Sigma J Eng Nat Sci, Vol. 43, No. 2, pp. 665–684, April, 2025

Sigma Journal of Engineering and Natural Sciences
Web page info: https://sigma.yildiz.edu.tr
DOI: 10.14744/sigma.2025.00028

Review Article

Insights into the use of composites reinforced with natural fibers in architectural applications, with a focus on kenaf fiber

Irem CEYLAN[1,*], Nese CAKICI ALP[1]

[1]*Department of Architecture, Kocaeli University, Kocaeli, 41380, Türkiye*

ARTICLE INFO

Article history
Received: 03 November 2023
Revised: 15 January 2024
Accepted: 02 March 2024

Keywords:
Architectural Materials; Kenaf Fiber; Natural Fiber Composites; Thermal Stability, Water Resistance

ABSTRACT

With energy saving becoming a strategic goal worldwide, protecting the environment and natural resources has come to the fore. In architecture, a method for saving for the protection of natural resources can be achieved by selecting building materials. Compared with synthetic materials, much less energy is spent producing and using natural fiber materials. Considering the kenaf plant, has a growth rate of 3-9 times faster than other plants and has a higher absorption capacity than all existing plants by absorbing almost 1.5 times its weight in CO_2. This article presents a literature review of Natural Fiber Composites (NFC), focusing on kenaf fiber, published between 2000-2021. This study aims to predict whether natural fiber composites can be a potential alternative to synthetic composites currently used in architectural applications because of their novel properties. The Systematic Literature Search (SLR) technique was used as the research methodology, and research questions and keywords were determined. The numerical data of the mechanical (tensile, flexural and impact strengths), water resistance, thermal stability, fire resistance and acoustic test results of the fibrous composites in the articles and the new properties gained from the natural fibrous material have been interpreted, and the potential for which architectural application areas can be used as an alternative to synthetic fiber composites used in architecture has been revealed. Because of these predictions, it has been determined that natural fiber materials with comparable mechanical, water resistance, thermal stability, fire resistance and acoustic properties can be an alternative to synthetic materials currently used in many application areas, such as roofs and structures in architecture. It is predicted that it will shed light on the use of innovative architectural materials by researchers and professionals in the future.

Cite this article as: Ceylan I, Cakici Alp N. Insights into the use of composites reinforced with natural fibers in architectural applications, with a focus on kenaf fiber. Sigma J Eng Nat Sci 2025;43(2):665–684.

INTRODUCTION

Energy saving has become a strategic goal worldwide, and it is possible to protect the environment and natural resources [1]. Looking at energy consumption, buildings account for almost 40% of global energy consumption [2]. It is also estimated that around 40% of carbon emissions come from the construction industry, 15% of which can be

---

***Corresponding author.**
*E-mail address: iremceylan-@hotmail.com

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkilic

Published by Yıldız Technical University Press, İstanbul, Turkey

attributed to the production of construction materials [3]. Therefore, to provide energy savings in buildings, priority should be given to evaluating the production and usage of materials. In recent years, the use of materials with natural content has come to the fore. They are considered alternatives that are less harmful to nature, less costly, and have the same mechanical properties as synthetic materials [1]. It is known that 60% less energy is consumed in the production process of natural fiber composites than in that of glass fiber composites [4]. With the use of natural content materials, energy savings will be achieved, and damage to nature will be reduced. Regarding buildings, heating and cooling systems have become the primary source of energy consumption in many countries. For this reason, researchers have increased their studies of preserving the existing energy and minimizing energy loss by materials used in buildings and thermal insulation materials [1]. According to the Grand View Research report (2016), insulation materials used in the building industry are inorganic. They are extruded polystyrene (XPS), expanded polystyrene (EPS), polyisocyanurate, and polyurethane foams [5]. Although these materials have high performance in thermal insulation, the damage they cause to the environment during the production process is severe. In addition, when it comes to recycling processes, according to Dong et al. (2023), XPS is practically identical to EPS and is not yet environmentally friendly material, and planning a successful treatment strategy for recycling is challenging [6]. Therefore, the energy used in the demolition/recycling processes is high.

Synthetic fibers used to reinforce composites in construction engineering are glass, carbon, aramid, and Kevlar. Although these synthetic fiber composites have good mechanical strength, they have high cost, high density, poor recycling, and are nonbiodegradable. To overcome these disadvantages, research on composites reinforced with natural fibers has been increasing in recent years. Natural fiber reinforced composites have satisfactorily high specific strength and modulus, light weight, low cost, and biodegradability [7]. Looking at the examples of composites reinforced with synthetic and natural fibers in the literature, it is seen that composites reinforced with natural fibers can show superior properties. In studies where synthetic fibers were added to geopolymers at a rate of 0.5%, Bhutta et al. (2019) achieved compressive strength values of 42.4 MPa when high-strengthsteel fibers were added and 31.83 MPa when carbon fibers were added [8]. In a study in which natural fibers were added to geopolymers at a rate of 0.5%, Alomayri and Low (2013) reached a compressive strength value of 46 MPa with the addition of alkaline-treated cotton fibers [9]. When alkaline-treated cotton fiber, high-strength steel fibers, and carbon fibers in the same proportions were compared, higher compressive strength values were obtained in the geopolymer reinforced with natural fibers. Natural fibers can be preferred over synthetic fibers in building structure applications.

In the literature, studies on composites obtained by reinforcing polymers with synthetic or natural fibers show that natural fiber composites can sometimes show superior properties. Considering polypropylene (PP), in the study conducted by Rijsdijk et al. (1993), the tensile strength of glass fiber reinforced PP composite was 43.6 MPa [10]. Zampaloni et al. (2007) reinforced PP polymer with kenaf, flax, sisal, and coir fibers, and the approximate tensile strength values were 51 MPa, 50 MPa, 35 MPa, and 10 MPa [11]. These results indicate that kenaf and sisal fibers can be an alternative to glass fibers to reinforce the PP matrix in architectural applications requiring tensile strength. Considering PLA, Wang et al. (2019), in their study on glass fiber reinforced PLA composite, the impact strength value was approximately 40J/m, flexural strength 90 MPa, and tensile strength 55 MPa [12]. Shih and Huang (2011) obtained an impact strength of approximately 23J/m, flexural strength of 78.6 MPa, and tensile strength of 65.4 for banana fiber reinforced PLA composite [13]. When these values are considered, synthetic fibers are preferable in applications requiring high impact and flexural strength, but can be applied as an eco-friendly alternative for applications requiring low impact and flexural strength. When applications requiring tensile strength are considered, PLA composite reinforced with banana fiber is an alternative that shows superior properties compared to glass fiber/PLA composite. Considering polyethylene (PE), Gaikwad and Mahanwar (2016) produced PET microfibers/PE and Henequen microfibers/PE composites. The tensile strength values of the composites are 20.12 MPa and 22.13 MPa, and the flexural strength values are 14.11 MPa and 46 MPa, respectively [14]. Within the scope of the study, it is seen that PE composite reinforced with natural fiber can be used as an alternative since it has a better tensile and flexural strength value than synthetic fiber. Considering polyester, El-Wazery et al. (2017) found a flexural strength value of 44.65 MPa for a polyester composite reinforced with fibers [15]. Prasad et al. (2011) produced bamboo-reinforced polyester and sisal fiber-reinforced polyester composites with flexural strength values of 126.20 MPa and 99.50 MPa, respectively [16]. Based on these results, bamboo and sisal fibers appear to be an alternative with superior properties to glass fiber in reinforcing polyester for architectural applications requiring flexural strength.

Looking at the thermal stability values of synthetic and natural fibers, it can be seen that natural fibers may have better properties. According to Liu and Yu (2005), the Tpeak values of PBO, Terlon, Kermel, and Kevlar29 are 556.5°C, 473.5°C, 411.2°C, and 480.0°C, respectively [17]. According to Asim et al.. (2020), the Tpeak values of cocoa bean husk, pineapple leaf, and almond shell are 627°C, 496°C, and 477°C, respectively [18]. According to Azwa and Yousif (2013), the Tpeak value of the kenaf fiber is 346°C [19]. Looking at these results from the literature, it is seen that some natural fibers have a better thermal stability value compared to synthetic fibers and can be used as an alternative in architectural applications.

Considering materials with natural content, such as cork, it was found that they can be an alternative to polymer materials that are difficult to degrade [6]. Polyethylene-containing materials are known to be a good vapor barrier and can be used as an alternative to synthetic materials in ceiling applications [20]. Bio-composite made with hay and natural resin was found to have good insulation properties and mechanical resistance [21]. Although composites with natural ingredients can be derived from different sources from nature (mineral, animal, etc.), it is argued that an ideal natural composite should be derived from short-cycle renewable plant resources [22]. Plant-based natural fiber composites, in addition to the low level of energy consumed in the production-use and waste processes, it minimize heat loss and reduce the carbon footprint by trapping air. For example, hemp acts as a carbon sink, trapping up to 2 tons of CO_2 per ton of fiber. Polymer composites reinforced with natural fibers can be used in architectural applications such as columns, beams, self-supporting structures, and external cladding [3]. In addition, sheathing materials containing wood and hemp fiber with a density of less than 60 kg/m^3 have the same thermal conductivity range (0.036 kW/mK) as expanded EPS [5]. Therefore, a suitable composite material that can be used for thermal insulation has emerged. Looking at examples in the literature of composite materials suitable for thermal insulation, a density of 310kg/m thermal conductivity of approximately 0.08W/mK was observed in lime panels reinforced with Hemp fiber [23]. Considering the use of barley straw, reed, cattail, and bent grass as raw material for thermal insulation, cattail has a thermal coefficient of ~0.055 W/mK, bent grass ~0.06 W/mK, reed ~0.08 W/mK, and barley ~0.065 W/mK [24]. Coconut and basalt fibers reinforced Portland cement show maximum improvement in thermal insulation, i.e., 6.5%–17.4% and 5.8%–17.1% [25]. The thermal conductivity of a reed panel is between 0.045 and 0.056 W/mK, that of Bagasse is 0.046 W/mK, and that of recycled cotton insulators is comparable to that of EPS, XPS, and sheep wool [26]. The thermal conductivity of the cattails fiber panels is between 0.0438 and 0.0606 W/mK [27]. The thermal insulation value of Hemp-reinforced bicomponent polyester is similar to that of commercially available products [28]. For structural applications, composites made with soybean oil-based resin, natural fibers (flax, recycled paper, and chicken feathers), E-glass fiber, and closed-cell structural foam have environmental advantages [29]. Jute-reinforced soybean oil-based resin composite can be used as an alternative in I-Beam applications [30]. In another study for structural applications, the fracture energy of concrete increased by almost 70% (efficient stress transfer) with the addition of hemp, whereas the tensile strength decreased slightly by 4% [31]. Jute-coir hybrid composites can also be used for door and window applications [32]. Examples of studies in the literature on the use of synthetic and natural fiber composites in architecture and the building industry are summarized above. These studies show that natural fibers are generally suitable for thermal insulation, acoustic insulation, and structural use. However, their architectural application areas are not mentioned in detail. For example, *with a focus on architectural applications*, the suitability for use in electrical insulation, semi-structure, roof, waterproofing, interior, etc., has not been investigated in detail.

There is no foresight in the literature regarding the use of composite materials in architecture in the study's scope. This study aims to evaluate the natural fiber composites studied mainly by the Polymer Engineering and Materials Engineering disciplines in the literature and reveal the areas where these composites can be used in architecture according to their changing mechanical, thermal, acoustic, physical, and chemical properties within the scope of this research. The Systematic Literature Search (SLR) technique was used as the research methodology, and the research questions and keywords were determined. The numerical data of the mechanical, chemical, and physical test results of the natural fiber reinforced composites in the articles and the new properties gained from the composites have been interpreted, and the potential for architectural application areas to be used as an alternative to synthetic fiber composites used in architecture has been revealed.

MATERIALS AND METHODS

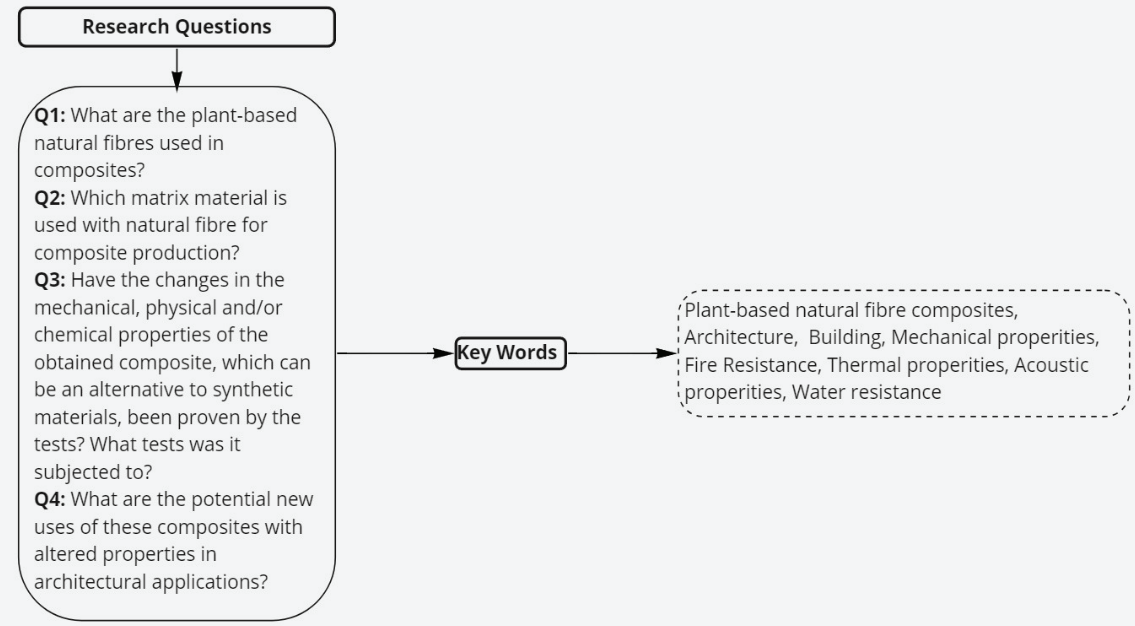
A Systematic Literature Review (SLR) was conducted to identify studies on natural fiber composites in the literature (see Figure 1.). As the first step of SLR, the research questions were identified. The research questions are,

- What are the plant-based natural fibers used in composites?
- Which matrix material is used with natural fiber for composite production?
- Have the changes in the mechanical, physical, and/or chemical properties of the obtained composite, which can be used as an alternative to synthetic materials, been proven by the tests? What tests was it subjected to?
- What are the potential new uses of these composites with altered properties in architectural applications?

In the second step, keywords were determined based on the research questions. These keywords are,

- Plant-based natural fiber composites
- Architecture
- Building,
- Mechanical properties (tensile, flexural and impact strengths),
- Thermal properties,
- Fire resistance
- Water resistance
- Acoustic properties,

Table 1 shows the research criteria included and excluded from the study. In the reviewed publications, special attention was paid to the performance of various mechanical,



Q1: What are the plant-based natural fibres used in composites?

Q2: Which matrix material is used with natural fibre for composite production?

Q3: Have the changes in the mechanical, physical and/or chemical properties of the obtained composite, which can be an alternative to synthetic materials, been proven by the tests? What tests was it subjected to?

Q4: What are the potential new uses of these composites with altered properties in architectural applications?

Plant-based natural fibre composites, Architecture, Building, Mechanical properities, Fire Resistance, Thermal properities, Acoustic properities, Water resistance

Figure 1. Research questions and keywords (Created by the Authors)

Table 1. Criteria of the research scope

Included criteria	Excluded criteria
Studies on natural fiber composites were published between 2000-2021.	Studies published outside the years of 2000-2021.
Articles published in English.	Articles published in a language other than English.
Plant-based fiber composites containing Kenaf, Hemp, Barkcloth, Luffa Cylindrica, Jute, Flax, Sisal, Coir, Banana, Henequen, Pneapple leaf, Bamboo, Indian almond fiber.	Studies involving other plant, animal, and mineral natural fiber.
Tensile, flexural and impact strengths, water resistance, thermal stability, fire resistance and sound absorption coefficient	Studies involving other properties
PP, PE, Epoxy, Bioepoxy, PLA, PCM, Polyester, Vinylester, and Polyurethane matrix materials	Studies involving other matrix materials

physical, thermomechanical, and sound absorption tests to determine the properties of the natural fiber composite and the test results to be stated in the article as numerical values. After this review, natural fiber composites and their changing properties after being composite were interpreted within the test results, and predictions were made about the application areas where they can be used as an alternative in architecture.

77 articles within the scope of the inclusion and exclusion criteria shown in Table 1 were examined, and the answers given to the research questions determined according to the articles reviewed were examined under the following headings.

INVESTIGATION OF NATURAL FIBER COMPOSITES

Studies on natural fiber-reinforced composites in the literature listed below were investigated in this study (Fig. 2). The authors made foresight about architectural usage areas:

- Barkcloth Reinforced Composites
- Jute Fiber Reinforced Composites
- Luffa Cylindrica Fiber (LCF) Reinforced Composite
- Flax Fiber Reinforced Composites

Barkcloth and the Epoxy Composite

According to Rwahwire and Musinguzi W.B. (2019), the Charpy impact test (notch impact test) results of epoxy

Figure 2. Natural fibers (Created by the Authors).

composites reinforced with Barkcloth[1] are higher than 20kJ/m². In addition, the determination of Shore hardness (hardness of plastic or flexible materials) is 72 [33]. The results show that epoxy polymer composites reinforced with Barkcloth are suitable for interior applications in mobile spaces (floating spaces, caravans, etc.).

Rwawiire et al. (2013) determined that when the non-woven barkcloth fabric was treated with alkaline treatment with 5% NaOH solution, the initial temperature required for cellulose degradation increased, and the thermal behavior was positively affected. The main strength of the fabric was 101.7N in the fiber direction and 23.5N in the opposite direction. In addition, in the thermograms obtained because of alkali treatment, it is seen that the fabric is stable at 200 °C [34]. On the basis of these results, it is predicted that alkali-treated barkcloth fabric can be used to strengthen composites. When combined with various materials, a potential thermal insulation material with natural fibers can be obtained in architecture.

Rwahwire et al. (2014), found that among the resin composites reinforced with barkcloth fabrics obtained from Ficus natalensis, Ficus brachypoda, and Antiaris toxicaria species, Ficus B. had the highest thermal conductivity with 0.224 W/mK, and Antiaris had the lowest thermal conductivity with 0.182 W/mK [35]. On the basis of these results, composites reinforced with barkcloth are used in thermal insulation applications. It is seen that the use of fibers obtained from the Antrais toxicaria species will give the most optimum result.

Rwawiire et al. (2017) studied four different barkcloth fiber sequences (BREC I 245, 45, 0, 90, BREC II 45, 245, 90, 0, BREC III 0, 90, 45, 245, BREC IV 90, 0, 245, 45), and various results were obtained. BREC III has the highest tensile strength of 29MPa, the highest tensile modulus of 4.8 GPa, and the highest elongation at a break of 1.04% [36]. Therefore, based on this study, barkcloth-reinforced composites with different degrees of fiber arrangement can be used in architectural applications with various needs. For example, in vertical structural applications requiring tensile strength, a composite produced with barkcloth fibers and resin with the BREC III sequence (0, 90, 45, 245) would be appropriate.

Rwawiire et al. (2015) performed creep tests to determine the dimensional stability of barkcloth fiber-reinforced epoxy composites. This study used DMA to determine the creep behavior of barkcloth-reinforced epoxy composites treated with alkali, enzyme, and plasma. According to the results, the composite with the most constant creep strength between 30°C and 100°C is the alkali-treated barkcloth composite [37]. Therefore, it is predicted that alkali-treated barkcloth composites can be used in structural or semi-structural architectural applications,

According to different studies, polymer composites reinforced with barkcloth have achieved successful results in high-frequency sound absorption [37], [38], [39]. Rwawiire et al. (2017) examined barkcloth's sound-absorbing and thermal insulation properties (obtained from Antiaris toxicaria) reinforced epoxy composites. According to the results, it was found to have lower thermal conductivity and higher sound absorption than other barkcloth composites [40]. Based on this study, the use of barkcloth-reinforced epoxy composite is appropriate for applications requiring sound absorption at a specific frequency. Therefore, it is concluded that composites reinforced with barkcloth can also be used in architectural applications requiring sound insulation.

Jute Fiber Composite

Sarker et al. (2019) found that New Fiber Architecture (NFA) significantly improved the mechanical properties and performance of natural jute plant fiber preforms based on graphene (one of the honeycomb braided structures of the carbon atom) developed with nano-surface engineering. Graphene-based NFA made with jute fiber preforms, jute fiber-epoxy composites, by arranging graphene derivatives and fibers in a parallel direction in nano-surface engineering processes, compared to unprocessed jute fiber composites, it has been reported that it increases the young modulus (modulus of elasticity) rate by ~324% and the tensile strength by ~110%. This opens up the potential to produce high-performance natural alternatives with different hardnesses depending on the applications. As a result, a composite with a new fiber architecture and

---

[1] Barkcloth (bark cloth) mentioned in the study obtained from Ficus Natalensis (Natal Fig) tree.

better mechanical performance has been developed. Some states that the graphene coating on jute fibers provides a robust interfacial bond and improved mechanical properties [41]. The jute plant fiber composites developed in this study are expected to be used in various building structure applications.

Prasob et al. (2019) investigated the viscoelastic and mechanical properties of reduced graphene oxide (rGO) and zirconium dioxide (ZrO2) filled jute/epoxy hybrid composites at various temperatures-especially below zero-. According to the results, the Tg value of the ZrO2-filled jute/epoxy composite is 85.5 °C and shows better mechanical properties than the rGO-filled composite at all temperature values. When the flexural strength values at 27°C are examined, it is seen that the 2% rGO filled composite has 62.64 MPa, the 2% ZrO2 filled composite has 64.14 MPa strength, and at -20°C, it is 58.31 MPa and 59.28 MPa, respectively [42]. Based on this study, it is concluded that ZrO2-filled jute/epoxy composite will be a more suitable choice than rGO-filled composite in the applications of exterior, roof, and structural elements that need to be resistant to various temperatures because of seasonal changes.

Amirabadi-Zadeh et al. (2021), showed that the flexural strength of the silica-treated graphene oxide (SiO2@GONPs) nano-hybrid reinforced jute fiber/epoxy (JF/EP) composite increased by 40% compared with that of the unreinforced jute/epoxy composite. In addition, the energy absorption capacity and impact resistance increased by 61% and 28% , respectively. These results strengthened the fiber and matrix bond because of nano-hybrid addition, and a more durable composite was obtained [43].

Sarker et al. (2018) applied graphene oxide (GO) and graphene (G) coatings to improve the mechanical properties of natural jute fibers. Because of this, the interface shear strength increased by ~236% and the tensile strength by ~96% [44]. Based on these results, it is predicted that composites reinforced with graphene-coated jute fibers can be an alternative to synthetic composites in various fields, such as automotive, marine vehicles, construction, and the aviation industry.

Karim et al. (2021) observed that when various chemical and physical treatments were applied to reduced graphene oxide-based jute fibers, the Young's modulus value increased by ~450% and the tensile strength by ~183% compared with untreated jute fiber composites [45]. On the basis of these results, it is predicted to be usable in horizontal and vertical building structure elements.

Chen et al. (2020) applied graphene oxide nano-layers as a surface treatment to polypropylene (PP) composites reinforced with jute fiber by the grafting method. As a result, the composite had 16.2% better tensile strength and 12.4% better flexural strength than the untreated jute/PP composite. In addition, the thermal resistance increased by approximately 6.5 °C [46].

Santos da Luz et al. (2020) created a composite material with fibers obtained from the NFL technique. The interfacial shear strength of the jute/epoxy composite reinforced with 1% GO is 575 MPa, and the tensile strength is 379 MPa [47]. It has been determined that amphiphilic graphene contributes to better interfacial bonding between the hydrophilic NFL and hydrophobic polymer matrix; therefore, a stronger composite is obtained. It is predicted that jute/polymer composites reinforced with graphene can be used in structural elements that require high strength in architectural applications.

Sridharan et al. (2016) observed that the delamination resistance increased in graphene nano-filled and NaOH alkali-treated jute/epoxy composites. According to the study results, compared with the untreated jute/epoxy composite, alkali treatment increased the resistance by 23.58%, and graphene nano-filling increased the resistance by 49.4% [48]. On the basis of these results, it is predicted to be suitable for interior furniture with various fixing applications according to different forms and designs.

According to Khalid et al. (2020), Jute-based green composites have a suitable strength/weight ratio, high damping ratio, low price, and corrosion resistance. Jute/carbon hybrid composites can replace composites reinforced with carbon fibers without losing tensile strength. These hybrid composites are used in various interior and exterior parts of vehicles [49].

Luffa Cylindrica (LCF) Fiber Composite

Premalatha et al. (2021) studied the effect of various chemicals processed on Luffa Clyndrica fibers (LCFs) on their physicochemical properties. It was observed that the crystallinity and thermal stability of the changed LCFs increased. Stearic acid treatment imparts superior thermal stability to LCFs. According to the TG (glass transition temperature) and&DTA (differential thermal analysis) results, the best thermal stability and kinetic high degradation activation energy of the fiber mainly depend on the cellulose structure. The increase in CI (crystalline index) values after chemical treatments shows that the fiber's cellulose has increased. According to the results, it has been proven that stearic acid-treated LCF (SALF) has superior properties compared with others. All changed LCFs are more permeable in the bonding process with polymer matrices [50].

Mohanta and Acharya (2015) determined the mechanical properties of the solid particle impact behavior of LC-reinforced epoxy composites. Tensile strength in single, two and three-layer composites, respectively: 16.50MPa, 18.00MPa, 15.00MPa, flexural strength; 24MPa, 28MPa, 26MPa, impact strength; 3.90 KJ/m^2, 4.90 KJ/m^2, 4.00 KJ/m^2 [51]. According to the results, it has been determined that the two-layer composite has better mechanical properties under impact, so it should be chosen as a composite for use in architectural applications in this direction.

According to Boynard et al. (2000), even with no surface treatment, Luffa fiber has a high potential to be used as a core layer in hybrid composites [52].

Boynard et al. (2003) studied LC fibers reinforced unsaturated polyester resin composites. LC fibers were treated with acetylation, and an increase in mechanical properties and a decrease in water absorption were determined due to this treatment. The flexural strength of the acetylation-treated composite is 41.94 MPa, which is higher than that of the untreated composite (37.13 MPa). The hygrothermal behavior was tested under different bending strengths (0MPa, 2.4MPa, 8MPa, 16MPa). It increased from 4.1% to 5.2% in the untreated composite and from 2.5% to 2.92% in the processed composite from 8MPa to 16MPa. This increase is probably due to the amount of water absorbed from the micro-cracks formed under load, and it is seen that the hygrothermal performance of the treated composite is superior [53]. High hygrothermal performance is required for the material used in wall construction because it is expected to be more heat-resistant, humidity, and water. As the hygrothermal performance of the acetylation-treated composite produced within the scope of this study increases, it is predicted that it can be used as an alternative to synthetic materials used in wall structures.

Flax Fiber Composite

In Jia Y. and Fiedler B (2013), alternative natural-content composites (flax fiber) pre-treated with furfuryl alcohol were presented. The effects of furfuryl alcohol pretreatment with different parameters on the mechanical properties were investigated. According to the results, it was observed that furfuryl alcohol pretreatment increased the moisture resistance and mechanical properties of the flax fiber (Young's modulus increased by up to 18%). An increase in the moisture resistance, tensile strength, and hardness of the treated composites was observed [54]. Based on these results, it is predicted that furfuryl alcohol-treated flax fiber composites will be used in wet area applications.

Slamani et al. (2021) aimed to develop a randomized complete block design used and treated flax fibers at the same quality level as glass fiber. According to the results, the cutting tool used for delamination affected the properties of the composite. In addition, the two-flute uncoated carbide end mill is the most suitable tool for cutting flax fiber reinforced composites. It has been concluded that it will be an alternative to glass fiber reinforced composites that can be used in the same applications because of the delamination process performed using the determined cutting tool [55]. Based on this result, the use of composites reinforced with flax fiber as a natural alternative is appropriate in architectural applications where glass fiber-reinforced composite materials are used.

Habibi et al. (2020) applied pressure after impact tests (CAI) to determine the impact tolerance and evaluate nonwoven flax fiber-reinforced epoxy composites. A 5% reduction in residual strength was observed when the impact energy range was lower than 3J. Based on these data, values above 3J are classified as critical impact energy, and the material's strength deteriorates [56].

Airinei et al. (2021) determined the dielectric and absorption properties of ethylene-propylene-diene monomer composites reinforced with flax fiber. According to the results, as the flax fiber ratio in the composites increased, the water intake increased to 20 phr. It was determined that the value of the dielectric parameters increased compared to the composite without flax fiber because the polar groups in the fibers caused a higher polarization orientation [57]. It is predicted that it can be an alternative material with natural content that can be used in architectural applications that require electrical insulation. The dielectric coefficient increased by adding flax fibers, thereby increasing the permeability.

Karslı and Aytaç (2014) investigated the properties of alkali-treated PLA/PC (80/10) composites reinforced with 10% volume/weight flax fiber. According to the results, the tensile strength of the fibers treated with 2% NaOH was approximately 54MPa, 10% treated at approximately 48MPa, and 5% treated at approximately 49MPa [58]. It is concluded that flax fibers treated with 2% NaOH have better interfacial bonds with the matrix, so it is predicted that it can be used in architectural applications where tensile strength is required.

Chegdania et al. (2020) investigated the thermal effect on the micro-tribo-mechanical behavior of natural fiber composites. It was observed that the temperature of the sample increased when the density of the PP matrix decreased and decreased when the density of the flax fibers increased. The highest elastic modulus value of flax fibers was observed at 60 °C, and the lowest plastic deformation during stretching occurred at this temperature [59]. On the basis of these results, it is seen that the mechanical properties increase with the addition of flax fiber to the composite, and it is predicted that it is suitable for architectural applications that require thermal insulation.

Kumar et al. (2020) investigated the mechanical, dynamic, and sound-absorbing properties of tri-methoxymethyl silane-treated flax/epoxy composites with different layers and fiber ratios. According to the test results, the highest tensile, flexural, impact strengths, and Shore D hardness values were observed in the four-layer composite with 45% flax fiber, 55% epoxy, and 2.98% voids, and these values were 91.07 MPa, 109.5 MPa, 1295.65 Jm-1, and 85.23, respectively. Considering the sound absorption properties of 0-6400 Hz, flax/epoxy composites provide superior sound absorbency at medium and high frequencies [60]. Thus, flax/epoxy composites are expected to be suitable for acoustic insulation in architectural applications.

STUDIES ON THE USE OF NATURAL FIBER COMPOSITES IN ARCHITECTURE

Today, building materials such as concrete and steel are being replaced by advanced composite materials such as fiber-reinforced polymers (FRPs) and fiber-reinforced cement (FRC). In summary, it is estimated that the usage areas of fiber/polymer composites will expand due to their advantages, such as high strength, lightness, corrosion resistance, and low cost [61]. For example, high strength, compressed thin walls can be made with composites reinforced with sisal fiber. Simultaneously, it can be used to apply facades, tankers, pipes, and long-lasting roof elements, strengthening the existing structure and structural elements [61]. These are examples of panels reinforced with natural fiber on concrete, cement, and sandstone blocks in the building.

Elsaid et al. (2020), according to the results of the impact test carried out within the scope of the study, found that while the crack and fracture rate was high in unreinforced concrete, in the hemp fiber reinforced concrete, the fibers helped to bridge the cracks and minimized the damage [62].

Zhao et al. (2019) used ramie and pineapple leaf fibers to reinforce mixtures prepared with various proportions of cement, fly ash, sand, and water materials. According to the results, the tensile strength of the composites reinforced with pineapple leaf fiber was higher than that of the composite reinforced with ramie fiber. Considering the NaOH and $Ca(OH)_2$ alkali treatments applied to both composites, it is seen that NaOH increases the tensile strength better in each composite. When we look at the water absorption and chloride erosion resistance rates, composite reinforced with ramie fiber absorbs less water than reinforced with Pineapple leaf. Therefore, it has higher water resistance, and when the penetration depths of chlorite are examined, it is seen to reach a lower level and, therefore, is more [63]. Based on the results, alternative natural fiber composites were predicted to be suitable for different architectural applications (ramie for water and chloride resistance, pineapple leaf fiber for mechanical strength).

Dávila-Pompermayer et al. (2020) investigated the effect of lechuguilla fibers applied to concrete as a curing agent, which can absorb 98% of water within 22 h and reach a daily desorption rate of 14%. The mixture uses Portland cement fly ash and silica fume as binders. When the compressive strengths obtained at the end of 56 days are examined, 400kg cement, 159.4 kg water, 1,782.8 kg aggregate, and 11.9 kg lechuguilla mixture showed the highest value with 50.5 MPa compared with mixtures with other fiber weights. However, the same amount of cement, water, and aggregate mixture (55.6 MPa) was observed to be lower [64]. According to the study results, it can be a natural fiber alternative for architectural applications but cannot completely replace the standard cement mixture.

Balasubramanian et al. (2015) used sisal fibers to increase the mechanical performance of concrete used in structural applications. According to the results of the study, the addition of 1.5% sisal fibers to 300 doses increases the compressive strength, the addition of 0.5% to 300 doses increases the tensile strength, and the addition of 1% to 300 doses increases the flexural strength compared with the standard concrete mix [65].

Castillo-Lara et al. (2020) FRFC was reinforced with 0.5%, 1%, and 1.5% vol. and alkali-treated henequen fiber. According to the results, the addition of fiber improved compressive and tensile strengths and plastic behavior. As observed at the peak point under pressure, there is no significant loss in strength. The highest compressive strength value was 1.78±0.05 MPa, which was observed in the concrete mix with 1.5% vol/wt added alkali-treated henequen fiber. The compressive strength of the PFC (fiber-free concrete mix) under the same conditions was 1.42±0.05 MPa. The compressive strength increased because of the addition of fiber [66]. On the basis of these results, it is predicted to be an alternative to the standard concrete mixture in structural elements, such as columns and beams, in architectural applications.

In addition, according to Siddiqui (2004), when 0.25% san fiber is added to concrete with fly ash, the tensile strength increases by 8-11% [67]. Reis et al. (2003) found that, adding coconut fiber to epoxy polymer concrete increases flexural strength more than concrete reinforced with glass and carbon fiber [68]. Savastano et al. (2005) sisal and eucalyptus fiber are successful binders for OPC [69] [70].

Brose et al. (2019) studied the application of coconut fiber-reinforced OPC (Standard Portland Cement) and hydrated lime panels placed on existing sandstone blocks on the east-west axis at an angle of 16°. When the compressive strength and fracture modulus are examined, the panel reinforced with coconut fiber has higher strength than the non-reinforced panel. Considering the annual energy consumption and energy gains in heating and cooling processes of the Energy Plus model created within the article, the facade wall application was made using 45cm Sandstone + 2cm Air Space + 2cm Coconut fiber panel. Compared to the application made using 45cm Sandstone, minimized the energy consumption and maximized the current energy-savings. As a result, a building material with improved mechanical and thermal properties has emerged [71].

Vijay et al. (2019) tested the physicochemical, thermal, shrinkage, and morphological characteristics of the fibers obtained from Saccharum Bengalense Grass (SB). According to the results confirmed by FTIR (Fourier Transform Infrared Spectroscopy), fibers have good chemical components as α-cellulose (53.45%), hemicellulose (31.45%) and low lignin (together with cellulose provide the woody structure and strength of the plant) (% 11.7). In addition, according to XRD (X-ray Diffraction Analysis) and tensile strength tests, SB fibers have a good crystallinity index and tensile strength. Thermal stability was determined using Thermogravimetric Analysis (TGA), showing that the maximum degradation of SB fibers occurred at 336°C, and the char residue was 16.4%. SEM was used to determine the morphological characteristics. Based on these results, the fibers can be used in roof coverings, door panels, furniture panels, interior panels, storage tanks, and pipes [72]. Various studies in the literature evaluate the performance of composites affected by environmental factors determined through accelerated ageing conditions. These studies include bamboo fiber [73], [74] hemp/sisal fibers [75], unidirectional natural fibers [76], flax fiber, coconut fiber [77], jute fiber [78], [79], Palmira fiber [80], hemp fiber and sisal fiber [79] and sisal fiber [81]. The studies covered both architecture and mobile spaces and are examined in the following sections.

When mobile spaces are examined, it is seen that PP (polypropylene) reinforced with talc-filled EPDM (ethylene-propylene-diene monomer) is frequently used in the production of interior and exterior parts in automobiles. In the study conducted in 2018, the mechanical and thermal properties of recycled bamboo fiber reinforced, talc-filled PP/EPDM composites harmonized with PP-g-MAH (maleic anhydride grafted polypropylene) were evaluated after ageing for 7 days in cells with 90 °C hot airflow. The aged composites showed a lower tensile modulus and tensile strength than the unaged and high PP-g-MAH components. In addition, flexural strength and flexural modulus are better in aged composites than in unaged composites [74]. This study shows that the composite can be used on exterior and interior architecture facades and will not decrease performance over time.

A Prediction of Architectural Space Usage Areas of Composites Obtained from Kenaf Fiber

The kenaf plant can absorb almost 1.5 times its weight of carbon dioxide. This rate is highest compared with other plants [62], [82]. This study shows that composites using kenaf fiber minimise environmental damage. In addition, studies in the literature have shown that it can have properties such as fire, water, and moisture resistance with various chemical processes. It is a natural weather-resistant strengthening material with features that can be used in exterior applications [75], [76]. The mechanical (tensile, flexural and impact strengths), water resistance, thermal stability, and acoustic properties of the composites reinforced with kenaf fibers evaluated within the scope of the study and the foresigths for usage areas are given in Tables 2-6.

Table 2. Studies involving kenaf fibers, which appear to be suitable for structural applications

Composite materials	Evaluated properties		Foresight for usage areas	Source
	Tensile strength	Flexural strength		
Hydrochloric acid-treated kenaf fiber (KTH)	16.0 ± 1.1 MPa		It is considered suitable for use in furniture structures.	[83]
%50 (%30Kenaf fiber, %70Polypropylene), %50Pineapple leaf fibers (PALF)	20.42MPa	51.70 MPa	Considering its tensile strength, it is foreseen to be suitable for use in furniture parts and semi-structures. When the flexural strength is considered, it can be used in horizontal structural elements.	[84]
Kenaf Fiber, Jute Fiber, Polyethene	22MPa		The treated composites, especially the 15% wt composite, showed increased tensile strength, better thermal stability, and higher activation energy. It is predicted that kenaf/jute/polyethene composites with 15% fiber loading and alkaline treatment with tert-butyl catechol can be used as reinforcement of vertical load-bearing structural members, in partial-structural applications and in high-temperature applications.	[85]
Bidirectional 30%Kenaf fiber, 70%PLA	30.25 MPa	71.42MPa	Composites with 30% fiber ratio have high tensile and excellent flexural properties. For this reason, it is predicted that kenaf fibre/PLA composites will be preferred in horizontal building and furniture structures.	[86]
Kenaf/Kenaf/Kenaf fabrics reinforced bioepoxy	33.57 MPa		When the tensile properties of the composite formed with three kenaf fabric layers are considered, it is predicted that it can be used in partial-structural elements.	[75]
Sisal/Kenaf/Sisal fabrics reinforced with bioepoxy	34.27 MPa		When the tensile properties of the composite formed with kenaf, sisal, and kenaf fabric layers are considered, it is predicted that it can be used in partial-structural elements.	[75]

Table 2. Studies involving kenaf fibers, which appear to be suitable for structural applications (continued)

Composite materials	Evaluated properties		Foresight for usage areas	Source
	Tensile strength	Flexural strength		
Kenaf/Sisal/Kenaf fabrics reinforced bioepoxy	35.31 MPa		Because of its high mechanical properties, it can be used in partial structural applications.	[75]
Unidirectional 30%Kenaf fiber, 70%PLA	50.26 MPa	54.17MPa	Composites with 30% fiber ratio have excellent tensile properties. For this reason, it is predicted that kenaf fibre/PLA composites will be preferred in vertical building structures and facade applications.	[86]
50% Kenaf fiber, 50% Bamboo fiber	55.28MPa		The BK composite is predicted to be suitable for use in vertical structural elements and facade applications because of its good tensile strength.	[87]
Hybrid composites were produced using 10%Microencapsulated PCM (MOCM), 30%kenaf, a natural fiber filler and PLA	60MPa	12MPa	According to the results, the use of K. fiber strengthened the tensile strength and elongation and both infills harmed the flexural strength. Thus, it is predicted that composites reinforced with kenaf are suitable for use in vertical structural applications that require tensile strength and elongation, and the use of unfilled PLA matrix in horizontal structural applications that require flexural strength.	[88]
Unsaturated polyester resin composites reinforced with a nonwoven kenaf fiber (KF) mat		60 MPa	Unsaturated polyester resin composites reinforced with a nonwoven kenaf fiber (KF) mat exposed to natural weathering conditions for 12 months showed high flexural strength. For this reason, it can be used in both horizontal structures and building envelopes.	[89]
Palm oil (EFB), Kenaf fiber (1:1) and Epoxy	62 MPa	113.14MPa	According to the results, as the kenaf fiber content increased, the flexural properties increased significantly. Therefore, the use of kenaf fiber and EFB (1:1 ratio) composites in the reinforcement of horizontal structural elements, facade and roof applications is suitable.	[90]
Palm oil (EFB), Kenaf fiber (1:4) and Epoxy	64.7 MPa	85MPa	According to the results, as the epoxy ratio increased, the tensile properties increased. Therefore, the use of kenaf fiber and EFB (1:4 ratio) composites in the reinforcement of vertical structural elements, facade and roof applications is suitable.	[90]
Kenaf fiber mat/Indian almond fiber mat/ Kenaf fiber mat	65 MPa	92 MPa	The K/I/K composite has a high maximum average flexural strength. It is predicted that K/I/K can be used in structural, roof, and facade applications because it has better tensile and flexural strength properties.	[91]
40%Kenaf fiber, 60%Vinylester	150 MPa	180 MPa	In terms of tensile strength and tensile modulus, the optimal tensile speeds are 0.3 and 0.1 m/min (150MPa), while for flexural strength (180MPa), the flexural modulus and compressive strength are 0.4 m/min. Therefore, the use of composites produced with different protrusion rates in the application phase of vertical and horizontal structural elements is appropriately expected.	[92]
48%Epoxy, 50%Kenaf, 2%Silicon Oxide 2%	168MPa	218MPa	The tensile and flexural strengths of the composite were high. Therefore, it is predicted that it can be used in horizontal and vertical structural elements and roof and facade applications.	[93]
Various concentrations of NaOH as alkali treated Kenaf fibers	622.16MPa		Because the tensile strength of the composite reinforced with kenaf fiber treated with 10% NaOH alkali is at its maximum value, its use in the reinforcement of vertical structural elements such as columns, roofs, and facades is expected as appropriate.	[94]

Table 3. Studies involving kenaf fibers, which seem to be suitable for wet areas, water resistance , and installation areas

Composite materials	Evaluated properties		Foresight for usage areas	Source
	Water absorption	Moisture uptake		
Kenaf/Kenaf/Kenaf fabrics reinforced bioepoxy	More than 5%		Because less water absorption is observed in the K/K/K composite, it is recommended to be used in wet and installation areas.	[75]
Kenaf/Sisal/Kenaf fabrics reinforced bioepoxy	5% of its weight		Because less water absorption is observed in the K/S/K composite, it is recommended to be used in wet and installation areas.	[75]
Sisal/Kenaf/Sisal fabrics reinforced bioepoxy	More than 5%		Because less water absorption is observed in the S/K/S composite, it is recommended to be used in wet and installation areas.	[75]
Kenaf Fiber, Jute Fiber, Polyethene	%5		The treated composites, especially the 15% wt composite, showed almost twice the water resistance observed in the alkali-treated composites. For this reason, it is recommended to be used in wet and installation areas.	[85]
%75 (%30Kenaf fiber, %70Polypropylene), %25Pineapple leaf fibers (PALF)		4% of its weight	It is recommended to be used in wet and installation areas.	[84]
Kenaf fiber mat/ Indian almond fiber mat/ Kenaf fiber mat		approximately 2% of its weight	Because of moisture absorption and biodegradation studies, K/I/K absorbs a little moisture. For this reason, it is recommended to be used in wet and installation areas.	[91]
50%Natural rubber (NR), 12.50%kenaf fiber, 37.50%Thermoplastic polyurethane (TPU)	below 1%		Because its water absorption is below 1%, it is foreseen that it can be used in areas that require water resistance.	[95]

Table 4. Studies involving kenaf fiber, which seem to be suitable for architectural applications requiring high thermal stability and electrical circuits, have been conducted in fire evacuation routes.

Composite materials	Evaluated properties		Foresight for usage areas	Source
	Thermal properties Td [Max]	Fire resistance		
35 %Kenaf 15% Recycled Carbon, 50%Cardanol	194.04°C	V0 (UL 90 HB)	According to the thermal characterization of the samples, cardanol enhanced and improved the thermal stability of kenaf hybridized with recycled carbon fiber. Owing to the V0 fire resistance level, it is predicted to be suitable for sensitive areas where electrical installations are located	[96]
25 %Kenaf 25% Recycled Carbon, 50%Cardanol	209.38°C	V0 (UL 90 HB)	The good thermal stability of kenaf hybridized with recycled carbon fiber and its V0 fire resistance level make it suitable for sensitive areas where electrical installations are located	[96]

Table 4. Studies involving kenaf fiber, which seem to be suitable for architectural applications requiring high thermal stability and electrical circuits, have been conducted in fire evacuation routes (continued)

Composite materials	Evaluated properties		Foresight for usage areas	Source
	Thermal properties Td [Max]	Fire resistance		
15 %Kenaf 35% Recycled Carbon, 50%Cardanol	216.27°C	V0 (UL 90 HB)	Because of the V0 fire resistance level, it is predicted to be suitable for roof and facade applications, sensitive areas where electrical installations are located.	[96]
Kenaf/Kenaf/Kenaf fabrics reinforced bioepoxy	313.33°C		Because it can stay intact up to 313.33°C, it is suitable for applications requiring high thermal stability.	[75]
Sisal/Kenaf/Sisai fabrics reinforced bioepoxy	314.33°C		Because it can stay intact up to 314.33°C, it is suitable for applications requiring high thermal stability.	[75]
Kenaf/Sisal/Kenaf fabrics reinforced bioepoxy	314.67°C		Because it can stay intact up to 314.67°C, it is suitable for applications requiring high thermal stability.	[75]
Hydrochloric acid-treated kenaf fiber (KTH)	338.3°C		Because it can stay intact up to 338.3°C, it is suitable for applications requiring high thermal stability..	[83]
Unsaturated polyester resin composites reinforced with a nonwoven kenaf fiber (KF) mat	419°C		Unsaturated polyester resin composites reinforced with a nonwoven kenaf fiber (KF) mat exposed to natural weathering conditions for 12 months. After that, the thermal properties still have high values. It is predicted to be suitable for facade applications and electrical installations.	[89]
Kenaf/epoxy hybrid nanocomposites		V-2 (UL 94 V)	Kenaf/epoxy hybrid nanocomposites have good flame retardance and relatively less flame dripping or ignition compared with kenaf/epoxy composites. Therefore, it is predicted that it is suitable in areas where semi-fire resistance is required.	[97]
montmorillonite (MMT)/ kenaf/epoxy		V-1 (UL 94 V)	MMT/Kenaf/Epoxy hybrid nanocomposites have good fire resistance and relatively less flame dripping or ignition. Therefore, it is predicted that it will be suitable in areas where electrical circuits are located and in fire evacuation routes and facade applications.	[97]
Organically modified MMT (OMMT)/kenaf/ epoxy		V-0 (UL 94 V)	The OMMT/Kenaf/epoxy hybrid nanocomposites have great and satisfactory fire resistance. Therefore, it is predicted that it is suitable for roof and facade applications, areas where electrical circuits are located, and fire evacuation routes.	[97]
3% Nano oil palm empty fruit bunch (OPEFB)/ kenaf/epoxy		V-0 (UL 94 V)	Kenaf/epoxy hybrid nanocomposites have good and satisfactory flame retardance and relatively less flame dripping or ignition compared with kenaf/epoxy composites. Therefore, it is predicted that it is suitable for roof and facade applications, areas where electrical circuits are located, and fire evacuation routes.	[97]

Table 5. Studies involving kenaf fibers, which seem to be suitable for mobile spaces that are more susceptible to impact and damping environments

Composite materials	Evaluated properties	Foresight for usage areas	Source
	Impact strength		
Palm oil (EFB), Kenaf fiber, Epoxy	3.06J	The use of EFB/kenaf fiber (4:1 ratio) composite in mobile spaces that are more susceptible to impact is suitable.	[90]
Indian Almond Fiber mat/ Kenaf Fiber mat/ Indian Almond Fiber mat	6kJ/m^2	Because of the impact studies, the I/K/I composite has a high maximum average impact strength due to the outer layer of I. almond fiber and greater impact absorption along the surface cracks. I/K/I shows better impact resistance and is suitable for damping environments..	[91]
2%Silicon (IV) oxide nanoparticle in the 48%epoxy, 50%kenaf fiber	6.10 kJ/mm^2	Maximum impact strength was observed in the composite containing 50% fiber and 2.0% volume silicon oxide. Compared with others, the composite has lower damage after the impact test. Therefore, it is foreseen to be suitable for use in mobile spaces.	[93]
Hybrid composites were produced using 20%Microencapsulated PCM (MOCM) 10%kenaf and, PLA	7MPa.	Hybrid composites produced with 20% microencapsulated PCM (MOCM) and 10% kenaf and PLA have good impact strength. Therefore, it is foreseen to be suitable for use in mobile spaces.	[88]
Kenaf/Sisal/Kenaf fabrics reinforced bioepoxy	7.3 kJ/mm^2	Hybrid composites produced with Kenaf, Sisal, and Kenaf mat layers have good impact strength. Therefore, it is foreseen to be suitable for use in mobile spaces.	[75]
Kenaf/Kenaf/Kenaf fabrics reinforced bioepoxy	7.5 kJ/mm^2	Hybrid composites produced with Kenaf, Kenaf, and Kenaf mat layers have good impact strength. Therefore, it is foreseen to be suitable for use in mobile spaces.	[75]
Sisal/Kenaf/Sisal fabrics reinforced bioepoxy	8.6 kJ/mm^2	Hybrid composites produced with Sisal, Kenaf, and Sisal mat layers have great impact strength. Therefore, it is foreseen to be suitable for use in mobile spaces.	[75]
30%Kenaf Fiber, 70%PLA	90.64 J/m.	Hybrid composites produced with Kenaf fiber and PLA have great impact strength. Therefore, it is foreseen to be suitable for use in mobile spaces and automobile parts.	[86]
1% Silicon (IV) oxide nanoparticle, 49%epoxy, 50%kenaf fiber	92J	Maximum impact strength was observed in the composite containing 50% fiber and 1.0% volume silicon oxide. Compared with others, the silane-treated composite has lower damage after the impact test. Therefore, it is foreseen to be suitable for use in mobile spaces.	[93]

Table 6. Studies involving kenaf fibers, which appear to be suitable for acoustic spaces

Composite materials	Evaluated properties		Foresight for usage areas	Source
	Bulk density	Absorption coefficient		
50% Kenaf fiber, 50% Bamboo fiber	140–150 kg/m^3	lower than 0.5	50:50 (kenaf/bamboo) hybrid composite displayed good sound absorption with maximum peak. It is predicted that the BK composite is suitable for use in acoustic spaces because of its high sound-absorbing ability.	[87]
Kenaf fibers binded with Polyvinyl alcohol	150 kg/m^3	0.72	Kenaf fibers bind to polyvinyl alcohol composites and have good sound absorption coefficients. It is predicted that the composite is suitable for use in acoustic spaces because of its high sound-absorbing feature.	[98]
Kenaf fiber	140–150 kg/m^3	0.85	Kenaf fibers have a good sound absorption coefficient. It is predicted that the composite is suitable for use in acoustic spaces because of its high sound-absorbing feature.	[99]
Kenaf fiber	200 kg/m^3	0.93	Kenaf fibers have a good sound absorption coefficient. It is predicted that the composite is suitable for use in acoustic spaces because of its high sound-absorbing feature.	[100]
50% Kenaf fiber, 50% PP		0.93	Kenaf fiber and PP composites have good sound absorption coefficients. It is predicted that the composite is suitable for use in acoustic spaces because of its high sound-absorbing feature.	[101]

RESULTS AND DISCUSSION

Studies on composites reinforced with natural fiber in the literature were evaluated, and predictions were made. As a result, in architectural applications,

- Considering facade applications, the materials should not lose performance over time due to external factors such as weather. According to studies in the literature, composite materials reinforced with sisal fiber have thin section thickness and high tensile strength and maintain these properties even after exposure to natural weather [79]. *Therefore, it is suitable for facade applications.* When the bamboo fiber-reinforced composites are examined, the flexural strength is 29.13+2.04 MPa when subjected to the ageing process (exposure to external conditions in a laboratory environment) [74]. *Consequently, it can be used in exterior applications.* The tensile strength of the composites reinforced with SB fiber is 33 ± 1.5 MPa. Because of the dehydration of water molecules from room temperature to 100°C, a weight loss of 2.13% and thermal stability can be achieved up to 336°C [72]. *These results make it durable for exterior applications against weather and external factors.* Considering the composite material reinforced with ramie fiber, it is seen that water and chloride resistances are superior compared to cement [63]. *Therefore, it can be used as a facade cladding material, especially in buildings near the sea.* In addition, according to the data obtained from Tables 2 and 4., the use of kenaf fiber reinforced composite is appropriate.
- Considering roof applications, material used should not lose its performance because of exposure to external conditions and should be durable [78]. *Because the composites reinforced with sisal fiber do not lose their mechanical properties after exposure to natural weather, they are suitable for roof applications.* In addition, according to the data obtained from. Tables 2 and 4 the use of kenaf fiber reinforced composite is appropriate.
- Considering building structure applications, materials require various mechanical strengths because of their application (column, beam, floor, or load-bearing wall) [102]. These requirements are high strength, tensile strength, or flexural strength, depending on the type of structural element. According to the results of tensile and four-point flexural tests applied on standard Portland cement and composite materials reinforced with sisal fiber in the literature, reinforced composite has 13.95MPa, and standard Portland cement has 9.24MPa values [65]. *Therefore, it is concluded that sisal can be preferred as a natural fiber alternative to building structure applications made with cement.* Considering that jute and carbon fiber are applied together, it is seen that the maximum strength of the epoxy composite reinforced with carbon fiber is 16566 N and 15333N in the epoxy composite reinforced with both carbon and jute fibers [49]. Using jute fiber has made the composite material more natural, and no significant loss of strength has occurred. *Therefore, it is suitable for structural applications.* The composite material reinforced with ramie and pineapple leaf fiber has higher tensile strength than unreinforced cement [63]. *Therefore, it is predicted to be used as a cement reinforcement in building structure applications.* In addition, according to the data obtained from Table 2. the use of kenaf fiber reinforced composite is appropriate.
- Considering semi-structural applications, the strength of the material to be used must be of value to meet the application. It is known that the mechanical performance of composites reinforced with bamboo fiber does not noticeably decrease even when subjected to the ageing process [74]. *Therefore, it is suitable for semi-structural applications.* Because the maximum strength value is high in composites reinforced with jute fiber [49], *it is ideal for semi-structural applications.* Considering the flax fiber reinforced composite, the tensile strength increased when treated with furfuryl alcohol [54]. *Therefore, the composite with increased tensile strength is suitable for semi-structural applications.* According to the study in which kenaf fiber and Indian almond fiber are used as reinforcement, it is seen that the tensile strength of epoxy resin is approximately 30MPa, almond fiber is 60MPa, and kenaf fiber is 90MPa. Because of this study, it was stated that the K/I/K composite could withstand high stress [91]. *Accordingly, it is suitable for semi-structural applications.* In addition, according to the data obtained from Table 2 the use of kenaf fiber reinforced composite is appropriate.
- Considering its thermal insulation applications, the material is expected to have high thermal stability and a low thermal conductivity coefficient for energy recovery. Since coconut fiber has a low thermal conductivity coefficient, it minimizes the energy consumed for heating and cooling [71]. *Therefore, it can be used in thermal insulation.* In a study on polymer composites reinforced with Luffa cylindrica, the thermal stability of alkali-treated fibers was found to be 500°C [50]. *Based on these result, it can be used in thermal insulation.* Considering the study on the composite material reinforced with kenaf and sisal fiber, thermal stability was achieved at 295°C [75]. *Therefore, it can be used in applications requiring thermal insulation up to 295°C.* In addition, according to the data obtained from Table 4 the use of kenaf fiber reinforced composite is appropriate.
- Considering sound insulation applications, the material used is expected to have a hollow structure and absorb sound and vibration. In the study, in the literature, bamboo, and kenaf fiber were used to reinforce the epoxy; the hollowness of kenaf fiber was 7.56%, and bamboo fiber was 4.37%. The sound absorption in the 500-3000 Hz frequency range is at the maximum level in the composite formed by hybridizing kenaf (50%) and bamboo (50%) fibers [87]. *Based on the acoustic performance of*

the material, depending on the frequency range, it is suitable for sound insulation. In addition, according to the data obtained from Table 6 the use of kenaf fiber reinforced composite is appropriate.

- Considering waterproofing applications, the material used must meet the desired performance criteria in the application area when flax fiber is treated with furfuryl alcohol and used as reinforcement to epoxy, water absorption after 243 h is 42.4% less than that of plain epoxy [54]. *Accordingly, it is suitable for waterproof applications.* In addition, according to the data obtained from Table 3, the use of kenaf fiber reinforced composite is appropriate.
- Considering interior applications, the material to be used must have various requirements according to the design to be applied. While strength is not expected in the materials to be applied decoratively, high mechanical properties for vehicle interiors or places susceptible to impact are. Because the mechanical properties of composites reinforced with jute fiber are high [49] their use in interior applications where the required strength is suitable. In addition to their high mechanical performance, SB fibers have a density of 1165 kg/cm3 [59]. *Consequently, it can be an alternative to synthetic fibers in applications requiring lightness.* In the study where kenaf and almond fiber were used as epoxy reinforcement, moisture absorption, and mechanical strength increased [91]. *Therefore, it is suitable for interior applications.* In a study on epoxy composites reinforced with Barkcloth, the impact strength results were higher than 20kJ/m^2, and the shore hardness was 72 [33]. *Accordingly, epoxy composites reinforced with barkcloth can be used as a natural alternative when a high-hardness material that requires impact resistance is needed in the design.* In a study in which kenaf and bamboo fibers were hybridized as reinforcements for epoxy composites, the tensile strength of unreinforced epoxy was 20.00MPa, kenaf fiber was approximately 40.00MPa, and bamboo fiber was approximately 55.00MPa [87]. *According to the results, hybridized composite suits interior applications requiring tensile strength.* In addition, according to the data obtained from Tables 2 and 5. the use of kenaf fiber reinforced composite is appropriate.
- Considering the installation applications, the material must have various properties depending on the type of installation (water, electricity, mechanical installation). These properties include fire resistance, water resistance, and high strength. Composites reinforced with SB fibers have a hard surface, provide thermal stability up to 336°C, and good water resistance [72]. *Therefore, they are suitable for installation applications.* In addition, according to the data obtained from. Tables 2, 3, 4, 5 and 6, the use of a kenaf fiber reinforced composite is appropriate.

This paper provides foresight about using natural fiber-reinforced composites in architectural fields, and there has been no review on this subject in the literature. It is thought to shed light on future studies, and different natural fiber composites for architectural use will be investigated on the basis of this study. Therefore, architectural usage can expand, and the use of these materials can decrease the thermal conductivity value in buildings, providing thermal energy savings. In addition, natural-containing composite materials, unlike synthetics, degrade in nature, therefore when the life of use is completed, the energy spent to destroy the material is less. Based on the data obtained from the literature, it is seen that less energy is consumed compared to synthetic materials in the life cycle covering all stages of production, use, and destruction. Therefore, the damage to nature caused by the construction sector can be reduced as the natural fiber reinforced composites usage areas increase. The kenaf plant is originally from South Asia, and its cultivation in Turkey has been encouraged in recent years. It is used in paper, net, and rope making worldwide. If the characteristics mentioned in this study are revealed, its cultivation in Turkey will provide economic benefits. In addition, it is possible to produce such a composite in every geographical region suitable for kenaf cultivation worldwide. Using the produced composite as a building material in any location will reveal the study's potential.

CONCLUSION

Composites reinforced with natural fibers have lower energy consumption and a lower carbon footprint than synthetic materials in all production, use, and demolition processes. Because they are sustainable, green, and eco-friendly, they support the concepts of energy recovery and sustainability, which have become strategic goal on the world agenda. In this article, using the SLR technique, the studies on natural fiber composites in the literature were examined in terms of their mechanical (tensile, flexural and impact strengths), water resistance, thermal stability, fire resistance and acoustic properties, and various predictions on architectural application areas were presented based on quantitative data.

The values of composites reinforced with synthetic fibers in the literature are

- The tensile strength of glass fiber reinforced PP is 43.6MPa,
- The impact strength of glass fiber reinforced PLA is 40J/m,
- The flexural strength of glass fiber reinforced PLA is 90MPa,
- The tensile strength of glass fiber reinforced PLA is 55MPa,
- The flexural strength of PET microfibers reinforced PE is 14.11MPa,
- The tensile strength of PET microfibers reinforced PE is 20.12MPa,
- The flexural strength of glass fiber reinforced polyester is 44.65MPa,

- The thermal stability of PBO, Terlon, Kermel, and Kevlar29 are 556.5°C, 473.5°C, 411.2°C and 480.0°C,

Considering the values for composites reinforced with synthetic fibers compared with those for composites reinforced with natural fibers,

- Considering the Barkcloth reinforced composites, it can be concluded that they are suitable for use in mobile architectures and impact-friendly environments because of the hardness level and impact properties of the composite formed.
- Considering the jute fiber reinforced composites, it is predicted that composites are created using various reinforcements. As a result, materials with high performance, rigidity, and robust mechanical performance have emerged that can suit many architectural elements.
- When composites reinforced with Luffa Cylindrica fiber are considered, they are understood to gain superior thermal stability with varying treatments of chemicals. Therefore, these composites are anticipated to be used in architectural applications requiring high temperatures and fire escape routes.
- Considering flax fiber reinforced composites, it is understood that their mechanical and moisture resistance properties increase because of various chemical treatments. Therefore, it can be concluded that these composites can be used in wet areas.
- Considering pineapple leaf fiber reinforced composites, they decreased the water absorbency of the composite and are suitable for use in wet areas.
- Considering the ramie fiber reinforced composites, due to their high level of resistance to chloride erosion, it can be concluded that they are suitable for buildings around seawater.
- Coconut fiber reinforced composites are anticipated to be used in high damping and fire environments due to their increased mechanical and thermal properties.
- Considering the SB fiber reinforced composites, it can be concluded that they can be used in fire environments because of their resistance to high temperatures.
- Considering the kenaf fiber reinforced composites, According to Figures Tables 2-6., it can gain different properties and is predicted to be used in various architectural applications such as;
    - o Facade,
    - o Roof,
    - o Building structure,
    - o Semi-structural applications,
    - o Thermal insulation,
    - o Sound insulation,
    - o Water isolation,
    - o Interior design applications,
    - o Installation

When composites reinforced with natural fibers are considered, they show superior properties compared to composites reinforced with synthetic fibers. Therefore, it is foreseen that it can be used as an alternative to synthetic fibers in facades, roofs, building structures, semi-structural, thermal insulation, sound insulation, waterproofing, interior, and installation applications.

CONSENT FOR PUBLICATION

The authors of this paper have consent for publication.

AUTHORSHIP CONTRIBUTIONS

Both Ceylan I. and Cakici Alp N. wrote the main manuscript text.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Abu-Jdayil B, Mourad AH, Hittini W, Hassan M, Hameedi S. Traditional, state-of-the-art, and renewable thermal building insulation materials: An overview. Constr Build Mater 2019;214:709–735. [CrossRef]

[2] Yang L, Yan H, Lam JC. Thermal comfort and building energy consumption implications—A review. Appl Energy 2014;115:164–173. [CrossRef]

[3] Fan M, Fu F, eds. Advanced high strength natural fibre composites in construction. UK: Elsevier; 2016. [CrossRef]

[4] Brosius D. Natural fiber composites slowly take root. Compos Technol 2006;12:32–37.

[5] Lafond C, Blanchet P. Technical performance overview of bio-based insulation materials compared to expanded polystyrene. Buildings 2020;10:81. [CrossRef]

[6] Dong Y, Kong J, Mousavi S, Rismanchi B, Yap PS. Wall insulation materials in different climate zones: A review on challenges and opportunities of available alternatives. Thermo 2023;3:38–65. [CrossRef]

[7] Begum K, Islam M. Natural fiber as a substitute to synthetic fiber in polymer composites: A review. Res J Eng Sci 2013;2278:9472.

[8] Bhutta A, Farooq M, Banthia N. Performance characteristics of micro fiber-reinforced geopolymer mortars for repair. Constr Build Mater 2019;215:605–612. [CrossRef]

[9] Alomayri T, Low IM. Synthesis and characterization of mechanical properties in cotton fiber-reinforced geopolymer composites. J Asian Ceram Soc 2013;1:30–34. [CrossRef]

[10] Rijsdijk HA, Contant MAAJM, Peijs AAJM. Continuous-glass-fibre-reinforced polypropylene composites: I. Influence of maleic-anhydride-modified polypropylene on mechanical properties. Compos Sci Technol 1993;48:161–172. [CrossRef]

[11] Zampaloni M, Pourboghrat F, Yankovich SA, Rodgers BN, Moore J, Drzal LT, et al. Kenaf natural fiber reinforced polypropylene composites: A discussion on manufacturing problems and solutions. Compos Part A Appl Sci Manuf 2007;38:1569–1580. [CrossRef]

[12] Wang G, Zhang D, Wan G, Li B, Zhao G. Glass fiber reinforced PLA composite with enhanced mechanical properties, thermal behavior, and foaming ability. Polymer 2019;181:121803. [CrossRef]

[13] Shih YF, Huang CC. Polylactic acid (PLA)/banana fiber (BF) biodegradable green composites. J Polym Res 2011;18:2335–2340. [CrossRef]

[14] Gaikwad P, Mahanwar P. Studies in effect of synthetic and natural microfibers on properties of high-density polyethylene-reinforced composite. Polym Plast Technol Eng 2017;56:131–140. [CrossRef]

[15] El-Wazery MS, El-Elamy MI, Zoalfakar SH. Mechanical properties of glass fiber reinforced polyester composites. Int J Appl Sci Eng 2017;14:121–131.

[16] Prasad AR, Rao KM, Gupta AVSSKS, Reddy BV. A study on flexural properties of wildcane grass fiber-reinforced polyester composites. J Mater Sci 2011;46:2627–2634. [CrossRef]

[17] Liu X, Yu W. Evaluating the thermal stability of high-performance fibers by TGA. J Appl Polym Sci 2006;99:937–944. [CrossRef]

[18] Asim M, Paridah MT, Chandrasekar M, Shahroze RM, Jawaid M, Nasir M, et al. Thermal stability of natural fibers and their polymer composites. Iran Polym J 2020;29:625–648. [CrossRef]

[19] Azwa ZN, Yousif BF. Characteristics of kenaf fibre/epoxy composites subjected to thermal degradation. Polym Degrad Stab 2013;98:2752–2759. [CrossRef]

[20] Al-Homoud MS. Performance characteristics and practical applications of common building thermal insulation materials. Build Environ 2005;40:353–366. [CrossRef]

[21] La Gennusa M, Llorach-Massana P, Montero JI, Peña FJ, Rieradevall J, Ferrante P, et al. Composite building materials: Thermal and mechanical performances of samples realized with hay and natural resins. Sustainability 2017;9:373. [CrossRef]

[22] Dittenber DB, GangaRao HV. Critical review of recent publications on use of natural composites in infrastructure. Compos Part A Appl Sci Manuf 2012;43:1419–1429. [CrossRef]

[23] Lawrence M, Fodde E, Paine K, Walker P. Hygrothermal performance of an experimental hemp-lime building. Key Eng Mater 2012;517:413–421. [CrossRef]

[24] Vėjelienė J, Gailius A, Vėjelis S, Vaitkus S, Balčiūnas G. Evaluation of structure influence on thermal conductivity of thermal insulating materials from renewable resources. Mater Sci 2011;17:208–212. [CrossRef]

[25] Asim M, Uddin GM, Jamshaid H, Raza A, Hussain U, Satti AN, et al. Comparative experimental investigation of natural fibers reinforced lightweight concrete as thermally efficient building materials. J Build Eng 2020;31:101411. [CrossRef]

[26] Asdrubali F, D'Alessandro F, Schiavoni S. A review of unconventional sustainable building insulation materials. Sustain Mater Technol 2015;4:1–17. [CrossRef]

[27] Luamkanchanaphan T, Chotikaprakhan S, Jarusombati S. A study of physical, mechanical, and thermal properties for thermal insulation from narrow-leaved cattail fibers. APCBEE Procedia 2012;1:46–52. [CrossRef]

[28] Korjenic A, Zach J, Hroudová J. The use of insulating materials based on natural fibers in combination with plant facades in building constructions. Energy Build 2016;116:45–58. [CrossRef]

[29] Dweib MA, Hu B, O'Donnell A, Shenton HW, Wool RP. All-natural composite sandwich beams for structural applications. Compos Struct 2004;63:147–157. [CrossRef]

[30] Alms JB, Yonko PJ, McDowell RC, Advani SG. Design and development of an I-beam from natural composites. J Biobased Mater Bioenergy 2009;3:181–187. [CrossRef]

[31] Merta I, Tschegg EK. Fracture energy of natural fibre reinforced concrete. Constr Build Mater 2013;40:991–997. [CrossRef]

[32] Asasutjarit C, Charoenvai S, Hirunlabh J, Khedari J. Materials and mechanical properties of pretreated coir-based green composites. Compos Part B Eng 2009;40:633–637. [CrossRef]

[33] Rwahwire S, Musinguzi WB. Impact resistance and shore hardness of barkcloth reinforced epoxy composites for interior automotive panels. Mater Sci Forum 2019;951:9–13. [CrossRef]

[34] Rwawiire S, Luggya GW, Tomkova B. Morphology, thermal, and mechanical characterization of bark cloth from Ficus natalensis. Int Scholarly Res Notices 2013;2013:925198. [CrossRef]

[35] Rwawiire S, Tomkova B. Comparative evaluation of thermal conductivity of bark cloth epoxy composites. In: Proceedings of the Fiber Society Conference, Liberec 2014;21.

[36] Rwawiire S, Tomkova B. Thermal, static, and dynamic mechanical properties of bark cloth (Ficus brachypoda) laminar epoxy composites. Polym Compos 2017;38:199–204. [CrossRef]
[37] Rwawiire S, Tomkova B, Gliscinska E, Krucinska I, Michalak M, Militky J, et al. Investigation of sound absorption properties of bark cloth nonwoven fabric and composites. Autex Res J 2015;15:173–180. [CrossRef]
[38] Rwawiire S, Tomkova B, Wiener J, Militky J, Kasedde A, Kale BM, et al. Short-term creep of barkcloth reinforced laminar epoxy composites. Compos Part B Eng 2016;103:131–138. [CrossRef]
[39] Rwawiire S, Tomkova B. Static and dynamic mechanical properties of barkcloth (Ficus natalensis)-reinforced epoxy composite. J Nat Fibers 2016;13:137–145. [CrossRef]
[40] Rwawiire S, Tomkova B, Militky J, Hes L, Kale BM. Acoustic and thermal properties of a cellulose nonwoven natural fabric (barkcloth). Appl Acoust 2017;116:177–183. [CrossRef]
[41] Sarker F, Potluri P, Afroj S, Koncherry V, Novoselov KS, Karim N. Ultrahigh performance of nanoengineered graphene-based natural jute fiber composites. ACS Appl Mater Interfaces 2019;11:21166–21176. [CrossRef]
[42] Prasob PA, Sasikumar M. Viscoelastic and mechanical behaviour of reduced graphene oxide and zirconium dioxide filled jute/epoxy composites at different temperature conditions. Mater Today Commun 2019;19:252–261. [CrossRef]
[43] Amirabadi-Zadeh M, Khosravi H, Tohidlou E. Preparation of silica-decorated graphene oxide nanohybrid system as a highly efficient reinforcement for woven jute fabric reinforced epoxy composites. J Appl Polym Sci 2021;138:49653. [CrossRef]
[44] Sarker F, Karim N, Afroj S, Koncherry V, Novoselov KS, Potluri P. High-performance graphene-based natural fiber composites. ACS Appl Mater Interfaces 2018;10:34502–34512. [CrossRef]
[45] Karim N, Sarker F, Afroj S, Zhang M, Potluri P, Novoselov KS. Sustainable and multifunctional composites of graphene-based natural jute fibers. Adv Sustain Syst 2021;5:2000228. [CrossRef]
[46] Chen Y, Chen W, Liang W, Wang Q, Zhang Y, Wang J, et al. Graphene oxide nanoplatelets grafted jute fibers reinforced PP composites. Fibers Polym 2020;21:2896–2906. [CrossRef]
[47] Da Luz FS, Garcia Filho FDC, Del-Rio MTG, Nascimento LFC, Pinheiro WA, Monteiro SN. Graphene-incorporated natural fiber polymer composites: A first overview. Polymers 2020;12:1601. [CrossRef]
[48] Sridharan V, Raja T, Muthukrishnan N. Study of the effect of matrix, fibre treatment, and graphene on delamination by drilling jute/epoxy nanohybrid composite. Arab J Sci Eng 2016;41:1883–1894. [CrossRef]
[49] Khalid MY, Nasir MA, Ali A, Al Rashid A, Khan MR. Experimental and numerical characterization of tensile property of jute/carbon fabric reinforced epoxy hybrid composites. SN Appl Sci 2020;2:577. [CrossRef]
[50] Premalatha N, Saravanakumar SS, Sanjay MR, Siengchin S, Khan A. Structural and thermal properties of chemically modified Luffa cylindrica fibers. J Nat Fibers 2021;18:1037–1043. [CrossRef]
[51] Mohanta N, Acharya SK. Mechanical and tribological performance of Luffa cylindrica fibre-reinforced epoxy composite. BioResources 2015;10:8364–8377. [CrossRef]
[52] Boynard CA, d'Almeida JRM. Morphological characterization and mechanical behavior of sponge gourd (Luffa cylindrica)–polyester composite materials. Polym Plast Technol Eng 2000;39:489–499. [CrossRef]
[53] Boynard CA, Monteiro SN, d'Almeida JRM. Aspects of alkali treatment of sponge gourd (Luffa cylindrica) fibers on the flexural properties of polyester matrix composites. J Appl Polym Sci 2003;87:1927–1932. [CrossRef]
[54] Jia Y, Fiedler B. Influence of furfuryl alcohol fiber pre-treatment on the moisture absorption and mechanical properties of flax fiber composites. Fibers 2018;6:59. [CrossRef]
[55] Slamani M, Karabibene N, Chatelain JF, Beauchamp Y. Edge trimming of flax fibers and glass fibers reinforced polymers composite–An experimental comparative evaluation. Int J Mater Form 2021;14:1497–1510. [CrossRef]
[56] Habibi M, Selmi S, Laperrière L, Mahi H, Kelouwani S. Post-impact compression behavior of natural flax fiber composites. J Nat Fibers 2020;17:1683–1691. [CrossRef]
[57] Airinei A, Asandulesa M, Stelescu MD, Tudorachi N, Fifere N, Bele A, et al. Dielectric, thermal, and water absorption properties of some EPDM/flax fiber composites. Polymers 2021;13:2555. [CrossRef]
[58] Karsli NG, Aytac A. Properties of alkali-treated short flax fiber reinforced poly(lactic acid)/polycarbonate composites. Fibers Polym 2014;15:2607–2612. [CrossRef]
[59] Chegdani F, El Mansori M, Bukkapatnam ST, El Amri I. Thermal effect on the tribo-mechanical behavior of natural fiber composites at micro-scale. Tribol Int 2020;149:105831. [CrossRef]
[60] Kumar SV, Kumar KS, Jailani HS, Rajamurugan G. Mechanical, DMA, and sound acoustic behaviour of flax woven fabric reinforced epoxy composites. Mater Res Express 2020;7:085302. [CrossRef]
[61] Azwa ZN, Yousif BF, Manalo AC, Karunasena W. A review on the degradability of polymeric composites based on natural fibres. Mater Des 2013;47:424–442. [CrossRef]

[62] Elsaid A, Dawood M, Seracino R, Bobko C. Mechanical properties of kenaf fiber reinforced concrete. Constr Build Mater 2011;25:1991−2001. [CrossRef]

[63] Zhao K, Xue S, Zhang P, Tian Y, Li P. Application of natural plant fibers in cement-based composites and the influence on mechanical properties and mass transport. Materials 2019;12:3498. [CrossRef]

[64] Dávila-Pompermayer R, Lopez-Yepez LG, Valdez-Tamez P, Juárez CA, Durán-Herrera A. Lechugilla natural fiber as internal curing agent in self-compacting concrete (SCC): Mechanical properties, shrinkage, and durability. Cem Concr Compos 2020;112:103686. [CrossRef]

[65] Balasubramanian JC, Selvan SS. Experimental investigation of natural fiber reinforced concrete in the construction industry. Int Res J Eng Technol 2015;2:179−182.

[66] Castillo-Lara JF, Flores-Johnson EA, Valadez-Gonzalez A, Herrera-Franco PJ, Carrillo JG, Gonzalez-Chi PI, et al. Mechanical properties of natural fiber reinforced foamed concrete. Materials 2020;13:3060. [CrossRef]

[67] Siddique R. Properties of concrete incorporating high volumes of class F fly ash and san fibers. Cem Concr Res 2004;34:37−42. [CrossRef]

[68] Reis JML, Ferreira AJM. The influence of notch depth on the fracture mechanics properties of polymer concrete. Int J Fract 2003;124:33−42. [CrossRef]

[69] Savastano Jr H, Warden PG, Coutts RSP. Microstructure and mechanical properties of waste fibre–cement composites. Cem Concr Compos 2005;27:583−592. [CrossRef]

[70] Srivastava V, Mehta PK, Nath S. Natural fiber in cement and concrete matrices—A review. J Environ Nanotechnol 2013;2:63−66. [CrossRef]

[71] Brose A, Kongoletos J, Glicksman L. Coconut fiber cement panels as wall insulation and structural diaphragm. Front Energy Res 2019;7:9. [CrossRef]

[72] Vijay R, Singaravelu DL, Vinod A, Paul Raj IDF, Sanjay MR, Siengchin S. Characterization of novel natural fiber from Saccharum bengalense grass (Sarkanda). J Nat Fibers 2019;17:1739−1747. [CrossRef]

[73] Fajardo Cabrera de Lima LDP, Santana RMC, Chamorro Rodríguez CD. Influence of coupling agent in mechanical, physical, and thermal properties of polypropylene/bamboo fiber composites: Under natural outdoor aging. Polymers 2020;12:929. [CrossRef]

[74] Inácio AL, Nonato RC, Bonse BC. Mechanical and thermal behavior of aged composites of recycled PP/EPDM/talc reinforced with bamboo fiber. Polym Test 2018;72:357−363. [CrossRef]

[75] Yorseng K, Rangappa SM, Pulikkalparambil H, Siengchin S, Parameswaranpillai J. Accelerated weathering studies of kenaf/sisal fiber fabric reinforced fully biobased hybrid bioepoxy composites for semi-structural applications: Morphology, thermo-mechanical, water absorption behavior, and surface hydrophobicity. Constr Build Mater 2020;235:117464. [CrossRef]

[76] Wang KF, Wang BL. A mechanical degradation model for bidirectional natural fiber reinforced composites under hydrothermal ageing and applying in buckling and vibration analysis. Compos Struct 2018;206:594−600. [CrossRef]

[77] Bazan P, Mierzwiński D, Bogucki R, Kuciel S. Bio-based polyethylene composites with natural fiber: Mechanical, thermal, and ageing properties. Materials 2020;13:2595. [CrossRef]

[78] Senthilrajan S, Venkateshwaran N. Ageing and its influence on vibration characteristics of jute/polyester composites. J Polym Environ 2019;27:2144−2155. [CrossRef]

[79] Yallew TB, Aregawi S, Kumar P, Singh I. Response of natural fiber reinforced polymer composites when subjected to various environments. Int J Plast Technol 2018;22:56−72. [CrossRef]

[80] Jain D, Sekhon H, Bera TK, Jain R. Comparison of different hydrophobic treatments for the durability improvement of palmyra natural fiber composites under hydrothermal ageing environments. J Nat Fibers 2020;17:1668−1682. [CrossRef]

[81] De Andrade Silva F, Toledo Filho RD, de Almeida Melo Filho J, Fairbairn EDMR. Physical and mechanical properties of durable sisal fiber–cement composites. Constr Build Mater 2010;24:777−785. [CrossRef]

[82] Mohanty AK, Misra M, Drzal LT, eds. Natural fibers, biopolymers, and biocomposites. FL: CRC Press; 2005. [CrossRef]

[83] Soatthiyanon N, Aumnate C, Srikulkit K. Rheological, tensile, and thermal properties of poly(butylene succinate) composites filled with two types of cellulose (kenaf cellulose fiber and commercial cellulose). Polym Compos 2020;41:2777−2791. [CrossRef]

[84] Feng NL, Malingam SD, Ping CW, Razali N. Mechanical properties and water absorption of kenaf/pineapple leaf fiber-reinforced polypropylene hybrid composites. Polym Compos 2020;41:1255−1264. [CrossRef]

[85] Rahman MR, Hamdan S, Jayamani E, Kakar A, Bakri MKB, Yusof FABM. Tert-butyl catechol/alkaline-treated kenaf/jute polyethylene hybrid composites: Impact on physico-mechanical, thermal and morphological properties. Polym Bull 2019;76:763−784. [CrossRef]

[86] Manral A, Bajpai PK. Static and dynamic mechanical analysis of geometrically different kenaf/PLA green composite laminates. Polym Compos 2020;41:691−706. [CrossRef]

[87] Ismail AS, Jawaid M, Naveen J. Void content, tensile, vibration and acoustic properties of kenaf/bamboo fiber reinforced epoxy hybrid composites. Materials 2019;12:2094. [CrossRef]
[88] Park JW, Shin JH, Shim GS, Sim KB, Jang SW, Kim HJ. Mechanical strength enhancement of polylactic acid hybrid composites. Polymers 2019;11:349. [CrossRef]
[89] Ariawan D, Salim MS, Mat Taib R, Ahmad Thirmizir MZ, Mohammad Ishak ZA. Durability of alkali and heat-treated kenaf fiber/unsaturated polyester composite fabricated by resin transfer molding under natural weathering exposure. Adv Polym Technol 2018;37:1420–1434. [CrossRef]
[90] Hanan F, Jawaid M, Md Tahir P. Mechanical performance of oil palm/kenaf fiber-reinforced epoxy-based bilayer hybrid composites. J Nat Fibers 2018;17:155–167. [CrossRef]
[91] Nampoothiri EN, Bensam Raj J, Thanigaivelan R, Karuppasamy R. Experimental investigation on mechanical and biodegradation properties of Indian almond–kenaf fiber-reinforced hybrid composites for construction applications. J Nat Fibers 2022;19:292–302. [CrossRef]
[92] Fairuz AM, Sapuan SM, Zainudin ES, Jaafar CNA. The effect of pulling speed on mechanical properties of pultruded kenaf fiber reinforced vinyl ester composites. J Vinyl Addit Technol 2018;24:E13–E20. [CrossRef]
[93] Parthipan N, Ilangkumaran M, Maridurai T, Prasanna SC. Effect of silane treated silicon (IV) oxide nanoparticle addition on mechanical, impact damage and drilling characteristics of kenaf fibre-reinforced epoxy composite. Silicon 2020;12:459–467. [CrossRef]
[94] Zahidah KA, Yuanita E, Kustiyah E, Chalid M. Tensile properties of kenaf fiber by alkalinization treatment: Effect of different concentration. IOP Conf Ser Mater Sci Eng 2019;703:012030. [CrossRef]
[95] Noor Azammi AM, Sapuan SM, Ishak MR, Sultan MTH. Physical and damping properties of kenaf fibre filled natural rubber/thermoplastic polyurethane composites. Def Technol 2020;16:29–34. [CrossRef]
[96] Dashtizadeh Z, Abdan K, Jawaid M, Dashtizadeh M. Thermal and flammability properties of kenaf/recycled carbon filled with cardanol hybrid composites. Int J Polym Sci 2019;2019:9168342. [CrossRef]
[97] Saba N, Jawaid M, Alrashed MM, Alothman OY. Oil palm waste based hybrid nanocomposites: Fire performance and structural analysis. J Build Eng 2019;25:100829. [CrossRef]
[98] Taban E, Soltani P, Berardi U, Putra A, Mousavi SM, Faridan M, et al. Measurement, modeling, and optimization of sound absorption performance of kenaf fibers for building applications. Build Environ 2020;180:107087. [CrossRef]
[99] Lim ZY, Putra A, Nor MJM, Yaakob MY. Sound absorption performance of natural kenaf fibres. Appl Acoust 2018;130:107–114. [CrossRef]
[100] Taban E, Valipour F, Abdi DD, Amininasab S. Mathematical and experimental investigation of sound absorption behavior of sustainable kenaf fiber at low frequency. Int J Environ Sci Technol 2021;18:2765–2780. [CrossRef]
[101] Hao A, Zhao H, Chen JY. Kenaf/polypropylene nonwoven composites: The influence of manufacturing conditions on mechanical, thermal, and acoustical performance. Compos Part B Eng 2013;54:44–51. [CrossRef]
[102] Maskell D, Thomson A, Walker P. Multi-criteria selection of building materials. Proc Inst Civil Eng Constr Mater 2018;171:49–58. [CrossRef]