Sugar Tech
https://doi.org/10.1007/s12355-025-01628-9

RESEARCH ARTICLE

Mechanical and Structural Characterization of Curauá Fiber, Sugarcane Biochar, and Poly(Lactic Acid) Hybrid Green Composites for Sustainable Biomass Utilization

Velmurugan Ganesan[1] · Jasgurpreet Singh Chohan[2] · Kumar Gengappan[3] · Prabhu Paramasivam[4] · Ramya Maranan[5] · Natrayan Lakshmaiya[6] · Suresh Kumar Shanmugam[7]

Received: 26 March 2025 / Accepted: 3 June 2025
© The Author(s), under exclusive licence to Society for Sugar Research & Promotion 2025

Abstract

Waste valorization has become a viable substitute for landfill disposal, underscoring the growing significance of environmentally friendly waste processing techniques. In this study, sugarcane biochar (SCB) derived from agricultural waste is used as an eco-friendly filler to reinforce Curaua fiber (CF)/polylactic acid (PLA) hybrid composites, aiming to enhance their sustainability. To improve the mechanical and structural properties, CF was pretreated with sodium bicarbonate solution ($NaHCO_3$) for different durations: 0 (A-type), 12 (B-type), 24 (C-type), 48 (D-type), 60 (E-type), 120 (F-type), and 240 h (G-type). Mechanical properties such as tensile, flexural, hardness, and impact strength were also evaluated for each treatment group. The results revealed that mechanical properties improved up to 60 h of treatment, with tensile and flexural strength reaching 56.32 MPa and 74.69 MPa, respectively. However, these properties reduced at 120 (49.85 MPa in tensile and 72.15 MPa in flexural) and 240 (47.81 MPa in tensile and 70.54 MPa in flexural) hrs, suggesting that excessive treatment caused over-removal of key fiber constituents, resulting in brittleness and reduced performance. DSC analysis of $NaHCO_3$-treated CF shows a shift in the moisture loss peak from 169 to 178 °C with longer treatment duration, indicating enhanced thermal stability. Enthalpy values decreased at shorter durations but stabilized at 127.2 J/g after 60 h, confirming structural relaxation and hemicellulose depletion. These novel hybrid biocomposites have a potential application in various structural and non-structural items, including food packaging, pharmaceuticals, sports equipment, and automobile interiors.

Keywords Curaua fiber · Sugarcane biochar · PLA · Hybrid composites · Biomass · Sustainable

Abbreviations

CF	Curaua fiber
PLA	Polylactic acid
$NaCHO_3$	Sodium bicarbonate
hrs	Hours
MPa	Megapascal
SCB	Sugarcane biochar
Wt.%	Weight percentage
CNT	Carbon nanotubes
TGA	Thermogravimetric analysis
SEM	Scanning electron microscopy
FTIR	Fourier transform infrared spectroscopy

✉ Velmurugan Ganesan
velresearch032@gmail.com

[1] Department of Mechanical Engineering, School of Engineering, Mohan Babu University, Tirupati, Andhra Pradesh 517 102, India

[2] Department of Mechanical Engineering, University Centre for Research and Development, Chandigarh University, Gharuan Mohali 140 413, India

[3] Department of Mechanical Engineering, Madanapalle Institute of Technology & Science, Madanapalle, Annamaya District, Andhra Pradesh 517 325, India

[4] Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, Punjab 140 401, India

[5] Division of Research and Development, Lovely Professional University, Jalandhar, Delhi G.T.Road, Phagwara, Punjab 144 411, India

[6] Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai, Tamil Nadu 602105, India

[7] Faculty of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu 626 126, India

Published online: 03 July 2025

DSC	Differential scanning calorimetry
µm	Micrometer
cm	Centimeters
°C	Degree celsius
RT	Room temperature
g/cm^3	Grams per cubic centimeter
RPM	Revolution per minute
g	Grams
min	Minute
Mm	Millimeter
mg	Milligrams
mL/min	Milliliter per minute
ASTM	American Society for Testing and Materials
mm^2	Square millimeter
mm^3	Cubic millimeter
kN	Kilonewton
J	Joule
SG	Specific gravity
F_w	Weights of the specimen after water absorption
F_i	Weights of the specimen before water absorption
kJ/m^2	Kilojoule per square meter

Introduction

Given the extensive use of natural raw materials and the emission of hazardous gases, contributing to the increase in greenhouse gases, the construction industry is considered one of the most polluting sectors today. Construction resources are widely utilized across the world, and there has been a growing global movement toward finding alternative materials, often derived from solid waste, to enhance sustainability (Benarab et al. 2025). As sustainable development gains traction in the construction sector, natural materials are increasingly being used in place of synthetic ones. This trend is particularly evident from a technological standpoint, as demonstrated by the widespread use of natural fibers as reinforcement in building materials (Li et al. 2025). Curaua (*Ananas erectifolius*) fiber (CF) has received less attention compared to other lignocellulosic fibers. Native to the Amazon, the plant has been traditionally used by Indigenous communities to make hammocks since before European colonization. There are four plant varieties: white, purple, red, and dazzling white. Due to its high cellulose content (70%), CF is now showing promise as a raw material in the important field of nanofiber production. Leao A.L (Leao et al. 2017) stated that the fibers' chemical composition is 7.5% lignin, 9.9% hemicellulose, and 73.6% cellulose. Compared to other fiber types, including jute (16%), sugarcane bagasse (25%), and coconut (43%), this fiber has a lower lignin content. Compared to fibers like sisal, coir, and sugarcane, CF exhibits a higher modulus of elasticity, a degree of crystallinity ranging from roughly 75.6%, and a tensile strength of about 1000 MPa due to its high cellulose content. According to research by Araújo et al. (Araujo et al. 2013), composites made with untreated CF and high-density polyethylene exhibit greater mechanical strength than the pure matrix. While incorporating 5–20% CF into the composite enhances its flexural and tensile strength, adding 25–30% fiber reduces the tensile strength compared to 20% while maintaining approximately the same flexural strength. Increasing the CF content for flexural and tensile performance also improved the elastic moduli.

Like all natural fibers, CF has certain disadvantages, including high hydrophilicity and significant water absorption. The incompatibility between natural fibers and hydrophobic polymeric matrices is a primary drawback when using them as reinforcements (Meddour et al. 2025). These characteristics contribute to dimensional instability, which may cause microcracking in composites, thereby reducing mechanical performance and impairing the load transfer from the matrix to the fiber (Luchese et al. 2024). Fiber surface modification is commonly performed through physical or chemical methods to increase the adhesion of the fiber to the matrix. This leads to alterations in the fiber surface and a reduction in moisture absorption. Without altering the chemical structure of the fibers, physical treatments (such as corona treatment, plasma treatment, and electron beam irradiation) modify the surface properties of the natural fibers, thereby improving the mechanical interlocking between fiber and matrix. In contrast, chemical treatments of natural fibers (for example, silane, alkalization or mercerization, and acetylation techniques) include the addition of a third substance to chemically alter the fiber surface, thus improving its compatibility with the polymer matrix (Atoui et al. 2024). Alsaeed et al., (Alsaeed et al. 2013) stated pre-treated date palm fibers for 24 h at an ambient temperature using varying concentrations (3%, 6%, and 9%) of NaOH solution, demonstrating that the tensile qualities of the natural fiber deteriorate with increasing NaOH percentage. The study discovered that the tensile characteristics of organic fiber decreased with increasing NaOH concentration. At the same time, higher NaOH concentrations were found to improve the fiber's surface properties by removing the waxy layer and improving the interfacial adhesion between the fiber and the matrix. As a result, the authors concluded that 6% NaOH is the optimal concentration for achieving a better strength. The effects of silane, acetyl, and alkaline treatments on the tensile characteristics of natural hemp fibers were investigated by Kabir et al. (Kabir et al. 2013). According to the experimental findings, chemically treated fibers exhibited lower tensile strength compared to untreated fibers. Specifically, silane treatment increased the fibers' failure strain, alkalization reduced their strength, and acetylation partially restored the strength loss. To the best of our knowledge, there is no

straightforward and environmentally friendly method to enhance the properties of CF and its adhesion to polymers that involves the use of an aqueous solution of sodium bicarbonate without the addition of other substances. Previously, sodium bicarbonate was used in combination with chromium sulfate solution to treat okra and coir fibers (Mir et al. 2012; Sultana et al. 2024). Zalacca fibers were treated with a 10% $NaHCO_3$ solution for 24, 120, and 240 h before undergoing sodium bicarbonate treatments, as reported by Raharjo et al. (Raharjo et al. 2019). SEM analysis was used to examine the morphological changes in the fiber surface. The authors concluded that the 120-h treatment resulted in the maximum tensile strength and elastic modulus. The cellulose fibers on the treated surface showed a rougher, cleaner surface. Similarly, Fiore et al. (Fiore et al. 2016) treated unidirectional sisal fiber with sodium bicarbonate for varying durations. Compared to untreated fibers, the researcher found that after 60 h, the tensile strength increased by 20% and elasticity improved by 45%.

The increasing demand for high-performance lightweight materials has been addressed by utilizing sustainable resources, particularly fibers and fillers. Fillers are solid additives incorporated into polymeric materials, typically altering their thermal behavior and enhancing their mechanical properties. In polymeric composites, fillers play a vital role by enhancing the distribution of stress (Kir et al. 2024). This enhancement is essential for ensuring that stresses and loads are uniformly distributed throughout the composite, thereby preventing localized weaknesses and maintaining structural integrity. Fillers can be either organic or inorganic, and both types have been successfully utilized in composite fabrication. Among them, carbon-based fillers are effectively used to get the high mechanical and thermal properties (Lewis et al. 2019; Yasim-Anuar et al. 2022). Carbon-based filler materials include carbon nanotubes (CNTs), graphene, and carbon black. Various thermochemical, chemical, and biological methods have recently been investigated for the transformation of biomass into biofuels, biochar, and syngas (Lekrine et al. 2024a). Usually, the biochar contains 65–90% carbon and also retains oxygen and aromatic compounds, contributing to its resistance to biological degradation (Rajendran et al. 2024). Due to the breakdown of weaker bonds during pyrolysis, biochar exhibits lower hydrogen content (0.5–4.2 wt%) compared to sugarcane bagasse, which normally contains 5–7 wt% hydrogen. A similar trend is observed in the level of oxygen, with biochar ranging from 10 to wt.%, while sugarcane bagasse contains 27–56 wt.% oxygen (Ahmed et al. 2021). Biochar also contains more carbon than bagasse, reaching up to 82 wt.% carbon, whereas bagasse contains up to 58 wt.% carbon. Among carbon-based filler materials, biochar stands out as a particularly innovative and eco-friendly option. It has been used in composite fabrication, with numerous research reports of enhanced mechanical properties (Zafeer et al. 2024). For example, Zhang et al.'s (Zhang et al. 2017) investigation of the thermal and flame-retardant properties of composites containing biochar shows a favorable relationship between biochar loading and matrices, which contributed to improved thermal resistance. The inclusion of 10 wt.% biochar significantly improves the flexural, tensile, and impact strength of the composites. According to Rajamani et al. (Rajamani et al. 2023), the composite containing 10% biochar exhibited mechanical strength and hardness improvements of 72% and 54%, respectively, compared to pure vinyl ester, accordingly. Minugu et al. (Minugu et al. 2022) developed biochar-epoxy composites with varying weight percentages of 2%, 4%, and 6% and thoroughly analyzed their solid erosion wear characteristics. Compared to plain epoxy, the biochar-epoxy composites showed a 52% increase in erosion and wear resistance, even with a modest 2% biochar content.

Since biodegradable materials are designed to decompose through the action of living organisms, they are currently receiving significant interest from academia and industries. Researchers are increasingly interested in using biopolymers derived from renewable sources, such as corn, cellulose, soy protein, and starches, to develop sustainable composites as alternatives to standard petroleum-based plastics. One such material, the thermoplastic biopolymer polylactide (PLA), can exist in either a completely amorphous or semicrystalline form (Rajeshkumar et al. 2021; Trivedi et al. 2023). Oksman et al. (Oksman et al. 2003) found that a composite made with flax fiber (30–40%) and PLA resin exhibited 50% higher strength than a comparable PP/flax fiber laminate. In the composite material, PLA's stiffness improved from 3.4 to 8.4 GPa, and no degradation of PLA was observed during processing. Lee et al. (Lee et al. 2010) concluded that adding a denim fabric layer to the PLA/denim composites increased their tensile strength. Among the samples tested, the three-layer denim-reinforced laminate showed the highest performance, with a tensile strength of 75.76 MPa and a tensile modulus of 4.65 GPa. Devnani and Sinha's (Devnani et al. 2022) study focused on the pyrolysis behavior, energy stimulation, characterization, and decomposition of melee fibers (cane grass). A 5% alkaline pretreatment significantly improves the mechanical, morphological, and thermal properties of PLA composites. Kim and Netravali (Kim et al. 2010) fabricated soy protein resin-based composite materials reinforced with mercerized sisal fibers and found that mercerization increased the sisal fibers' fracture strain (36.2%) and Young's modulus (12.2%), respectively. Mudoi and Sinha (Mudoi et al. 2024) conducted a non-isothermal thermogravimetric analysis (TGA) to examine the thermal degradation of biological resin and animal fiber-based composites. The TGA results showed that the temperature range of 200–435 °C exhibited the highest mass loss (> 60%).

This study presents a novel approach to enhancing the mechanical, thermal, and morphological properties of Curauá fiber (CF) through sodium bicarbonate ($NaHCO_3$) treatment—a technique that has been rarely explored in previous literature. A comprehensive analysis of the pretreated CF was conducted by using scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA), revealing substantial surface modifications and improved thermal stability across varying treatment durations (12, 24, 48, 60, 120, and 240 h). Furthermore, this work presents the novel fabrication of PLA-based hybrid biocomposite reinforced with $NaHCO_3$-treated CF and a constant 5 wt.% sugarcane biochar (SCB) via compression molding as the processing method. The resulting hybrid composites underwent an extensive evaluation of their mechanical (tensile, flexural, impact, and hardness tests), thermal, density, and water absorption properties. Overall, the present work contributes to the development of sustainable materials by providing a cost-effective and eco-friendly path to improve the CF-based biocomposites.

Experimental Works

Materials

Ober S/A Indústria e Comércio, located in Parque Industrial Recanto, Nova Odessa, Brazil, was the source of the imported Curauá fiber. The initial fiber's length was 20 cm. To remove the surface contaminants, the fibers were immersed in distilled water. After the fibers were allowed to air-dry naturally for 20 days at room temperature (RT = 35 °C) to remove any remaining moisture. Sugarcane husk, used as a waste-derived raw material, served as the precursor for biochar production. To create biochar, the biomass was pyrolyzed at 550 °C for four hours in a muffle furnace. The resulting biochar was irregular in size and gritty. The size of the ground biochar particles was measured using a sieve analysis method with a mesh size of 100 µm, ensuring uniformity after the ball milling process. The milling was conducted at a 10:1 ball-to-powder ratio to achieve a consistent particle size distribution. According to previous research, 10 wt.% of biochar loading produced the optimal mechanical properties; hence, a 5% loading of sugarcane biochar was selected for this research. The PLA matrix was sourced from A.L. Polymer, Chennai, Tamil Nadu, India, with a density of 1.24 g/cm^3 and a melting temperature

Fig. 1 Extraction process of sugarcane biochar from sugarcane biomass

between 160 and 190 °C. Figure 1 shows the extraction process of sugarcane biochar from sugarcane biomass.

Chemical Treatment of Curaua Fiber

In the present research, sodium bicarbonate ($NaHCO_3$) was selected for its kind nature compared to sodium hydroxide (NaOH), a naturally occurring compound used for natural fiber modifications, as it is biodegradable, non-toxic, and has less impact on fiber degradation. It provides a friendly approach toward modification to aid in the interaction between the fiber and matrix, hence improving the matrix bonding. After soaking in a 10 wt% $NaHCO_3$ solution for 12, 24, 48, 60, 120, and 240 h at room temperature, the CF was rinsed with distilled water and dried in an oven at 40 °C for 24 h. As is widely known, an aqueous solution of sodium bicarbonate is mildly alkaline due to the production of hydroxide ions and carbonic acid. Equations (1) and (2) explain this reaction. Figure 2 depicts the possible chemical reactions occurring during $NaHCO_3$ pretreatment.

$$NaHCO_3 + H_2O \rightarrow Na^+ + HCO_3 \quad (1)$$

$$HCO_3^- + H_2O \leftrightarrows H_2CO_3 + OH^- \quad (2)$$

It can be suggested that the interaction is similar to what occurs during a conventional mercerization treatment, as the OH groups found in the fibers primarily correspond to alcoholic hydroxyls, which behave as weak acids.

Composite Fabrication

The matrix is made of PLA, a polymer with a density of 1.24 g/cm^3. The biocomposite material was created using the Brabender Plastograph mixer. First, 74.67 g of PLA (80 wt.%) was melted at 180 °C and mixed for two minutes at 50 rpm. To improve the homogeneity of the resulting material, 14 g of chopped CF fibers (5–10 mm, 15 wt.%) and 4.67 g of sugarcane biochar (5 wt.%), derived from burning the CF petiole, were added. The mixture was then blended for 15 min. Afterward, the mixture is dried in an oven at 60 °C for 48 h. Using a hydraulic compression molding process, biocomposite plates measuring $300 \times 300 \times 3$ mm^3 are created by applying 180 °C and 5 MPa pressure for 10 min. To reduce residual stress and increase structural stiffness, the plates were gradually cooled, following a staged protocol: 100 °C for two min, 80 °C for five min, and 55 °C for three min. Table 1 summarizes the fabrication of different types of composites. Figure 3 shows the CF/SCB/PLA hybrid composite fabrication process.

Table 1 Fabrication of hybrid composites based on different durations of $NaHCO_3$ treatment

Sl. no.	Symbols	PLA (wt.%)	Biochar (wt.%)	Curaua fiber (wt.%)	$NaHCO_3$ treatment (h)
1	A	80	5	15	Raw-0
2	B	80	5	15	CF-12
3	C	80	5	15	CF-24
4	D	80	5	15	CF-48
5	E	80	5	15	CF-60
6	F	80	5	15	CF-120
7	G	80	5	15	CF-240

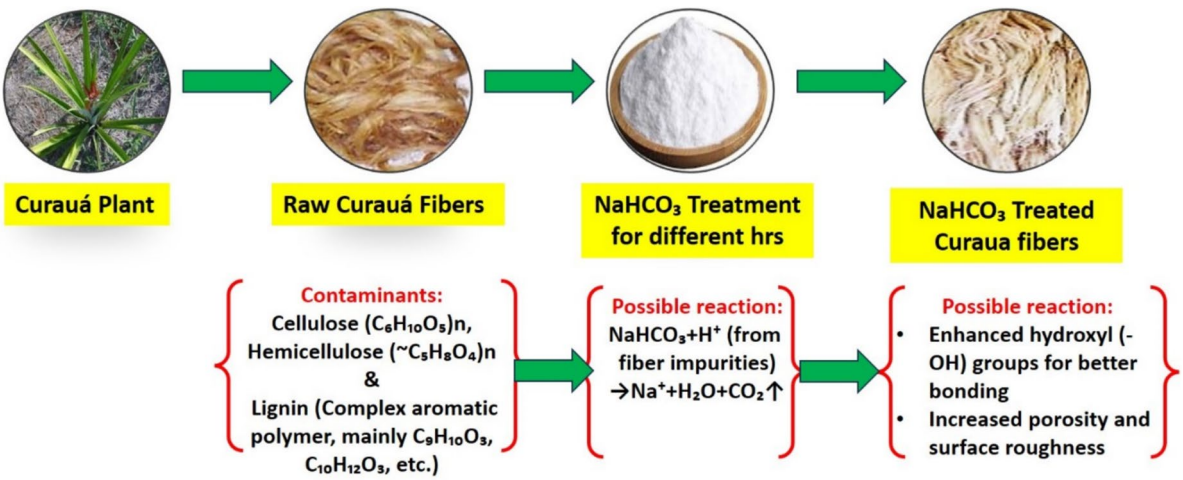

Fig. 2 Possible chemical reaction during $NaHCO_3$ treatment

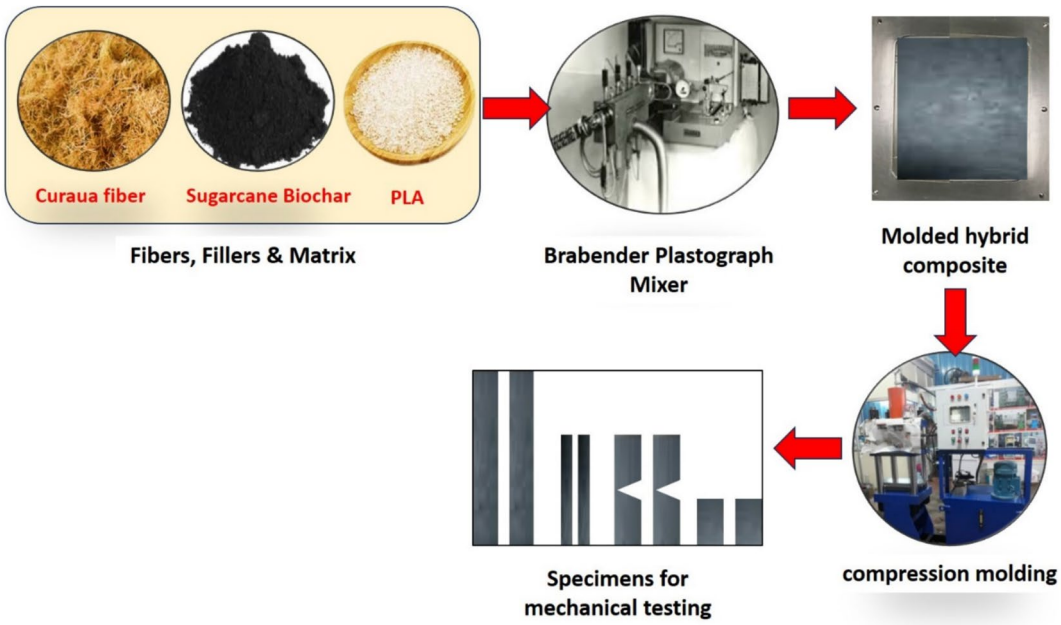

Fig. 3 Fabrication process of CF/SCB/PLA-based hybrid composite

Material Characterization

Fourier Transform Infrared (FTIR) Analysis

The attenuated total reflectance (ATR) method of SHIMADZU IRTracer-100 FTIR spectroscopy was used to analyze the alterations in the basic functional structures of raw, $NaHCO_3$-treated CF fibers, and sugarcane biochar. The FTIR spectra were recorded in the range of 4000–500 cm^{-1}.

Thermogravimetric Analysis (TGA)

TGA of raw and chemically pretreated CF fibers was carried out through the Netzsch-STA 2500 Regulus equipment based on the standard of ASTM E1131-03. The tests were performed under a nitrogen condition with a flow rate of 50 mL/min, using a mean specimen mass of 12 mg.

Differential Scanning Calorimetry (DSC)

The thermal characteristics of raw and pretreated CF fibers were examined through a DSC Netzsch-STA 2500 Regulus device. For the DSC investigation, a heating rate of 20 °C/min was used by the ASTM D3418-82 standard. To analyze the thermal behavior, the temperature range used in the current research was 20–350 °C, with a sample mass of approximately 8 mg.

Mechanical Characterization

A tensile test was performed based on the ASTM D 3039 ($250 \times 25 \times 3$ mm^3) standard at room temperature using a universal testing machine (Model Instron 5567) equipped with a 20-kN load cell with a crosshead speed of 2.5 mm/min. The flexural test was conducted on the same apparatus at room temperature with a crosshead speed of 2 mm/min based on the ASTM D 7264 ($70 \times 12.7 \times 3$ mm^3) standard. An Instron 120D Model testing equipment was used to perform the Izod impact test utilizing a 5.5 J hammer in compliance with ASTM D256 ($65 \times 12.7 \times 3$ mm^3). Based on the ASTM D 2240 (25×25 mm^2) standard, the Shore D hardness test was carried out. Each test was repeated five times, and the arithmetic mean of the measurements was reported for each mechanical property.

Density measurement

The liquid pycnometer technique was used to measure the density of PLA/CA/sugarcane biochar-based hybrid materials in compliance with ISO 1183. Before testing, the pycnometer was dried at 25 °C, and its tare weight was measured. Specimens were pulverized to fine powder (200 µm) and introduced into the pycnometer to fill 1/4 of its volume. The weight of the pycnometer containing the sample was measured. After that, distilled water was gradually added to the pycnometer while intermittently shaking the pycnometer to avoid the formation of air bubbles. After filling, the weight of the pycnometer was measured. The same procedure was

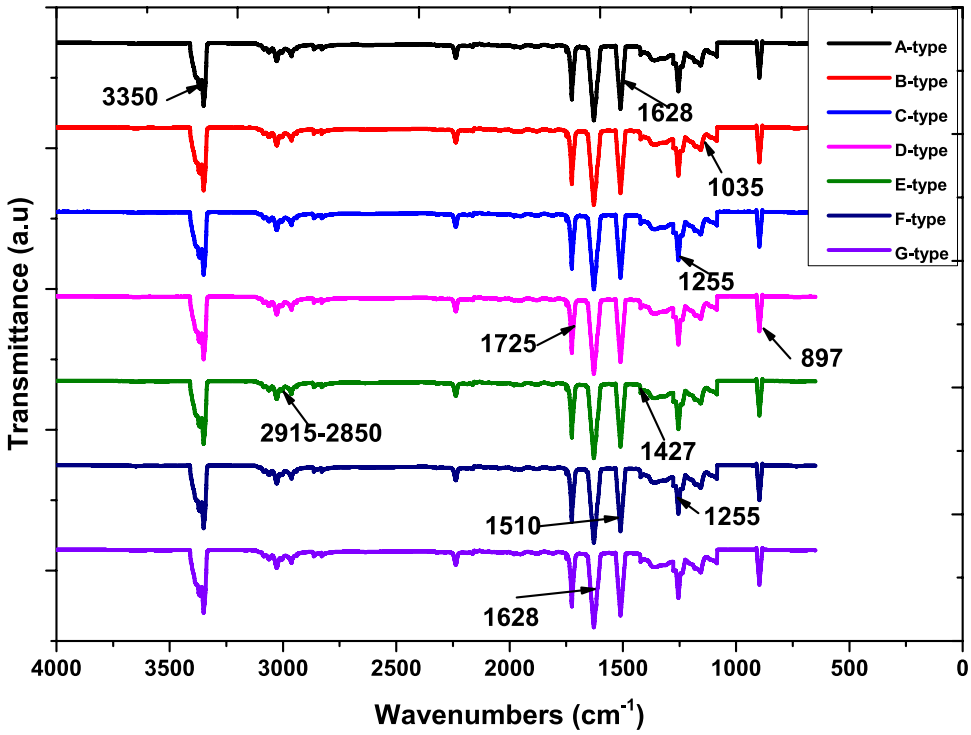

Fig. 4 FTIR analysis of CF fiber pretreated with different durations

repeated without samples to account for accurate density calculation. For each composite sample, three measurements were made to avoid experimental errors. Finally, Eq. (3) was used to calculate density.

$$Density = \left(\frac{B/A}{(D-A)-(C-B)} \right) \times SG \tag{3}$$

where A—weight of the empty pycnometer container and cover, B—weight of the container, a cover, and composite specimens before adding distilled water, C—weight of the container, a cover, and composite specimens after adding distilled water, D—weight of the container and its cap after distilled water without sample, SG—specific gravity of the distilled water used.

Water Absorption Behavior

The moisture absorption test was conducted as per the ASTM D 570 standard with dimensions of 76.2 × 25.4 × 3 mm^3 (rectangular specimen). The specimens were immersed in a water container for various durations. After the first hour, tweezers were used to carefully remove the samples from the container. After that, the specimens were weighed, and Eq. (4) was used to determine the amount of water absorption. After 2, 3, 5, 12, 24, 48, 72, 96, 168, 192, 216, and 240 h, the same procedure was repeated until the completion of the entire test.

$$\text{Water absorption} = \frac{F_w - F_i}{F_i} \times 100 \tag{4}$$

Weights of the specimen before and after water absorption are denoted by the symbol F_i and F_w, respectively.

Results and Discussion

FTIR Analysis

The FTIR analysis of the untreated and sodium bicarbonate ($NaHCO_3$)-treated CF was investigated after several hours of treatment (12, 24, 48, 60, 120, and 240 h). The results pointed to significant alterations in the chemical structure of the fibers, notably in their contents of cellulose, hemicellulose, and lignin. These important alterations, such as the removal of amorphous constituents like hemicellulose and lignin, are best illustrated by the region between 500 and 4000 cm^{-1}. In untreated CF, a strong absorption peak centered around 3350 cm^{-1} is attributed to the stretching vibration of hydroxyl (-OH) bonds that are traditionally linked with cellulose. This peak represents the intensity of the hydrogen bonding interactions in the cellulose envelope. The bands located in the region of 2915–2850 cm^{-1} are due to the –CH (carbon-hydrogen) bonds, which are typical of both cellulose and hemicellulose. Evidence of hemicellulose embedded in the fiber–matrix is indicated by the absorption peak at 1725 cm^{-1}, due to the C=O stretch vibration

of ester carbonyl groups within the hemicellulose region. In addition, the peak at 1255 cm^{-1} is associated with the C–O stretching vibrations of acetyl residues of hemicellulose (Spinacé et al. 2009). Figure 4 shows the FTIR analysis of CF fibers pretreated with different durations.

The absorption peak around 1628 cm^{-1} indicates that raw CF fibers still contain some lignin in an integral form. Additionally, the peak at around 1510 cm^{-1} confirms the presence of lignin due to the aromatic ring vibrations in structural parts of lignin, further confirming its existence. The absorption bands observed are associated with the peaks in Fig. 4, with the band at 1035 cm^{-1} corresponding to the C–O–C bond in cellulose, hemicellulose, and lignin as well. The peak due to bending vibrations of CH_2 typically seen at 1427 cm^{-1} confirms the presence of polysaccharide and Curauá fibers (Teyar et al. 2024). Further, the peak at 897 cm^{-1}, which represents glycoside ring bonds (β-glycosidic linkages), confirms the crystalline character of the fiber. A slight decrease in the intensity of the hemicellulose- and lignin-associated bands at 1725 cm^{-1}, 1255 cm^{-1}, and 1628 cm^{-1} is observed upon $NaHCO_3$ treatment for 12 and 24 h, indicating a degree of surface modification of the fibers. These decreases imply partial degradation of some hemicellulose bands, while the rest of the structure remains almost untouched. Most of the cellulose peaks remain unchanged, and due to the shared core structure of cellulose, these peaks are generally retained (Monteiro et al. 2014).

When analyzing the FTIR spectra after treatment durations of 48 and 60 h, a significant decline in the peak intensity at 1725 cm^{-1} (associated with hemicellulose) is observed. This is considered to be a result of hemicellulose degradation. A decrease in the peaks at 1628 cm^{-1} and 1510 cm^{-1} (associated with lignin) suggests that some lignin has been removed. The intensity at 1255 cm^{-1}, which is attributed to hemicellulose, also decreases further, confirming the chemical changes within the fiber (Cardoso et al. 2014). There is an increase in fiber surface exposure due to the removal of hemicellulose and lignin, suggesting an increase in hydrophilicity, as indicated by the enhanced intensity of the hydroxyl (–OH) stretching peak at 3350 cm^{-1}. A more distinct effect is observed after 120 h of treatment, where the hemicellulose and lignin absorption peaks are more substantially diminished. The band at 1725 cm^{-1} is almost completely obliterated, indicating extensive hemicellulose degradation and a more exposed cellulose structure. Furthermore, the 1628 cm^{-1} and 1510 cm^{-1} peaks continue to decrease, showing progressive delignification. The peak at 1427 cm^{-1}, now more prominent due to the relatively higher cellulose content, also increases in intensity, as cellulose becomes the dominant component after the removal of non-cellulosic constituents (Lekrine et al. 2025).

The treatment with $NaHCO_3$ for 140 h leads to the FTIR spectra showing a notable reduction in the peaks corresponding to hemicellulose or lignin, which indicates their removal. The structure of the highly purified cellulose is indicated by the decreased intensity of the bands at 1725 cm^{-1} and 1255 cm^{-1}. The sharpened and more prominent characteristic peaks of cellulose at 1432 cm^{-1} and 897 cm^{-1} indicate greater crystallinity. The fiber's increasing cellulose-rich matrix composition is further evidenced by the strong reduction of lignin-related peaks at 1628 cm^{-1} and 1510 cm^{-1}, confirming the removal of lignin. Composite materials can be fabricated more readily from the purified fibers, showing that the $NaHCO_3$ treatment is effective in removing hemicellulose and lignin from Curauá fibers (Dembri et al. 2025). Coir and sisal have been reported to undergo similar transformations when treated with an alkaline solution, while Liu et al. (Liu et al. 2004) made additional confirmatory observations on natural grass fibers, noting that $NaHCO_3$ treatment aids in altering the fibers' composition.

Thermogravimetric Analysis (TGA)

The comparison between untreated and sodium bicarbonate ($NaHCO_3$)-treated CF over differing treatment durations (12, 24, 48, 60, 120, and 240 h), as shown through thermogravimetric analysis (TGA), reveals a two-stage thermal degradation process. The thermal curves demonstrate how chemical treatment impacts the thermal stability of CF fibers. Similar to other natural fibers, CF exhibits a primary moisture loss below 150 °C, followed by the decomposition of hemicellulose, cellulose, and lignin at higher temperatures. The thermal disintegration of cellulose occurs at approximately 380 °C, while both hemicellulose and lignin decompose in the range of 245–390 °C. With longer treatment duration, the non-cellulosic constituents are gradually eliminated, which, in turn, reduces the moisture sensitivity of the CF fibers (Dembri et al. 2024). Figure 5 presents the TGA of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites. In TGA, the variations in the curves are minimal. This may happen due to the following reasons:

Sodium Bicarbonate Treatment's Mildness

Compared to stronger bases like sodium hydroxide, $NaHCO_3$ qualifies as a weaker alkaline agent, which would be suitable for aggressive fiber treatments. Its chemical action is mild, primarily working on surface impurities and the more loosely associated hemicellulose/lignin. These effects will modify the fiber composition to some extent; however, the effects on the bulk thermal stability of the cellulose-rich structure will remain unchanged (Ganesan et al. 2025).

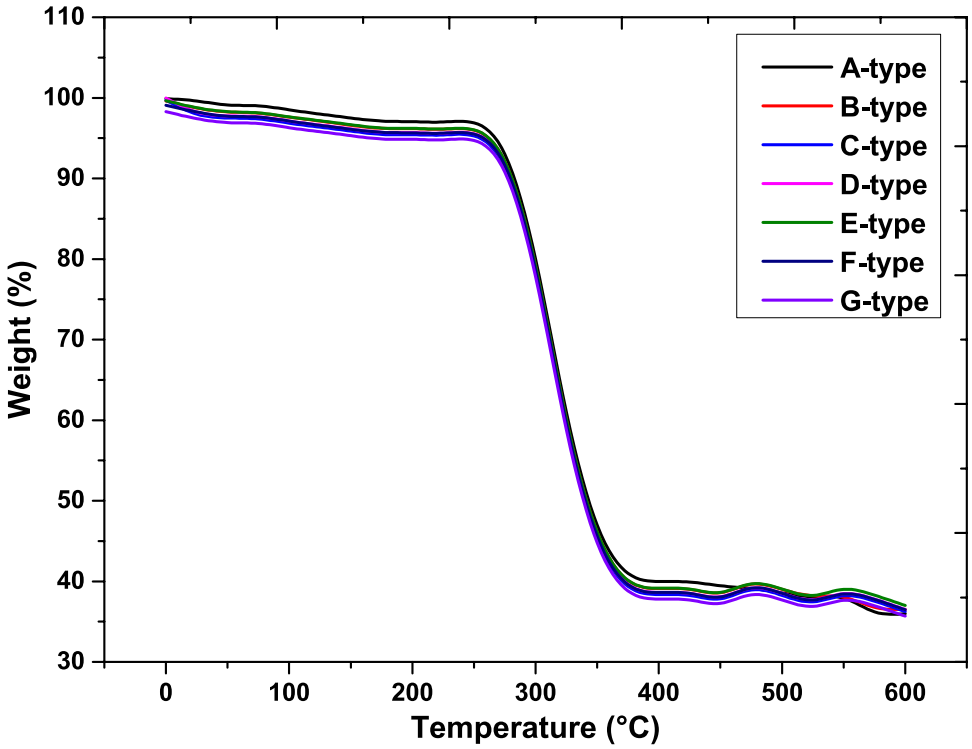

Fig. 5 TGA of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

Minimal Thermal-Degradable Component Removal

Although some non-cellulosic elements may be gradually removed over time, their overall impact during thermal degradation, particularly within 245 to 390 °C, is likely not significant enough to cause noticeable changes in the degradation peaks on the TGA curve.

Decomposition Peak Overlap and Measurement Sensitivity

The thermal degradation temperatures of hemicellulose, cellulose, and lignin are often designated. The major thermal event for the cellulose, around 380 °C, will mask any shifts from minor constituents that are subtle, even if some removal occurs (Ganesan et al. 2024).

Composite Effects in Hybrids of CF, SCB, and PLA

As the TGA was conducted on the CF/SCB/PLA hybrid composites, the thermal behavior was an integrated response from all three constituents. The effects of fiber treatment may also be masked by the thermal properties of the PLA and SCB matrices, which would further decrease observable differences (Velmurugan et al. 2024).

An untreated CF fiber shows a distinct peak corresponding to hemicellulose degradation in the thermogravimetric curves (DTG). After treating the fibers with $NaHCO_3$ for 12 h and 24 h, the intensity of this peak slightly decreases, indicating the initial stages of hemicellulose breakdown. With treatment durations of 48 to 60 h, the peak further decreases, suggesting progressive hemicellulose removal. A most substantial reduction in weight loss due to hemicellulose is observed in CF fibers treated for 120 h, indicating significant chemical alteration (Velmurugan et al. 2023a). By the 240-h mark, this peak disappears entirely from the graph, indicating that near-complete hemicellulose degradation has occurred, resulting in a structure more dominated by cellulose. Figure 6 illustrates the DTG analysis of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites.

The maximum degradation temperatures of CF fibers change with variations in treatment time. Untreated CF fibers have an approximate maximum degradation temperature of 362 °C. Fibers treated for 12, 24, 48, 60, 120, and 240 h exhibit respective degradation temperatures of 353, 342, 340, 337, 330, and 324 °C. The gradual decrease in thermal resistance over time is a result of cellulose pyrolysis and lignin removal, which paradoxically enhances the fiber's overall thermal char-forming behavior. In contrast to the treated degradation temperature, a notably higher char residue formation is observed after treatment. Fibers treated for 240 h show approximately 20% char yield, underscoring their increased potential for carbonization (Dalla Libera Junior et al. 2020). These results are also reflected in the TGA and closely align with findings from the FTIR analysis. The results further validate that, as treatment time increases, there is a progressive reduction in hemicellulose and lignin content. Alkaline-treated sisal and coir fibers have also shown similar thermal behavior, demonstrating

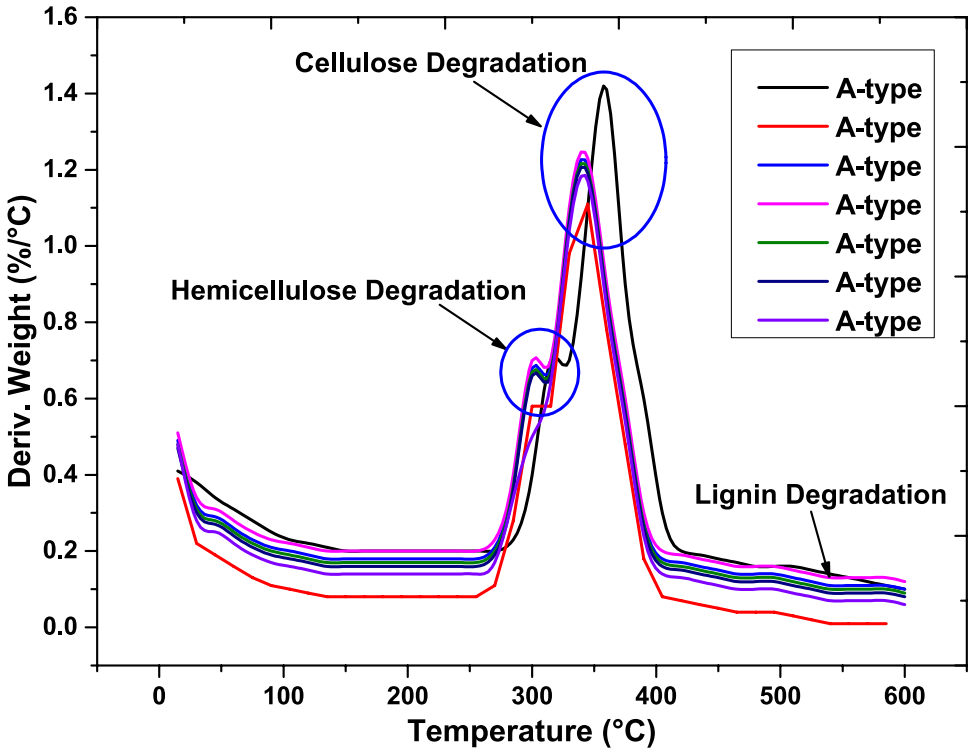

Fig. 6 DTG analysis of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

the compositional transformation of fibers due to $NaHCO_3$ treatment. While prolonged treatment results in a shift in thermal stability, it significantly improves the fiber's char-forming ability, providing better insulation against fire and extreme temperature (Matheswaran et al. 2023).

Differential Scanning Calorimetry (DSC) Analysis

Differential scanning calorimetry (DSC) studies on untreated and sodium carbonate ($NaHCO_3$)-treated CF over varying treatment durations (12, 24, 48, 60, 120, and 240 h) help elucidate the fibers' thermal transitions. DSC thermograms for the $NaHCO_3$-treated CF fibers retain a similar overall shape to that of the untreated fibers, indicating that the basic thermal characteristics of the fibers remain largely unchanged with treatment. The DSC graphs display an endothermic peak at approximately 169 °C, corresponding to moisture loss in the untreated CF fibers (Velmurugan et al. 2023b). This peak shifts in the treated fibers depending on the duration of treatment. For the treated fibers, the peak is observed at 165 °C, 170 °C, 174 °C, 176 °C, 177 °C, and 178 °C for treatment durations of 12, 24, 48, 60, 120, and 240 h, respectively. The slight reduction in peak temperature for the 12- and 24-h treated fibers suggests an increase in thermally sensitive amorphous cellulose content. As the treatment progresses, the peak temperature becomes more stabilized, indicating that a greater proportion of ordered (crystalline) cellulose structure is retained within the fiber–matrix (Sisti et al. 2018).

In addition, structural changes due to the treatment were confirmed by the small endothermic peaks associated with cellulose decomposition observed in the $NaHCO_3$-treated CF. The exothermic peaks between 250 and 320 °C, linked to hemicellulose decomposition, are also observed in TGA. The emphasis on hemicellulose depletion increases over time, with the peaks gradually shifting with longer treatment duration. The untreated CF has an enthalpy with a value of approximately 130.5 J/g. Treated fibers at 12 and 24 h show decreased enthalpy values of 128.3 J/g and 126.5 J/g, respectively, indicating some structural relaxation of cellulose due to hemicellulose depletion. However, CF with 48 h exhibits tighter polymer chains, resulting in a higher enthalpy value of 148.7 J/g, which could be attributed to the rearrangement of the fiber structure influenced by $NaHCO_3$. After 60 h of treatment, the values tend to stabilize around 127.2 J/g, with 120 h of treatment showing a slight decline. The value continues to decrease after 240 h, reaching an approximate value of 124.8 J/g, indicating an increasingly relaxed fiber structure (De Oliveira et al. 2024). Figure 7 shows the DTG analysis of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites.

These findings indicate that the treatment of Curauá fibers with $NaHCO_3$ alters their thermal properties as a result of structural rearrangement. For the shorter treatment durations (12–24 h), there is an observed decrease in enthalpy, attributed to the partial removal of hemicellulose and relaxation of cellulose chains. The increase in enthalpy noted at 48 h suggests a temporary reorganization of cellulose chains, making

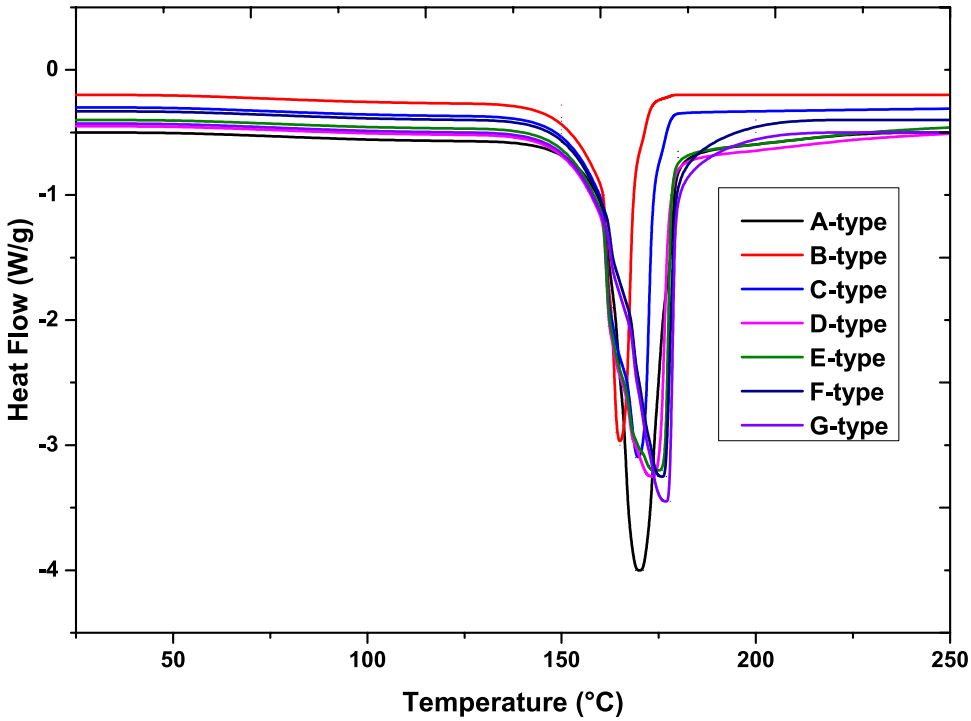

Fig. 7 DTG analysis of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

the fiber–matrix more thermally stable. However, longer treatment durations (60–240 h) result in a gradual decrease in enthalpy, indicating pronounced structural changes due to loss of hemicellulose and some lignin. These results are in good agreement with FTIR and TGA and provide evidence that $NaHCO_3$ treatment is effective in altering the thermal properties of natural CF.

Mechanical Characterization

Tensile and Flexural Properties

The incorporation of sodium bicarbonate ($NaHCO_3$) into Curauá fibers (CF) significantly improves the tensile and flexural strength of PLA/SCB/CF hybrid biocomposites. The treatment modifies the chemical structure of the fiber surface by removing some amorphous surface components, such as swelling hemicellulose and other impurities, thereby enhancing fiber–matrix interfacial adhesion. With $NaHCO_3$ treatment at 12 h, there is only minimal modification of CF as it does not efficiently remove surface impurities and amorphous materials. A substantial amount of hemicellulose and other non-cellulosic constituents remains, which impairs proper interfacial bonding with the PLA matrix. Consequently, the tensile strength (36.98 MPa) and flexural strength (43.25 MPa) of B-type hybrid biocomposites remain lower compared to composites treated for longer durations. This insufficient bonding also results in poor stress transfer due to the presence of partially untreated fiber components, diminishing overall mechanical performance. The lower tensile and flexural moduli can be attributed to the more flexible, less rigid fiber structure. Although the addition of 5 wt.% sugarcane biochar (SCB) provides some reinforcement, it proves largely ineffective, as the fiber treatment is insufficient to allow the biochar to significantly improve interface bonding (Bajpai et al. 2014). Figure 8 demonstrates the tensile strength and modulus of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites.

At 24 h (42.35 MPa in tensile & 53.21 MPa in flexural) and 48 h (46.47 MPa in tensile and 62.54 MPa in flexural) of treatment, additional improvements in mechanical properties become noticeable. This is due to the partial removal of hemicellulose, which aids fiber–matrix adhesion by reducing hydrophilicity and enabling better load transfer, thereby enhancing both tensile strength and flexural strength. The most significant impact on the flexural and tensile moduli is observed at this stage, with the highest value. This performance is attributed to the partial retention of hemicellulose, which offers an optimal balance between stiffness and flexibility. The fiber structure becomes sufficiently rigid to deliver high modulus values while remaining compatible with the PLA matrix (Sanjeevi et al. 2021). Additionally, the presence of biochar further contributes to increased stiffness by acting as a secondary reinforcement and restricting polymer chain mobility. Compared to the untreated or minimally treated fibers, the B-type and C-type hybrid biocomposites demonstrate remarkable improvement in mechanical performance, particularly in terms of modulus of elasticity. Figure 9 demonstrates the flexural strength and modulus of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites.

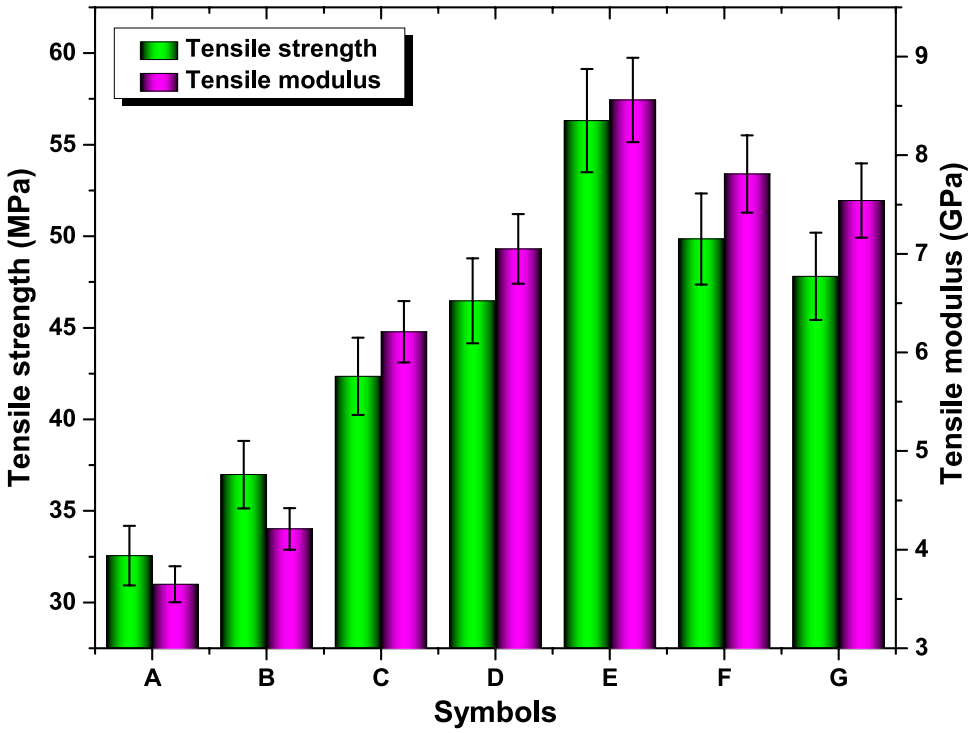

Fig. 8 Tensile strength and modulus of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

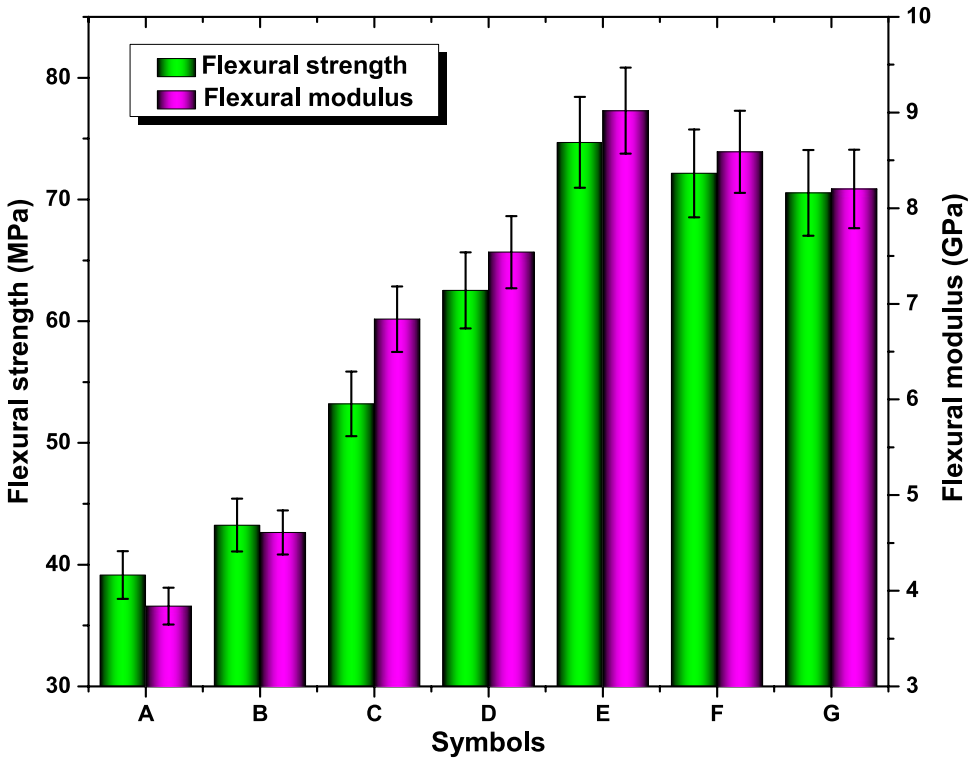

Fig. 9 Flexural strength and modulus of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

The inclusion of 5 wt.% biochar plays a significant role in enhancing the composite by providing the additional interfacial bonding and restricting polymer chain mobility. However, biochar alone cannot compensate for weak fiber–matrix adhesion, highlighting the necessity for adequate fiber treatment. Mechanical properties gradually improve up to 60 h of treatment (56.32 MPa in tensile & 74.69 MPa in flexural) but decline at 120 h (49.85 MPa in tensile & 72.15 MPa

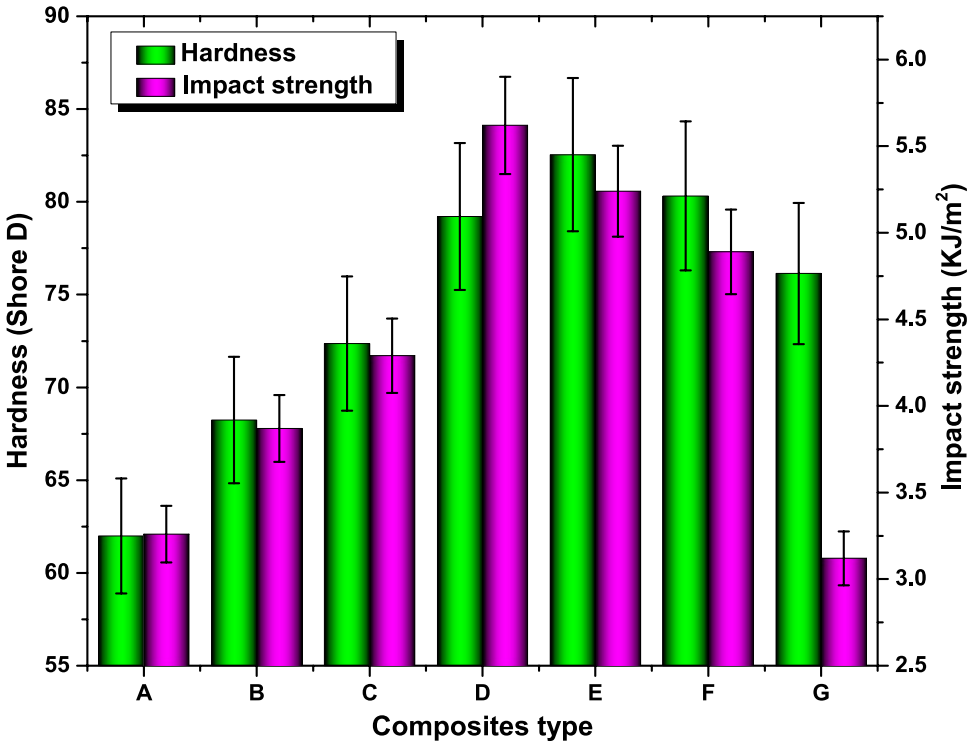

Fig. 10 Hardness and impact strength of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

in flexural) and 240 h (47.81 MPa in tensile & 70.54 MPa in flexural). This suggests that excessive treatment results in the over-removal of essential fiber constituents, leading to brittleness and poor mechanical performance. Similar results were reported by Faris et al. (Al-Oqla et al. 2022) and Lekrine et al. (Lekrine et al. 2024b) for polypropylene biocomposites reinforced with DPFs and WF/PLA composites, respectively. Treatments beyond 60 h., particularly at 120 and 240 h., remove a significant amount of hemicellulose and partially degrade amorphous cellulose, resulting in over-etched fibers, making them more brittle and weaker in tensile strength. Since hemicellulose serves as a natural binder between fibrils, its depletion reduces the integrity of fiber–polymer bonding. As a result, the fibers became more prone to fracturing under lower tensile loads. Furthermore, excessive $NaHCO_3$ exposure may offer additional surface roughness, which negatively impacts the mechanical performance (Sekar et al. 2020).

Hardness and Impact Properties

The Shore D hardness of PLA hybrid biocomposites using 5 wt.% sugarcane biochar and sodium bicarbonate ($NaHCO_3$)-treated Curauá fibers (CF) varies with the treatment duration, reflecting changes in fiber–matrix interaction and composite structural integrity. Hardness indicates the material's resistance to indentation, and it is influenced by fiber reinforcement, biochar addition, and interfacial bonding among the material's constituents. According to the results, the hardness increases with treatment time up to a certain level, after which it starts to decrease. The E-type (i.e., 48-h treatment) biocomposite demonstrates the highest Shore D hardness (82.54 Shore D), which corresponds to the maximum removal of hemicellulose and surface impurities, resulting in strong fiber–matrix adhesion and greater composite density. The inclusion of biochar also contributes to the hardness, acting as a rigid filler that restricts polymer chain mobility and increases the overall material stiffness (Kumar et al. 2023).

At lower treatment times (12 and 24 h), the Shore D hardness value (68.24 & 72.36 Shore D, respectively) is relatively low due to the incomplete removal of hemicellulose, which results in weaker adhesion between the fiber and matrix. Residual hemicellulose may lead to microvoid formation or weakened interfacial bonds, which lowers the composite surface's resistance to indentation. However, treatment at 48 h (79.81 Shore D) and 60 h (82.54 Shore D) creates optimal modification to fiber morphology, improving the material's load-bearing capacity and giving the highest hardness values. Beyond 60 h, especially for 120 and 240 h, there is a decrease in Shore D hardness with a value of 80.32 for F-type & 76.14 for G-type, respectively. The reasons behind this may be fiber degradation with excessive hemicellulose removal and partial amorphous cellulose degradation (Wang et al. 2018). These changes render the fibers more brittle and less effective as mechanical reinforcement, leading to a softer material with less hardness. The reduction in hardness with prolonged treatment aligns

with impact resistance trends, where over-treatment compromises the reinforcing capability of the fibers. Figure 10 demonstrates the hardness and impact strength of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites.

The Izod impact test is a method for evaluating impact strength and determining the material's ability to absorb and disperse impact loads and pressures. It is an additional tool to assess the structural integrity of the materials. PLA hybrid biocomposites reinforced with SCB and CF fibers treated with sodium bicarbonate (10% $NaHCO_3$) for varying processing durations (0, 12, 24, 48, 60, 120, and 240 h) show variations in impact resistance as illustrated in Fig. 10. The findings of the Izod impact tests indicate that sodium bicarbonate pretreatment significantly influences the impact behavior of the hybrid composites. The D-type biocomposite (48 h treated) exhibited the highest impact strength of 5.62 kJ/m^2, indicating an optimal balance between matrix adhesion and fiber structure. However, the CF fibers that were treated for more than 48 h eventually lose their impact strength, likely due to fiber embrittlement (Alagumalai et al. 2021). Reduced impact resistance in plant-fiber-based biocomposites has been previously reported by several researchers (Ramesh et al. 2019). The enhanced interfacial adhesion between the PLA and treated CF results in more fiber breaks during impact testing, which lowers the impact resistance of the hybrid biocomposites. It occurs because fiber pull-out dissipates more energy than fiber breakage. Compared to the A-type biocomposite, the impact resistance of the B and C types increased by 15.76% and 24%, respectively. However, as compared to the other fabricated hybrid composites, the G-type biocomposite exhibited the least amount of impact resistance (3.12 kJ/m^2). In comparison, Tokoro et al.'s (Tokoro et al. 2008) reported on PLA biocomposite reinforced with pretreated bamboo fibers (1.51 kJ/m^2), and Sarmin et al.'s (Sarmin et al. 2023) documented 2.39 kJ/m^2 for a bioepoxy material based on date palm fibers. Both values are lower than the D (5.62 kJ/m^2) type hybrid composite.

Microstructural analysis

Scanning electron microscopy (SEM) images of the transverse and longitudinal surface topography of raw and sodium bicarbonate-treated (10% $NaHCO_3$) CF fibers at various treatment durations (12, 24, 48, 60, 120, and 240 h) are shown in Fig. 11. The untreated CF fibers display the natural oils and wax on their surface and exhibit limited fibrillation. Figure 11a–g demonstrates that the untreated CF fiber surface seems smoother than the rougher surface observed in sodium bicarbonate-treated CF fibers. The pretreatment chemical action eliminates the hemicelluloses and lignins, hydrogen bonds on the fiber surface, thereby enhancing the degree of roughness (Geremew et al. 2024; Rao et al. 2024). This increased roughness encourages bonding between the fibers and the matrix, as a rougher surface promotes better mechanical interlocking with the matrix. At the same time, longer treatment exhibits the fiber breakdown, which is explained by using the tensile testing observation.

The SEM analysis of the tensile fractured specimens (Fig. 12a–g) investigates the influence of sodium bicarbonate ($NaHCO_3$) treatment on the fiber–matrix interaction and failure mechanisms in PLA/SCB/CF hybrid biocomposites. The untreated composite, referred to as PLA/SCB/RCF, exhibits weak interfacial bonding, which results in fiber pull-out and void formation, both of which negatively impact the load transfer. In composites treated for 12 and 24 h, there is some partial removal of hydrolysis-induced hemicellulose, which helps to increase the bonding; however, evidence of some fibers debonding and pulling out remains present (Sabziparvar et al. 2024). At 48 and 60 h of treatment, the fiber surfaces exhibited improved roughness, promoting enhanced mechanical interlocking with the PLA matrix and resulting in notable improvements in tensile strength and modulus. SEM imaging on E-type composites showed the best fiber–matrix adhesion with minimal voids and cohesion failure, indicating effective distribution of stress (Lakshmaiya et al. 2022b). The addition of 5 wt.% biochar further improves the bonding as it acts as a reinforcing agent that inhibits crack propagation. However, longer treatment, such as 120 and 240 h, leads to the removal of the excess hemicellulose and weakening of the fiber structure. This promotes the fiber embrittlement, indicating a lowering of the tensile properties (Zhang et al. 2024). Therefore, an optimum treatment duration of 48–60 h provides the most favorable results in fiber strength, bonding, and mechanical performance.

Density Measurement

Measuring the density of PLA/SCB/CF hybrid biocomposites provides the consequences of $NaHCO_3$ treatment durations on fiber morphology, interaction of the fiber and the matrix, and overall structural compactness of the composite. Unlike other studies that estimate density depends on different filler ratios, this research maintains a constant biochar content of 5 wt% and detaches the impact of fiber treatment duration (0, 12, 24, 48, 60, 120, and 240 h). Changes in density show how well the materials stick together, how much hemicellulose and impurities have been removed, and how strong the composite structure is due to better mixing of the materials. Figure 13 demonstrates the density profiles of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites.

The results demonstrate that hybrid composite density is influenced by the $NaHCO_3$ treatment durations of CF, primarily alteration in chemical structure, surface topography, and the interaction of fiber and matrix. The untreated CF (A-type) exhibits a comparatively low density of 1.29 g/cm^3,

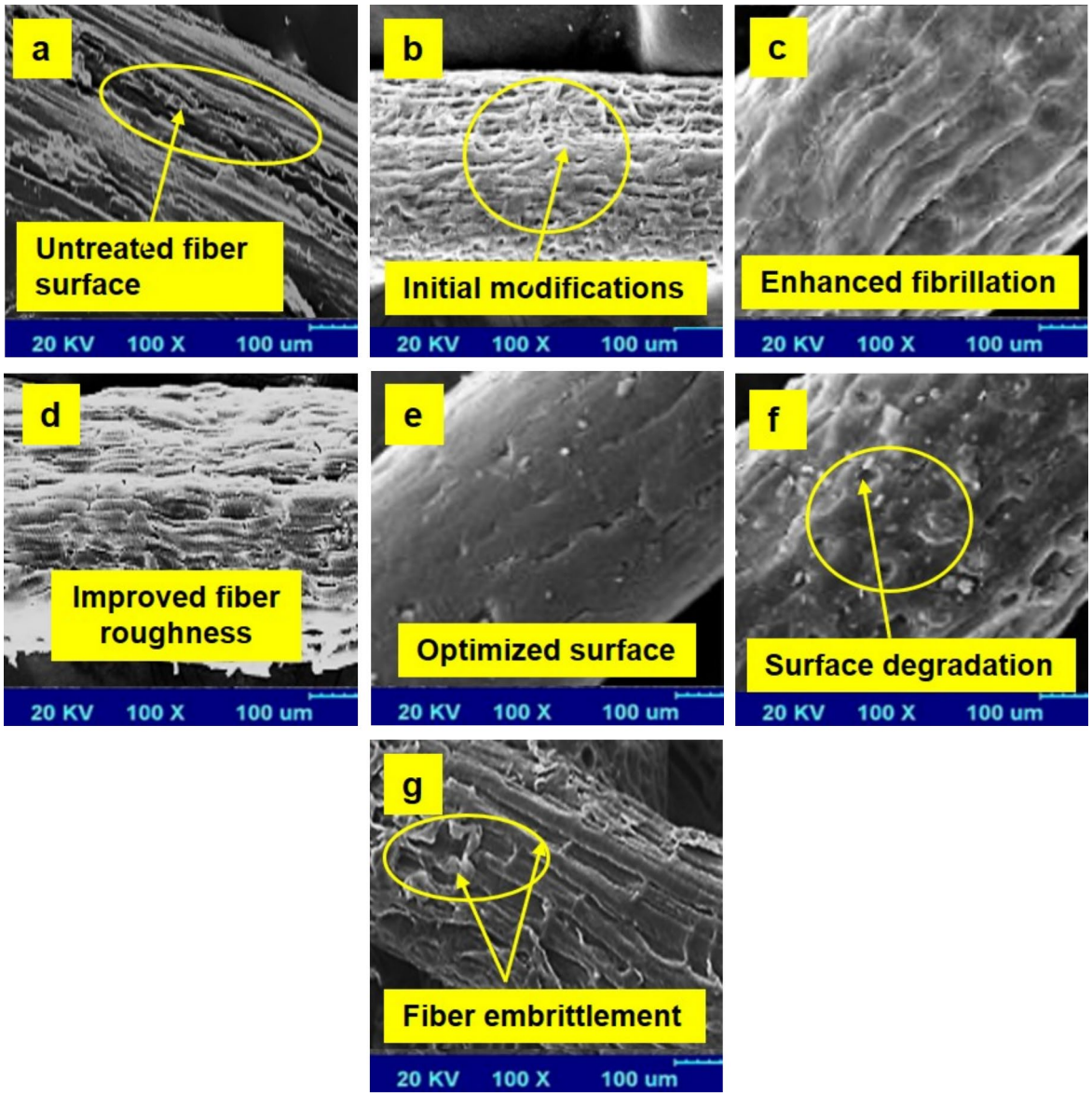

Fig. 11 Microstructural analysis of CF fiber (**a**) untreated and $NaHCO_3$ treated (**b**) 12 h, (**c**) 24 h, (**d**) 48 h, (**e**) 60 h, (**f**) 120 h, (**g**) 240 h

attributed to the presence of surface contaminants and residual hemicellulose. These presenting components contribute to the formation of microvoids at the fiber–matrix interface, resulting in ineffective packing within the composite. As the treatment duration increases up to 60 h, the remaining amorphous and hemicellulose components are effectively removed. This action enhances the fiber–matrix wettability and interfacial adhesion, reducing porosity and improving fiber–matrix compactness in the composite (Zaini et al. 2024). From this, composite density increases from 1.29 to 1.44 g/cm^3. This phase shows concurrent improvements in mechanical properties.

A significant reduction in density was observed in composites reinforced with CF treated for 120 h (F-type, density of 1.36 g/cm^3) and 240 h (G-type, density of 1.36 g/cm^3). This decrease is attributed to the over-degradation of hemicellulose and partial hydrolysis of type I amorphous cellulose, which makes the fibers more brittle and reduces their mass density. The over-treated fibers exhibit microcracks and surface erosion, leading to lower fiber bulk density and increased composite void content, both contribute to the reduced overall composite density (Government et al. 2024; Rao et al. 2024). Additionally, excessive removal of hemicellulose weakens the bonding strength between the fiber and the PLA matrix, increasing the likelihood of poorly compacted regions and microvoid formation during processing. The inclusion of biochar at a constant rate of 5 wt.% impacts the density

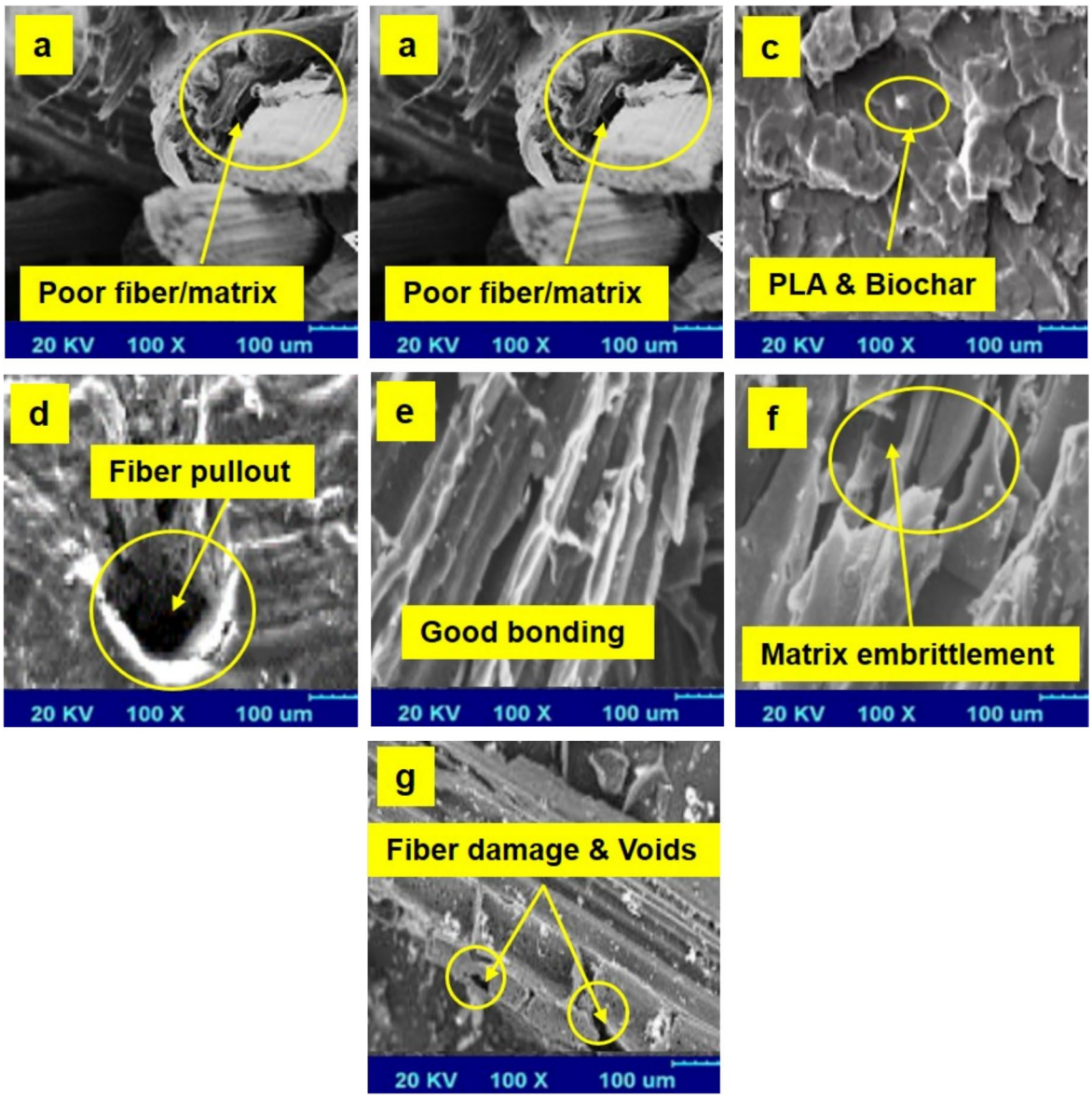

Fig. 12 Microstructural analysis of CF/SCB/PLA-based hybrid composites after tensile strength (**a**) untreated and $NaHCO_3$ treated (**b**) 12 h, (**c**) 24 h, (**d**) 48 h, (**e**) 60 h, (**f**) 120 h, (**g**) 240 h

patterns. Biochar contributes to interfacial adhesion due to its porous structure and high surface area while restricting polymer chain mobility (Latha et al. 2023). However, since its concentration remains constant across all treatment durations, its influence on density does not vary significantly. It ensures biochar is present constantly at 5%. And therefore, the observed density variations are primarily governed by the structural modifications of the fibers rather than changes in biochar proportion. The optimal combination of fiber modification and density enhancement occurs at 48–60 h of treatment, where hemicellulose removal significantly improves fiber–matrix bonding while preserving the structural integrity of the fiber (Alagarsamy et al. 2024).

Water Absorption Characteristics

Water absorption is one of the key properties that affect the lifespan and the functionality of biocomposites reinforced with natural fibers. The water absorption behavior of PLA/SCB/CF hybrid biocomposites is notably influenced by the duration of sodium bicarbonate ($NaHCO_3$) treatment applied to the CF fibers. Since the biochar content is maintained at a constant of 5 wt%, variations in

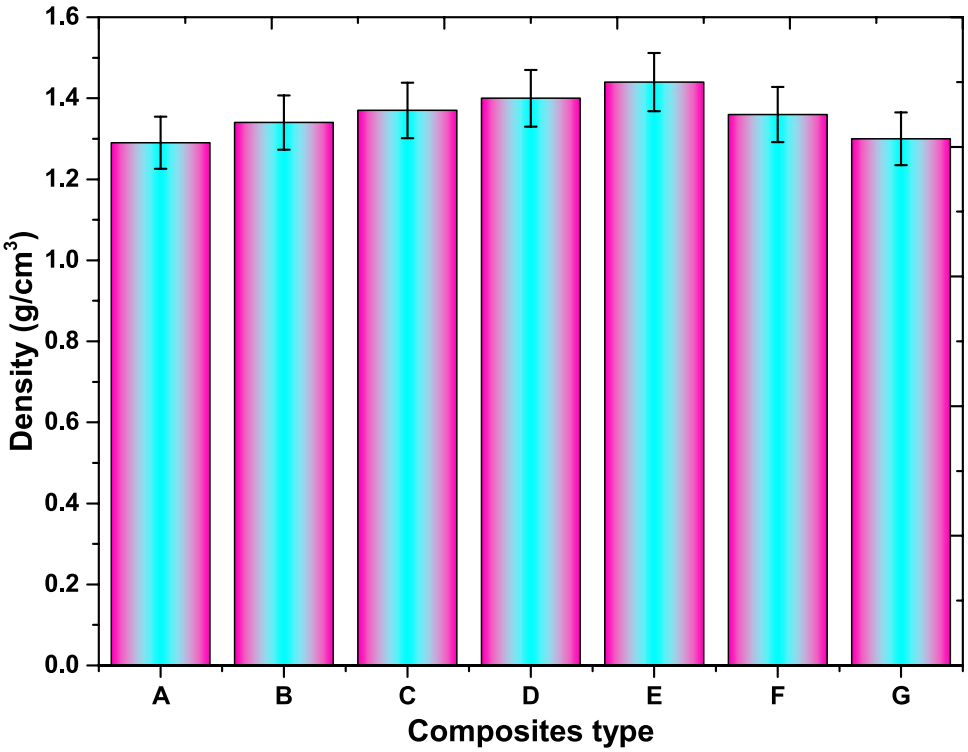

Fig. 13 Density of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

water uptake are primarily governed by changes in fiber structure and fiber and matrix interaction. The results suggest that untreated CF (A-type) exhibits the highest water absorption due to its high hemicellulose content, which promotes hydrophilicity and facilitates moisture intake via capillary action. As treatment duration increases, water absorption decreases, reaching an optimal reduction at a treatment duration of 48–60 h. Figure 14 demonstrates the

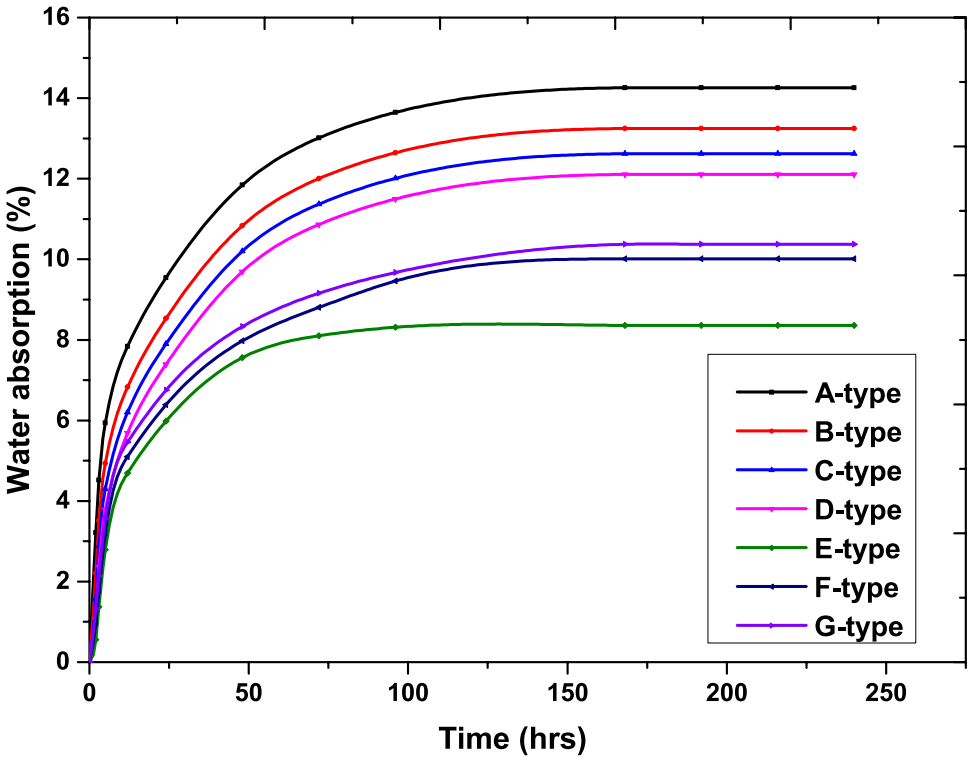

Fig. 14 Water absorption behavior of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites

water absorption behavior of raw and $NaHCO_3$-treated CF/SCB/PLA hybrid composites.

This trend occurs because moderate hemicellulose removal (12, 24, 48, and 60 h) reduces the number of -OH groups capable of attracting water while enhancing fiber–matrix bonding, which restricts water's permeation (Shifa et al. 2024). As the treatment improves interfacial bonding, lowers the void ratio, and results in a more compact composite structure, the E-type composite exhibits the least water absorption. These factors collectively reduce water ingress into the composite. However, water absorption begins to rise again after 60 h, particularly at 120 and 240 h. This increase is attributed to the excessive treatment, which causes fiber fragmentation, enlarged porosity, and microcrack formation on the fiber surface. Overtreated fibers become more brittle and are less capable of effectively bonding with the PLA matrix, increasing the microvoid population and weakening the overall composite structure, thereby leading to greater water absorption (Panneerselvam et al. 2025).

Furthermore, the presence of biochar plays an important role in managing water retention. Due to its high surface area and porous structure, biochar can retain some moisture. However, in this experiment, its water-repellent characteristic reinforces the fiber–matrix interface, thereby enhancing the moisture resistance by limiting excess moisture diffusion. As a result, biochar contributes to the overall water resistance of the composite. In summary, the water absorption behavior of PLA hybrid biocomposites is strongly influenced by the fiber treatment duration (Al Abdallah et al. 2024; Azka et al. 2024). Moderate treatment (48–60 h) improves fiber surface chemistry, enhances interfacial adhesion, and reduces voids, leading to the lowest water absorption. Conversely, insufficient treatment (0–24 h) retains hydrophilic hemicellulose, while excessive treatment (120–240 h) causes fiber brittleness and increased porosity, resulting in high water uptake. Therefore, an optimal treatment duration of around 60 h is necessary to enhance the water resistance and long-term durability of the hybrid biocomposites.

The uniform trend in water absorption during the first exposure period (up to ~ 96 h) is a diffusion mechanism, which is typical of natural fiber-reinforced composites. It is largely governed by Fickian diffusion, which is a diffusion-controlled process where water molecules advance toward the fiber–matrix interface, water evaporation equilibrium.

From a practical perspective, the fact that water absorption follows a linear or predictable rate should not necessarily be a disadvantage; it has certain benefits as well:

Predictability and Design Assurance

This property enables the engineers to model and forecast moisture effects, which gives them confidence in the humid environment material selection and design for automotive interiors, packaging, consumer goods, etc. (Sanjeevi et al. 2021).

Material Integrity Maintained

The composites do not undergo swelling, delamination, or degradation; the dimensional stability volume increases with time. Retention of sample water uptake during the test suggests water retention is in good equilibrium, especially for the CF-60 sample treated for 60 h, which had the lowest water uptake and the highest tensile strength.

Optimized Treatment Limits Moisture Sensitivity

The treatment of Curauá fibers using $NaHCO_3$ improved adhesion to the fiber–matrix as well as reduced water absorption by increasing the barrier and aiding in degassing pore entrances, thus enhancing interfacial bonding. The findings indicate that CF-60 (E-type) has the best fit for practical use as it balances the mechanical properties with water resistance (Lakshmaiya et al. 2022a).

Thus, the linear absorption curve observed does not negatively impact applicability; rather, it offers a stable and convenient moisture response.

Conclusion

This research comprehensively analyzed the impact of sodium bicarbonate ($NaHCO_3$) treatment on the microstructural, thermal, mechanical, and physical properties of PLA/SCB/CF hybrid biocomposites reinforced with 5 wt.% of sugarcane biochar. The $NaHCO_3$ treatment of the fiber surfaces significantly enhanced the fiber–matrix adhesion due to effective removal of hemicellulose and other surface impurities, which promoted improved mechanical interlocking.

- FTIR investigation confirms that sodium bicarbonate treatment removes the hemicellulose and lignin gradually from Curauá fibers, as indicated by the regular degradation of absorption peaks (1725, 1628, 1510, and 1255 cm^{-1}), while the sharpening and retention of cellulose peaks (1432 and 897 cm^{-1}) are the indications of increased cellulose content and crystallinity of the fibers.
- TGA confirms that hemi and lignin content are reduced with the sodium bicarbonate treatment of Curauá fibers. This results in a lower thermal degradation temperature while significantly increasing char residue (up to ~ 20% at 240 h). This indicates enhanced thermal stability and fire resistance through improved carbonization potential. DSC investigation shows $NaHCO_3$ treatment gives nota-

ble changes to the thermal and structural properties of CF. Initial enthalpy reduction is linked to hemicellulose removal, a peak in thermal stability at 48 h corresponds to the observed cellulose chain modifications, and gradual enthalpy reductions at longer durations indicate an increase in fiber relaxation and compositional alterations.

- Evaluating the mechanical properties of the untreated composites, the tensile strength was recorded at 32.56 MPa. After 60 h of $NaHCO_3$ treatment, the strength improved to 56.32 MPa due to enhanced fiber–matrix adhesion. The modulus of elasticity also followed this trend, reaching 8.56 GPa at 60 h. Similarly, flexural strength increased from 39.14 MPa to 74.69 MPa and impact strength rose from 3.26 kJ/m^2 to 5.62 kJ/m^2. At 60 h of $NaHCO_3$ treatment, the highest hardness values of 82.54 Shore D were indicated. These results suggest optimal fiber surface modification and strong fiber–matrix adhesion. In contrast, the 12-h and 24-h treatments exhibit 68.24 and 72.36 values of Shore D, respectively. However, a decline in mechanical properties was observed at longer treatment durations, i.e., 120 h and 240 h, indicating fiber embrittlement.
- The addition of 5 wt.% sugarcane biochar significantly enhanced the composite's performance. Through micro- and ultra-void filling, the biochar improved interfacial adhesion, enabling more efficient load transfer. This improvement was reflected in the mechanical properties, where biochar-reinforced composites outperformed their non-biochar composites by 8–10% in both tensile and flexural strength. Furthermore, the inclusion of biochar contributed to greater thermal stability, by promoting char formation and delaying the onset of thermal degradation.
- The density of the hybrid biocomposites increases from 1.29 g/cm^3 (untreated) to a maximum of 1.44 g/cm^3 at 60 h of $NaHCO_3$ treatment. This enhancement indicates better fiber–matrix interaction and lower porosity. However, longer treatment durations (120 and 240 h) lower the density to 1.36 g/cm^3, which is caused by fiber degradation and porosity.
- The water absorption of PLA/SCB/CF hybrid biocomposites shows a significant decrease from 9.84% (untreated) to 4.26% at 60 h of $NaHCO_3$ treatment, indicating lower porosity and stronger interfacial bonding. Between 120 and 240 h, absorption increases due to fiber degradation and enhanced void content, confirming 48–60 h as the optimal treatment window for improving durability while reducing moisture uptake.

Application and Future Scope of the Research

The $NaHCO_3$-treated Curauá fiber (CF)/SCB/PLA hybrid biocomposites, containing 5 wt.% sugarcane biochar, exhibit great potential in lightweight, biosustainable, and thermally stable material-reliant industrial and engineering sectors. With higher mechanical properties, lower water absorption, and better interface adhesion, these biocomposites are suitable for automotive interior panels, door trims, dashboard components, and acoustical insulation. Enhanced Shore D hardness and thermal resistance commercially expand their uses in furniture, casings for household electronics, and packaging trays where strength, lightweight, and biodegradability are needed. The contribution of biochar to fire retardancy and dimensional stability enhances the value of these materials for eco-friendly construction, partition panels, ceiling boards, and other lightweight insulating building materials.

While this study establishes an optimal fiber treatment duration for enhanced biocomposite performance as 48–60 h, further work could be done to hybridize other natural fibers or nanoparticles to the specific properties of the composite. In addition, the long-term environmental durability of the composites, including UV exposure, microbial attack, and cyclic loading, requires additional investigation to confirm their suitability for outdoor or high-wear applications. Moreover, life cycle analysis (LCA) and techno-economic evaluations would assess the sustainable production scale of these green composites and their ecological impact. Investigating additive manufacturing (3D printing) with these biocomposite formulations could advance design and fabrication possibilities in biofabrication and customized structural components.

Strength and Weakness of the Current Study

Strengths

Holistic Approach to Characterization

- To understand the relation between the composite's performance and various fiber treatment durations, a multi-technique analysis was conducted, including DSC, SEM, TGA, FTIR, tensile, flexural, impact strength, Shore D hardness, water absorption, and density.

Treatment Duration Optimization

- The study's key contribution is highlighting a specific duration of 48–60 h that is beneficial for altering the surface topography in terms of thermal, mechanical, and moisture resistance properties, thereby aiding industrial implementation.

Sustainable Action

- The ecological sustainability, waste valorization, and the production of environmentally friendly composites.

Weakness

Lack of Defined Long-Term Durability Testing

- The study failed to approach either long-term aging or any environmentally induced aging, such as UV exposure or microbial resistance, which poses a practical challenge for real-world use.

Concentration of Fibers: Limited Study

- Only one type of fiber and filler with constant amounts was utilized with the PLA matrix. The impact of proportionate changes in the fiber or filler content on the attributes of the composite was not investigated.

Acknowledgements The authors thank the Mohan Babu University, Tirupati, Andhra Pradesh, India, for the technical assistance.

Author Contributions Velmurugan Ganesan and Jasgurpreet Singh Chohan helped in conceptualization, writing—an original draft, methodology. Prabhu Paramasivam and Ramya Maranan contributed to investigation, testing and evaluation. Kumar Gengappan, Natrayan Lakshmaiya and Suresh Kumar Shanmugam helped in review and editing.

Funding No funding was received for this research work.

Data Availability The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics Approval Not applicable.

Consent for Publication Yes. All permission granted.

Consent to Participate Not applicable.

References

Al Abdallah, H., and B. Abu-Jdayil. 2024. Enhancement of water absorption properties of date palm fibers-based composites via alkaline treatment. *Sustainable Chemistry and Pharmacy* 37 : 101375.

Ahmed, K., M. Hasan, and J. Haider. 2021. Electrical and mechanical properties of sugarcane bagasse pyrolyzed biochar reinforced polyvinyl alcohol biocomposite films. *Journal of Composites Science* 5 (9): 1–14. https://doi.org/10.3390/jcs5090249.

Al-Oqla, F. M., M. T. Hayajneh, and M. M. Al-Shrida. 2022. Mechanical performance, thermal stability and morphological analysis of date palm fiber reinforced polypropylene composites toward functional bio-products. *Cellulose* 29 (6): 3293–3309.

Alagarsamy, M., P. Pitchipoo, and S. Kumar. 2024. Comprehensive characterization of spathe fibres extracted from *Cocos nucifera*: Physical, chemical, mechanical, thermal, and acoustic properties for insulation applications. *Materials Research Express* 11 (7): 75503.

Alagumalai, V., V. Shanmugam, N. K. Balasubramanian, Y. Krishnamoorthy, V. Ganesan, M. Försth, G. Sas, F. Berto, A. Chanda, and O. Das. 2021. Impact response and damage tolerance of hybrid glass/kevlar-fibre epoxy structural composites. *Polymers* 13(16):2591. https://doi.org/10.3390/polym13162591.

Alsaeed, T., B. F. Yousif, and H. Ku. 2013. The potential of using date palm fibres as reinforcement for polymeric composites. *Materials and Design* 43:177–184. https://doi.org/10.1016/j.matdes.2012.06.061.

Araujo, J. R., C. B. Adamo, M. V. Costa e Silva, and M. De Paoli. 2013. Antistatic-reinforced biocomposites of polyamide-6 and polyaniline-coated curauá fibers prepared on a pilot plant scale. *Polymer Composites* 34 (7): 1081–1090.

Atoui, S., A. Belaadi, B. X. Chai, M. M. S. Abdullah, A. Al-Khawlani, and D. Ghernaout. 2024. Extracting and characterizing novel cellulose fibers from *Chamaerops humilis* rachis for textiles' sustainable and cleaner production as reinforcement for potential applications. *International Journal of Biological Macromolecules* 276 (2): 134029.

Azka, M. A., S. M. Sapuan, H. Abral, E. S. Zainudin, and F. A. Aziz. 2024. An examination of recent research of water absorption behavior of natural fiber reinforced polylactic acid (PLA) composites: A review. *International Journal of Biological Macromolecules* 268(1):131845. https://doi.org/10.1016/j.ijbiomac.2024.131845.

Bajpai, P. K., I. Singh, and J. Madaan. 2014. Development and characterization of PLA-based green composites: A review. *Journal of Thermoplastic Composite Materials* 27 (1): 52–81. https://doi.org/10.1177/0892705712439571.

Benarab, M., A. Belaadi, A. Bedjaoui, M. Boumaaza, and D. Ghernaout. 2025. Characterizing novel cellulosic fibers extracted from *Vicia faba* plant waste stems as a promising reinforcement for applications in sustainable textile and lightweight biocomposites. *International Journal of Biological Macromolecules* 307:141940.

Cardoso, P.H.M., F.L. Bastian, and R.M.S.M. Thiré. 2014. Curaua fibers/epoxy laminates with improved mechanical properties: effects of fiber treatment conditions. In *Macromolecular Symposia*. Wiley Online Library, pp. 63–70.

Dalla Libera, V., Jr., R. M. Leão, V. Franco Steier, and S. M. da Luz. 2020. Influence of cure agent, treatment and fibre content on the thermal behaviour of a curaua/epoxy prepreg. *Plastics, Rubber and Composites* 49 (5): 214–221.

Dembri, I., A. Belaadi, A. Lekrine, M. Boumaaza, M. Jawaid, A. S. Ismail, and D. Ghernaout. 2025. Structural and thermal properties of Alkali-treated biomass fibers and W. robusta waste reinforced PLA hybrid biocomposites. *Case Studies in Thermal Engineering* 70:106170. https://doi.org/10.1016/j.csite.2025.106170.

Dembri, I., A. Belaadi, A. Lekrine, M. Jawaid, A. S. Ismail, and D. Ghernaout. 2024. Effect of alkaline treatment on the thermo-physicochemical and mechanical properties of biochar powder/Washingtonia robusta fibers/PLA hybrid biocomposites. *Journal of Materials Research and Technology* 33:9735–9751. https://doi.org/10.1016/j.jmrt.2024.12.018.

Devnani, G. L., and S. Sinha. 2022. Utilization of natural cellulosic African teff straw fiber for development of epoxy composites:

Thermal characterization with activation energy analysis. *Journal of Natural Fibers* 19 (13): 6564–6575.

Fiore, V., T. Scalici, F. Nicoletti, G. Vitale, M. Prestipino, and A. Valenza. 2016. A new eco-friendly chemical treatment of natural fibres: Effect of sodium bicarbonate on properties of sisal fibre and its epoxy composites. *Composites Part B: Engineering* 85:150–160.

Ganesan, V., J. S. Chohan, A. Damodharan, P. Paramasivam, and R. Maranan. 2025. High-performance biocomposites: leveraging lotus fiber and waste Kigelia pinnata fruit shell biochar for enhanced mechanical and fire-retardant properties. *Polymer Bulletin* 82(9):3927–3961. https://doi.org/10.1007/s00289-025-05702-w.

Ganesan, V., V. Shanmugam, and V. Alagumalai. 2024. Composites Part C : Open access optimisation of mechanical behaviour of calotropis gigantea and prosopis juliflora natural fibre-based hybrid composites by using Taguchi-Grey relational analysis. *Composites Part c: Open Access* 13:100433. https://doi.org/10.1016/j.jcomc.2024.100433.

Geremew, A., P. De Winne, T. A. Demissie, and H. De Backer. 2024. Surface modification of bamboo fibers through alkaline treatment: Morphological and physical characterization for composite reinforcement. *Journal of Engineered Fibers and Fabrics* 19:15589250241248764.

Government, R. M., and E. T. Okeke. 2024. Effect of particle size on the properties of avocado pear wood fiber/low-density polyethylene composite enhanced by pretreatment. *Materials Testing* 66 (1):22–35.

Kabir, M. M., H. Wang, K. T. Lau, and F. Cardona. 2013. Tensile properties of chemically treated hemp fibres as reinforcement for composites. *Composites Part b: Engineering* 53:362–368.

Kim, J. T., and A. N. Netravali. 2010. Composites : Part A Mercerization of sisal fibers : Effect of tension on mechanical properties of sisal fiber and fiber-reinforced composites. *Composites Part A* 41 (9): 1245–1252. https://doi.org/10.1016/j.compositesa.2010.05.007.

Kir, M., M. Boudiaf, A. Belaadi, M. Boumaaza, M. Bourchak, and D. Ghernaout. 2024. Extracting and characterizing of a new vegetable lignocellulosic fiber produced from C. humilis palm trunk for renewable and sustainable applications. *International Journal of Biological Macromolecules* 281:136495.

Kumar, S., R. Dang, A. Manna, S. Sharma, S. P. Dwivedi, A. Kumar, C. Li, and M. Abbas. 2023. Effect of chemically treated kenaf fiber on the mechanical, morphological, and microstructural characteristics of PLA-based sustainable bio-composites fabricated via direct injection molding route. *Biomass Conversion and Biorefinery* 14 (24): 31383–31399.

Lakshmaiya, N., V. Ganesan, P. Paramasivam, and S. Dhanasekaran. 2022a. Influence of biosynthesized nanoparticles addition and fibre content on the mechanical and moisture absorption behaviour of natural fibre composite. *Applied Sciences* 12(24):13030. https://doi.org/10.3390/app122413030.

Lakshmaiya, N., S. Kaliappan, P. P. Patil, V. Ganesan, J. A. Dhanraj, C. Sirisamphanwong, T. Wongwuttanasatian, S. Chowdhury, S. Channumsin, M. Channumsin, and K. Techato. 2022b. Influence of oil palm nano filler on interlaminar shear and dynamic mechanical properties of flax/epoxy-based hybrid nanocomposites under cryogenic condition. *Coatings* 12(11):1675. https://doi.org/10.3390/coatings12111675.

Latha, A. D., A. S. Kumar, S. J. Singh, and C. Velmurugan. 2023. Experimental investigations of flammability, mechanical and moisture absorption properties of natural flax / NanoSiO_2 based hybrid polypropylene composites. *SILICON* 15:7621–7637. https://doi.org/10.1007/s12633-023-02611-3.

Leao, A. L., I. Cesarino, I. S. Machado, and R. M. Kozlowski. 2017. Curaua fibers-the queen of the fibers. *Natural fibers: properties, mechanical behavior, functionalization and applications*: 83–106.

Lee, J. T., M. W. Kim, Y. S. Song, T. J. Kang, and J. R. Youn. 2010. Mechanical properties of denim fabric reinforced poly (lactic acid). *Fibers and Polymers* 11:60–66.

Lekrine, A., A. Belaadi, I. Dembri, M. Jawaid, A. S. Ismail, M. M. S. Abdullah, B. X. Chai, A. Al-Khawlani, and D. Ghernaout. 2024a. Thermomechanical and structural analysis of green hybrid composites based on polylactic acid/biochar/treated W. filifera palm fibers. *Journal of Materials Research and Technology* 30:9656–9667. https://doi.org/10.1016/j.jmrt.2024.06.033.

Lekrine, A., A. Belaadi, I. Dembri, M. Jawaid, A. S. Ismail, and D. Ghernaout. 2025. Fiber treatment impact on the thermal behavior of biomass/palm-fibers polylactic-acid hybrid biocomposites. *Materials Chemistry and Physics* 338:130651. https://doi.org/10.1016/j.matchemphys.2025.130651.

Lewis, J., M. Miller, J. Crumb, M. Al-Sayaghi, C. Buelke, A. Tesser, and A. Alshami. 2019. Biochar as a filler in mixed matrix materials: Synthesis, characterization, and applications. *Journal of Applied Polymer Science* 136 (41): 48027.

Li, C., C. Feng, L. Zhang, L. Zhang, and L. Wang. 2025. Direct ink writing of polymer-based materials—A review. *Polymer Engineering & Science* 65 (2): 431–454.

Liu, W., A.K. Mohanty, L.T. Drzal, P. Askel, and M. Misra. 2004. Effects of alkali treatment on the structure, morphology and thermal properties of native grass fibers as reinforcements for polymer matrix composites. *Journal of Materials Science* 39:3.

Luchese, C. L., J. B. Engel, and I. C. Tessaro. 2024. A review on the mercerization of natural fibers: Parameters and effects. *Korean Journal of Chemical Engineering* 41 (3): 571–587.

Matheswaran, M., P. Suresh, G. Velmurugan, and M. Nagaraj. 2023. Evaluation of agrowaste/nanoclay/SiO2-based blended nanocomposites for structural applications: comparative physical and mechanical properties. *SILICON* 15:7095-7108. https://doi.org/10.1007/s12633-023-02570-9.

Meddour, A., A. Belaadi, M. Boumaaza, M. Bourchak, and D. Ghernaout. 2025. Enhancing Syagrus romanzoffiana lignocellulosic fibers' properties by ecological treatment with sodium bicarbonate for applications in sustainable lightweight biocomposites. *International Journal of Biological Macromolecules* 298:140062. https://doi.org/10.1016/j.ijbiomac.2025.140062.

Minugu, O. P., M. Panchal, R. Gujjala, S. Ojha, A. Krzyzak, and D. Kumar. 2022. Effect of biomass-biochar content on the erosion wear performance of biochar epoxy composites. *Polymer Composites* 43 (5): 3189–3203.

Mir, S. S., S. M. N. Hasan, M. J. Hossain, and M. Hasan. 2012. Chemical modification effect on the mechanical properties of coir fiber. *Engineering Journal* 16 (2): 73–84.

Monteiro, S. N., F. M. Margem, N. Tonini Simonassi, R. L. Loiola, and M. P. Oliveira. 2014. Characterization of curaua fibers by infrared spectroscopy. In *Materials Science Forum*, Trans Tech Publ 325–329.

Mudoi, M. P., and S. Sinha. 2024. Thermal degradation study of natural fibre through thermogravimetric analysis. *Materials Today: Proceedings* 99:92–97.

Oksman, K., M. Skrifvars, and J.-F. Selin. 2003. Natural fibres as reinforcement in polylactic acid (PLA) composites. *Composites Science and Technology* 63 (9): 1317–1324.

Oliveira, J. M., V. M. Z. Sousa, L. A. Teixeira, R. M. Leão, R. C. M. Sales-Contini, V. F. Steier, and S. M. da Luz. 2024. The role of chemical treatments on curaua fibers on mechanical and thermal behavior of biodegradable composites. *Applied Sciences* 14 (22): 10621.

Panneerselvam, T., B. Krishnakumar, and S. Raghuraman. 2025. Evaluation of mechanical properties and water absorption characteristics in chemically treated banana and abaca fiber–reinforced

composites. In *Surface modification and coating of fibers, polymers, and composites*, Elsevier. 429–444.
Raharjo, P. W., R. Soenoko, A. Purnowidodo, and A. Choiron. 2019. Characterization of sodium bicarbonate treated zalacca fibers as composite reinforcements. *Evergreen* 6 (1): 29–38.
Rajamani, P., A. Veerasimman, G. Palani, V. Shanmugam, S. Rajendran, and A. Subbaiah. 2023. Enhancing vinyl ester properties with eco-friendly sustainable biochar filler. *Polymer Composites* 44 (12): 8344–8352.
Rajendran, S., G. Palani, V. Shanmugam, A. Kanagaraj, A. Veerasimman, and U. Marimuthu. 2024. Comparative analysis of mechanical and erosion performance of cashew and sugarcane waste based biochar-reinforced polyester composites. *Cleaner Engineering and Technology* 18 : 100718.
Rajeshkumar, G., S. A. Seshadri, G. L. Devnani, M. R. Sanjay, S. Siengchin, J. P. Maran, N. A. Al-Dhabi, P. Karuppiah, V. A. Mariadhas, and N. Sivarajasekar. 2021. Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites–A comprehensive review. *Journal of Cleaner Production* 310 : 127483.
Ramesh, P., B.D. Prasad, and K.L. Narayana. 2019. Morphological and mechanical properties of treated kenaf fiber/MMT clay reinforced PLA hybrid biocomposites. In *AIP Conference Proceedings.* AIP Publishing 2057:020035.
Rao, J., S. Singh, P. J. Ramulu, T. F. Santos, C. M. Santos, and S. MR, I. Suyambulingam, and S. Siengchin. 2024. Effect of chemical treatment on physio-mechanical properties of lignocellulose natural fiber extracted from the bark of careya arborea tree. *Heliyon* 10 (5): e26706.
Sabziparvar, A., D. Taleponga, and M. R. Foruzanmehr. 2024. Enhancing hydration and internal curing in cementitious mixes: The impact of pre-treated milkweed fibres. *Case Studies in Construction Materials* 20 : e03079.
Sanjeevi, S., V. Shanmugam, S. Kumar, V. Ganesan, G. Sas, D. J. Johnson, M. Shanmugam, A. Ayyanar, K. Naresh, and R. E. Neisiany. 2021. Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites. *Scientific Reports* 11 (1): 13385.
Sarmin, S. N., M. Jawaid, S. A. Zaki, A. M. Radzi, H. Fouad, R. Khiari, S. Rahayu, and M. H. M. Amini. 2023. Enhancing the properties of date palm fibre reinforced bio-epoxy composites with chitosan–Synthesis, mechanical properties, and dimensional stability. *Journal of King Saud University-Science* 35 (7) : 102833.
Sekar, S., S. Suresh Kumar, S. Vigneshwaran, and G. Velmurugan. 2020. Evaluation of mechanical and water absorption behavior of natural fiber-reinforced hybrid biocomposites. *Journal of Natural Fibers* 19(5):1772–1782. https://doi.org/10.1080/15440478.2020.1788487.
Shifa, S. S., M. M. H. Kanok, and M. S. Haque. 2024. Effect of alkali treatment on mechanical and water absorption properties of biodegradable wheat-straw/glass fiber reinforced epoxy hybrid composites: A sustainable alternative for conventional materials. *Heliyon* 10 (16): e35910.
Sisti, L., S. Kalia, G. Totaro, M. Vannini, A. Negroni, G. Zanaroli, and A. Celli. 2018. Enzymatically treated curaua fibers in poly (butylene succinate)-based biocomposites. *Journal of Environmental Chemical Engineering* 6 (4): 4452–4458.
Spinacé, M. A. S., C. S. Lambert, K. K. G. Fermoselli, and M.-A. De Paoli. 2009. Characterization of lignocellulosic curaua fibres. *Carbohydrate Polymers* 77 (1): 47–53.
Sultana, S., M. Mukta, M. H. Rahaman, N. N. Keya, M. S. A. Dola, M. K. H. Shishir, M. S. Alam, and G. M. A. Khan. 2024. EDTA-treated fibrillated cellulose bio-adsorbents from okra plant biomass and their performance on toxic divalent metal ions attenuation from aqueous solution. *Biomass Conversion and Biorefinery* 15(10):15853–15866. https://doi.org/10.1007/s13399-024-06259-w.
Teyar, S., H. Gheribi, M. Boumaaza, A. Belaadi, B. X. Chai, M. M. S. Abdullah, I. M. H. Alshaikh, A. Al-Khawlani, and D. Ghernaout. 2024. Analyzing the strelitzia juncea cellulosic fibers mechanical properties' experimental data using various statistical methods. *Journal of Natural Fibers* 21 (1): 2394142.
Tokoro, R., D. M. Vu, K. Okubo, T. Tanaka, T. Fujii, and T. Fujiura. 2008. How to improve mechanical properties of polylactic acid with bamboo fibers. *Journal of Materials Science* 43:775–787.
Trivedi, A. K., M. K. Gupta, and H. Singh. 2023. PLA based biocomposites for sustainable products: A review. *Advanced Industrial and Engineering Polymer Research* 6 (4): 382–395.
Velmurugan, G., J. S. Chohan, R. Velumayil, D. Elil Raja, M. Abraar, J. Gunasekaran, M. Nagaraj, and N. Mohan Raj. 2024. Driving into the future: Nano graphene and silicon dioxide enriched kevlar composites for automotive applications. *SILICON* 16:3873–3890. https://doi.org/10.1007/s12633-024-02977-y.
Velmurugan, G., S. S. Kumar, J. S. Chohan, A. J. P. Kumar, T. Manikandan, D. E. Raja, K. Saranya, M. Nagaraj, and P. Barmavatu. 2023a. Experimental investigations of mechanical and dynamic mechanical analysis of bio-synthesized CuO/ramie fiber-based hybrid biocomposite. *Fibers and Polymers* 16(9):1–18. https://doi.org/10.1007/s12221-023-00432-0.
Velmurugan, G., S. S. Kumar, J. S. Chohan, R. Sathish, S. P. Selvan, S. A. M. Abraar, D. E. Raja, M. Nagaraj, and S. Palani. 2023b. Hybrid calotropis gigantea fibre-reinforced epoxy composites with SiO2's longer-term moisture absorbable and its impacts on mechanical and dynamic mechanical properties. *Materials Research Express* 10 (11) : 115302.
Wang, F., M. Yang, S. Zhou, S. Ran, and J. Zhang. 2018. Effect of fiber volume fraction on the thermal and mechanical behavior of polylactide-based composites incorporating bamboo fibers. *Journal of Applied Polymer Science* 135 (15): 46148.
Yasim-Anuar, T. A. T., L. N. Yee-Foong, A. A. Lawal, M. A. A. Farid, M. Z. M. Yusuf, M. A. Hassan, and H. Ariffin. 2022. Emerging application of biochar as a renewable and superior filler in polymer composites. *RSC Advances* 12 (22): 13938–13949.
Zafeer, M. K., R. A. Menezes, H. Venkatachalam, and K. S. Bhat. 2024. Sugarcane bagasse-based biochar and its potential applications: A review. *Emergent Materials* 7 (1): 133–161. https://doi.org/10.1007/s42247-023-00603-y.
Zaini, L. H., A. Solt-Rindler, C. Hansmann, S. Veigel, and W. Gindl-Altmutter. 2024. Lightweight cellulosic insulation panels made from oil palm trunk fibers. *Industrial Crops and Products* 222 : 119497.
Zhang, Q., H. Cai, K. Yang, and W. Yi. 2017. Effect of biochar on mechanical and flame retardant properties of wood–plastic composites. *Results in Physics* 7:2391–2395.
Zhang, Y., Q. Li, Y. Chen, Y. Cao, J. Wang, J. Yang, L. Xie, X. Chai, L. Zhang, and S. Wang. 2024. Effects of facile chemical pretreatments on physical-chemical properties of large clustered and small monopodial bamboo microfibers isolated by steam explosion. *Industrial Crops and Products* 207 : 117747.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.