

Research

Cyclic thermal treatment parameters of bagasse particle reinforced epoxy bio-composites for sustainable applications

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Abstract

The demand for sustainable, high-performance materials has led to increased interest in bio-based composites. However, optimizing the mechanical properties of such materials for engineering applications remains a challenge. This study addresses this gap by developing and characterizing an epoxy-based biocomposite reinforced with sugarcane bagasse particles, focusing on the influence of cyclic thermal treatment on its properties. The bagasse particles were chemically treated with 1 M NaOH to remove impurities, improve interfacial bonding with the epoxy matrix, and enhance the overall composite performance. The treated particles were pulverized to 470 µm and incorporated into the epoxy matrix (0–20 wt%) using the hand layup method. The composites were divided into untreated and thermally treated groups, with the latter subjected to cyclic thermal treatment (100 °C for 3 h over 7 days). Mechanical, wear, and water absorption properties were evaluated, while fractured surface morphologies were analyzed using SEM. Results revealed that cyclic thermal treatment significantly enhanced the composites' performance, with the 15 wt% heat-treated composite showing optimal properties: density of 1.102 g/cm³, flexural strength of 29.13 MPa, ultimate tensile strength of 103.50 MPa, impact strength of 3.49 kJ/m², hardness of 64.70 HS, and wear indices of 0.034 mg. These findings demonstrate that alkali treatment and cyclic thermal treatment synergistically enhance the performance of bio-composites, making them suitable for diverse applications, including automotive, aerospace, and other engineering fields.

Keywords Sustainable materials · Bagasse particles · Thermal-cyclic treatment · Epoxy · Biocomposites

1 Introduction

Composite materials are frequently employed in the fabrication of various constructions, including buildings, bridges, and structures such as boat hulls, swimming pool panels, race car bodies, shower stalls, bathtubs, storage tanks, and many more [1]. Among the well-known various types of composite utilized for various application polymer matrix composites (PMC) are the materials that are commonly employed due to their numerous benefits, such as their cost-effectiveness, lightweight nature, and capacity to be processed at low temperatures [2–4]. PMCs utilize two kinds of polymers as matrices: thermoplastics and thermosetting polymers. Thermoplastic materials are the predominant choice for bio-fiber

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matrices, with polypropylene (PP), polyethylene, and polyvinyl chloride (PVC) being the most commonly used thermoplastics for this purpose. On the other hand epoxy, and polyester resins are examples of thermosetting matrices [5]. Due to its distinctive attributes, epoxy resin has become a widely utilized matrix in advanced composite materials on a global scale. These characteristics encompass its notably elevated durability, minimal reduction in size, enhanced resilience against moisture, improved mechanical properties, adaptable processing capabilities, and superior handling [6].

Polymer-based materials have recently surfaced as the preferred materials for a diverse array of applications. More advanced polymer-based materials are now regularly generated as a substitute for alternative materials, notably in domains where polymers were previously considered inappropriate [7]. The majority of the limitations associated with polymers are addressed during the manufacturing of composite materials, rendering them feasible. The adaptability to advantageous environmental effects is also being explored by scientists and scholars [8]. The development of bio-derived composites constitutes a means by which polymers are being altered to fulfill human requirements and become appropriate for technical intentions. Biocomposites, which incorporate biomaterials can be biopolymer-based and/or possess natural reinforcements [9, 10]. In the current global environment, there is a prevailing inclination towards the utilization of biodegradable or "green" materials. This shift is primarily driven by the pressing concerns surrounding plastics' persistence, the limited availability of landfill space, the depletion of petroleum resources, the emissions generated through incineration, and the potential risks posed to living organisms. Consequently, there is an increasing recognition of the imperative need for environmental preservation and tolerance for zero wastes, thus, advocating for the adoption of "green" composite or biocomposite materials. These environmentally friendly materials possess the advantage of being derived from renewable resources [11–14]. The continuous expansion of humanity's environmental consciousness has further catalyzed the exploration, advancement, and practical application of more sustainable materials. Consequently, this trend often leads to the emergence of bio-based products, which, owing to their origins in renewable sources, confer environmental benefits and contribute to long-term sustainability. The development of bio-composite has given rise to an alternative solution for fulfilling people's everyday needs, be it furniture, housing, decking, flooring, lightweight automotive components, or sports equipment [7, 15].

Natural fillers offer advantageous attributes such as stiffness, resistance to impact, and pliability. Moreover, they are also sustainable and exist in copious amounts [16]. Natural filler-based bio-composites are increasingly utilized in various industries such as automotive, electronics, construction, packaging, and more [17, 18]. However, the natural fillers, particularly fibers, exhibit significant heterogeneity with varying characteristics across different regions [19]. This variability in properties is influenced by factors like geographical location, vegetation, species, plant or animal parts/types, extraction method, and mode of application in the matrix. Consequently, the production of bio-composites has been an ongoing subject of research, with a growing demand for exploring the promising and unique attributes of sustainable natural fillers as bio-reinforcements in polymer bio-composites for diverse applications [20, 21].

Bagasse fiber or particles are a widely available natural filler that is frequently used. Bagasse is the residue of sugarcane stalks after they are crushed to extract juice. Sugarcane bagasse comprises a firm material made up of cellulose, which makes up roughly 40–50% of its composition, as well as hemicellulose, which accounts for 25–35%. The remaining constituents consist of lignin, wax, and various other substances [22, 23]. Several researchers have found that sugarcane bagasse-reinforced composites outperform composites reinforced with glass fiber in terms of specific mechanical qualities like stiffness, flexibility, and modulus. Due to its abundance and low processing cost, it can be an ideal material for reinforcing bio-composites as it is renewable and less expensive. The age, source, and various surface treatment processes of the bagasse can affect the mechanical properties of the composite [22, 24]. Elmeniawy et al. [25] conducted a study on the mechanical properties and corrosion behavior of composites made from low-density polyethylene reinforced with sugarcane bagasse fibers. This research aimed to investigate whether cellulose and cellulignin fibers derived from sugarcane bagasse waste could be used to strengthen a thermoplastic polymer matrix. The fiber loading varied from 10 to 30 wt%. To enhance the bonding between the fibers and the matrix, the fibers underwent a chemical modification through alkali treatment. The results showed that sugarcane bagasse fibers, similar to other natural fibers, improved the strength of polyethylene. The treated SCB fibers exhibited a significant increase in both tensile strength (13%) and tensile modulus (196%) compared to the neat LDPE. In another research conducted by Sivarao et al. [23] the impact of sugarcane bagasse fibers (10, 20, 30, 40%) on the mechanical properties of high density polyethylene was investigated. To prepare the bagasse fibers, they were treated with a 5% solution of sodium hydroxide and then combined with the HDPE matrix using the hot-pressing technique. The findings indicated a reduction in both the tensile strength and elasticity as the amount of bagasse fiber in HDPE increased.

The focus of this study is to develop composites from the mixture of epoxy that is reinforced with treated bagasse particles and subject part of the samples to cyclic thermal treatment. Cyclic thermal treatment for composites reinforced

with either natural or synthetic fillers has been reported to enhance the performance of the composites and reduce their moisture content [26, 27]. The application of heat treatment has been revealed to result in the breakdown of cell walls, which has a significant potential for bonding interaction with hydrophobic thermoplastic. This is due to the removal of the lignin that covers fiber surfaces. However, Nasser et al. [28] have pointed out that heat treatment at higher temperatures can alter the properties of the composite conversely. For instance, when heat treatment is conducted at temperatures of 140 °C, 155 °C, and 170 °C, the chemical filler components of the composite can degrade, thereby affecting its mechanical, physical, thermal, and mold resistance qualities. This observation was made in a study conducted by Lan et al. [29] which focused on the mechanical properties of the diglycidyl ether of bisphenol A epoxy resin (EP) reinforced with a 20% fiber glass (GF) with a layered structure after undergoing high-temperature aging. The study revealed that as the aging tests were conducted in the temperature range of 85–145 °C in air, the tensile and flexural properties of the GF/EP composite decreased. Hence this study focuses on developing composites from epoxy resin reinforced with chemically treated sugarcane bagasse particles, employing a novel approach that involves subjecting part of the samples to cyclic thermal treatment. While earlier research has investigated bagasse-reinforced composites, the influence of cyclic thermal treatment on their properties remains unexplored. To address this research gap, the study evaluates the impact of cyclic thermal treatment on the mechanical, thermal, and water absorption properties of bagasse-reinforced epoxy composites. The sugarcane bagasse particles are chemically treated with 1 M NaOH to improve interfacial bonding and eliminate impurities, followed by the fabrication of epoxy-based composites containing varying weight fractions of the treated particles. Selected composite samples are then subjected to cyclic thermal treatment, with the resulting changes in their properties thoroughly analyzed. This study's originality lies in its innovative combination of chemical treatment and cyclic thermal treatment of bagasse particles. This dual-treatment approach, not previously reported, is expected to synergistically enhance the performance of the composites. By improving their mechanical, thermal, and water resistance properties, this approach offers an eco-friendly solution for diverse engineering applications. In conclusion, this research contributes to the growing body of knowledge on sustainable materials by demonstrating the potential of treated bagasse-reinforced epoxy composites for applications in the automotive, construction, and aerospace industries.

2 Materials and methods

2.1 Materials

The materials utilized in this investigation encompass sodium hydroxide, bagasse fiber, Bisphenol A diglycidyl ether epoxy resin and diethylene triamine curative, commonly known as hardener. The bagasse fiber, procured from sugarcane plants were.

were acquired from the urban center of a farmland situated at the Federal University of Technology Akure Ondo State, Nigeria while the epoxy resin, hardener, and sodium hydroxide were procured from Pascal Scientific Limited, Akure, Ondo State, Nigeria. Every of the equipment used in this research are listed in subsequent section.

2.2 Treatment and processing of bagasse particles

The bagasse fibers (BF) were rinsed thoroughly with distilled water and dried at 60 °C for 24 h in an oven (model-KX350A KENXIN) to condition the fibers and reduce moisture content as shown in Fig. 1. The fibers were chemically treated with 1 M NaOH at 50 °C for 4 h in an ultrasonic water bath, followed by washing with tap water and rinsing with distilled water to achieve a neutral status as validated by a litmus paper test. After washing, the treated fibers were oven-dried at 60 °C for another 24 h. This process of treatment given to the fiber was similar to that of dombeya fiber in a research conducted by Onuh et al. [30]. Following oven drying, the fibers were crushed with a crushing machine, ground with a ball mill, and sieved to a fine powder of < 450 µm. Figure 1 shows the treated and pulverized bagasse fibers, respectively.

2.3 Fabrication of composite

The composites were produced using an open mold hand lay-up method, which requires minimal equipment and tools, making it a cost-effective option suitable for prototypes and small-scale production. This technique is versatile and can accommodate various part sizes and shapes, from simple to complex geometries. In contrast to other composite manufacturing methods that necessitate specialized equipment, hand lay-up can be performed with basic, widely available

Fig. 1 **a** Sugarcane Bagasse fibers and **b** Pulverized fibers



tools. Additionally, this process allows for the use of various reinforcement materials, such as textiles, mats, unidirectional roving, and chopped or woven fibers, offering flexibility in customizing the composite to meet specific requirements [30]. The particles were incorporated (within the range of 5 to 20 wt%) into the epoxy matrix while the epoxy resin and hardener were added in a ratio of 2:1. This method of fabrication The epoxy resin, hardener, and bagasse particles were mixed manually with a glass rod stirrer for 5 min within a plastic container to get a proper mix. The compounded mixtures were then introduced into molds specifically designed for each property to be investigated. The samples were allowed to cure in the molds at an ambient temperature of $24 \pm 1^\circ\text{C}$ before extraction from the molds. After extraction, the composites were allowed to further cure at room temperature condition for 72 h. The cured samples as shown in Fig. 2 were then divided into two sets before being subjected to further treatment and testing in accordance with the ASTM standards. Three samples were developed for each composition and a total of 242 samples were developed. Details regarding the formulation and constituent amounts utilized are provided in Table 1. In general the open mold hand lay-up technique is highly applicable for real-world manufacturing due to its cost-effectiveness, simplicity, and versatility. This method is ideal for low-volume production, prototyping, and small-scale applications, making it suitable for industries that require custom, small-batch composites, such as automotive, aerospace, and construction. Additionally, the flexibility to use a range of reinforcement materials allows the composites to be tailored for specific mechanical properties, such as strength and durability, which are essential in various applications. By using easily accessible tools and materials, this fabrication method can be implemented in both research settings and commercial-scale production with reduced investment in specialized equipment. The adaptability of this technique also allows it to be used for producing composites with complex geometries, enhancing its utility for diverse applications.

Fig. 2 Fabricated Composite Samples (after 5 h of curing time)



Table 1 Design of composite

Sample Composition (wt %)	Epoxy (g)	Hardener (g)	Bagasse particles (g)
Control	120	60	-
5	114	57	9
10	108	54	18
15	102	51	27
20	96	48	36

It is important to note that after 72 h of curing time, the samples were machined to ensure uniform sizes of the bio-composite samples.

2.4 Cyclic thermal treatment

The developed composites were divided into two sets before testing and characterization. One set was subjected to cyclic thermal treatment while the other set was untreated. The thermal treatment of the reinforced epoxy composites was conducted in an oven at a temperature of 100 °C for 3 h daily for 7 days as shown in the temperature–time graph presented in Fig. 3. After reaching the required temperature, the samples were allowed to cool to an ambient temperature of $24 \pm 1^\circ\text{C}$ each day. This cyclic heating and cooling of the composites were performed continuously for 7 days, which represents 7 cycles. A similar treatment has been carried out by Azimpour-Shishevan et al. [31] although on different materials (basalt fiber-reinforced epoxy composites) and different working temperatures (between -40 and $+120^\circ\text{C}$). Also, in a research carried out by Fahmi, [32], the developed composite (polyester-based composites) was heated in an oven at 100°C for 1 h and then cooled in the open with a variety of thermal cyclic 30, 40, and 50 times. Figure 4 shows a flow chart of the experimental procedure carried out.

2.5 Evaluation and characterization of developed samples

The samples developed were in triplicates as three trials were carried for each composite developed. The test conducted are explained in subsequent section.

Fig. 3 Cyclic Temperature–Time Graph for Bagasse-Epoxy-based Composites and Control Sample

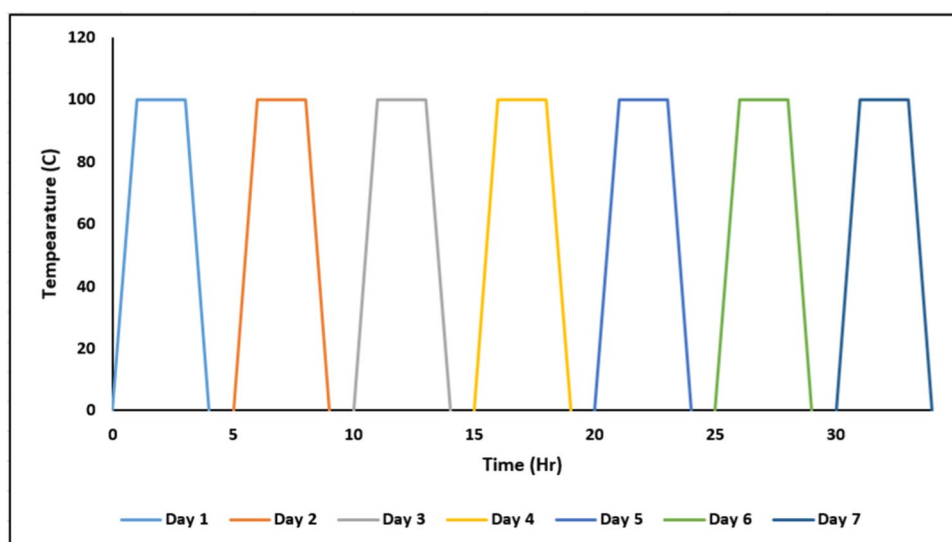
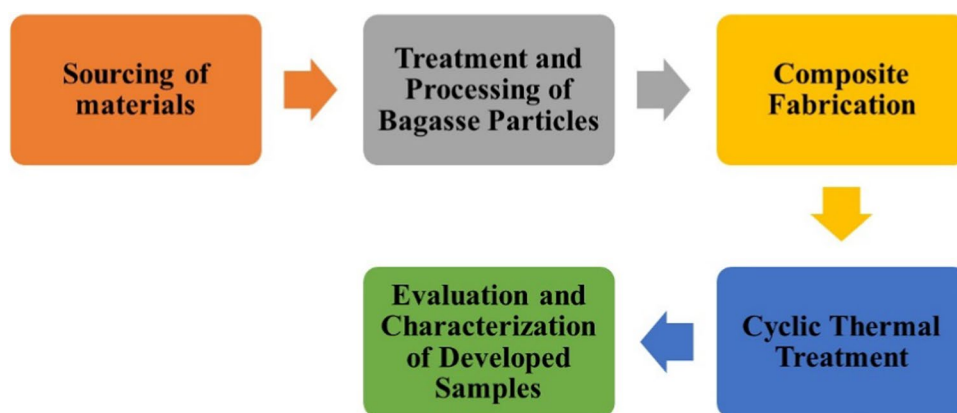


Fig. 4 Flow chart of experimental procedure



2.6 Flexural test

The flexural test was carried out using the 3-Point Bending Test in accordance with ASTM D790 standards [33]. The tests were carried out with the help of an Instron Series 3369 universal testing machine. The length, width, and thickness of the specimens used were 120 mm, 15 mm, and 3 mm, respectively. The test was carried out using a displacement control rate of 10 mm/min. The test speed was set to 5 mm/min over a 65 mm span. The representative values were computed by taking the average of the three samples examined for each composition.

2.7 Tensile test

A tensile test was carried out on an Instron series 3369 universal testing machine in accordance with the ASTM D638-14 standard [34]. The specimens used were dumb-bell-shaped measuring an overall length, gauge length, width and thickness are 115, 33, 10 and 3 mm, respectively. The test was carried out using a 10 kg load cell and a 5 mm/min crosshead speed. Three tests were performed three times for each of the manufactured samples to ensure the correctness and reliability of the results.

2.8 Impact test

The sample was subjected to an impact test using a Charpy impact testing machine in conformity with ISO 179. Samples with dimensions 80 mm × 10 mm × 3 mm were used. Samples were put horizontally on the machine, with a gap of 60 mm between support lines. The gauge was initially read, and then a suspended handle that swung and fractured the sample was released. After the sample had been fractured, the final reading was taken. Three test pieces were tested for each sample from where the average value was chosen as the representative value.

2.9 Hardness test

The hardness test was carried out using a Shore D hardness tester in accordance with ASTM D2240-00 [35]. To do this, the samples were placed on the tester stand's smooth surface before being indented with a force of 15 kgf on each sample within 15 s. The average of the five values obtained was used for analysis.

2.10 Wear test

The wear (abrasion) test was performed to examine a material's wear properties and determine the composite's suitability for a certain wear application. The samples were examined using a Taber abrasive tester model TSC-A016 in accordance with ASTM D 1044–13 [36], a standard test protocol for the resistance of transparent polymers to surface abrasion. The initial weight of the sample was determined before the test. The weight after abrasion testing was

collected after putting each sample on the Taber abrasive tester at 150 rpm for 10 min. The wear samples were created using a 100 mm diameter mold with a thickness of 3 mm. The wear index of each sample was calculated using Eq. (1).

$$\text{Wear index} = \frac{W_1 - W_2}{\text{RPM}} * 100 \quad (1)$$

where W_1 is the initial weight, W_2 is the final weight after surface abrasion and RPM is revolutions per minute which were 200 rpm for this test.

2.11 Water absorption

Water absorption tests were carried out in accordance with ASTM D5229M-12 standards [37]. 250 cm³ of water medium was distributed into plastic containers to conduct the test. The original weight of each sample was determined by chemical weighing balance where readings were taken every day for five weeks. Before each weighing session, the specimens were removed and washed with a fresh cloth. The data acquired during the experiment were used to calculate the weight gained using Eq. 2. Where $W\%$ is the percentage water absorption, W_o is the oven-dry weight, and W_t is the weight of the sample after time t .

$$W\% = \frac{W_t - W_o}{W_o} * 100 \quad (2)$$

2.12 Density measurement

The densities of the samples were determined by cutting them into 4 mm diameter pieces. Quarz's Rock Density Tester AU-300R was used to determine the density. The machine determined the weight and volume of each specimen.

2.13 Microstructural examination

Scanning Electron Microscope (Model: JEOL JSM-6480LV) was used to analyze the bagasse fibers as well as the surfaces of the fractured composites and control samples. With the use of silver paste, the samples were securely adhered on stubs. A thin layer of platinum coating was vacuum evaporated onto the surface of the composite specimens to increase conductivity before photomicrographs were taken at a voltage of 15 kV.

3 Results and discussion

3.1 Microstructural investigation

The SEM analysis of treated bagasse particles reveals intricate details of the material's microstructure. The first image Fig. 5a, shows a complex network of cellulose fibers, which serve as the primary reinforcement for the composite. These fibers appear elongated, thin, and rough, indicating their high surface area and potential for bonding with matrix materials, which is essential for enhancing tensile strength and improving the overall mechanical performance of the biocomposite. The rough surface texture may increase the interfacial interaction between the fibers and the matrix, potentially improving the material's load transfer capacity. The second image Fig. 5b further illustrates the heterogeneous distribution of hemicellulose and lignin within the sugarcane bagasse particulates. Hemicellulose, being more flexible, surrounds the cellulose network, while lignin, acting as the matrix material, is concentrated in certain areas, providing structural support. This distribution is crucial as it influences the mechanical properties of the material, with the lignin possibly improving the overall stiffness and integrity of the fiber structure.

A critical observation from the SEM images is the visible presence of pores and voids, particularly at 200 μm magnification (Fig. 5b). These voids, introduced during the treatment process, suggest an increase in material porosity, which could influence the mechanical properties by reducing the strength of the material. However, these pores might also contribute to improved water absorption, depending on their size and distribution, and could benefit specific applications requiring such properties. The irregular shape and distribution of these voids may cause variability in the composite's overall

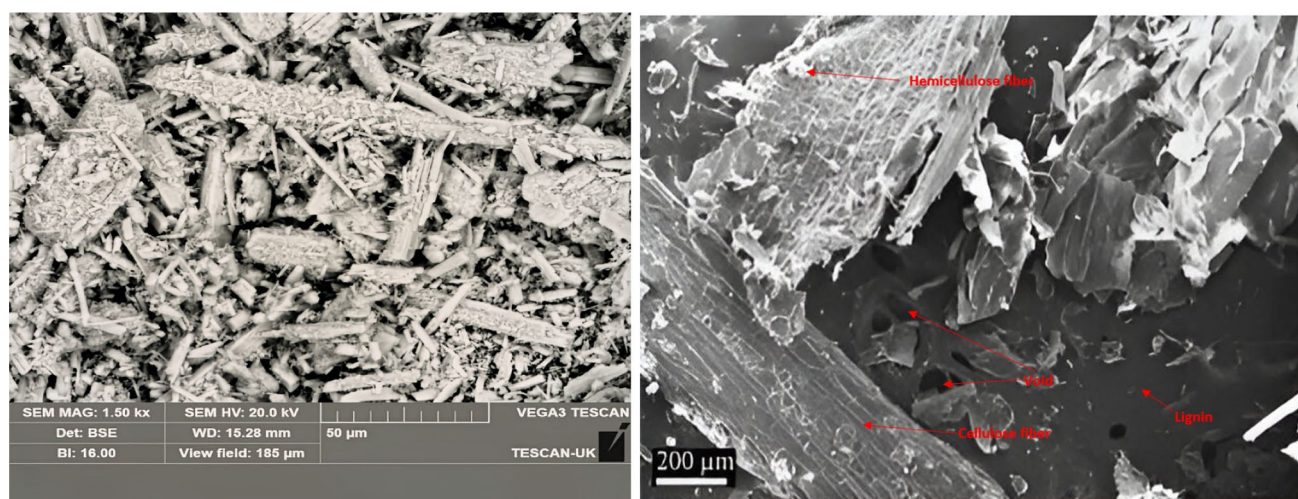


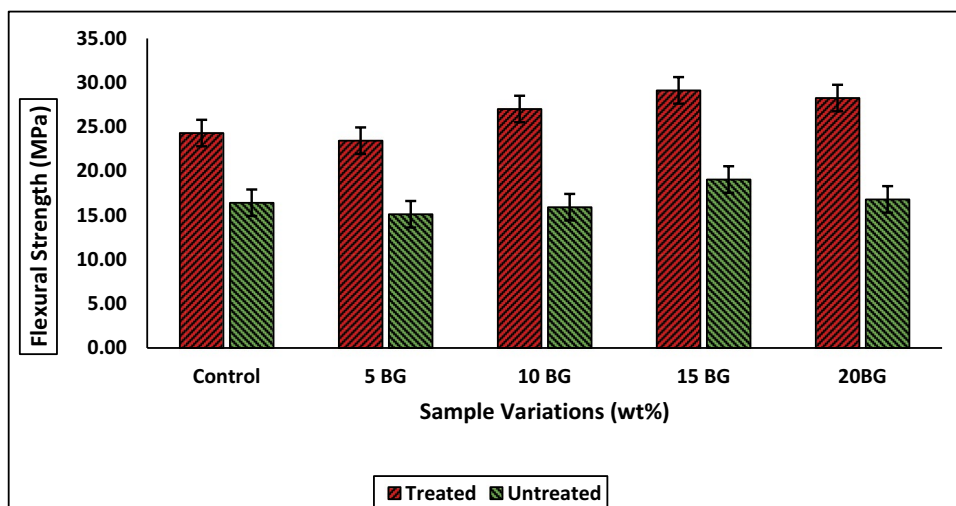
Fig. 5 SEM Image of the Treated Bagasse Particles; **a** at 50 μm ; **b** at 200 μm

performance, making it crucial to control the treatment process for consistent results. Additionally, some irregularities in the shape and distribution of fibers were observed. These features may impact the fiber-matrix interaction, potentially leading to areas of weak bonding that could reduce the overall mechanical properties of the biocomposite. Despite these irregularities, the elongated fibrous structures, with minimal voids at lower magnification, suggest that the fibers retain sufficient integrity, which is essential for reinforcing the composite material and contributing to its structural strength. In summary, the SEM images reveal that the treated bagasse particles exhibit a morphology that offers both advantages and challenges for composite applications. The rough, elongated fibers provide good reinforcement potential, while the presence of voids and the irregular distribution of components highlight areas for improvement in fiber treatment and composite design.

3.2 Flexural properties

Flexural results are often used to assess the ideal materials for creating components that can endure loads without flexing. The flexural strength of the composites (both treated and untreated) was significantly influenced by the reinforcement content and thermal treatment, as shown in Fig. 6. Initially, a steady increase in flexural strength was observed with reinforcement content rising from 5 wt% to 15 wt%, followed by a decline at 20 wt%. This trend highlights an optimum reinforcement level of 15 wt%. The enhancement in flexural strength can be attributed to the effective dispersion of bagasse particles within the epoxy matrix, which improves the stress transfer mechanism between the filler and the

Fig. 6 Flexural Strength of treated and untreated composite samples



matrix. The slight decrease at 20 wt% can be explained by the agglomeration of bagasse particles. At higher filler concentrations, the increased tendency for the particles to cluster together reduces the effective surface area for bonding with the matrix, leading to poor stress transfer. The local stress concentrations generated by the agglomerated particles act as points for crack initiation, resulting in premature failure under flexural loads. Such behavior has been reported by previous researchers [38]. The improvement in flexural strength can be primarily attributed to the alkali treatment of the bagasse particles, which makes them more rigid and enhances their interaction with the epoxy matrix. The treatment increases the compatibility between the filler and matrix, forming a more efficient stress transfer mechanism. The composite containing 15 wt% untreated bagasse exhibited a 16% increase in flexural strength compared to the control. This is due to the localized high-interaction zones created by the compatibilizing effects of the alkali treatment, as these areas resist deformation under load. At 20 wt%, the agglomeration of particles reduces the overall interaction between the epoxy matrix and the reinforcement. The filler load becomes excessive, and the resin fails to adequately penetrate the particle clusters, resulting in weak bonding at the filler-matrix interface. This poor bonding creates microvoids, weak zones, and points for crack propagation, leading to a reduction in the overall mechanical integrity of the composite. Agglomeration-induced defects were observed in other studies [39], which support the theory that high filler content can compromise composite properties when poor dispersion occurs. Similar results were observed by Bolasodun et al. [16] when sugar cane bagasse was used as reinforcement in a polyester matrix and another research done by Babu et al., [13].

Thermal treatment further improved the flexural properties. The cyclic heat treatment enhanced the crosslinking density within the epoxy matrix, promoting a stronger and more rigid network. This process reduced moisture content in the bagasse particles, minimizing the interference moisture can cause during bonding, thereby strengthening the filler-matrix interface. The heat treatment also alleviates residual stresses caused by differences in the thermal expansion rates between the matrix and the filler during curing [40–42]. This results in a more stable composite, reducing internal stresses that could cause deformation under load. For example, at 15 wt% bagasse reinforcement, the thermally treated composite exhibited a 20% increase in flexural strength compared to the untreated composite, and a 77% increase relative to the untreated control. This significant improvement can be attributed to the enhanced crosslinking and reduced moisture content in the matrix, which contributes to a stronger and more stable composite.

The flexural modulus as shown in Fig. 7 also increased with higher reinforcement content, peaking at 20 wt% in both treated and untreated composites, as shown in Fig. 6. The modulus reflects the stiffness of the material and, like the strength, was significantly improved by thermal treatment. The increased rigidity is attributed to the inherent stiffness of the bagasse particles, which limit the mobility of the epoxy polymer chains, reducing deformation under stress. The optimum flexural modulus for the treated composite at 20 wt% was 1.091 GPa, representing a 91% increase compared to the treated control. This increase is supported by the improved filler-matrix adhesion due to the heat treatment, which results in better load transfer. However, at very high filler concentrations, agglomeration can lead to poor dispersion, creating microstructural defects that may reduce the modulus. This trend is observed in particle-reinforced composites and is supported by previous research, where high filler loadings led to poor dispersion and reduced material performance [43]. Table 2 shows the values of the flexural properties of each of the composites.

Fig. 7 Flexural Modulus of treated and untreated composite samples

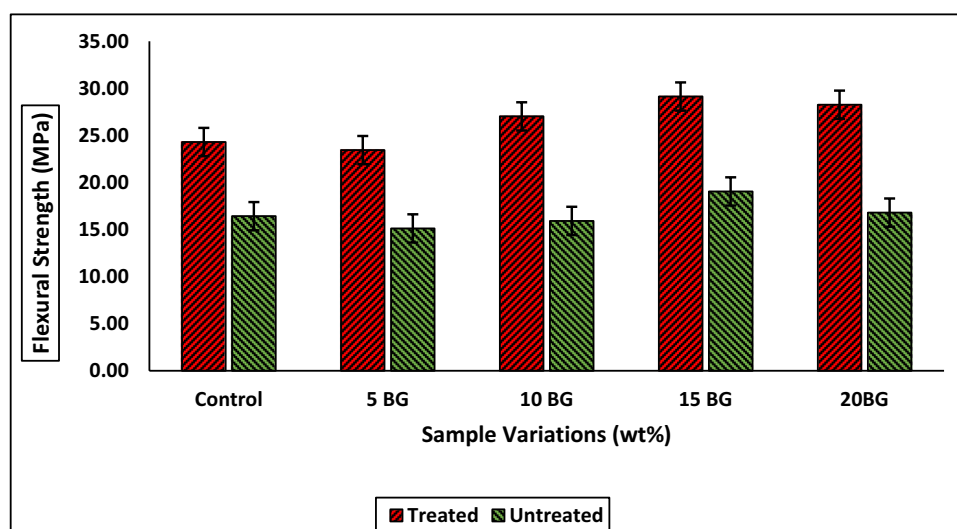


Table 2 Flexural properties values of treated and untreated composites

Sample variation (wt. %)	Flexural strength (MPa)		Flexural modulus (GPa)	
	Treated	Untreated	Treated	Untreated
Control	24.30	16.42	0.572	0.542
5 BG	23.44	15.12	0.627	0.576
10 BG	27.02	15.92	0.829	0.598
15 BG	29.13	19.05	0.635	0.592
20BG	28.26	16.80	1.091	0.713

3.3 Tensile properties

The results presented in Fig. 8 show the ultimate tensile strength (UTS) of both reinforced composites and control samples. The UTS increases steadily with reinforcement content up to 15 wt%, followed by a decline at 20 wt%. This trend aligns with findings from Oladele et al. [10], where moderate reinforcement levels improved mechanical properties, but excessive additions reduced strength. The UTS improvement at 15 wt% can be attributed to strong interfacial bonding between the bagasse particles and the epoxy matrix, which facilitates efficient stress transfer and minimizes microvoids or defects that can serve as stress concentrators. Additionally, even dispersion of the particles at 15 wt% promotes uniform stress distribution, further enhancing tensile strength. At 20 wt%, the decline in UTS results from particle agglomeration due to reduced inter-particle spacing. This agglomeration creates localized stress concentrations, impeding efficient stress transfer and weakening the composite. Additionally, poor resin penetration into particle clusters leads to inadequate wetting and weak interfacial bonding, further compromising the mechanical integrity [16, 31]. The treated composites exhibited superior UTS compared to untreated counterparts. For instance, the 15 wt% treated composite showed a 42% increase in UTS compared to the untreated 15 wt% composite and a remarkable 229% enhancement over the untreated control. This improvement is attributed to heat treatment, which reduces moisture content in the bagasse particles, enhancing compatibility with the epoxy matrix. Moisture typically interferes with interfacial bonding, reducing composite strength. Moreover, heat treatment may increase the crystallinity of the epoxy matrix, improving its mechanical stability and load-bearing capacity, which further enhances UTS.

The tensile modulus results, shown in Fig. 9, display trends similar to the flexural modulus, with values increasing as reinforcement content rises, peaking at 20 wt% for both treated and untreated composites. The treated composites consistently showed higher tensile modulus values than untreated ones. This improvement can be attributed to heat treatment, which reduces the moisture content in bagasse particles, mitigating plasticization effects that lower stiffness. By strengthening the particle–matrix interface and ensuring better load transfer, heat treatment enhances the overall stiffness of the composites. At 20 wt%, the tensile modulus of the treated composite reached 0.71 GPa, representing a

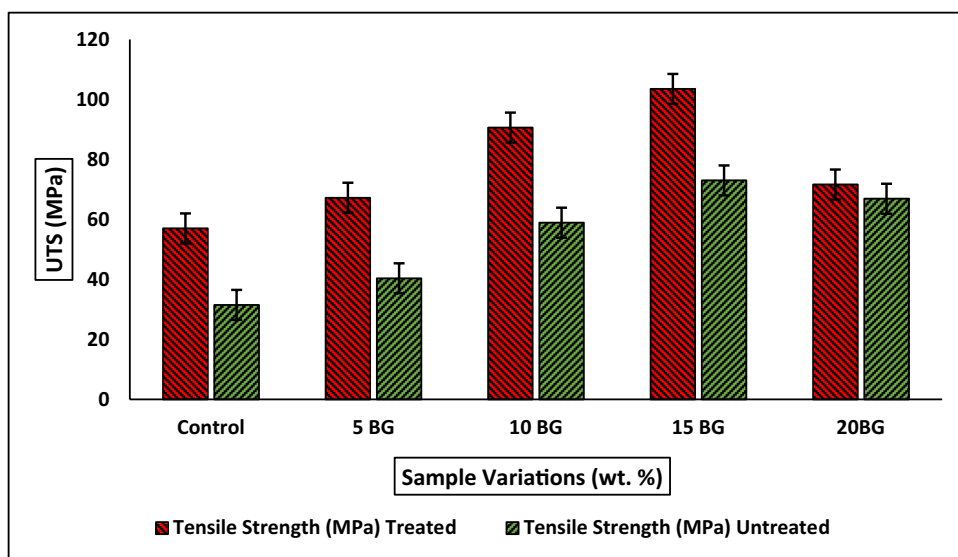
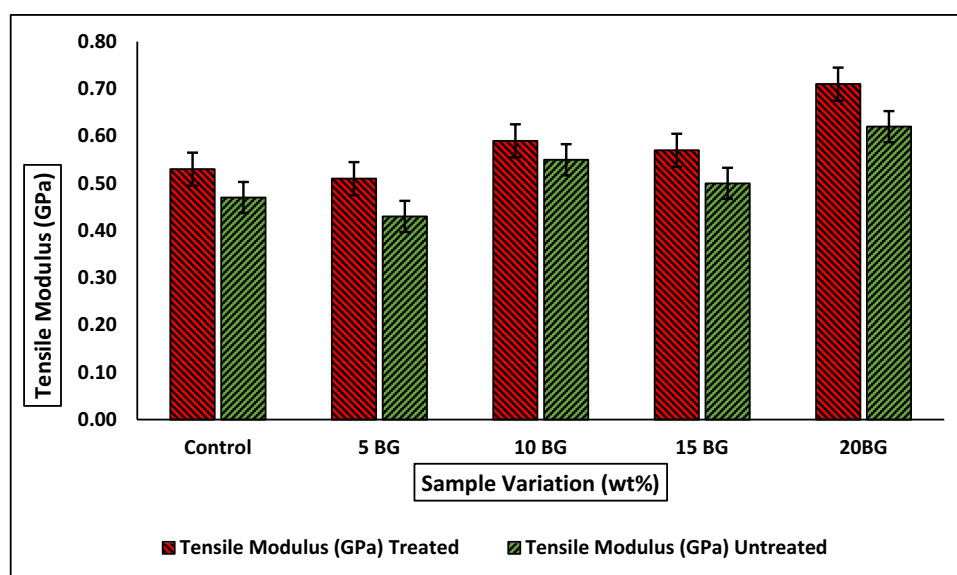
Fig. 8 Ultimate tensile strength of treated and untreated composite samples

Fig. 9 Tensile modulus of treated and untreated composite samples



40% increase compared to the treated control (0.53 GPa) and a 51% increase over the untreated control (0.47 GPa). The untreated 20 wt% composite also demonstrated significant improvement, with a 32% increase relative to the untreated control, highlighting the inherent contribution of reinforcement to stiffness. However, the superior modulus observed in the treated composites underscores the additional benefits of heat treatment, such as improved interfacial adhesion and particle dispersion. The densely packed reinforcement at 20 wt% further contributes to enhanced load-bearing capacity, which explains the observed modulus improvement. In general, the trends in UTS and tensile modulus demonstrate that moderate reinforcement levels (15–20 wt%) and heat treatment significantly enhance the tensile properties of the composites. The increase in UTS at 15 wt% arises from strong interfacial bonding, uniform stress distribution, and reduced defects, whereas the decline at 20 wt% results from particle agglomeration and poor stress transfer. In contrast, the tensile modulus improvements at 20 wt% are due to higher reinforcement concentration and moisture reduction via heat treatment, which strengthens the interface and improves load transfer. These findings underscore the importance of optimal reinforcement content and surface treatment in achieving enhanced mechanical performance in composites. Table 3 provides detailed values of the tensile properties for each composite.

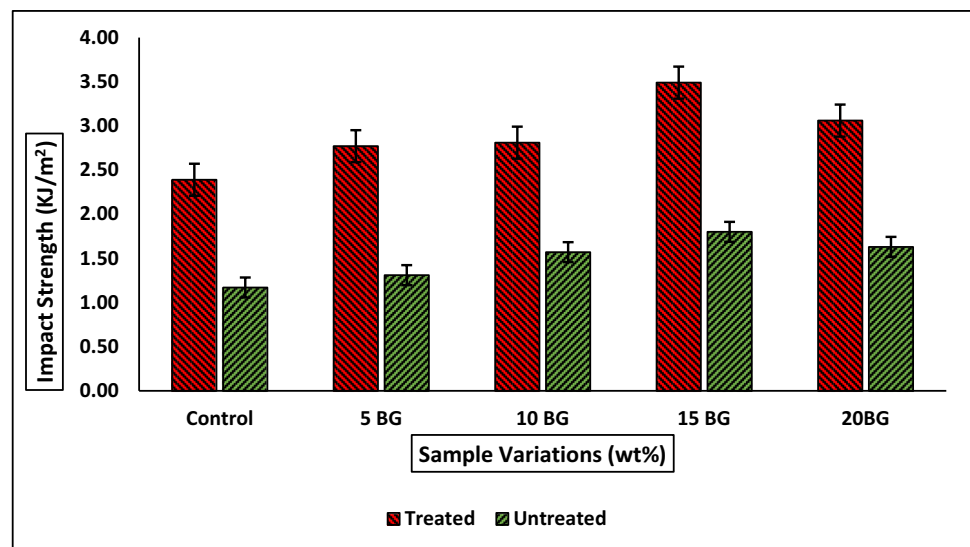
3.4 Impact strength

The effect of using bagasse particles as reinforcement in the epoxy matrix under both heat-treated and non-heat-treated conditions is demonstrated in Fig. 10, showing a similar trend to the response observed for flexural and tensile strengths (Figs. 6 and 8). Both heat-treated and non-heat-treated composite samples exhibited improved impact strength compared to the control sample, with the heat-treated samples consistently outperforming the non-heat-treated ones. This enhancement in the heat-treated samples can be attributed to two primary factors: the elimination of moisture and impurities, and improved interfacial interaction. Heat treatment effectively removes residual moisture and volatile organic compounds present in the bagasse particles. The presence of moisture or impurities typically weakens the interfacial adhesion between the epoxy matrix and the reinforcement, leading to stress concentration

Table 3 Tensile Properties values of treated and untreated composites

Sample variation (wt. %)	Tensile strength (MPa)		Tensile modulus (GPa)	
	Treated	Untreated	Treated	Untreated
Control	57.00	31.50	0.53	0.47
5 BG	67.23	40.37	0.51	0.43
10 BG	90.61	58.91	0.59	0.55
15 BG	103.50	73.00	0.57	0.50
20BG	71.63	66.89	0.71	0.62

Fig. 10 Impact Strength of treated and untreated composite samples



points that initiate failure during impact loading. By eliminating these detrimental factors, heat treatment improves the surface compatibility of the bagasse fibers with the epoxy matrix, leading to a stronger interfacial bond. This allows for efficient energy transfer and dissipation during impact. Thermal analysis studies, such as Thermogravimetric Analysis (TGA) [27], support this explanation, as the weight loss at lower temperatures correlates with the removal of moisture and volatiles. Furthermore, the improved interfacial bonding facilitated by heat treatment ensures that the stress applied during impact is uniformly distributed across the matrix and reinforcement. This prevents fiber pull-out and reduces crack propagation, which are common failure modes in composites with poor interfacial bonding. Fractography studies using Scanning Electron Microscopy (SEM) as seen in Figs. 16, 17, 18 could further confirm this by showing fewer voids and improved matrix-particle adhesion in heat-treated samples compared to non-heat-treated samples. The optimal reinforcement content of 15 wt.% resulted in the highest impact strengths of 3.49 kJ/m² and 1.80 kJ/m² for heat-treated and non-heat-treated composites, respectively. This performance aligns with the concept of balanced reinforcement distribution, where the particle loading provides sufficient stress transfer while maintaining adequate matrix continuity for energy absorption. However, at higher reinforcement content (20 wt.%), a decline in impact strength was observed, likely due to increased particle agglomeration and reduced matrix availability. Excessive particle loading tends to form weak interfacial zones and stress concentration points due to inadequate epoxy matrix coverage, which compromises the energy-absorbing capacity of the composite. This phenomenon aligns with previous studies by Abdollahiparsa et al. [44], Oladele et al. [2], and Panicker et al. [38], where excessive filler content led to decreased mechanical properties due to particle clustering and poor stress transfer. In summary, the enhanced impact strength at optimal reinforcement levels is a result of improved interfacial adhesion achieved through heat treatment and the uniform distribution of bagasse particles. These factors promote efficient energy dissipation during impact, whereas excessive reinforcement content introduces defects that initiate premature failure. Table 4 shows the values of the impact strength of each of the composites.

Table 4 Impact strength values of treated and untreated composites

Impact Strength (KJ/m ²)		
Sample variation (wt. %)	Treated	Untreated
Control	2.39	1.17
5 BG	2.77	1.31
10 BG	2.81	1.57
15 BG	3.49	1.80
20BG	3.06	1.63

3.5 Hardness

Figure 11 shows the hardness of the composites and the control samples under both heat-treated and non-heat-treated conditions. The results indicate that all composite samples exhibited higher hardness values than the control samples, regardless of heat treatment. This increase in hardness can be attributed to the enhanced interfacial bonding between the bagasse reinforcement and the epoxy matrix, which improves the load transfer mechanism and overall rigidity of the composites. A rising trend in hardness was observed in the 5–15 wt.% range of bagasse particle reinforcement, with the optimal hardness values recorded at 15 wt.% for both heat-treated and non-heat-treated samples. Specifically, the heat-treated composites achieved a hardness of 64.70 HS, while the non-heat-treated composites recorded 62.50 HS, resulting in a 7% enhancement in hardness compared to their respective control samples. This improvement can be linked to effective interlocking of fibers [45] within the matrix and the stiffening effect induced by the reinforcement, as reported in similar studies by Panicker et al. [38], where polyester composites reinforced with bagasse fibers showed initial hardness improvements before declining at higher reinforcement content. A similar trend was also observed by Oladele et al. [2] with moringa oleifera fruit pod waste as reinforcement in an epoxy matrix. At 20 wt.% reinforcement, a slight decline in hardness was observed. This reduction can be attributed to particle agglomeration and increased porosity within the matrix, which create weak points and reduce the effectiveness of load transfer [46]. As reinforcement content increases beyond the optimal range, these defects inhibit the rigidity and hardness enhancement. The heat-treated composites consistently demonstrated greater hardness improvements compared to the non-heat-treated composites. The heat treatment process reduces microvoids and porosity, which are areas of stress concentration that weaken the material. By minimizing these voids, heat treatment enhances the composite's ability to withstand mechanical loads. Additionally, heat treatment induces changes in the molecular structure of the epoxy matrix, improving its resistance to deformation. This process also aligns the thermal expansion properties of the matrix and reinforcement more closely, reducing the risk of delamination or crack formation caused by thermal stress during temperature fluctuations. In summary, the optimal hardness improvement observed at 15 wt.% reinforcement is attributed to effective particle–matrix bonding, reduced microvoids, and structural changes induced by heat treatment. The heat treatment process not only strengthens interfacial adhesion but also minimizes structural defects, resulting in enhanced hardness values. Table 5 presents the specific hardness values for all composite samples.

3.6 Wear property

This study compared the wear characteristics of the developed composite materials with the control sample, as shown in Fig. 12. Wear tests were conducted to evaluate the impact of bagasse particle reinforcements on the wear behavior of the material surfaces. The results revealed that the composite materials, both heat-treated and non-heat-treated, exhibited significantly improved wear resistance compared to the epoxy resin control. The wear resistance enhancement can be

Fig. 11 The hardness of treated and untreated composite samples

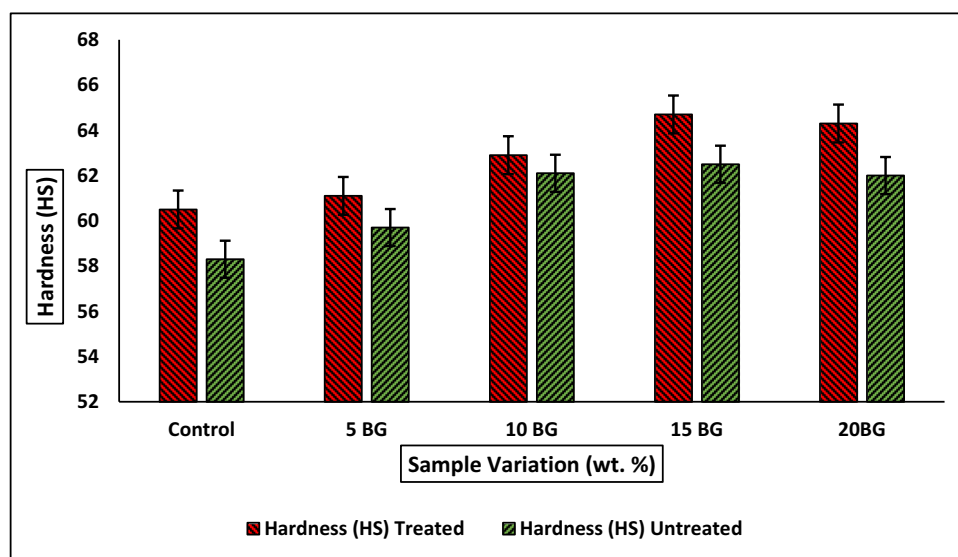
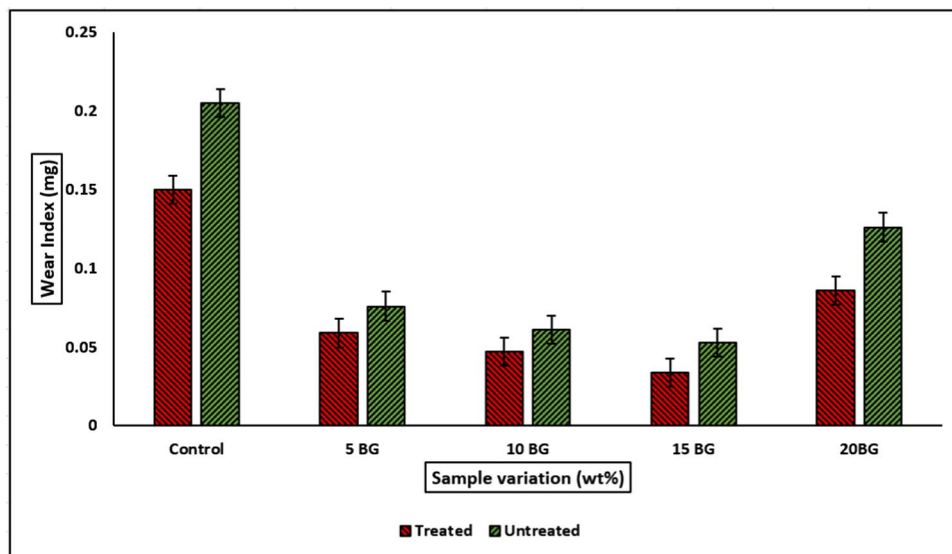


Table 5 Hardness values of treated and untreated composites

Hardness (HS)		
Sample variation (wt. %)	Treated	Untreated
Control	60.50	58.30
5 BG	61.1	59.7
10 BG	62.9	62.1
15 BG	64.70	62.50
20BG	64.30	62.00

Fig. 12 Wear index of treated and untreated composite samples

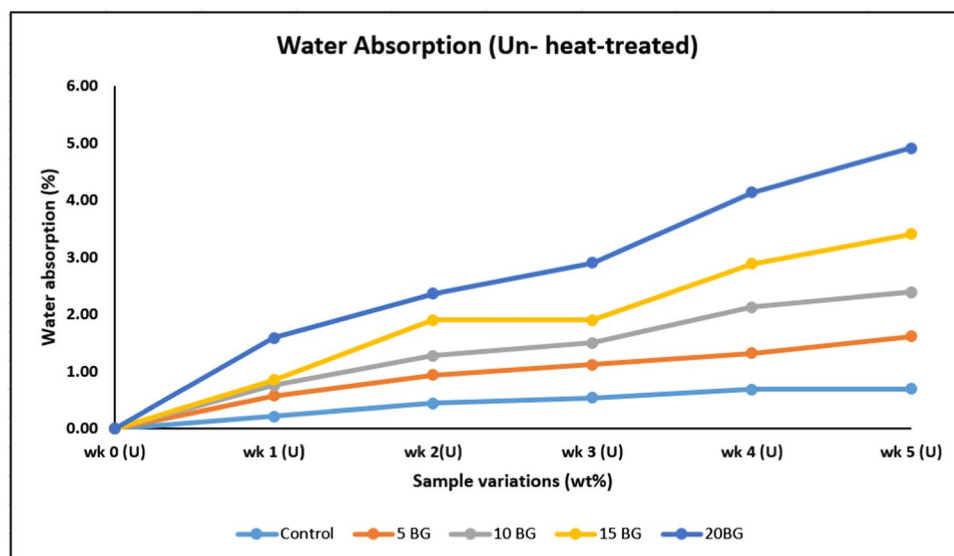
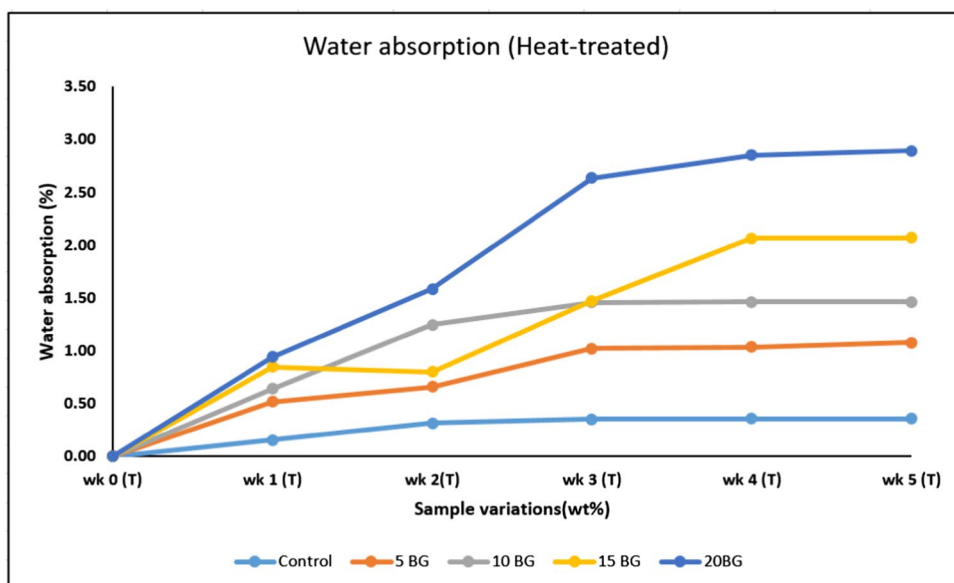
attributed to the incorporation of bagasse particles into the epoxy matrix, which creates a more complex and reinforced structure. The presence of bagasse particles helps absorb and redistribute the stresses associated with surface abrasion, thereby inhibiting the propagation of wear within the composite materials. All the developed composites demonstrated a lower wear index, indicating superior wear resistance when compared to the control sample. The non-heat-treated composites exhibited a higher wear index than their heat-treated counterparts, suggesting that heat-treated composites possess superior wear resistance. This improvement can be attributed to the heat treatment process, which enhances the crosslinking and curing of the epoxy matrix. A more robust curing process results in a harder and more durable matrix, thereby reducing susceptibility to wear. The improved crosslink density effectively strengthens the interfacial bonding between the matrix and the bagasse reinforcements, enhancing the composite's ability to resist abrasion. The optimal wear resistance was observed at 15 wt.% bagasse reinforcement, where the wear index values were 0.034 mg for heat-treated samples and 0.053 mg for non-heat-treated samples. At this reinforcement level, the composites achieved the best balance between particle dispersion and matrix continuity, allowing for effective load distribution and minimal material loss under wear conditions. These findings align with previous studies by Oladele et al. [2], Ramesh et al. [47], and Shalwan and Yousif [48], which demonstrated that the addition of reinforcements significantly improves the wear resistance of epoxy-based composites [10]. In summary, the incorporation of bagasse particles into the epoxy matrix enhances the wear resistance of the material, with heat-treated composites showing superior performance due to improved crosslinking and matrix curing. These results highlight the potential of bagasse-reinforced composites for applications where surface abrasion resistance is critical. Table 6 provides detailed values of the wear index for each of the composite samples.

3.7 Water absorption

The water absorption properties of all the composites and the control samples under investigation were presented in Figs. 13 and 14 showing the influence of a 5-week immersion period. The data illustrated in the graphs clearly show that an increase in the reinforcement content is directly related to a higher percentage of water absorption for both

Table 6 Wear Index values of treated and untreated composites

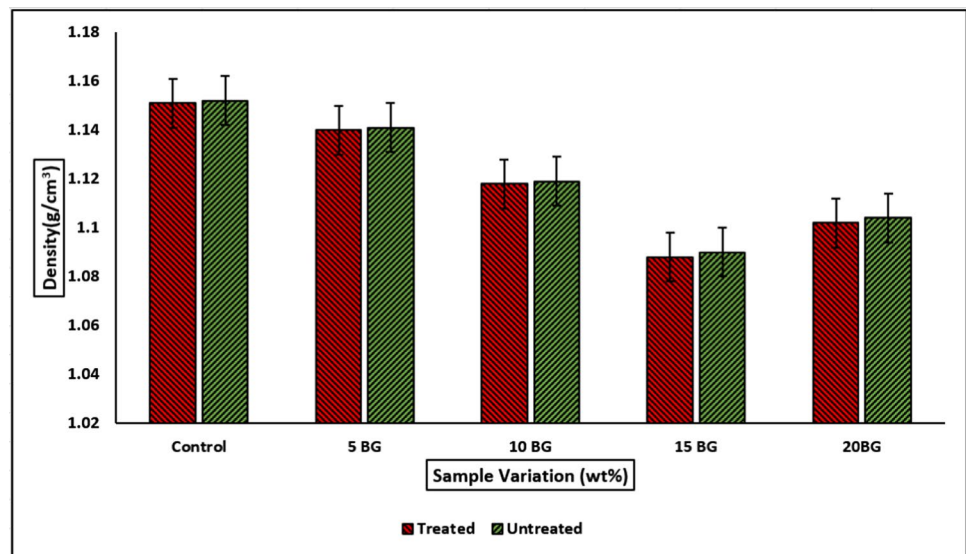
Wear Index		
Sample variation (wt. %)	Treated	Untreated
Control	0.150	0.205
5 BG	0.059	0.076
10 BG	0.047	0.061
15 BG	0.034	0.053
20BG	0.086	0.126

Fig. 13 Water absorption of untreated composite samples in a wet environment**Fig. 14** Water absorption of treated composite samples in a wet environment

types of composites. This finding may be attributed to the natural reinforcements' inherent hydrophilic properties as reported by Abdullah and Sujana, [49] and many other researchers. In Fig. 12, it was noted that the non-heat-treated composite did not reach saturation after 5 weeks, unlike the control which reached saturation in 3 weeks. A similar pattern was observed for composites reinforced with other natural materials such as paper particles and sisal fiber [10], as well as bamboo fibers and calcite particles [2]. The data from the experiments indicated that a longer immersion period would result in a higher absorption rate for the reinforced composites. This continuous increase beyond

Table 7 Water absorption values of treated and untreated composites

Sample Variation (wt. %)	wk 0 (U)	wk 1 (U)	wk 2(U)	wk 3 (U)	wk 4 (U)	wk 5 (U)
Un-Treated Composites						
Control	0	0.2236	0.4472	0.5450	0.6865	0.6973
5 BG	0	0.5810	0.9388	1.1215	1.3241	1.6183
10 BG	0	0.7557	1.2765	1.5063	2.1296	2.3956
15 BG	0	0.8531	1.9078	1.9078	2.8889	3.4122
20BG	0	1.594	2.3632	2.9093	4.1355	4.9155
Treated composites						
Control	0	0.1576	0.3152	0.3553	0.3589	0.3603
5 BG	0	0.5204	0.6592	1.0204	1.0359	1.0799
10 BG	0	0.6429	1.2466	1.4604	1.4619	1.4625
15 BG	0	0.8503	0.8008	1.4724	2.0663	2.0685
20BG	0	0.9434	1.5879	2.635	2.8517	2.895

Fig. 15 Density of treated and untreated composite samples

the fifth week without reaching a saturation point suggests the need for further investigation into water absorption rates beyond 5 weeks.

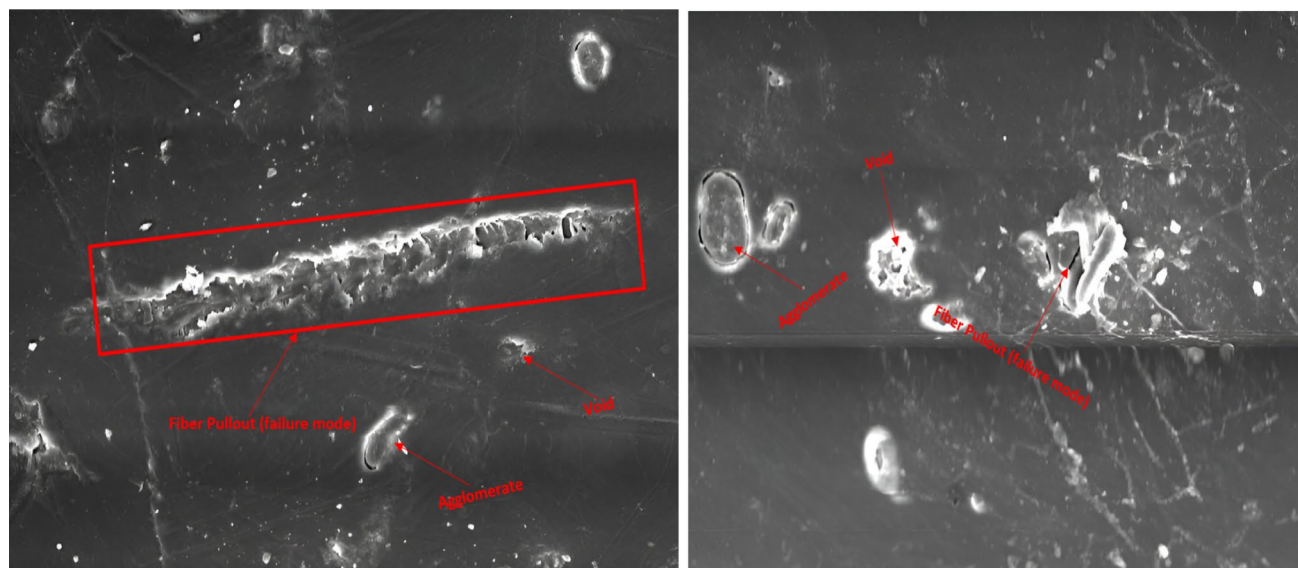
The observation in Fig. 14 revealed that the rate of water absorption for the heat-treated composites was lower than that of the non-heat-treated composites in Fig. 13. It was discovered that saturation was reached at the fourth week for the heat-treated reinforced composites while saturation was observed at the third week for the control. This lower rate of water absorption in comparison with the non-heat-treated composites was attributed to further curing and crosslinking of the epoxy matrix during heat treatment resulting in a more tightly bonded and less porous structure. The increased crosslinking reduces the pathways for water penetration, while the reduction in microvoids and porosity in the material contributes to better resistance to water penetration for the heat-treated epoxy composites. Heat treatment can effectively eliminate or minimize voids where water can be absorbed. Moreover, the heat-treated composites exhibited increased hydrophobicity, meaning they repel water to a greater degree, further reducing the water absorption rate. Table 7 shows the values of the water absorption of each of the composites.

3.8 Density

Figure 15 illustrates the behavior of an epoxy composite reinforced with bagasse particles in both heat-treated and non-heat-treated in relation to density. It was observed that there was a decrease in density from 5-20wt% when the reinforcing materials were added to the epoxy matrix, with 20 wt% showing the lowest density of 1.088 gcm^{-3} for heat-treated

Table 8 Densities values of treated and untreated composites

Sample variation (wt. %)	Density	
	Treated	Untreated
Control	1.151	1.152
5 BG	1.14	1.141
10 BG	1.118	1.119
15 BG	1.088	1.09
20BG	1.102	1.104

**Fig. 16** SEM images at 50 μm for both **a** at 5wt. % un-heat-treated, and **b** at 5wt. % heat-treated sugar cane (bagasse) particles reinforced epoxy composites

composite and 1.090 gcm^{-3} for non-heat-treated composite. It was found that all the samples with reinforcements had lower densities compared to the epoxy reinforcement (1.237 gcm^{-3}) which can be attributed to the inherent density of both the matrix and the reinforcement. By adding bagasse particles to the epoxy resin, the overall density of the composite materials decreases. This is because the particles displace some of the epoxy resin, which has a higher density, thus reducing the overall density of the composite material. In the same vein, it was discovered that the heat-treated composites have slightly lower densities compared to the non-heat-treated composites as minimal mass loss or volume change occurs during heat treatment at a relatively low temperature (100°C) for the heat-treated composite materials. The bagasse particles and epoxy matrix do not undergo significant changes in mass or volume at this temperature. Low-temperature heat treatment may not cause significant phase changes or chemical reactions in the bagasse particles or epoxy matrix that would alter the overall density; however, epoxy resins are known for their stability at moderate temperatures and do not readily decompose or change in density at this operating temperature. Hence, since all the developed composites have low densities compared to the epoxy matrix, they are therefore suitable materials for structural applications due to their lightweight potential. Table 8 shows the values of the density of each of the composites.

3.9 Microstructure examination

Figures 16, 17 and 18 show the SEM micrographs of the fractured surfaces of both untreated and treated epoxy composites reinforced with varying amounts of bagasse (BG). Figure 16 (a-b) represents the microstructure of the composite with 5 wt% BG, while Fig. 17 (a-b) presents the 15 wt% BG composites, which exhibit the optimum mechanical properties, as discussed earlier. Finally, Fig. 18 (a-b) displays the composites with 20 wt% BG. From the SEM images, it is evident that the bagasse particles were well dispersed within the epoxy matrix, especially in the composites with higher BG content (15 wt% and 20 wt%). At 5 wt% BG, Fig. 16 reveals a rough and porous surface morphology with visible voids

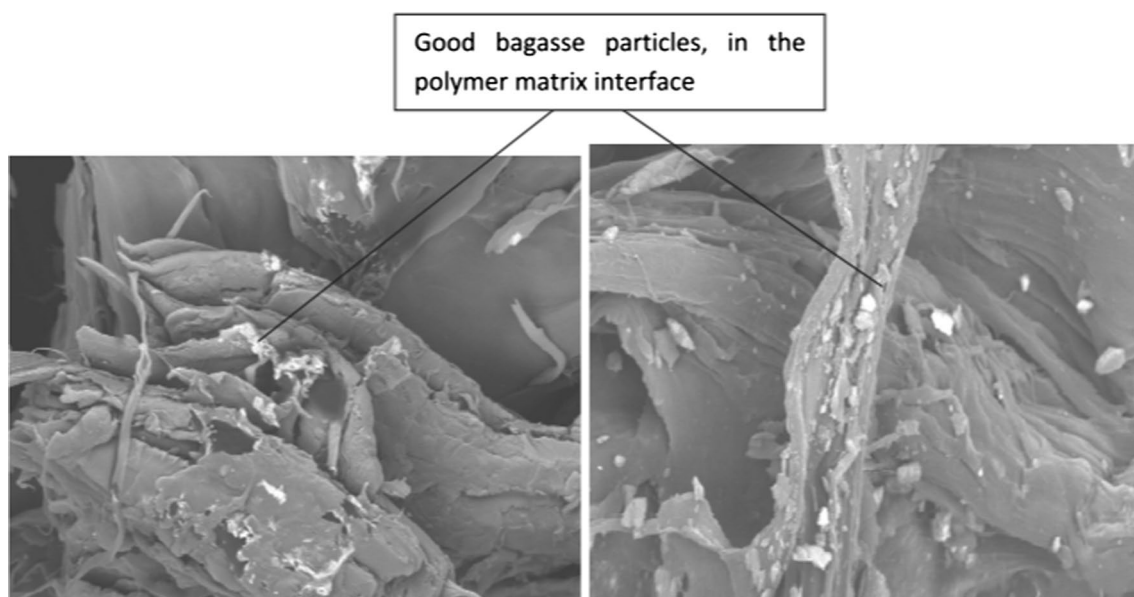


Fig. 17 SEM images at 50 μm for both **a** at 15wt. % un-heat-treated and **b** at 15wt. % heat-treated sugar cane (bagasse) particles reinforced epoxy composites

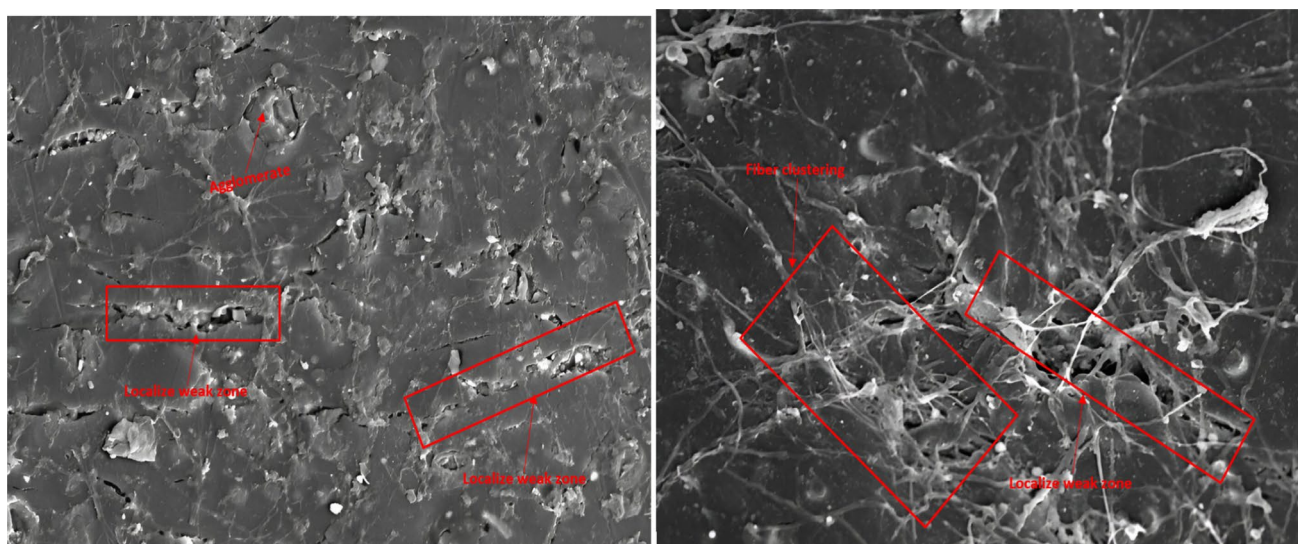


Fig. 18 SEM images at 50 μm for both **a** at 20wt. % un-heat-treated and **b** at 20wt. % heat-treated sugar cane (bagasse) particles reinforced epoxy composites

and agglomerates, indicating poor particle–matrix interaction and weak bonding. These characteristics suggest the potential failure modes of debonding between the reinforcement and the matrix, and particle pullout during mechanical loading. The surface roughness in these micrographs is a clear indication of insufficient bonding, as the surface appears irregular, with visible gaps between the bagasse particles and the polymer matrix. It was also observed that the size of fiber pullout in Fig. 16a is larger than that of 16b this is due to the heat treatment given to Fig. 16b causing the matrix and the reinforcement to have good adhesion. The heat treatment can enhance the surface properties of the bagasse fibers, making them more compatible with the polymer matrix. This stronger bond between the matrix and reinforcement reduces the extent of fiber pull-out, as the reinforcement particles are more securely anchored within the matrix. Therefore, the pull-out size for the heat-treated composites is smaller compared to the untreated ones, as the enhanced bonding reduces the likelihood of the fibers being pulled out during mechanical testing. Additionally, the heat treatment can help remove residual moisture and volatiles within the bagasse particles, which could otherwise weaken the

composite interface. This results in a more uniform and stronger material, contributing to the smaller fiber pull-out size in the heat-treated composites.

As the BG content increases to 15 wt%, Fig. 17 shows a much smoother surface morphology with more uniformly distributed bagasse particles. The microstructure suggests better dispersion and adhesion between the particles and the matrix, which can contribute to the higher mechanical properties observed in the 15 wt% composite. The surface roughness in these images is less pronounced, indicating better interfacial bonding. The particle–matrix interface appears strong, and no visible pullout or delamination is observed, suggesting improved stress transfer between the reinforcement and the epoxy matrix. The failure mode in this case is likely to involve matrix cracking or fiber fracture, as the strong interface prevents particle debonding. At 20 wt% BG, Fig. 18 shows a more agglomerated structure with less uniform distribution of bagasse particles, leading to an increase in surface roughness. The excessive amount of filler results in poor dispersion, creating localized weak zones that compromise the composite's mechanical properties. This agglomeration leads to poor bonding between the reinforcement and the matrix, which can result in failure modes such as particle debonding and poor stress transfer, leading to a decrease in overall strength. The rough, fragmented surface seen in these SEM images aligns with the previously discussed decline in strength at higher BG content. Fiber clustering was observed at this composition, which also contributes to the reduced properties, as discussed above. This clustering reduces the overall surface area available for interaction with the polymer matrix. As a result, the decreased surface area limits the bonding between the reinforcement (bagasse particles) and the epoxy matrix, weakening the overall composite structure. The poor bonding results in inefficient stress transfer between the matrix and the reinforcement, leading to a decline in mechanical properties such as strength and stiffness. In summary, the SEM analysis highlights the importance of achieving proper dispersion and strong bonding between the bagasse particles and the epoxy matrix. The morphology of the composite plays a significant role in its mechanical performance. The smoother surfaces observed at 15 wt% BG correlate with better interfacial bonding and improved mechanical properties. In contrast, the rougher, agglomerated surfaces at higher BG content suggest poor bonding, which can lead to reduced performance and potential failure due to poor stress transfer.

4 Conclusion

The effect of cyclic thermal treatment on the performance of bagasse particle-reinforced epoxy composites was evaluated, leading to the following conclusions:

- Cyclic heat treatment significantly enhanced the properties of the developed composites. Specifically, the heat-treated composites exhibited superior mechanical properties and physical properties, highlighting the potential of cyclic thermal treatment for the development of bio-composites with improved performance and durability.
- The optimum performance was observed in composites with 15 wt% heat-treated bagasse particles, which showed substantial improvements in tensile strength (103.50 MPa), flexural strength (29.13 MPa), impact strength (3.49 kJ/m²), hardness (64.70HS) and wear index (0.034 mg) having density of 1.088 g/cm³ and good absorption rate. These enhancements were attributed to the improved bonding between the bagasse particles and the epoxy matrix, which resulted in better stress transfer and structural integrity. It was also observed that mechanical properties started to decrease beyond the 15 wt% reinforcement content, indicating an optimal loading range of 5–15 wt% for maximum performance. This result can also be supported by its microstructure.
- With respect to the improved properties, composites containing 15 wt% heat-treated bagasse particles can be considered ideal for a variety of applications, particularly in the automotive industry. These composites are suitable for the manufacturing of lightweight components such as armrests, dashboards, bumpers, door panels, and other body parts. By reducing the weight of vehicle components, these composites will contribute to a reduction in fuel consumption and CO₂ emissions, supporting sustainability goals and promoting a greener environment.
- Future research will focus on exploring the long-term performance of these composites under various environmental conditions, including exposure to moisture, UV radiation, and extreme temperatures. Further studies will also examine the potential for scaling up the production of these bio-composites for large-scale industrial applications. This work has the potential to positively influence society by promoting the use of sustainable materials in the manufacturing of lightweight, durable composites, ultimately contributing to a reduction in environmental impact and fostering a shift toward green technologies in various industries.

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Author contributions Ilesanmi, Michael Akinbamiyori: developed, performed the experiments, analyzed the data and contributed to the final manuscript. Isiaka Oluwale Oladele and Anuoluwapo Samuel Taiwo: conceived the study, supervised the project, critical feedback and helped shape the research and the manuscript. Samuel Olumide Falana: took the lead in writing the manuscript. Linus Nnabuike Onuh, Samson Olugbenga Adelani, and Olanrewaju Favor Olajesu: contributed to the final version of the manuscript. All authors have accepted responsibility for the entire content of this manuscript and consented to its submission to the journal, reviewed all the results and approved the final version of the manuscript.

Data availability The authors confirm that the data supporting the findings of this study are available within the article. Also, raw data were generated at Department of Metallurgical and Materials Engineering, Federal University of Technology P.M.B. 704, Akure, Ondo State, Nigeria which will be made available from the corresponding author [Samuel Olumide Falana].

Declarations

Ethics approval and consent to participate The collection of bagasse fiber used in this study adhered to all applicable Nigerian and Federal university of Technology Akure guidelines for plant collection and research. The material was sourced from a reputable farm plantation in Akure, Ondo State, ensuring sustainable cultivation practices and minimizing any impact on wild populations. As the sugar fiber are readily available from its sugar cane plantation, no specific permissions or licenses were required for their collection in this context. However, this study was conducted with a strong commitment to ethical considerations and environmental responsibility. Collection methods were non-destructive, focusing on harvesting mature leaves while leaving the plants intact to support their long-term health and productivity.

Competing interests The authors declare no competing interests.

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References

1. Yadav M, Arya A. Fabrication and mechanical testing of bagasse and coconut coir hybrid. *Int J Techn Res Appl*. 2021;9:56–63.
2. Oladele OI, Akinwekomi AD, Akinseye JG, Falana SO, Oke SR. Evolution of bamboo derivative fiber-mollusk shell based calcite particulate hybrid reinforced epoxy bio-composites for sustainable applications. *J Compos Mater*. 2024;58:2597–622. <https://doi.org/10.1177/0021983241270966>.
3. Owoyemi HT, Adewuyi BO, Oladele IO, Falana SO, Oyegunna SA, Ajileye JO. Silver nanoparticles reinforced polyethersulfone composite for sustainable application. *Discover Polymers*. 2024. <https://doi.org/10.1007/s44347-024-00007-z>.
4. Thandavamoorthy R, Devarajan Y. Study on the characteristics of Napier grass fibre reinforced porcelain filler particulates poly lactic acid matrix biocomposite. *J Reinforced Plastics Comp*. 2024. <https://doi.org/10.1177/07316844241253912>.
5. Saber D, Abdelnaby AH. Recent developments in natural fiber as reinforcement in polymeric composites: a review. *Asian J Appl Sci Technol*. 2022;6:56–75. <https://doi.org/10.38177/ajast.2022.6308>.
6. Abdullahi M. Effect of visco-elastic parameters and activation energy of epoxy resin matrix reinforced with sugarcane bagasse powder (SCBP) using dynamic mechanical analyzer (DMA). *Am J Polymer Sci Technol*. 2018;4:53. <https://doi.org/10.11648/j.ajpst.20180403.11>.
7. Arpitha GA, Verma SM, Gorbatyuk A, Khan TR, Sobahi AM, Asiri S, Siengchin S. Bio-composite film from corn starch based vetiver cellulose. *J Nat Fibers*. 2022; 1: 1–11. <https://doi.org/10.1080/15440478.2022.2068174>.
8. Rangappa SM, Siengchin S, Dhakal HN. Green-composites: Ecofriendly and sustainability. *Appl Sci Eng Progr*. 2020;13:183–4. <https://doi.org/10.14416/j.asep.2020.06.001>.
9. Mahmud MA, Belal SA, Gafur MA. Development of a biocomposite material using sugarcane bagasse and modified starch for packaging purposes. *J Market Res*. 2023;2023(24):1856–74. <https://doi.org/10.1016/j.jmrt.2023.03.083>.
10. Oladele O, Isiaka O, Samuel OF, Onuh LN, Precious EN, Isaiah OO, Samson OA. Sustainable and Light Weight Cellulose-Based Hybrid Reinforced Epoxy Composites for Automotive Application. *Adv Technol Mater*. 2022;49:1–14. <https://doi.org/10.24867/ATM-2024-2-001>.
11. Yeshanew D, Wolela A. Advance research in textile engineering development and characterization of chipboard from sugarcane bagasse and jute fiber. *Adv Res Text Eng*. 2019;4:2–5.
12. Akorede AO, Dauda B, Adeyemi MM. The influence of chemical treatment on mechanical properties and biodegradability of sugarcane fiber filler epoxy resin. *Am J Eng Res*. 2019;8:233–42.
13. Babu RD, Kumar S, and Raju JS. Review on mechanical investigation on sugarcane and glass fibre composite material. *Journal of Critical Reviews*. 2021; 8: 385–389. <http://www.jcreview.com/admin/uploads/files/61bb1a6c81d808.17964786.pdf>

14. Shinde S, Mane K, and Jakukore V. Review of sugarcane bagasse and luffa fiber composites. *Proceedings of National conference on relevance of engineering and science for environment and society*. 2021; 75–84. <https://doi.org/10.21467/proceedings.118.11>
15. Luo M, Zhang X, Jun Wu, Zhao J. Modifications of polysaccharide-based biomaterials under structure-property relationship for biomedical applications. *Carbohydr Polym*. 2021;266: 118097. <https://doi.org/10.1016/j.carbpol.2021.118097>.
16. Bolasodun B, Durowaye S, Akano T. Synthesis and characterization of sugarcane bagasse and pineapple leaf particulate reinforced polyester resin matrix composites. *Gazi Univ J Sci*. 2022;35:1091–100. <https://doi.org/10.35378/gujs.787964>.
17. Haque S, Karim FE, Islam MR, Siddique AB. Mechanical characterization of luffa-bagasse fiber reinforced polymer-based hybrid composite. *Text Leather Rev*. 2023;6:252–70. <https://doi.org/10.31881/tlr.2022.111>.
18. Nguyen DD, Vadiel M, Shobana S, Arvindnarayan S, Dharmaraja J, Priya RK, Nguyen-Tri P, Kumar G, Chang SW. Fabrication and modeling of prototype bike silencer using hybrid glass and chicken feather fiber/hydroxyapatite reinforced epoxy composites. *Prog Org Coat*. 2020;148: 105871. <https://doi.org/10.1016/j.porgcoat.2020.105871>.
19. Makinde-Isola BA, Taiwo AS, Oladele IO, Akinwekomi AD, Adelani SO, Onuh LN. Development of sustainable and biodegradable materials: a review on banana and sisal fibre based polymer composites. *J Thermoplast Compos Mater*. 2023. <https://doi.org/10.1177/08927057231186324>.
20. Jaramillo AF, Medina C, Flores P, Canales C, Maldonado C, Castaño Rivera P, Rojas D, Meléndrez MF. Improvement of thermomechanical properties of composite based on hydroxyapatite functionalized with alkylsilanes in epoxy matrix. *Ceram Int*. 2020;46:8368–78. <https://doi.org/10.1016/j.ceramint.2019.12.069>.
21. Babatunde FO, Omotayo AB, Oluwole Ol, Ukoba K. A review on waste-wood reinforced polymer matrix composites for sustainable development. *IOP Conf Ser*. 2021;1107: 012057. <https://doi.org/10.1088/1757-899x/1107/1/012057>.
22. Mahmud A, Rahman F. Sugarcane bagasse – A source of cellulosic fiber for diverse applications. *Heliyon*. 2021;7: e07771. <https://doi.org/10.1016/j.heliyon.2021.e07771>.
23. Sivarao S, Jamaludin Z, Salleh MS, Ali AM, Vatesh UK, Pujari S, Sivakumar S, Ramesh S, Lee A, et al. Effects of sugarcane bagasse fibers on the mechanical behavior of high density polyethylene. *J Eng Sci Technol*. 2021;16:4214–20.
24. Patel PK, Tiwari P. Experimental study on the mechanical (tensile strength) performance of sugarcane bagasse fiber reinforced epoxy composite. *Int J Res Eng Sci Manag*. 2019;2:11–3.
25. Elmeniaawy M, Mansour A, Hamdy A, Saber D. Mechanical properties and corrosion behavior of sugarcane bagasse fiber reinforced low-density polyethylene composites. *Egypt Int J Eng Sci Technol*. 2021;36:63–71. <https://doi.org/10.21608/eijest.2021.80884.1072>.
26. Asyiqin N, Nasharudin M. The effect of heat treatment and chemical treatment on natural fiber to the durability of wood plastic composites – a review. *J Mater Explor Find*. 2023. <https://doi.org/10.7454/jmef.v2i2.1023>.
27. Raja T, Devarajan Y. Thermal evaluation of porcelain filler particles in basalt fibre-reinforced polymer composites for thermal applications. *J Therm Anal Calor*. 2024;149:4529–41. <https://doi.org/10.1007/s10973-024-13015-9>.
28. Nasser RA, Mansour MMA, Salem MZM, Ali HM, Aref LM. Mold invasion on the surface of wood/polypropylene composites produced from aqueous pretreated wood particles, part 1: date palm midrib. *BioResources*. 2017;12:4078–92. <https://doi.org/10.15376/biores.12.2.4078-4092>.
29. Lan Z, Deng J, Xu Z, Ye Z, Nie Y. Study of heat treatment effect on mechanical properties of epoxy resin reinforced with fiberglass. *Polymers*. 2023. <https://doi.org/10.3390/polym15122734>.
30. Onuh LN, Oladele IO, Falana SO, Olumuyiwa I, Adegun MH, Adelani SO, Agbabiaka GO. Optimizing biomedical facilities performance with dombeya fiber-paper particle hybrid reinforced epoxy composites. *Sci Eng Technol*. 2024;1:14–31. <https://doi.org/10.54327/set2024/v4.i1.114>.
31. Azimpour-shishevan F, Akbulut H, Mohtadi-bona MA. Effect of thermal cycling on mechanical and thermal properties of basalt fiber-reinforced epoxy composites. *Bull Mater Sci*. 2020. <https://doi.org/10.1007/s12034-020-2059-y>.
32. Fahmi H. Thermal cyclic resistance polyester resin composites reinforce fiber nut shells. *IOP Conf Ser*. 2017. <https://doi.org/10.1088/1755-1315/97/1/012036>.
33. ASTM D790–15e2, Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials, American Standard Testing and Measurement (ASTM International), west Conshohocken, pa, 2015
34. ASTM D638–14: Standard test method for tensile properties of plastics, ASTM international, west Conshohocken, pa, 2014.
35. ASTM D2240–00, Standard test method for rubber property durometer hardness, part ii Rubber Nat. Synth. Gen. Test methods carbon black, vol. 9, no.1, pp. 1–8, 2000.
36. ASTM D1044–13. Standard test method for resistance of transparent plastics to surface abrasion. West Conshohocken, PA: ASTM International, 2013.
37. ASTM D5229M-12, standard test method for moisture absorption properties and equilibrium conditioning of polymer matrix composite materials, 2012
38. Panicker AM, Maria R, Rajesh KA, Varghese TO. Bit coir fiber and sugarcane bagasse fiber reinforced eco-friendly polypropylene composites: development and property evaluation thereof. *J Thermoplast Compos Mater*. 2020;33:1175–95. <https://doi.org/10.1177/0892705718820403>.
39. Raja T, Ali MN, Shashi Kumar ME, et al. Study on the characteristics of novel natural fiber extracted from *Coccinia grandis* plant vine: a novel material for engineering applications. *Int J Adv Manuf Technol*. 2024. <https://doi.org/10.1007/s00170-024-13967-0>.
40. Ivone LS, Edmea L, Jivaldo RM, Igor SM, Caroline LM, Leonardo ER. Effect of heat treatment on mechanical properties of nano-tio₂/ppr composites. *Braz Dent J*. 2009;20:205–10. <https://doi.org/10.19825/j.issn.1002-1396.2023.04.10>.
41. Viljanen EK, Skrifvars M, Vallittu PK. Dendritic copolymers and particulate filler composites for dental applications: degree of conversion and thermal properties. *Dent mater*. 2007;23:1420–7.
42. Gudayu AD, Steuernagel L, Meiners D, Woubou AM. Sisal fiber reinforced polyethylene terephthalate composites; fabrication, characterization and possible application. *Polymers Polymer Comp*. 2022. <https://doi.org/10.1177/09673911221103317>.
43. Raja T, Devarajan Y, Logesh K, Rajiv A, Jagdish Upadhye V, Tiwari K. An in-depth investigation into the utilization of nettle fiber-reinforced epoxy composites with embedded MgO nanoparticles. *J Reinf Plast Compos*. 2024. <https://doi.org/10.1177/07316844241266650>.

44. Abdollahiparsa H, Shahmirzaloo A, Teuffel P, Blok R. A review of recent developments in structural applications of natural fiber-reinforced composites (NFRC). *Comp Adv Mater*. 2023. <https://doi.org/10.1177/26349833221147540>.
45. Dehury J, Mohanty J, Biswas S, Bhagat V. Physical, mechanical and water absorption behavior of bi-directional jute/glass fiber reinforced epoxy composites. *Int J Eng Res*. 2017;6:1–6.
46. Thandavamoorthy R, Yuvarajan D, Jayavelu UP, Vijay J, Upadhye LS, Sathish K. Sustainable innovations: mechanical and thermal stability in palm fiber-reinforced boron carbide epoxy composites. *Results Eng*. 2024; 24: 103214. <https://doi.org/10.1016/j.rineng.2024.103214>
47. Ramesh M, Atreya T, Aswin US, Eashwar H, Deepa C. Processing and mechanical property evaluation of banana fiber reinforced polymer composites. *Procedia Eng*. 2014;97:563–72.
48. Shalwan A, Yousif BF. Influence of date palm fibre and graphite filler on mechanical and wear characteristics of epoxy composites. *Mater Des*. 2014;59:264–73.
49. Abdullah AH, Sujan D. Mechanical performance of cockle shell particles (CSP) and oil palm fibre (OPF) reinforced epoxy composite. *Int J Eng Mater Manuf*. 2017;2:58–66. <https://doi.org/10.26776/ijemm.02.03.2017.03>.

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