (82.09 kJ/m² and 0.255J respectively), showing greater energy absorption capability even at high fiber loadings (Table 2).

Table 2. The results of tensile test

Sample	Ultimate Tensile Srength (MPa)	Modulus of Elasticity(MPa)	Ductility (%)
KSF 10%	23.522 ± 8.36	439.94 ± 26.48	4.50 (brittle)
KSF 15%	20.739 ± 6.79	408.67 ± 18.32	3.50 (brittle)

Even greater enhancement of tensile strength was obtained (Yaghoobi and Fereidoon, 2017) when they added 1 wt.% multi-walled carbon nanotubes (MWCNTs) to polypropylene/kenaf fiber composites. The nano-reinforcement resulted in a 13.8% enhancement in tensile strength over non-reinforced biocomposites, implying that hybridization with nano-fillers can successfully overcome some disadvantages of natural fibers and enhance thermal stability. In a similar vein, the significance of physical dimensions, where 5 mm fiber length yielded higher tensile and flexural strength in kenaf/polyester composites (Razavi *et al.,* 2023). Their research also underscored the importance of alkali treatment to improve fiber-matrix adhesion and minimize water absorption. The capability of these composites to be maximized has also been resolved by optimizing parameters of fibers. (Suherman *et al.,* 2021) found that 1 cm fiber length and 30 wt.% content delivered the best mechanical performance in epoxy composites, with flexural strength and impact strength achieving values of 85 MPa and 338 kJ/m², respectively. This enhanced performance was due to improved dispersion of short fibers in the matrix, which reduces entanglement and enhances stress transfer.

To interpret these results, researchers have employed a variety of experimental methodologies. Fiber preparation methods are axiomatic: (Andilolo *et al.,* 2017) used a mechanized process that involved soaking, drying, grinding, and screening to provide regular fiber size, while adhering to TAPPI standards in determining chemical makeup. Mechanical tests, conducted by several researchers like Yaghoobi and Fereidoon, conformed to ASTM standards and tested tensile strength, Young's modulus, and impact resistance under different reinforcement schemes.

Surface treatment has been a central area of interest, as it significantly affects fiber-matrix compatibility. Alkali treatment, commonly used in literature, eliminates hemicellulose and improves adhesion. In one novel method, (Park *et al.,* 2015) used rice-washed water to enhance fiber reactivity, an eco-friendly alternative that improved mechanical performance and interfacial bonding. Likewise, (Mohammed *et al.,* 2023) incorporated zinc oxide (ZnO) nanoparticles into kenaf fibers to further enhance the interfacial zone, thus improving flexural strength and stiffness.

In addition to mechanical properties, thermal and moisture resistance properties have also been critically examined. (Lee *et al.,* 2016) reported that poor resin coverage leads to hydrolytic degradation, highlighting the importance of efficient matrix encapsulation. In agreement with this, (Salim *et al.*, 2023) found that alkali-treated kenaf fibers exhibited much lower water absorption, maintaining mechanical properties in wet conditions because of the removal of hemicellulose.

Advanced statistical modeling has been used by researchers to forecast and optimize performance results. For instance, Saravanan *et al.*, (2024) applied a Design of Experiments (DoE) and Central Composite Design (CCD) in assessing hybrid composites consisting of kenaf, jute, and glass fibers. They came up with the best fiber treatment, orientation, and filler loading combinations. It also backed mechanical testing using statistical comparison of treated and untreated fibers, enhancing the significance of uniform chemical modification.

kenaf fiber-reinforced biocomposites show significant mechanical, thermal, and environmental advantages when fiber parameters and treatments are optimally optimized. Studies have repeatedly shown that fiber loading of about 30 wt.%, fiber lengths of 5 mm to 10 mm, and surface modifications using alkali or nanoparticles greatly improve composite performance. The application of statistical methods and green treatments also signifies a step toward scalable and sustainable solutions in composite engineering. However, some issues like moisture sensitivity and formation of interfacial voids at high fiber contents still remain and need to be addressed.

Kenaf fibers have also become a viable candidate in the search for eco-friendly, high-performance biocomposites because of their superior mechanical properties, renewability, and minimal environmental footprint. Of the most important mechanical properties, impact strength is important to determining a composite's capability to absorb and dissipate energy when subjected to sudden loading conditions. Research has indicated that an increase in kenaf fiber content can increase significantly the impact resistance of composites. For example, 15 wt.% kenaf fiber-reinforced composites showed improved impact strength of 82.09 kJ/m² and impact energy absorption of 0.255 J, as compared to the 10wt.% fiber-reinforced composites with 68.657kJ/m² and 0.223J, respectively. The above findings evidently show that the increased content of fibers increases the energy absorption capacity of the composite (Table 3). These enhancements in impact performance highlight the promise of kenaf-reinforced biocomposites for use in situations where mechanical shock resistance is paramount., Yet to maximize this promise, additional research into optimizing fiber processing conditions, chemical surface modification, and the addition of environmentally friendly nano-reinforcements is needed., These advances will probably broaden the scope of industrial uses for kenaf-based composites and spur innovation in green material science.

Table 3. Summary of reactor performance

Sample	Impact Strength (kJ/m^{-2})	Impact Energy (J)
KSF 10%	68.657 ± 4.89	0.223
KSF 15%	82.090 ± 5.56	0.255

3.2 Chemical Treatments and Interfacial Bonding: A Microscopic Perspective

The bio-char yield for both processes was computed using **Eq. 1** and **2** (Sharma and Kaur, 2019 & 2022):

$$m_{Bio-char} = (M_3 - M_2) \quad \text{Eq. 1}$$

$$Yield_{Bio-char} = \frac{m_{Bio-char}}{m_{raw}} \times 100\% \quad \text{Eq. 2}$$

Where M_1 = mass of conversion chamber + Feed (in grams), M_2 = mass of conversion chamber (in grams), M_3 = …..

The SEM images in Figure 4 reveal varying degrees of fiber pull-out and interfacial failure. In Images A and B (10 wt.% fiber loading), the relatively clean surfaces left behind after fiber pull-out suggest a weaker interfacial bond between the untreated kenaf fibers and the epoxy matrix. This weaker bond allows for easier debonding and subsequent sliding of the fibers out of the matrix during fracture. The increased fiber length in Image B appears to promote more fiber bridging, where longer fibers remain embedded in the matrix on both sides of the fracture surface, hinting at a slightly more effective stress transfer compared to the shorter fibers in Image A.

3.3 Alkali Treatment

Alkali treatment (e.g., NaOH) removes impurities like wax, lignin, and hemicellulose from kenaf fibers, exposing a cleaner, cellulose-rich surface (Mutasher *et al.,* 2011). It also increases surface roughness and surface energy, which enhance fiber-matrix interlocking and adhesion. If the biocomposites shown in Figure 4 were alkali-treated, we would expect reduced fiber pull-out, more fiber breakage, and a more irregular fracture surface—indicative of better stress transfer and crack resistance.

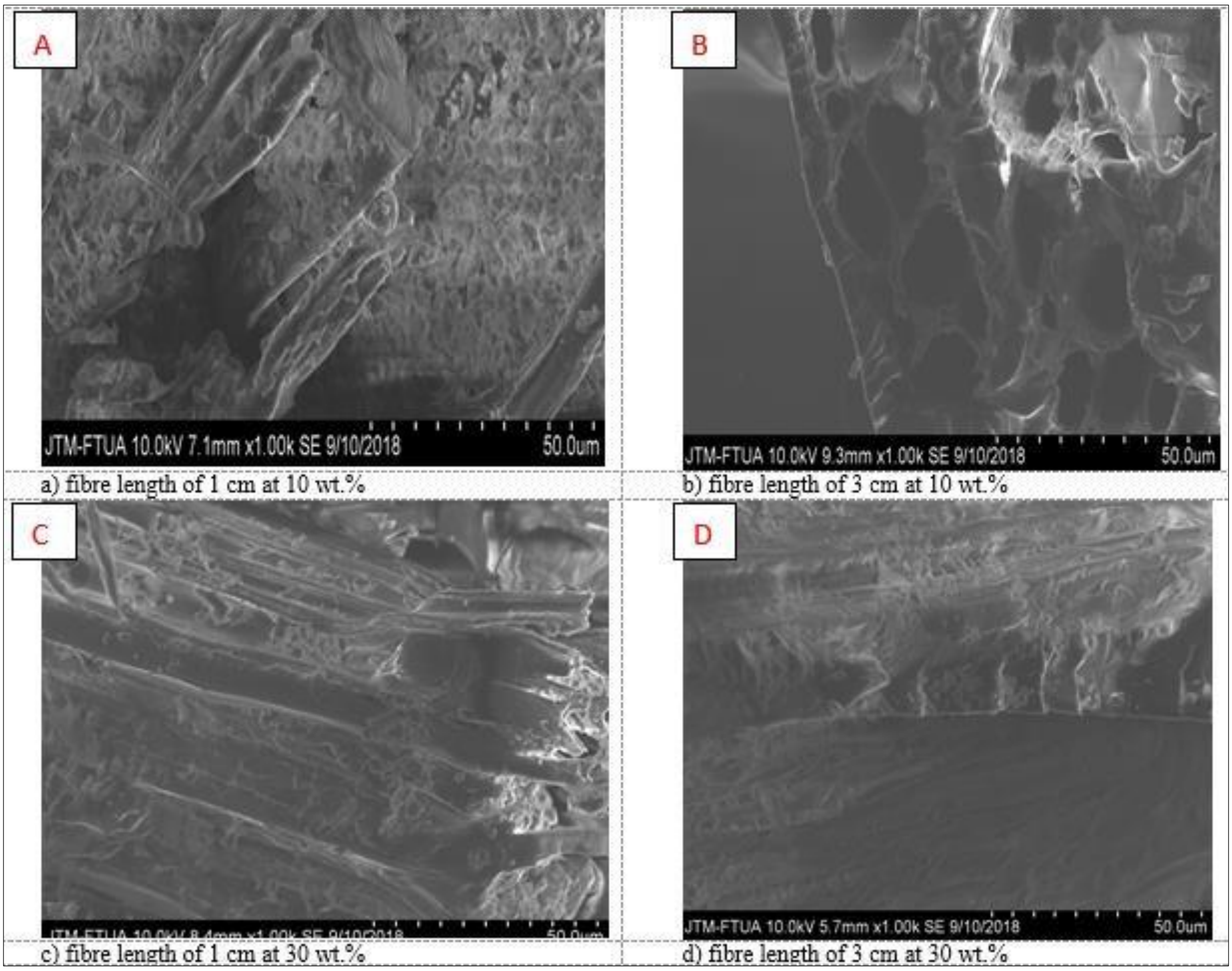

Figure 4. Scanning electron microscopy (SEM) images of the fracture surface of kenaf fibre/epoxy biocomposites.

a) Moisture Sensitivity and Water Absorption Effects:

Untreated kenaf fibers are hydrophilic and tend to absorb moisture, leading to fiber swelling, micro-cracking, and weakened interfacial adhesion. This results in increased fiber pull-out, reduced fiber bridging, and overall degradation in tensile and flexural strength. Studies confirm that alkali treatment significantly lowers water absorption, preserving the fiber-matrix interface and improving the long-term durability of the composite.

b) Fracture Morphology in Relation to Fiber Loading:

At low fiber loading (10 wt.%, Images A and B), enhanced interfacial bonding via alkali treatment is especially critical for stress transfer due to the fewer fibers present. At high loading (30 wt.%, Images C and D), the increased fiber-fiber interaction still benefits from improved adhesion to prevent premature pull-out and ensure durability under moisture exposure. In both cases, alkali treatment shifts fracture mechanisms towards fiber breakage and cohesive failure.

Kenaf fiber-reinforced composites show great promise for sustainable material development due to their mechanical strength, renewability, and eco-friendliness. Alkali treatment is key to overcoming major drawbacks like poor interfacial bonding and moisture sensitivity. Future work should focus on direct SEM comparisons of treated vs. untreated composites to validate these benefits and guide the design of more durable, high-performance biocomposites.

The significant potential of kenaf fiber-reinforced biocomposites as sustainable alternatives to conventional materials. The judicious manipulation of fiber content, length, and critically, surface treatments, emerges as paramount in tailoring the mechanical performance of these composites. Notably, alkali treatment consistently demonstrates its efficacy in enhancing fiber-matrix interfacial bonding and mitigating the inherent moisture sensitivity of kenaf fibers, thereby paving the way for improved durability and broader applicability. While the incorporation of nano-reinforcements offers a promising avenue for further augmenting mechanical and thermal properties, future research should continue to explore optimized treatment methodologies and processing parameters. Direct microscopic evidence comparing treated and untreated interfaces, coupled with long-term durability assessments under diverse environmental conditions, will be crucial in fully realizing the potential of kenaf fiber biocomposites for widespread industrial adoption and in advancing the field of sustainable materials science.

Conclusion

Kenaf fiber-reinforced biocomposites have demonstrated significant potential as sustainable alternatives to synthetic composites, offering a combination of mechanical advantages, renewability, and environmental benefits. The optimization of these composites involves careful consideration of fiber loading and length, with research indicating that a fiber content of approximately 30 wt.% and a length of 5–10 mm yield the best mechanical properties, particularly in terms of impact strength. However, achieving these optimal properties requires meticulous management of void formation and matrix wetting. Surface treatments, especially alkali treatment, play a crucial role in enhancing the interfacial adhesion between the fibers and the matrix. These treatments remove surface impurities, increase fiber roughness, and improve surface energy, leading to better stress transfer and overall mechanical performance.

One of the primary challenges in developing kenaf fiber biocomposites is their sensitivity to moisture, which can compromise the material's integrity and performance. Chemical modifications have proven effective in addressing this issue by reducing water absorption and maintaining the strength of the fiber-matrix interface. Scanning electron microscopy (SEM) analyses have revealed that untreated composites often exhibit interfacial failure and fiber pull-out, emphasizing the importance of treatments that promote fiber breakage and cohesive failure as indicators of stronger bonding. The incorporation of nano-reinforcements and the application of statistical optimization methods, such as Design of Experiments (DoE) and Central Composite Design (CCD), have further advanced the development of tailored composite designs. To fully realize the industrial potential of kenaf fiber biocomposites and solidify their role in sustainable material development, ongoing research is focused on advanced processing techniques, innovative surface modifications, and comprehensive long-term durability assessments.

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