Journal of Materials Research and Technology 32 (2024) 4304–4315

Contents lists available at ScienceDirect

Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

# Enhancing mechanical performance and water resistance of Careya-Banana fiber epoxy hybrid composites through PLA coating and alkali treatment

H. Jeevan Rao[a,***], S. Singh[a], Narender Singh[a], P. Janaki Ramulu[b], Thiago F. Santos[c], Caroliny M. Santos[c], P. Senthamaraikannan[d], Indran Suyambulingam[f], Femiana Gapsari[e,*], Rudianto Raharjo[e], Sanjay Mavinkere Rangappa[g,**], Suchart Siengchin[g]

[a] Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, 201313, India
[b] Department of Mechanical Engineering, School of Mechanical, Chemical and Materials Engineering, ASTU, Adama, Ethiopia
[c] Postgraduate Program in Chemical Engineering, Technology Center, Federal University of Rio Grande do Norte, Av. Prof. Sen. Salgado Filho, 3000, Natal, Rio Grande do Norte, 59072-970, Brazil
[d] Department of Mechanical Engineering, K.S.R College of Engineering, KSR Kalvi Nagar, Tiruchengode, Tamil Nadu, India
[e] Mechanical Engineering Department, Faculty of Engineering, Brawijaya University, MT, Haryono 167, Malang, 65145, Indonesia
[f] Sophisticated Testing and Instrumentation Centre (STIC), Department of Mechanical Engineering, Alliance School of Applied Engineering, Alliance University, Bengaluru - 562106, Karnataka, India
[g] Natural Composites Research Group Lab, Department of Materials and Production Engineering, The Sirindhorn International Thai-German School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok, Thailand

ARTICLE INFO

Handling Editor: SN Monteiro

*Keywords:*
Natural fiber composites
NaOH treatment
*Careya arborea* fiber
banana fiber
Hybrid composites

ABSTRACT

The ongoing research focuses on exploring the potential of *Careya arborea* (CA) fiber, banana fiber (BF), and epoxy composites as sustainable alternatives to petroleum-based products and synthetic fibers. The aim is to enhance the interfacial bonding and overall performance of these composites while reducing reliance on traditional materials. The study investigates the adhesion between CA fiber, BF (both chemically treated), and epoxy with polylactic acid (PLA) coating. Specifically, it examined how the PLA coating affects the mechanical properties, including tensile strength, flexural strength, impact resistance, and water absorption behavior, of the fabricated composites. Mechanical characterizations of the composite specimens are conducted following ASTM standards. The PLA-coated and NaOH-treated specimens significantly improved their tensile strength (20.56%) and flexural strength (16.7%), and significantly reduced their water absorption capacity (by 47.6%) compared to the untreated ones. These findings highlight the promise of using treated natural fibers and PLA coatings to create more sustainable and high-performance composite materials.

## 1. Introduction

The growing concern over the environmental impact of petroleum-based products and synthetic fibers has fuelled extensive research into alternative materials that are sustainable, eco-friendly, and capable of matching or even surpassing the performance of their conventional counterparts. Therefore, the quest for sustainable and environmentally friendly materials has driven extensive research into developing alternative substitutes for petroleum-based products and synthetic fibers. One of the promising avenues in this endeavour is the utilization of natural fibers in composite materials.

The historical roots of incorporating natural fibers as reinforcement in composite materials stretch back to ancient civilizations, which utilized plant fibers for this purpose. Today, natural fiber composites have emerged as an environmentally friendly substitute for composites reinforced with glass or carbon fibers. By leveraging natural fibers as reinforcement, these materials not only address waste disposal issues but also play a role in minimizing environmental pollution [1,2]. Natural fibers, particularly in the context of sustainable materials, have gained prominence as a widely adopted technology with numerous

---

[*] Corresponding author.
[**] Corresponding author.
[***] Corresponding author.

*E-mail addresses:* iprhjeevanrao@gmail.com (H.J. Rao), memi_kencrut@ub.ac.id (F. Gapsari), mcemrs@gmail.com (S. Mavinkere Rangappa).

https://doi.org/10.1016/j.jmrt.2024.08.190
Received 25 March 2024; Received in revised form 24 August 2024; Accepted 29 August 2024

applications. These fibers offer several advantages over traditional glass fibers, making them competitive in contemporary industrial applications. Natural-fiber reinforced composites offer a multitude of benefits compared to their synthetic-fiber reinforced counterparts, including renewability, reduced abrasiveness to equipment, biodegradability, high specific strength, cost-effectiveness, non-corrosive properties, non-hazardous nature, and manufacturing versatility [3,4].In recent decades, there has been a growing societal awareness of environmental concerns. A notable example of this is the United Nations' 2030 Agenda for Sustainable Development, which has garnered the support of more than 190 countries. Within this agenda, specific goals have been set to address environmental issues, including objectives related to recyclable plastics (goal 12) and the reduction of plastic bag usage (goal 14), particularly aimed at preserving the cleanliness of our oceans. To enhance sustainability in the composites industry, it is essential to conduct both foundational and transformative research, with the ultimate goal of creating entirely eco-friendly or "green" composites [5,6]. Moreover, natural fibers are characterized by their user-friendly nature and absence of the toxicity commonly found in mineral reinforcements like glass fibers. Lignocellulosic fibers can be sourced from a variety of origins, including wood, annual plants, agroforestry waste, or as by-products from industrial processes such as textile or paper production [7,8].

In China, a significant portion of the country's bamboo resources is dedicated to the construction of houses, furniture, composite boards, flooring, and various wood-based products [9,10]. The bamboo industry also plays a pivotal role in Bangladesh's economic growth, particularly in terms of harvesting, production, and marketing activities [11]. Meanwhile, in Thailand, extensive oil palm plantations are found in regions like Krabi, Suratthani, Chumphon, and other districts, covering approximately 3250 square kilometers and yielding 700,000 to 800,000 tonnes of raw palm oil annually. The production of palm oil has been steadily increasing due to its cost-effectiveness, driving the expansion of the industry. Additionally, the methods employed in oil palm production include the assessment of palm fruit bunch quality. Notably, about 12% of the oil palm bunch consists of waste oil palm residue, which finds applications in various fields, including fiber manufacturing and fuel production [12].

Germany and many other industrialized and developing nations across the world have embraced the use of natural fiber-reinforced polymer composites made from materials like flax, sisal, hemp, and kenaf in the automotive sector. These composites are employed in a wide array of applications, such as door panels, seat backs, dashboards, package trays, head restraints, and seatback linings [13].

Research by Research by Mautner et al. [14] and Prakoso et al. [15] also demonstrated that natural fibers can be effectively used in composite materials, exhibiting remarkable mechanical properties, environmental benefits, and broad industrial applications. However, the current research extends this groundwork by introducing novel treatment methods to enhance the performance of these composites further. Anguita et al. [16] also reported significant improvements in the tensile strength and water resistance of natural fiber composites through the utilization of similar treatments. The current study focuses on the integration of Careya arborea (CA) fiber and banana fiber (BF) within epoxy composites, with the overarching goal of exploring alternative materials to replace traditional synthetic fibers and petrochemical products. These natural fibers are selected for their potential as eco-friendly, renewable resources that can serve as reinforcements in composite materials [17,18].

This research investigates the interfacial bonding and overall performance of composites made from chemically treated CA fiber and BF combined with epoxy resin. The study explores how polylactic acid (PLA) coating and NaOH treatment enhance the mechanical properties—tensile strength, flexural strength, impact resistance, and water absorption—of these composites. Four configurations are tested: untreated, PLA-coated, NaOH-treated, and both PLA-coated and NaOH-treated. Results, based on ASTM standard tests [19], show significant improvements in mechanical properties and reduced water absorption, highlighting the potential for developing sustainable, high-performance composite materials. These findings offer eco-friendly alternatives to traditional petrochemical products and synthetic fibers, with broad industrial applications.

## 2. Materials and methods

### 2.1. Materials

The current work uses epoxy composites made by hand layup process in combination with CA fiber extracted in our lab and BF fiber procured from Renus Jute Creations - Hyderabad, Telangana. India. The deciduous Careya arborea tree can reach a height of 10–15 m and bears pale yellow blooms with a hint of scarlet. The CA fiber, which has a lower cost of fiber, was taken from the CA tree's bark. BF production 1.8 million tons for the fiber India. There are many different uses for BF in the construction, aerospace, marine, textile, and automotive industries [17] CA fibers and BF were chopped in accordance with the mold's measurements. Alide Engineering Services supplies the matrix material in the form of epoxy resin (Araldite LY-556) and the matching hardener (Araldite HY-951). Density = 1.16 g/cm$^3$, tensile strength = 85–95 MPa, tensile modulus = 35–38 GPa, and viscosity = 10000–12000 MPa s are the characteristics of matrix material epoxy. Vruksha Composites supplied woven BF. Tensile strength = 120 MPa, tensile modulus = 69 MPa, density = 1.3 kg/cm$^3$, and elongation = 1.7% are the characteristics of BF.

#### 2.1.1. Alkaline treatment on fiber

In this work, 6% NaOH is applied to woven BF and CA fiber. At room temperature (RT), BF was immersed in the alkaline solution for 4 h. The BF was then taken out of the solution and washed several times with floating water before being submerged in the HCl solution to get rid of the NaOH adhesive. Fiber rinsed with water once more and dried in sunlight for 36 h and removed moisture from the fiber using oven set at 60 °C. The reaction in fiber during alkali treatment based on

$$(\text{Fiber} - \text{OH} + \text{NaOH}) \rightarrow (\text{Fiber} - \text{O}{-}\text{Na}+ + \text{H}_2\text{O}) \tag{1}$$

#### 2.1.2. PLA coating on fiber

PLA pellets were initially submerged in the chloroform solution for 6 h. After that, the mixture was manually agitated and heated to 60 °C to ensure that the PLA was evenly distributed throughout the chloroform solution. Weaved BF were soaked in PLA solvent and allowed to soak for 6 min before being removed. In the end, coated fibers were dried for 36 h at ambient temperature and for 3 h in a hot air oven at 60 °C. PLA's mechanical and physical characteristics are displayed in Table 1.

#### 2.1.3. Fabrication of composite laminates

The BF and CA fiber epoxy composite was created using a mild steel mold that measured 300 mm by 300 mm and had a 6 mm thickness. Because of its flexibility, the hand lay-up process is utilized to fabricate

**Table 1**
Physical & Mechanical attributes of PLA.

| Properties | PLA Values | CA fiber | BF |
|---|---|---|---|
| Tensile strength (MPa) | 21–60 | 48.29 | 430 |
| Density (g/cm$^3$) | 1.21–1.25 | 1140 kg/m$^3$ | 0.95 |
| Tensile modulus | 27–16 | – | – |
| Melting temperature (°C) | 173–178 | 248 | 120 |
| Glass Transition Temperature (°C) | 45–60 | – | – |
| Impact strength (J/m$^2$) | 13 | 27.89 | – |
| Youngs modulus (GPa) | 0.35–35 | 8–21.6 | 23 |

hybrid composite laminates. BF layers are cut and marked in accordance with the measurements of the mold. The amount of resin is determined by taking the fabric's GSM into consideration. With the aid of a vertical stirrer, the low temperature curing epoxy resin LY-556 and the hardener HY-951 are added to the epoxy resin at a weight ratio of 10:1 and completely mixed. The weight of CA fiber is kept constant at 40%. Table 2 displays the composite laminates with the names CA1+BA1, CA2+BA2, CA3+BA3, and CA4+BA4, which are composed of varying amounts of untreated, coated, treated, and treated & coated material. Ultimately, the laminates are sliced using a hack saw to create test specimens that meet ASTM requirements for testing and characterization [19]. The investigation involved monitoring the water absorption percentage of all hybrid composites at specified time intervals: 10, 20, 30, 40, 50, and 60 days. After fabrication of the composites there were few defected observations made that portions voids, resin rich zones, misalignments of fiber, and poor wettability of the fiber and matrix.

Fig. 1 illustrates the surface alteration of BF both before and after treatment.

### 2.2. Methods

#### 2.2.1. Tensile test

The ASTM D-3039 standard [19] is followed while testing the tensile strength of prepared hybrid composite specimens. The specimens are rectangular in shape and measure 250 x 25 × 4 mm. Three distinct specimens are subjected to a tensile test: untreated, PLA coated, NaoH treated, and PLA coated and NaOH treated. The specimen was subjected to a load at RT during the test until it broke. The stress-strain curve that is created is used to calculate tensile strength.

#### 2.2.2. Flexural test

Both the tensile and the flexural tests were carried out at RT using UTM (Biss, Nano plug and play Servo hydraulic machine, 100 Tonne) in accordance with ASTM D-790 [20]. The specimen, measuring 165 × 20 × 3 mm was subjected to a flexural test at a crosshead speed of 1 mm/min. Five specimens of each composite were tested, and the average values of tensile strength and tensile modulus, along with their standard deviations, were reported.

#### 2.2.3. Impact test

The Izod impact test was conducted on the notched specimens in accordance with ASTM D256 using a digital impact testing machine (Presto Izod/Charpy Impact testing machine) [21]. For this test, specimens with measurements of 65 × 13 × 3 mm and a 2.5 mm notch thickness were created. Five specimens of each composite composition were tested, and the average values of the impact strength and energy, along with their standard deviations, were reported.

#### 2.2.4. Water absorption test

In this work, a water absorption test is used to evaluate the proportion of water absorbed by the CA fiber/BF reinforced epoxy hybrid composite constructions. The water absorption test is conducted with salt-free RT water. The test specimens are prepared in accordance with ASTM D-570 [22] requirements for water absorption. The specimen used for the water absorption test has the following measurements: 30 × 30 × 4 mm. The specimen's initial weight is determined prior to the water absorption test.

**Table 2**
Nomenclature of composites.

| Composites | BF (wt)% | CA fiber (wt) % | Alkaline treatment (wt) % | PLA coating (wt) % |
|---|---|---|---|---|
| CA1+BF1 | 60% | 40% | – | – |
| CA2+BF2 | 60% | 40% | – | 4% |
| CA3+BF3 | 60% | 40% | 6% | – |
| CA4+BF4 | 60% | 40% | 6% | 4% |

## 3. Results and discussion

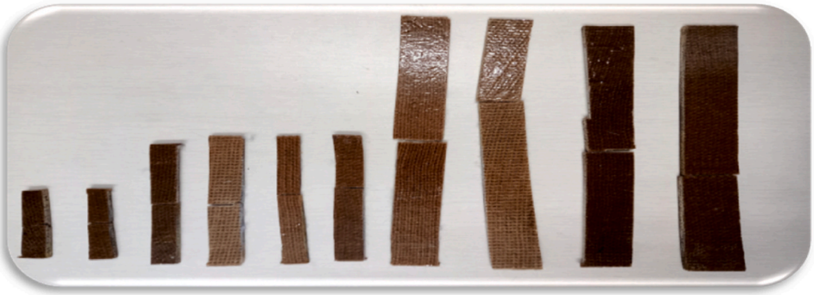
Scanning electron microscopy (SEM) is undoubtedly an excellent way to observe the surface of fibers and interfacial adhesion between fiber-matrix. Fig. 2 exhibited SEM images of untreated CA fiber/BF epoxy hybrid composites, which showed pits on break surface of a composite (CA1+BF1) could indicate areas where the material fractured or experienced some form of mechanical damage. Pits might result from the separation of fibers from the matrix causing localized stress concentrations. The untreated CA fiber/BF epoxy hybrid composites exhibited fiber break surface refers to the cross-section of the individual fibers within the composite material [1,23]. Examining this surface provided insights into the fiber's mechanical properties and how it interacts with the matrix. The presence of irregularities or features on the fiber break surface might indicate variations in fiber properties or potential mechanical damage. The hybrid composites CA1+BF1 presented rupture surface refers to the area where the composite material has fractured or broken. This can include both the epoxy and the CA fiber/BF. Analyzing the rupture surface can help determine the mode of failure (e.g., fiber pull-out, matrix cracking, interfacial debonding) and provide insights into the overall hybrid composite's mechanical behavior. Examining the bonding interface in SEM images of CA1+BF1 revealed the low quality of the bond, the presence of voids, and the potential for fiber-matrix debonding. As shown in Fig. 2a, the bonding between untreated CA fiber/BF and the epoxy matrix is weak, and the fiber of the cross-section of the composites is pulled out. The poor adhesion between untreated CA fiber/BF (Fig. 2b and 2c) and epoxy matrix always leads to poor mechanical performance, Fig. 2d shows that there was no proper resin distribution through the fiber surface, this would impact on interfacial bonding of the composites, fibers would break due to impact loading and delamination may occurs.

Recently, polymer coating on natural fibers has been the most proficient way for enhancing the compatibility with the polymer matrix. The polymer coating on natural fibers makes them more hydrophobic, stiff, and strong [3,6]. Polymer coating offers a better interfacial bonding and acts as a protective layer which opposes moisture absorption [5,7]. Several scientists have made efforts to apply a polymer coating onto cellulosic fibers, aiming to enhance their hydrophobic properties. This, in turn, leads to an improvement in the bonding at the interface, consequently reducing the water absorption tendencies of cellulosic fiber-reinforced polymer composites (CFPCs) [9,20]. Fig. 3a, b, and 3c show the SEM micrographs of the fracture surfaces of PLA-coated CA fiber/BF epoxy hybrid composites subjected to a tensile load. In the case of PLA-coated CA fiber/BF epoxy hybrid composites, breakages of fiber and fiber-matrix debonding were noticeable owing to good fiber matrix compatibility, observed as in Fig. 3a and b. From Fig. 3b and 3c the breakages, and pores inside the fiber of polymer matrix was not observed in PLA-coated (CA2+BF2), and NaOH-treated + PLA-coated CA fiber/BF epoxy hybrid composites (CA4+BF4), which shows less swelling of CA fiber/BF in these epoxy hybrid composites. Fractured surface of PLA-coated CA fiber/BF epoxy hybrid composites (CA2+BF2) indicates superior bonding between fiber and matrix as a response of the PLA coating (Fig. 3d) compared to untreated CA fiber/BF epoxy hybrid composites (CA1+BF1). The polymer coating of CA fiber/BF with PLA, has led to notable alterations in their surface characteristics, particularly in terms of porosity inside the fibers, and the occurrence of breakages of fibers on smooth surfaces showed in Fig. 3.

These changes are attributed to the polymer coating and induced fiber-matrix chemical bonding by PLA coating. These alterations in surface characteristics of CA fiber/BF could result in visible changes to the fiber's surface texture, potentially affecting its overall appearance and properties. Therefore, the uniform characteristics of surface was observed on the polymer coating of CA fiber/BF with PLA, suggests a more homogenous surface, but PLA-coated CA fiber/BF epoxy hybrid

**CA fiber** **BF** **Epoxy resin and Hardner**

**Male and female Dies** **Fibers and resin dispersion** **Developed composite**



**Sample for various tests**

**Fig. 1.** Surface alteration of BF both before and after treatment.

composites (CA2+BF2), have more implications positives for applications such as hybrid composites.

Fig. 4 illustrates the SEM micrographs that correspond to the NaOH-treated hybrid composites of CA fiber/BF embedded in an epoxy matrix. The visual examination of the micrographs reveals significant improvements in the surface characteristics of the NaOH-treated CA fiber/BF (referred to as CA3+BF3) as shown Fig. 4a. This enhancement can be attributed to the removal of lignin, hemicelluloses, and wax from the fibers' surface through the alkalization process using NaOH. The result of this treatment is evident in the emergence of a rougher surface morphology in the fibers. This heightened roughness is a distinctive trait of the treated CA fiber/BF and signifies the successful elimination of hemicellulose and other extraneous surface impurities. Refer to Fig. 4c for a visual representation of these effects, as observed in the study by Madhu et al. [12]. Additionally, the removal of these surface contaminants from the fibers has a twofold positive impact. Firstly, it promotes an increase in both the mechanical interlocking between the fibers and the epoxy matrix and the ensuing bonding reaction. This mechanical interlocking and improved bonding are advantageous attributes for enhancing the adhesion between the fiber and matrix phases, as depicted in Fig. 4d. This outcome is in line with the findings reported by Mwaikambo and Ansell [13]. Furthermore, the microscopic analysis, as demonstrated in Fig. 4d, indicates a noteworthy transformation in the interfacial interaction between the NaOH-treated CA fiber/BF and the epoxy matrix. The gap that once existed between these elements has been notably reduced, leading to a more intimate and cohesive connection between the fibers and the matrix. This reduction in the gap and the subsequent augmentation of interfacial adhesion signifies an overall improvement in the composite material's structural integrity and mechanical properties [2,21,22]. The SEM micrographs displayed in Fig. 4 provide a comprehensive visual representation of the positive effects of NaOH treatment on the hybrid composites consisting of CA fiber/BF and an epoxy matrix. The alkalization process removes surface impurities, enhances surface roughness, promotes mechanical interlocking, and strengthens the bonding reaction between the fibers and the matrix. These improvements culminate in a more closely integrated interface, contributing to the overall enhancement of the composite material's performance characteristics [24,25]. Fig. 2 indicating the small pits on the surface are associated with defects during fabrication, and the high mount of fiber volume fraction absorbed the maximum amount of matrix, hence the internal layers were not able to be wetted properly, this may lead to create the defects in the samples. Since it is advised to perform the chemical treatment before the preparation of composite, it would minimize the defects in the composite.

In a similar experimental context, researchers delved into the properties of epoxy hybrid composites made CA fiber/BF NaOH-treated + PLA-coated (CA4+BF4). This investigation revealed intriguing characteristics with versatile potential across various industries. The results demonstrated the ability to tailor these properties at different scales, as depicted in Fig. 5a. However, after the CA fiber/BF being NaOH-treated + PLA-coated, a strong bond between the epoxy and the fibers was noticed and the no pits on breaking surface in the CA fiber/BF surface

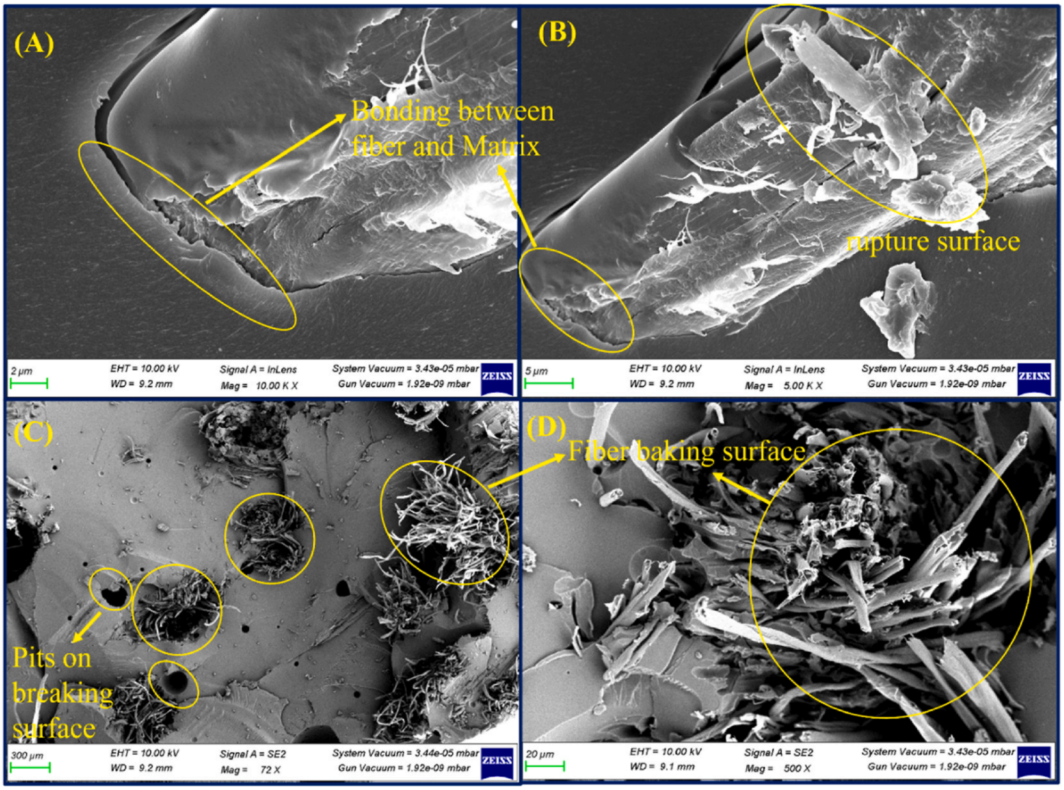


**Fig. 2.** SEM of untreated CA fiber/BF epoxy hybrid composites a) BF bonding with matrix, b) Surface of the BF after breaking, c) CA/BF braking pits, d) Breaking of CA/BF fiber bunches.

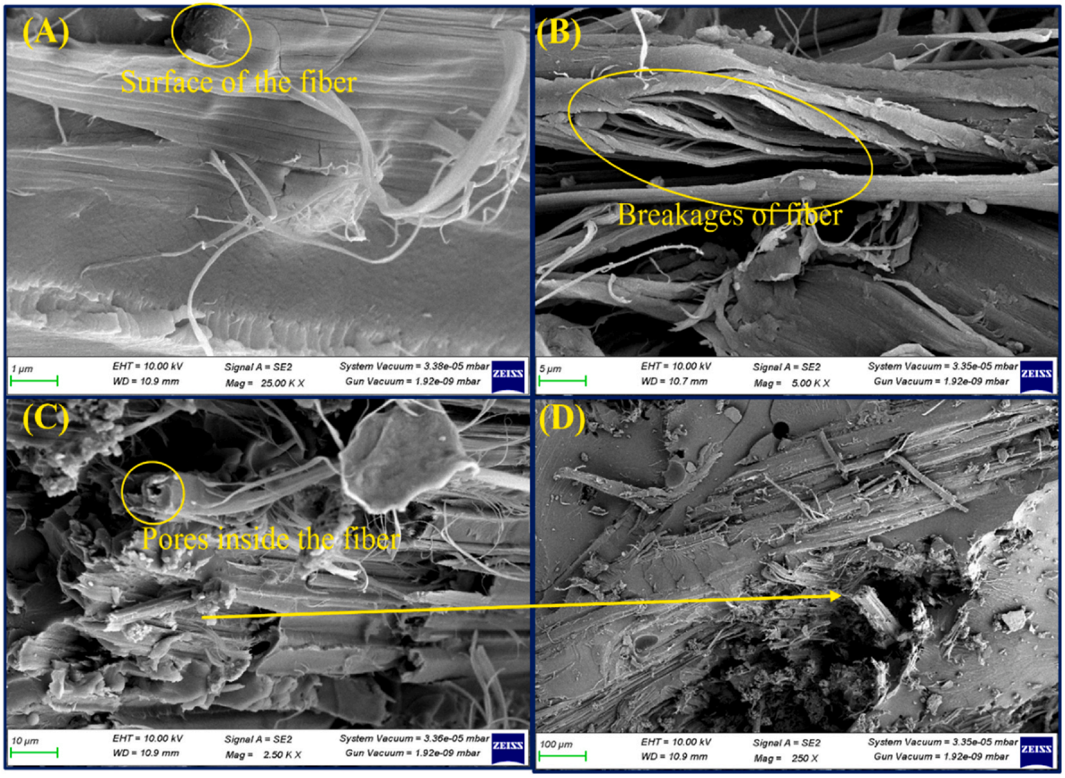


**Fig. 3.** SEM of PLA-coated CA fiber/BF epoxy hybrid composites a) CA fiber surface after debonding, b) Rupture of the fiber, c &d) Damages portion of BF and CA fiber.

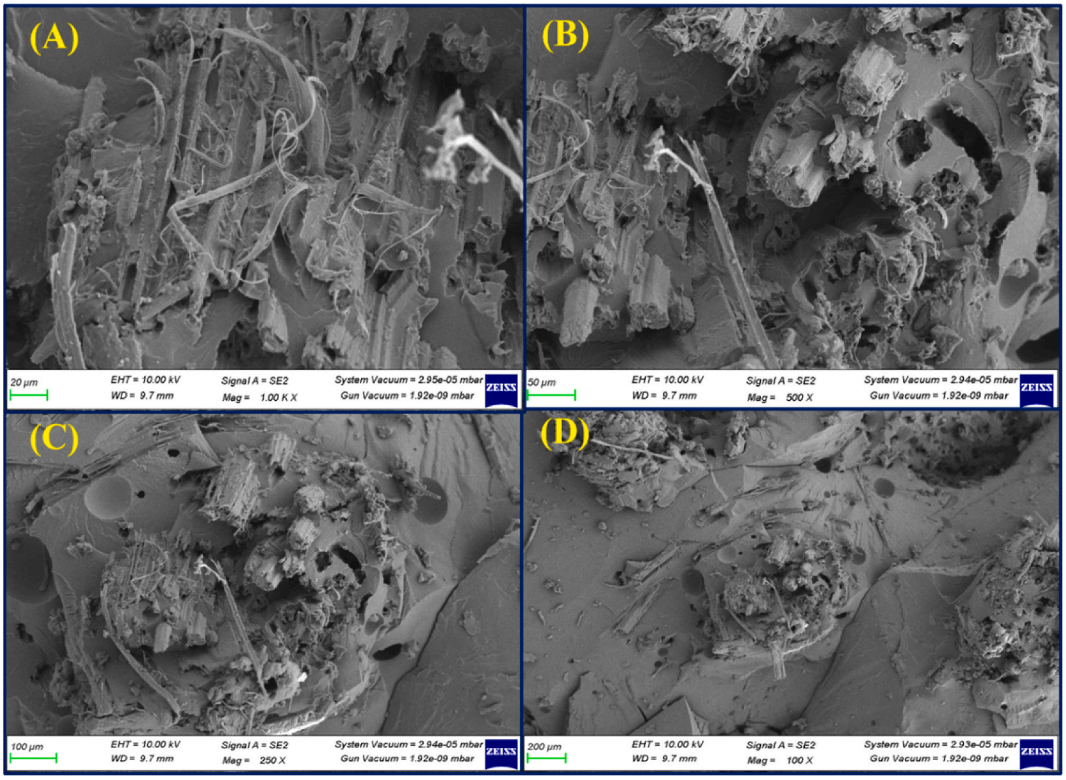


**Fig. 4.** SEM of NaOH-treated CA fiber/BF epoxy hybrid composites a) Pull out portions of the Banana/CA fiber peels, b)Matrix separated portion,c &d) Pores on the matrix with damaged fibers.

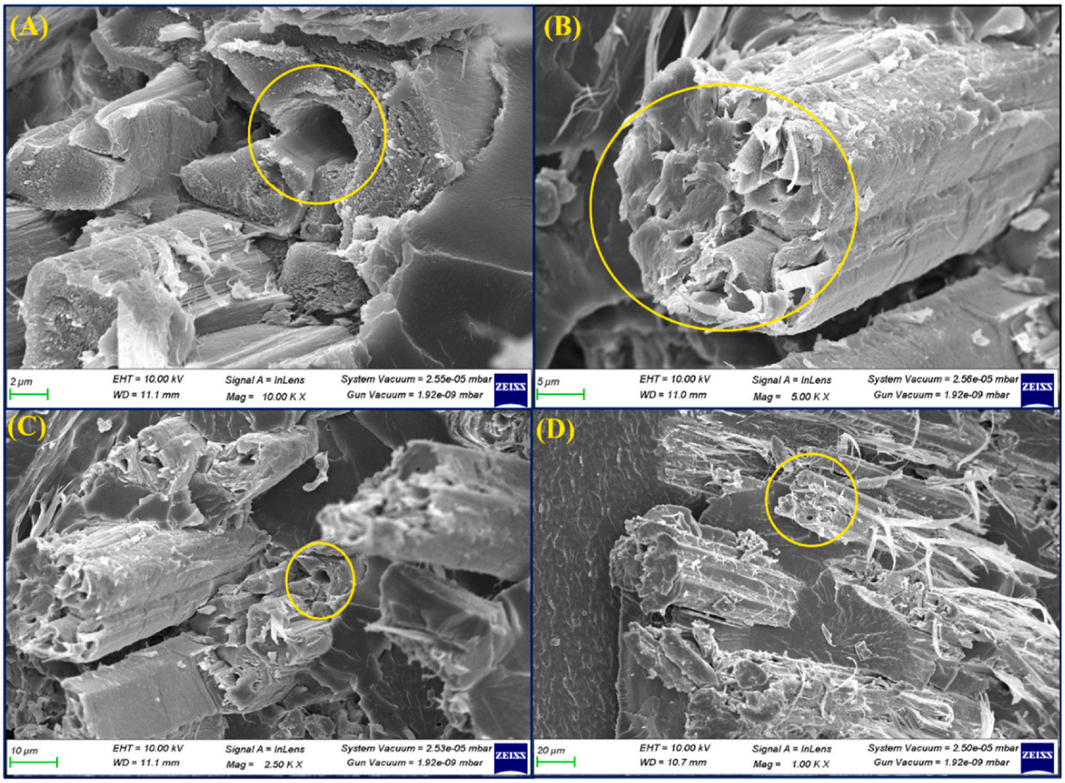


**Fig. 5.** SEM of NaOH-treated + PLA-coated CA fiber-BF epoxy hybrid composites, a) Clear matrix fiber bonding, b) Pores on fiber cross section, c) Uneven fiber breakage. d) Fiber rupture peels.

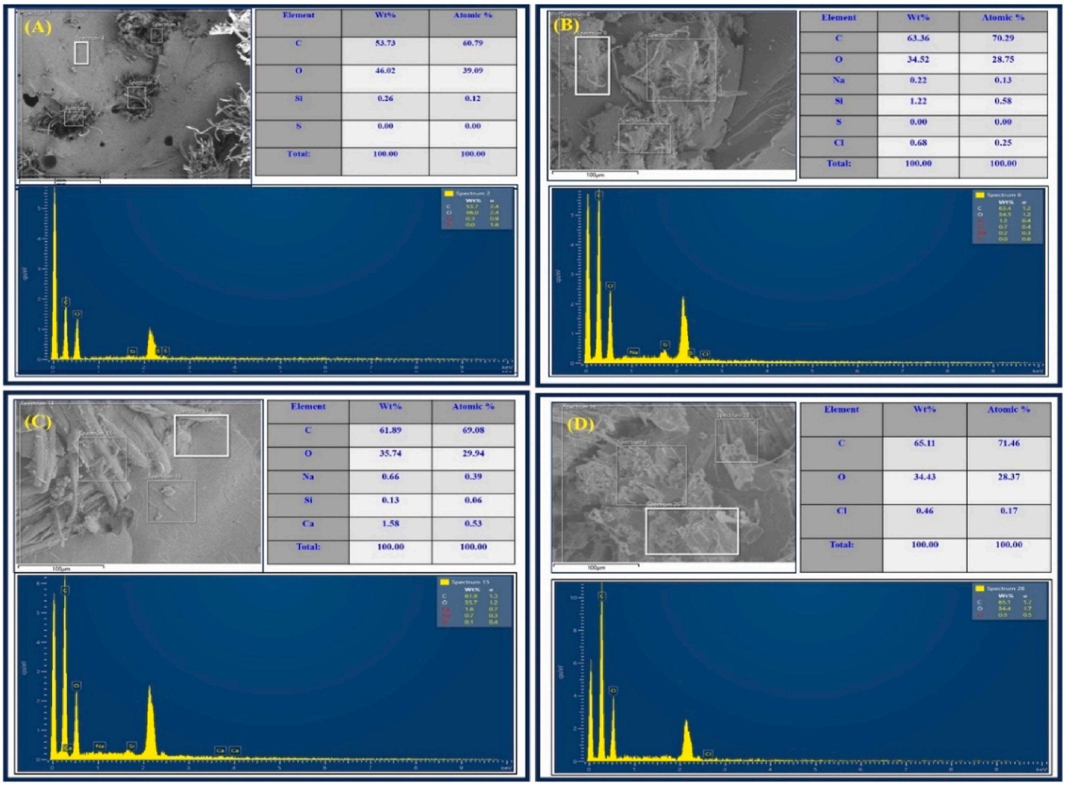
were visible as shown Fig. 5a and b. This substantial improvement in bonding was attributed to the enhanced compatibility between the CA fiber/BF and the epoxy matrix. This compatibility led to the reduction of interfacial tensions, which in turn prevented the detachment of fibers from the matrix during mechanical loading. This phenomenon was well-documented by Sanjay et al. [27]. It's worth noting that a noteworthy contrast emerged when comparing the mechanical properties of the individual CA fiber/BF in the NaOH-treated + PLA-coated scenario with those of CA1+BF1, CA2+BF2, and CA3+BF3. In instances where there was a stronger bonding between the CA fiber/BF and the matrix, as observed in treated-NaOH + coated-PLA, the mechanical characteristics of individual fibers may be compromised shown in Fig. 5d. This phenomenon is highlighted in Fig. 5d, as documented by Hemath et al. [28]. The substantial enhancement in bonding between the CA fiber/BF and the matrix in the treated-NaOH + PLA-coated configuration was primarily attributed to the increased surface roughness of the fibers compared to those in the CA1+BF1, CA2+BF2, and CA3+BF3 configurations. This, in turn, facilitated a superior interaction between the CA fiber/BF and the epoxy matrix, leading to the remarkable mechanical properties observed. Then, the CA fiber/BF turns out to be broken at the cross section without being pulled out, as well as shows that the interfacial adhesion between CA fiber/BF and epoxy matrix has been greatly improved.

The modified CA fiber/BF by NaOH treatment + PLA coating (CA4+BF4) have more positive outcome of this novel approach was seen in form of increased resistance properties (strength, flexural, and stress Vs strain) for epoxy hybrid composites made from CA fiber/BF NaOH-treated + PLA-coated. The lowest resistance properties were offered by untreated and uncoated CA fiber/BF (CA1+BF1), which was lower than those of treated + coated CA fiber/BF hybrid composites (CA4+BF4), PLA-coated CA fiber/BF hybrid composites (CA2+BF2), NaOH-treated CA fiber/BF hybrid composites (CA3+BF3), respectively, as shown in Figs. 10 and 11.

Fig. 6 demonstrates energy dispersive X-ray spectroscopy (EDAX) analysis outcomes for hybrid composites consisting of epoxy and CA fiber/BF in various conditions: untreated, PLA-coated, treated with NaOH, and treated with both PLA and NaOH.

The analysis unveils the presence of diverse chemical elements within these composites, including C, O, Na, Si, S, Cl and Ca. The initial *C* weight percentage in untreated CA fiber/BF is 53.73%, which is comparatively lower than the corresponding percentages in PLA-coated, NaOH-treated, and PLA-coated + NaOH-treated CA fiber/BF, as indicated in Fig. 6. Similarly, the *O* wt.% in untreated CA fiber/BF (CA1+BF1) is 46.02%, also less than that found in PLA-coated, NaOH-treated, and PLA-coated + NaOH-treated CA fiber/BF (CA2+BF2, CA3+BF3, and CA4+BF4). Then, was noted that the application of NaOH treatment significantly increases the *Ca* content to 1.58% and has a pronounced impact on the strain properties of the plant fibers, as previously reported [29]. Table 3 provides a comprehensive presentation of quantitative elemental data for the untreated CA fiber/BF (CA1+BF1), PLA-coated CA fiber/BF (CA2+BF2), NaOH-treated CA fiber/BF (CA3+BF3), and PLA-coated + NaOH-treated CA fiber/BF (CA4+BF4), presenting both weight and atomic percentages. The EDAX analysis method employed in this research is widely recognized for both qualitative and quantitative elemental analysis. This study delved into the chemical composition of the hybrid composites of epoxy and CA fiber/BF in various conditions: untreated, PLA-coated, treated with NaOH, and treated with both PLA and NaOH. These composites are primarily composed of cellulose, lignin, hemicelluloses, and waxes. Interestingly, the detailed chemical composition of these hybrid composites, including CA1+BF1, CA2+BF2, CA3+BF3, and CA4+BF4, has not been previously documented by other researchers.

The fundamental chemical elements in these composites are C and O. Inorganic elements such as Si, S, Na, Cl, and Ca are also present on the surface of the CA fiber/BF, albeit in trace amounts, as visualized in Fig. 6. Table 3 reveals that a certain amount of Na is detectable on the CA fiber/BF following NaOH treatment, while Si is observed in the case of PLA coating, as detailed in Table 3. This could be attributed to the changes occurring on the surface of the CA fiber/BF due to chemical treatments and polymer coatings, resulting in distinct bond formations.



(A)

| Element | Wt% | Atomic % |
|---|---|---|
| C | 53.73 | 60.79 |
| O | 46.02 | 39.09 |
| Si | 0.26 | 0.12 |
| S | 0.00 | 0.00 |
| Total: | 100.00 | 100.00 |

(B)

| Element | Wt% | Atomic % |
|---|---|---|
| C | 63.36 | 70.29 |
| O | 34.52 | 28.75 |
| Na | 0.22 | 0.13 |
| Si | 1.22 | 0.58 |
| S | 0.00 | 0.00 |
| Cl | 0.68 | 0.25 |
| Total: | 100.00 | 100.00 |

(C)

| Element | Wt% | Atomic % |
|---|---|---|
| C | 61.89 | 69.08 |
| O | 35.74 | 29.94 |
| Na | 0.66 | 0.39 |
| Si | 0.13 | 0.06 |
| Ca | 1.58 | 0.53 |
| Total: | 100.00 | 100.00 |

(D)

| Element | Wt% | Atomic % |
|---|---|---|
| C | 65.11 | 71.46 |
| O | 34.43 | 28.37 |
| Cl | 0.46 | 0.17 |
| Total: | 100.00 | 100.00 |

**Fig. 6.** EDAX of (A) untreated, (B) PLA-coated, (C) NaOH-treated, and (D) PLA-coated + NaOH-treated in CA fiber-BF epoxy hybrid composites.

**Table 3**
Quantitative elemental of unmodified and modified CA fiber/BF.

| Elements | CA1 + BF1 | | CA2 + BF2 | | CA3 + BF3 | | CA4 + BF4 | |
|---|---|---|---|---|---|---|---|---|
| | %Weight | %Atomic | %Weight | %Atomic | %Weight | %Atomic | %Weight | %Atomic |
| C | 53.73 | 60.79 | 63.36 | 70.29 | 61.89 | 69.08 | 65.11 | 71.46 |
| O | 46.02 | 39.09 | 34.52 | 28.75 | 35.74 | 29.94 | 34.43 | 28.37 |
| Na | 0.00 | 0.00 | 0.22 | 0.13 | 0.66 | 0.39 | 0.00 | 0.00 |
| Si | 0.26 | 0.12 | 1.22 | 0.58 | 0.13 | 0.06 | 0.00 | 0.00 |
| S | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cl | 0.00 | 0.00 | 0.68 | 0.25 | 0.00 | 0.00 | 0.46 | 0.17 |
| Ca | 0.00 | 0.00 | 0.00 | 0.00 | 1.58 | 0.53 | 0.00 | 0.00 |
| **Total** | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

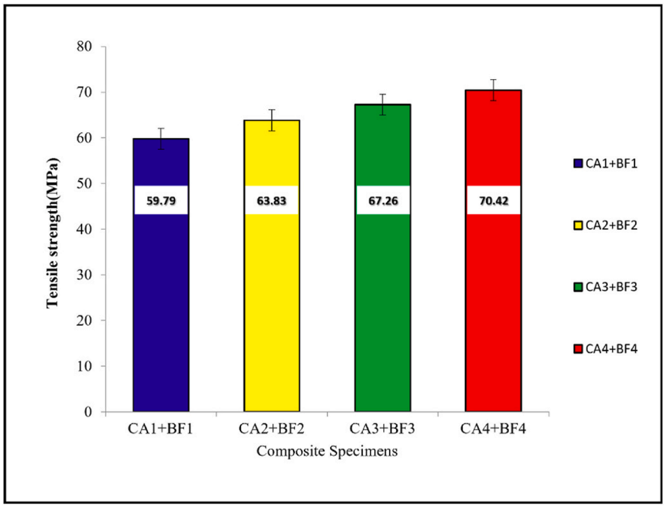


**Fig. 7.** Tensile strength of untreated and treated CA fiber/BF epoxy hybrid composites.

### 3.1. Tensile strength

Fig. 7 illustrates the tensile strength of untreated, PLA-coated, NaOH-treated, and NaOH-treated + PLA-coated CA fiber/BF epoxy hybrid composites. A notable increase in tensile strength was observed with both NaOH treatment and PLA coating of the fibers, indicating enhanced mechanical properties of the epoxy hybrid composite. The comparison of tensile between untreated and treated CA fiber/BF epoxy hybrid composites, depicted in Fig. 7, demonstrates consistently higher values for the treated composites. This improvement can be attributed to the successful surface modification, resulting in more effective reinforcement. As depicted in Fig. 7, the tensile strengths of the epoxy hybrid composite were measured at 59.79 MPa for the untreated sample, 63.83 MPa for the PLA-coated sample, 67.26 MPa for the alkali-treated sample, and 70.42 MPa for the PLA-coated + alkali-treated CA fiber/BF composite. Notably, the untreated CA fiber/BF composite (CA1+BF1) exhibited the lowest tensile strength, primarily due to inadequate adhesion between the fiber and the matrix [30,31]. The specimens of PLA-coated CA fiber/BF composite (CA2+BF2), alkali-treated CA fiber/BF composite (CA3+BF3), and alkali-treated + PLA-coated CA fiber/BF composite (CA4+BF4) have 6.8%, 12.5%, and 17.8% more tensile strength compared to CA1+BF1, respectively. The increase in tensile strength of CA-BF composites by alkali treatment was significantly good and consistent with that obtained by Arthanarieswaran et al., [14]. Alkali treatment increases the surface roughness of CA fiber/BF by the removal of hemicelluloses, lignin, and wax resulting in improved interfacial adhesion between CA fiber/BF and matrix, as reported by other researchers [12,28,32]. The increase in roughness of the surface after alkali treatment can be seen in Fig. 3, was noticeable that PLA-coated CA fiber/BF composite (CA2+BF2) was higher tensile strength than (CA1+BF1) but lower tensile strength than other treated composites (CA3+BF3, and CA4+BF4) due to average bonding between CA fiber/BF, and matrix as shown in Figs. 2 and 4. Among all CA fiber/BF epoxy hybrid composites, CA4+BF4 has the maximum values of tensile strength, which are 15.1% (10.63 MPa), 9.4% (6.59 MPa), and 4.5% (3.16 MPa), respectively, higher than that of CA4+BF4. It occurs due to strong interfacial adhesion between CA fiber/BF and matrix as shown in Fig. 5. The strong adhesion in composite CA4+BF4 may be due to the combined effect of alkali treatment and PLA coating. Finally, was concluded that an increase in tensile strength follows the order: CA4+BF4 > CA3+BF3 > CA2+BF2 > CA1+BF1.

### 3.2. Flexural strength

In Fig. 8, the flexural strengths of untreated, PLA-coated, NaOH-treated, and NaOH-treated + PLA-coated CA fiber/BF epoxy hybrid composites are presented. A notable improvement in flexural strength was observed with NaOH treatment and PLA coating of CA fiber/BF, highlighting the enhancement in the epoxy hybrid composite's mechanical properties. Specifically, the untreated CA fiber/BF reinforced epoxy hybrid composite specimen (CA1+BF1) demonstrated lower flexural strength, attributed to inadequate surface wetting and poor fiber-epoxy bonding. Conversely, all treated CA fiber/BF epoxy hybrid composites exhibited superior flexural strength compared to the untreated counterparts, underscoring the efficacy of surface modification. As depicted in Fig. 8, the flexural strengths of the epoxy hybrid composite were measured at 79.2 MPa for the untreated sample, 83.6 MPa for the PLA-coated sample, 88.5 MPa for the alkali-treated sample, and 89.8 MPa for the PLA-coated + alkali-treated CA fiber/BF composite. This reinforces the understanding that the untreated CA fiber/BF composite (CA1+BF1) displayed the lowest flexural strength due to inadequate fiber-matrix adhesion [26].

The flexural strength of the PLA-coated CA-BF epoxy hybrid

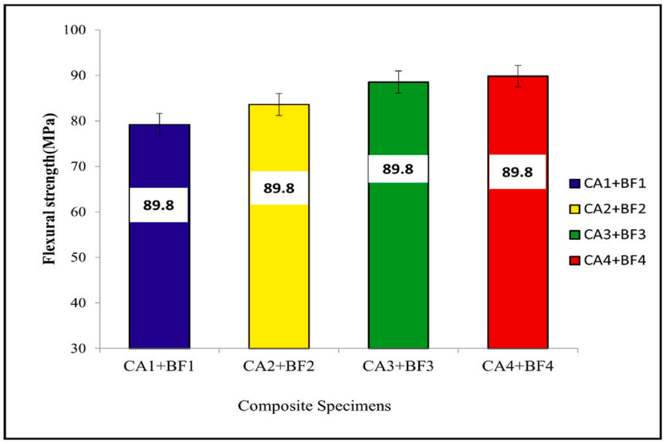


**Fig. 8.** Flexural strength of untreated and treated CA fiber/BF epoxy hybrid composites.

composite specimen (CA2+BF2) exhibited a 5.6% increase compared to the untreated hybrid composite specimen (CA1+BF1). Similarly, the flexural strength of the NaOH-treated CA fiber/BF epoxy hybrid composite specimen (CA3+BF3) demonstrated an 11.7% increase compared to the untreated CA fiber/BF epoxy hybrid composite specimen (CA1+BF1). The highest strength of the flexural value was offered by NaOH-treated and PLA-coated CA fiber/BF epoxy hybrid composite specimen (CA4+BF4). The NaOH-treated and PLA-coated CA fiber/BF epoxy hybrid composite have a flexural strength of 89.8 MPa. The NaOH-treated and PLA-coated CA fiber/BF epoxy hybrid composite (CA4+BF4) has 13.4% more strength of the flexural than the untreated CA fiber/BF epoxy hybrid composite (CA1+BF1) due to enhancement in interfacial bonding between fiber and matrix. The specimens of PLA-coated CA fiber/BF composite (CA2+BF2), alkali-treated CA fiber/BF composite (CA3+BF3), and alkali-treated + PLA-coated CA fiber/BF composite (CA4+BF4) have 5.6%, 11.7%, and 13.4% more flexural strength compared to CA1+BF1, respectively. The increase in strength of the flexural of CA fiber/BF composites by alkali treatment was significantly good compared with that obtained by Puttegowda Madhu et al. [33] and Yadav & Gupta, [34]. Alkali treatment increases the surface roughness of CA-BF by the removal of hemicelluloses, lignin, and wax resulting in improved interfacial adhesion between CA-BF and matrix, as reported in other studies [27,35–38].

It was observed that the flexural strength of the PLA-coated CA fiber/BF composite (CA2+BF2) surpassed that of (CA1+BF1) but remained lower than that of other treated epoxy hybrid composites (CA3+BF3 and CA4+BF4), attributed to the moderate bonding between CA fiber/BF and the matrix. Notably, among all CA fiber/BF epoxy hybrid composites, CA4+BF4 exhibited the highest flexural strength values, surpassing the others by 5.6% (10.6 MPa), 11.7% (6.2 MPa), and 13.4% (1.3 MPa), respectively. The notable increase in flexural strength in epoxy hybrid composite CA4+BF4 can be attributed to the robust interfacial adhesion between CA fiber/BF and the matrix. This strong adhesion and resulting high flexural strength were achieved through the combined effects of alkali treatment and PLA coating. Consequently, it was concluded that the order of increasing flexural strength is as follows: CA4+BF4 > CA3+BF3 > CA2+BF2 > CA1+BF1.

### 3.3. *Impact strength*

Fig. 9 illustrates the impact strength of untreated CA fiber/BF epoxy hybrid composites (CA1+BF1) compared to treated counterparts with PLA-coated (CA2+BF2), NaOH treated (CA3+BF3), and NaOH treated + PLA-coated (CA4+BF4), as depicted. An adverse effect of NaOH treatment and PLA coating on CA fiber/BF (CA4+BF4) was observed, resulting in a notable reduction in the impact strength of the epoxy hybrid composite, as indicated in Fig. 9. Interestingly, the impact test results exhibited a reverse trend compared to the tensile and flexural tests. It was evident that the impact strength decreased for CA fiber/BF epoxy hybrid composites, notably with NaOH treated + PLA-coated (CA4+BF4), despite having enhanced fiber-matrix adhesion [38]. This occurred because during the test of impact strength, energy absorption by CA fiber/BF epoxy hybrid composites, mainly depends upon CA fiber/BF pull-out process, whereas NaOH treated + PLA coated (CA4+BF4) provides a strong bonding between CA fiber/BF and matrix (epoxy) which minimizes fibers pull out and hence decreases in the impact strength [39,40]. It was observed that the impact strength of the treated CA fiber/BF -reinforced epoxy hybrid composite specimen (CA4+BF4) was lower, primarily due to excessive surface wetting and the establishment of strong fiber-epoxy bonding. Conversely, untreated CA fiber/BF epoxy hybrid composites exhibited superior impact strength compared to the treated counterparts (CA2+BF2, CA3+BF3, and CA4+BF4), highlighting the effectiveness of surface modification techniques.

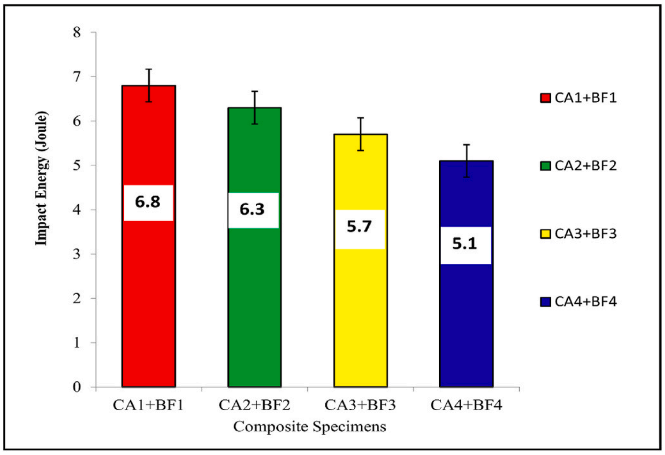


**Fig. 9.** Impact Energy of untreated and treated CA fiber/BF epoxy hybrid composites.

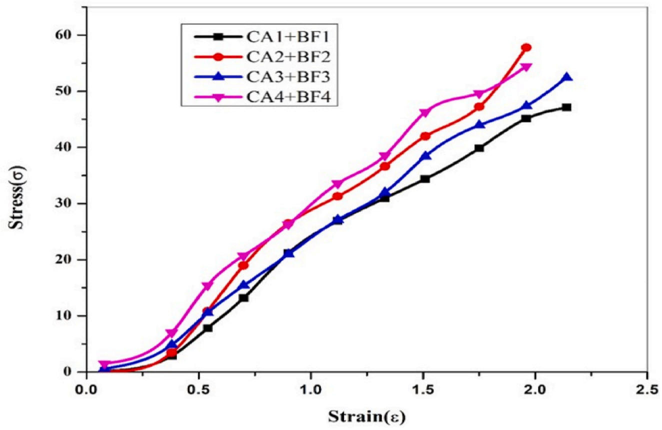


**Fig. 10.** Stress-strain of untreated and treated CA fiber/BF epoxy hybrid composites.

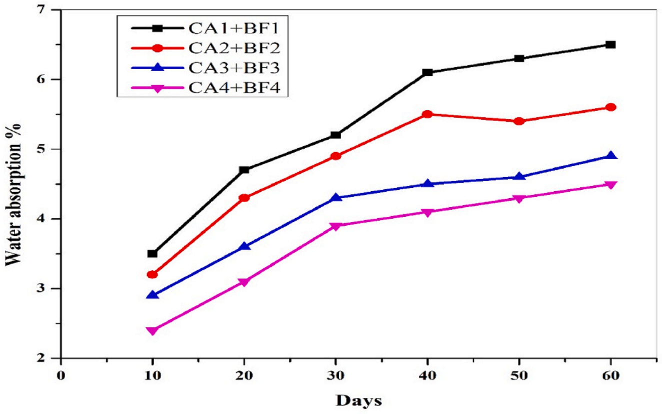


**Fig. 11.** Water absorption of untreated and treated CA fiber/BF epoxy hybrid composites.

As exhibited in Fig. 9, the impact strength of the epoxy hybrid composite was 5.1 J PLA-coated + alkali-treated, 5.7 J alkali-treated, 6.3 J PLA-coated, and 6.8 J untreated CA fiber/BF. The untreated CA fiber/BF composite (CA1+BF1) has the highest impact strength because of poor fiber-matrix adhesion, also superior CA fiber/BF pull out and hence increase in the impact strength [13,19,26]. The percentage decrease in impact strength of the PLA-coated CA fiber/BF epoxy hybrid composite specimen (CA2+BF2) was 7.4% less impact strength than the untreated hybrid composite specimen (CA1+BF1). The percentage decrease in impact strength of the NaOH-treated CA fiber/BF epoxy hybrid composite specimen (CA3+BF3) was 16.2% less impact strength than untreated CA fiber/BF epoxy hybrid composite specimen (CA1+BF1). The lowest impact strength value was offered by NaOH-treated + PLA-coated CA fiber/BF epoxy hybrid composite specimen (CA4+BF4). The NaOH-treated + PLA-coated CA-BF epoxy hybrid composite has an impact strength of 5.1 J. The NaOH-treated + PLA-coated CA fiber/BF epoxy hybrid composite (CA4+BF4) has 25% less impact strength than the untreated CA fiber/BF epoxy hybrid composite (CA1+BF1) due to enhancement in interfacial bonding between CA-BF and matrix. The specimens of PLA-coated CA-BF composite (CA2+BF2), alkali-treated CA-BF composite (CA3+BF3), and alkali-treated + PLA-coated CA-BF composite (CA4+BF4) have 7.4%, 16.2%, and 25% less impact strength compared to CA1+BF1, respectively. Alkali treatment increases the surface roughness of CA fiber/BF by the removal of hemicelluloses, lignin, and wax promoting in improved interfacial adhesion between CA fiber/BF and epoxy, also PLA-coated CA fiber/BF epoxy hybrid composite (CA2+BF2) was lower impact strength than (CA1+BF1) but higher impact strength than other treated epoxy hybrid composites (CA3+BF3, and CA4+BF4) due to average bonding between CA fiber/BF, and epoxy. Then, all CA fiber/BF epoxy hybrid composites, CA4+BF4 has the minimum values of impact strength, which untreated have more 33.3% (1.7 J), PLA-coated have more 23.5% (1.2 J), and NaOH-treated have more 11.8% (0.6 J) compared to CA4+BF4, respectively. It occurs due to strong interfacial adhesion between CA fiber/BF and epoxy matrix. The strong adhesion, and inferior impact strength in epoxy hybrid composite CA4+BF4 was due to the combined effect of alkali treatment and PLA coating, as well as was concluded that a decrease in impact strength follows the order: CA1+BF1 > CA2+BF2 > CA3+BF3 > CA4+BF4.

### 3.4. Stress vs strain

Fig. 10 presents the typical tensile stress–strain (σ–ε) curves for both untreated and treated CA-BF epoxy hybrid composites (CA1+BF1, CA2+BF2, CA3+BF3, and CA4+BF4). The tensile strength of untreated CA-BF epoxy hybrid composites was observed to be lower compared to that of modified counterparts. This trend was consistent for the tensile modulus and percentage of elongation at break as well. In the case of untreated and uncoated CA-BF epoxy hybrid composites (CA1+BF1), as well as PLA-coated, NaOH-treated, and NaOH-treated + PLA-coated CA-BF epoxy hybrid composites (CA2+BF2, CA3+BF3, and CA4+BF4, respectively), the stress–strain response exhibited linear proportionality until failure. However, all epoxy hybrid composites reinforced with CA fiber/BF (CA1+BF1, CA2+BF2, CA3+BF3, and CA4+BF4) displayed a simplified shape in their stress–strain curves. For the CA2+BF2, and CA3+BF3 epoxy hybrid composites showed an intermediate modulus in the initial stage of loading, which was taken as the tensile modulus, ε, after which the load reached a maximum point taken as the tensile strength, σ, and corresponding initial failure strain, ε. Subsequently, when the CA-BF epoxy hybrid composites (CA2+BF2, and CA3+BF3) began to fail, the high-ductility fibrous reinforcement (CA fiber/BF) held the load without instantaneous failure. The uncoated CA-BF epoxy hybrid composites (CA1+BF1) have enhancement in tensile strength, and elongation compared to that of PLA-coated, NaOH-treated, and NaOH-treated + PLA-coated CA-BF epoxy hybrid composites, CA2+BF2, CA3+BF3, and CA4+BF4 respectively. The NaOH-treated CA-BF epoxy hybrid composites (CA3+BF3) compared to CA1+BF1, and CA2+BF2 have the behavior of rigid material in stress–strain shape due to enhanced surface roughness was caused removal of non-cellulosic constituents. The enhancement in the tensile properties of the CA-BF epoxy hybrid composites by NaOH-treatment align with the observed improvements in strength properties resulting from chemical treatment [41–43].

The surface modification through NaOH-treatment and PLA-coating of CA fiber/BF exhibited a beneficial impact, leading to enhanced tensile properties in its epoxy hybrid composites [44]. This was credited to NaOH-treatment that produces an efficient stress transfer by enhancement in the surface roughness followed by enhancement in interfacial bonding between CA-BF -epoxy [45]. To confirm the change in surface roughness after NaOH-treatment and PLA-coating, SEM analysis of CA-BF epoxy hybrid composites rupture was also performed and observed an improvement in surface roughness for NaOH-treated + PLA-coated CA-BF compared to untreated (CA1+BF1), as shown in Figs. 2 and 5. The values of the highest tensile strength were offered by NaOH-treated and PLA-coated CA fiber/BF epoxy hybrid composites (CA4+BF4), credited to the combined effect of chemical treatment and polymer coating. The epoxy hybrid composites CA4+BF4, has better behavior in stress–strain curve as compared to those of epoxy hybrid composites CA1+BF1, CA2+BF2 and CA3+BF3 respectively [46]. Also, the epoxy hybrid composites (CA4+BF4), exhibited a behavior rigid, and linear curve in stress–strain obeying Hooke's law compared to CA1+BF1, CA2+BF2 and CA3+BF3 respectively. Moreover, elongation (ductility) was decreased for epoxy hybrid composites (CA4+BF4), compared to those of CA1+BF1, CA2+BF2 and CA3+BF3 respectively. Polymer coating of CA fiber/BF helps to improve the hydrophobic behavior of CA fiber/BF and optimal enhancement in surface roughness thereby a strong interfacial bonding with epoxy matrix [47]. The enhanced surface roughness by treatment and coating is shown in Fig. 5. From Fig. 10 was perceived that all the epoxy hybrid composites (CA1+BF1, CA2+BF2, CA3+BF3 and CA4+BF4) presented nonductile behavior, but CA4+BF4 showed lowest nonductile behavior compared to others. This occurred due to curvature of the strain in NaOH-treated + PLA-coated epoxy hybrid composites indicates that the CA1+BF1, CA2+BF2, and CA3+BF3 have a significantly lower rigidity when compared to the CA4+BF4 [48]. Finally, the fracture point of the CA4+BF4 occurred at the fracture strength, σ, and corresponding failure strain, ε superior to CA1+BF1, CA2+BF2, and CA3+BF3. Because CA4+BF4 has better behavior in stress–strain due to surface characteristics caused by NaOH-treatment + PLA-coating in CA fiber/BF compared to CA1+BF1, CA2+BF2, and CA3+BF3. The strong adhesion, and superior performance of the stress–strain curve observed in epoxy hybrid composite CA4+BF4 were attributed to the synergistic effect of NaOH-treatment and PLA coating. It was concluded that the stress–strain behavior followed the order: CA4+BF4 > CA3+BF3 > CA2+BF2 > CA1+BF1. Notably, epoxy hybrid composite CA4+BF4 exemplifies a material capable of preventing instantaneous failure [49–52].

### 3.5. Water absorption vs days

The water absorption capacity of the hybrid composite consisting of epoxy and CA fiber/BF different conditions, namely untreated (CA1+BF1), PLA-coated (CA2+BF2), treated with NaOH (CA3+BF3), and treated with both PLA and NaOH (CA4+BF4), is primarily influenced by the interaction at the fiber-matrix interface. Analysis of Fig. 11 reveals that the initial water absorption rate is higher up to 40 days, after which a saturation state is reached. For CA1+BF1 and CA2+BF2, water absorption is higher, while for CA3+BF3 and CA4+BF4, this occurs within 30 days. The elevated water absorption of the untreated CA fiber/BF composite (CA1+BF1) is attributed to the hydrophilic nature of the CA fiber/BF and their high cellulose content [15,53]. Conversely, the lowest water absorption is observed in the composite with NaOH-treated and PLA-coated CA fiber/BF (CA4+BF4) [45].

The elimination of lignin and hemicelluloses through chemical treatment promotes strong bonding between the fiber and epoxy matrix. The PLA coating serves as an effective protective barrier against water absorption [45,54]. The positive impact of NaOH-treatment and PLA-coating on the water absorption behavior of CA-BF epoxy hybrids is evident. This enhancement is linked to improved interfacial bonding facilitated by NaOH-treatment, leading to increased surface roughness [55,56]. The composite CA4+BF4, benefiting from both

NaOH-treatment and PLA-coating, demonstrates the lowest water absorption rate. Remarkably, the order of water absorption performance is as follows: CA4+BF4 > CA3+BF3 > CA2+BF2 > CA1+BF1. This hierarchy is attributed to the synergistic effects of NaOH-treatment and PLA-coating, highlighting the strong adhesion and exceptional water absorption behavior of CA4+BF4. In summary, this investigation underscores the crucial role of the fiber-matrix interface in determining water absorption in epoxy hybrid composites with CA fiber/BF. The combination of NaOH-treatment and PLA-coating offers the most favorable water absorption characteristics, surpassing other composite variations. These insights provide valuable guidance for optimizing water resistance in such hybrid composites.

## 4. Summary and conclusions

The current work targeted and executed on the hybrid composite consisting of epoxy and Careya (CA) fiber/banana fiber (BF) combination for the first time for hybridization of the natural fiber with chemical treatment and polylactic acid (PLA) coating. The composite enhanced with PLA coating and analyzed results and findings are concluded here.

- The individual characteristics of CA fiber/BF affect the tensile strength of hybrid composite specimens. It is observed that Tensile strength and Flexural strength of PLA coated and NaOH treated CA fiber/BF reinforced hybrid composite specimen (CA4+BF4) are improved. The impact energy of the composite (CA1+BF1) increased with PLA coating and NaOH treatment compared with (CA2+BF2), (CA3+BF3), and (CA4+BF4).
- It is observed that impact strength, energy absorption by CA fiber/BF epoxy hybrid composites, mainly depends upon CA fiber/BF pull-out process, whereas NaOH treated + PLA coated (CA4+BF4) provides a strong bonding between CA fiber/BF and matrix (epoxy) which minimizes fibers pull out and hence decreases in the impact strength.
- Tensile strength and Flexural strength of the PLA coated and NaOH treated CA fiber/BF reinforced hybrid specimens (CA4+BF4) are improved compared with untreated hybrid composite structure (CA1+BF1).
- The tensile strength of untreated CA fiber/BF epoxy hybrid composites is found to be lower than those of modified CA fiber/BF epoxy hybrid composites.
- The Impact energy and water absorption capacity of PLA coated and NaOH treated CA fiber/BF reinforced hybrid composite specimen (CA4+BF4) decreases compared with untreated hybrid composite specimen (CA1+BF1).
- The elimination of lignin and hemicelluloses through chemical treatment promotes strong bonding between the fiber and epoxy matrix and the PLA coating serves as an effective protective barrier against water absorption, also it shows positive impact of NaOH-treatment and PLA-coating on the water absorption behavior of CA fiber/BF epoxy hybrids is evident.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

[1] Sahu P, Gupta MK. Eco-friendly treatment and coating for improving the performance of sisal composites. Polym Test 2021;93. https://doi.org/10.1016/j.polymertesting.2020.106923.

[2] Diharjo K, Gapsari F, Andoko A, Wijaya MN, Mavinkere Rangappa S, Siengchin S. Flammability and thermal resistance of Ceiba petandra fiber-reinforced composite with snail powder filler. Polym Compos 2024;45:4947–60. https://doi.org/10.1002/pc.28100.

[3] Thyavihalli Girijappa YG, Mavinkere Rangappa S, Parameswaranpillai J, Siengchin S. Natural fibers as sustainable and renewable resource for development of eco-friendly composites: a comprehensive review. Front Mater 2019;6. https://doi.org/10.3389/fmats.2019.00226.

[4] Andoko A, Gapsari F, Prasetya R, Mudjib A, Sanjay S, Rangappa M. Walikukun fiber as lightweight polymer reinforcement : physical , chemical , mechanical , thermal , and morphological properties. Biomass Convers Biorefinery 2023. https://doi.org/10.1007/s13399-023-05203-8.

[5] Al-Maharma AY, Al-Huniti N. Critical review of the parameters affecting the effectiveness of moisture absorption treatments used for natural composites. J Compos Sci 2019;3. https://doi.org/10.3390/jcs3010027.

[6] Gapsari F, Darmadi DB, Juliano H, Hidayatullah S, Suteja Mavinkere Rangappa S, et al. Modification of palm fiber with chitosan-AESO blend coating. Int J Biol Macromol 2023;242:125099. https://doi.org/10.1016/j.ijbiomac.2023.125099.

[7] Mohammed M, Jawad AJM, Mohammed AM, Oleiwi JK, Adam T, Osman AF, et al. Challenges and advancement in water absorption of natural fiber-reinforced polymer composites. Polym Test 2023;124:108083. https://doi.org/10.1016/j.polymertesting.2023.108083.

[8] Randis Fellicia DM, Rus TY, Sulaiman AM. Isolation and extraction of microcellulose from pineapple leaves fiber. Mech Explor Mater Innov 2024;1:61–6. https://doi.org/10.21776/ub.memi.2024.001.02.4.

[9] Velusamy K, Navaneethakrishnan P, Rajeshkumar G, Sathishkumar TP. The influence of fiber content and length on mechanical and water absorption properties of Calotropis Gigantea fiber reinforced epoxy composites. J Ind Text 2019;48:1274–90. https://doi.org/10.1177/1528083718763778.

[10] Anam K, Purnowidodo A, Ananta B, Kumar PKAV. The effect of load steps and initial crack length on stress distribution of fiber metal laminates. Mech Explor Mater Innov 2024;1:54–60. https://doi.org/10.21776/ub.memi.2024.001.02.3.

[11] Alagesan PK. Recent advances of hybrid fiber composites for various applications. Hybrid Fiber Compos. 2020. https://doi.org/10.1002/9783527824571.ch17.

[12] Madhu P, Sanjay MR, Pradeep S, Subrahmanya Bhat K, Yogesha B, Siengchin S. Characterization of cellulosic fibre from Phoenix pusilla leaves as potential reinforcement for polymeric composites. J Mater Res Technol 2019;8. https://doi.org/10.1016/j.jmrt.2019.03.006.

[13] Mwaikambo LY, Ansell MP. Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization. J Appl Polym Sci 2002;84:2222–34. https://doi.org/10.1002/app.10460.

[14] Mautner A, Kwaw Y, Weiland K, Mvubu M, Botha A, John MJ, et al. Natural fibre-nanocellulose composite filters for the removal of heavy metal ions from water. Ind Crops Prod 2019;133. https://doi.org/10.1016/j.indcrop.2019.03.032.

[15] Prakoso MW, Baroroh DN, Setswalo K. Water absorption rate of kenaf fiber (KF)/hydroxiteapatite (HA) in simulated sea water. Mech Explor Mater Innov 2024;1:35–41. https://doi.org/10.21776/ub.memi.2024.001.01.5.

[16] Anguita JV, Smith CTG, Stute T, Funke M, Delkowski M, Silva SRP. Dimensionally and environmentally ultra-stable polymer composites reinforced with carbon fibres. Nat Mater 2020;19(3):317–22. https://doi.org/10.1038/s41563-019-0565-3.

[17] Mohammed L, Ansari MNM, Pua G, Jawaid M, Islam MS. A review on natural fiber reinforced polymer composite and its applications. Int J Polym Sci 2015;2015:243947. https://doi.org/10.1155/2015/243947.

[18] Espinach FX. Advances in natural fibers and polymers. Materials 2021;14. https://doi.org/10.3390/ma14102607.

[19] ASTM D4762-18, Standard Guide for Testing Polymer Matrix Composite Materials, 15.03 , developed by subcommittee: d30.01 , Pages: 25, DOI: 10.1520/D4762-18, ICS Code: 83.140.20.

[20] ASTM D790-17, Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials, 08.01, Pages: 12, DOI: 10.1520/D0790-17, ICS Code: 29.035.20.

[21] ASTM D256-23e1, Standard test methods for determining the Izod pendulum impact resistance of plastics, 08.01 , Pages: 20, DOI: 10.1520/D0256-23E01, ICS Code: 29.035.20.

[22] ASTM D570-22, Standard test method for water absorption of plastics, 08.01, Pages: 4, DOI: 10.1520/D0570-22, ICS Code: 83.120.

[23] Andoko A, Gapsari F, Wijatmiko I, Diharjo K, Rangappa SM, Siengchin S. Performance of carbon fiber (CF)/Ceiba petandra fiber (CPF) reinforced hybrid polymer composites for lightweight high-performance applications. J Mater Res Technol 2023;27:7636–44. https://doi.org/10.1016/j.jmrt.2023.11.103.

[24] Melo Ká, Santos T, Santos C, Fonseca R, Dantas N, Aquino M. Influence of fiber content in the water absorption and mechanical properties of sisal fiber powder composites. Hybrid fiber compos. John Wiley & Sons, Ltd; 2020. p. 369–80. https://doi.org/10.1002/9783527824571.ch16.

[25] Gupta MK, Singh R. PLA-coated sisal fibre-reinforced polyester composite: water absorption, static and dynamic mechanical properties. J Compos Mater 2019;53:65–72. https://doi.org/10.1177/0021998318780227.

[26] Gapsari F, Purnowidodo A, Hadi P. Flammability and mechanical properties of Timoho fiber-reinforced polyester composite combined with iron powder filler. J Mater Res Technol 2022;21:212–9. https://doi.org/10.1016/j.jmrt.2022.09.025.

[27] Sanjay MR, Madhu P, Jawaid M, Senthamaraikannan P, Senthil S, Pradeep S. Characterization and properties of natural fiber polymer composites: a comprehensive review. J Clean Prod 2018;172. https://doi.org/10.1016/j.jclepro.2017.10.101.

[28] Hemath M, Mavinkere Rangappa S, Kushvaha V, Dhakal HN, Siengchin S. A comprehensive review on mechanical, electromagnetic radiation shielding, and thermal conductivity of fibers/inorganic fillers reinforced hybrid polymer composites. Polym Compos 2020;41. https://doi.org/10.1002/pc.25703.

[29] Kurpińska M, Pawelska-Mazur M, Gu Y, Kurpiński F. The impact of natural fibers' characteristics on mechanical properties of the cement composites. Sci Rep 2022;12:20565. https://doi.org/10.1038/s41598-022-25085-6.

[30] Santos CM, Santos TF, Rangappa SM, Macedo M, Aquino M, Alves SM, et al. Physical & mechanical and chemical properties on papaya tree bast fibers from different portions. Biomass Convers Biorefinery 2023. https://doi.org/10.1007/s13399-023-04513-1.

[31] Gapsari F, Djakfar L, Handajani RP, Yusran YA, Hidayatullah S, Suteja, et al. The application of timoho fiber coating to improve the composite performance. Results Eng 2022;15:100499. https://doi.org/10.1016/j.rineng.2022.100499.

[32] Narayanasamy Psssrp P Balasundar P, Ramkumar T. Extraction and characterization of new natural cellulosic chloris barbata fiber. J Nat Fibers 2018; 15:436–44. https://doi.org/10.1080/15440478.2017.1349015.

[33] Madhu P, Mavinkere Rangappa S, Khan A, Al Otaibi A, Al-Zahrani SA, Pradeep S, et al. Experimental investigation on the mechanical and morphological behavior of Prosopis juliflora bark fibers/E-glass/carbon fabrics reinforced hybrid polymeric composites for structural applications. Polym Compos 2020;41:4983–93. https://doi.org/10.1002/pc.25768.

[34] Yadav A, Gupta MK. Development and characterization of jute composites for sustainable product: effect of chemical treatments and polymer coating. Mater Res Express 2019;7:15306. https://doi.org/10.1088/2053-1591/ab5bd9.

[35] Hu C, Zhou Y, Zhang T, Jiang T, Zeng G. Effect of fiber modified by alkali/polyvinyl alcohol coating treatment on properties of sisal fiber plastic composites. J Reinf Plast Compos 2020;39:880–9. https://doi.org/10.1177/0731684420934866.

[36] Gupta MK. Investigations on jute fibre-reinforced polyester composites: effect of alkali treatment and poly(lactic acid) coating. J Ind Text 2020;49:923–42. https://doi.org/10.1177/1528083718804203.

[37] Vinod A, Vijay R, Singaravelu DL, Sanjay MR, Siengchin S, Moure MM. Characterization of untreated and alkali treated natural fibers extracted from the stem of Catharanthus roseus. Mater Res Express 2019;6. https://doi.org/10.1088/2053-1591/ab22d9.

[38] Sahu P, Gupta MK. Lowering in water absorption capacity and mechanical degradation of sisal/epoxy composite by sodium bicarbonate treatment and PLA coating. Polym Compos 2020;41:668–81. https://doi.org/10.1002/pc.25397.

[39] Goud G, Rao RN. Effect of fibre content and alkali treatment on mechanical properties of Roystonea regia-reinforced epoxy partially biodegradable composites. Bull Mater Sci 2011;34:1575–81. https://doi.org/10.1007/s12034-011-0361-4.

[40] Gapsari F, Mudjib Sulaiman A, Putri TM, Juliano H, Djakfar L, Handajani RP, et al. Influence of calcium carbonate fillers on pine fiber reinforced polyester composites. Polym Compos 2022:1–12. https://doi.org/10.1002/pc.26692.

[41] Fiore V, Scalici T, Nicoletti F, Vitale G, Prestipino M, Valenza A. A new eco-friendly chemical treatment of natural fibres: effect of sodium bicarbonate on properties of sisal fibre and its epoxy composites. Compos Part B Eng 2016;85:150–60. https://doi.org/10.1016/j.compositesb.2015.09.028.

[42] Chaitanya S, Singh I. Ecofriendly treatment of aloe vera fibers for PLA based green composites. Int J Precis Eng Manuf Technol 2018;5:143–50. https://doi.org/10.1007/s40684-018-0015-8.

[43] Fiore V, Sanfilippo C, Calabrese L. Influence of sodium bicarbonate treatment on the aging resistance of natural fiber reinforced polymer composites under marine environment. Polym Test 2019;80:106100. https://doi.org/10.1016/j.polymertesting.2019.106100.

[44] Bessadok A, Marais S, Gouanvé F, Colasse L, Zimmerlin I, Roudesli S, et al. Effect of chemical treatments of Alfa (Stipa tenacissima) fibres on water-sorption properties. Compos Sci Technol 2007;67:685–97. https://doi.org/10.1016/j.compscitech.2006.04.013.

[45] Venkateshwaran N, ElayaPerumal A, Alavudeen A, Thiruchitrambalam M. Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites. Mater Des 2011;32:4017–21. https://doi.org/10.1016/j.matdes.2011.03.002.

[46] Moreira K, Santos T, Santos C, Fonseca R, Melo M, Aquino M. Analysis of the physical and mechanical properties of A biobased composite with sisal powder. Biobased compos. Wiley; 2021. p. 143–51. https://doi.org/10.1002/9781119641803.ch10.

[47] Melo K, Santos T, Santos C, Fonseca R, Dantas N, Aquino M. Experimental analysis of styrene, particle size, and fiber content in the mechanical properties of sisal fiber powder composites. Hybrid fiber compos. Wiley; 2020. p. 351–67. https://doi.org/10.1002/9783527824571.ch16.

[48] Prasad MG, Girimath AG, Rao S, Vinekar AJ, Patil DC, Timmanagoudar SN, et al. Investigation of mechanical properties of sisal fiber reinforced polymer composites. Adv J Grad Res 2017;1:40–8. https://doi.org/10.21467/ajgr.1.1.40-48.

[49] Santos T, Santos C, Fonseca R, Melo K, Aquino M. Natural fibres based phenolic composites. Phenolic polym. Based compos. Mater. Singapore: Springer Singapore; 2021. p. 65–75. https://doi.org/10.1007/978-981-15-8932-4_4.

[50] Shomran AT, Faisal BM, Hussein EK, Santos T, Fatima K. Determination of the fatigue behavior of the composite Single-Stringer structure based on the quasi-static method. Eastern-European J Enterp Technol 2023;2:15–23. https://doi.org/10.15587/1729-4061.2023.277911.

[51] Shomran AT, Faisal BM, Hussein EK, Santos T, Fatima K. Identifying some regularities of the fatigue behavior of the reinforced carbon-fiber with Al2O3 nanoparticles composite structure of the prosthesis foot. Eastern-European J Enterp Technol 2023;1:32–9. https://doi.org/10.15587/1729-4061.2023.274573.

[52] Hussein EK, Faisal BM, Subhi KA, Santos T, Ghouali S, Asyraf M, et al. Perspective chapter: viscoelastic mechanical equivalent models. In: Haidar ZS, editor. Biomimetics. Rijeka: IntechOpen; 2022. https://doi.org/10.5772/intechopen.108065.

[53] Sujon MAS, Habib MA, Abedin MZ. Experimental investigation of the mechanical and water absorption properties on fiber stacking sequence and orientation of jute/carbon epoxy hybrid composites. J Mater Res Technol 2020;9:10970–81. https://doi.org/10.1016/j.jmrt.2020.07.079.

[54] Sanjeevi S, Shanmugam V, Kumar S, Ganesan V, Sas G, Johnson DJ, et al. Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites. Sci Rep 2021;11. https://doi.org/10.1038/s41598-021-92457-9.

[55] Saha A, Kumar S, Zindani D. Investigation of the effect of water absorption on thermomechanical and viscoelastic properties of flax-hemp-reinforced hybrid composite. Polym Compos 2021;42:4497–516. https://doi.org/10.1002/pc.26164.

[56] Hamdan MHM, Siregar JP, Cionita T, Jaafar J, Efriyohadi A, Junid R, et al. Water absorption behaviour on the mechanical properties of woven hybrid reinforced polyester composites. Int J Adv Manuf Technol 2019;104:1075–86. https://doi.org/10.1007/s00170-019-03976-9.