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ORIGINAL ARTICLE

Characterization of novel cellulosic plant fiber reinforced polymeric composite from *Ficus benjamina* L. stem for lightweight applications

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Abstract

The development of innovative reinforcement and the expansion of their potential applications will be aided by research on unique natural fibers in polymer-based composites. In this work, new cellulosic fibers were mechanically separated from the stem of *Ficus benjamina L.* and reinforced in polyester matrix. The effect of varying fiber parameters (weight percentage and length) on the tensile, flexural, hardness, impact, water absorption, and thermal characteristics was investigated in this study. It was revealed that the composite sample with a length of 40 mm and a weight percentage of 30 wt% had the maximum mechanical properties. The impact, tensile, hardness, and flexural strength of composite found to be 9.31 kJ/m^2, 77.71 MPa, 88 HRRW, and 87.4 MPa respectively, which are comparative to many natural fibers investigated. However, increased fiber content will increase the composite water absorption which leads to failure of the composite system. As compared to the pure polyester resin, the heat stability temperatures of composites raised by 62.49%. The surface characteristics and fractured surface of the composites were examined using scanning electron microscopy and the fibers had better interfacial bonding with the polyester matrix with reduced failure mechanisms.

Keywords *Ficus benjamina* L. stem fiber · Polymer composite · Natural fiber · Fractography · Mechanical characterization · Water absorption

1 Introduction

Renewable, sustainable, and eco-friendly materials are gaining popularity. Nature has provided several renewable, eco-friendly sources. Identifying new raw material sources is crucial for industry sustainability [1, 2]. Natural fibers may experience better market circumstances in the future due to global environmental concerns. Their biodegradability appeals to modern environmental requirements. Polymers and natural fibers from renewable resources are used in sustainable composites for lightweight structural purposes. Natural fiber may bring up fresh scientific perspectives for cutting-edge uses. They have low density, resilience to corrosion, less tool wear, specific strength, and modulus, as well as being ecologically benign [3–7]. The glass, carbon, kevlar, nylon, etc. are frequently employed in structural applications [8]. But now they are replaced with natural fiber, since synthetic material's life cycle, disposal causes the most immediate economic and societal impacts [9]. Although employing natural fibers has numerous benefits, they nevertheless fall short in terms of temperature resistance, robustness, and mechanical properties. Recent studies have concentrated on enhancing these characteristics to lessen drawbacks. Plant fiber strength depends on plant components, topography, and extraction method. Size, type, orientation, reinforcement quantity, bonding nature, physical/chemical reinforcement property, and manufacturing method influence polymer composite

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Table 1 Mechanical characteristics and optimal loading of different natural fibers reinforced with polymer composites

S.No	Fiber	Method	Matrix	Optimum fiber		Tensile strength MPa	Tensile modulus GPa	Flexural strength MPa	Flexuralmodulus GPa	Hardness	Impact strength kJ/m^2	Reference
				Length in mm	Loading Wt.%							
1	*F. benjamina* L. Stem	Hand Layup	Polyester	40	30	77.71	1.26	87.4	1.85	88	9.31	This work
2	Coconut Coir Fiber	Hand Layup	Polyester	-	30	12.4	0.9	22.1	-	80	2.1	[20]
3	Snake Grass Fiber	Hand Layup	Polyester	30	25	35.89	0.481	75.29	-	-	15.99	[21]
4	Shorea Robusta Fiber	Hand Layup	Polyester	0.005 -0.01	20	14.02	0.960	26.16	-	2.6	1.81	[22]
5	Sugarcane Leaf Sheath Fibers	Hand Layup	Polyester	-	30	9.25	0.83	14.24	-	21	1.01	[20]
6	Treated Bent Grass Fiber	Hand Layup	Polyester	7	40	23.46	-	128.6	-	70.86	-	[23]
7	Treated Sisal Fiber	Compression Molding	Polyester	30	30	105	-	6380	-	-	-	[24]
8	Sansevieria cylindrica Fiber	Compression Molding	Polyester	30	40	75.75	1.102	84	-	95	3	[25]
9	Treated Tamarind Fibers	Hand Layup	Polyester	10 -15	25	30.6	3.085	41.1	-	-	3.865	[26]
10	Areca Fruit Husk Fiber	Compression Molding	Polyester	-	40	68.20	1.32	73.91	76	68.26	1.62	[27]
11	Tamarind Fruit Fiber	Compression Molding	Polyester	50-100	40	77.4	1.4	88.5	90	73	1.5	[9]
12	Cissus quadrangularis Stem Fiber	Hand Layup	Polyester	40	30	90.200	1.400	103.040	92	107	2.250	[28]
13	Pineapple/Flax	Compression Molding	Epoxy	10	17.5(Both)	23.04	-	49.3	19.8	64.3	-	[29]
14	Kenaf Fiber	Hand Layup	Epoxy	-	40	105		165	78	3.85	-	[30]
15	Treated Luffa Fiber	Compression Molding	Epoxy	30	6	18.3	0.0101	220		3.4		[31]
16	Treated Kenaf Fiber	Hand Layup	Epoxy	-	40	118	-	178	78	4.23	-	[30]

Fig. 1 Photographs of (**a**) *F. benjamina* L. plant; (**b**, **c**) Extracted stem fiber; (**d**) FBSF reinforced composite at different weight percentage

attributes [10]. When polymer composites are reinforced with high-strength fibers, stress is transferred to the matrix before failure, whereas low-strength fibers cause failure, restricting composite performance.

Table 2 Properties of liquid and cured polyester resin utilized to prepare composite

Liquid resin	
Appearance	Yellow viscous liquid
Density	1.25±0.10 gm/cc
Viscosity at 25 °C	200 – 300 cP
Volatile content (wt.%)	41 ± 1
Specific gravity at 25 °C	1.12 ± 0.01
Acid value (mg KOH/g)	25 ± 4
Cured resin	
Tensile strength	34.0 MPa ± 1.5 MPa
Tensile modulus	1.0 GPa ± 0.3 GPa
Shear strength	4.10 MPa ± 1.01 MPa
Impact strength	0.55 J/cm^2 ± 0.06 J/cm^2
Flexural strength	44.67 MPa ± 1.15 MPa
Flexural modulus	1.63 GPa ± 0.17 GPa
Elongation at break	1.20% ± 0.24%
Melting point	280^{0}c
Rockwell hardness	62 HRRW ± 3HRRW

Polyester is a suitable material to use for making composites for multi-engineering applications. It is all because of the polyester matrix easy availability and manufacturing capability [11]. Polyester matrices are very sticky, stiff, dimensionally stable, and heat and fire resistant because of their strongly cross-linked aromatic structure [11]. Polyester resins are less brittle and exhibit less cure shrinkage when fibers, particle fillers, or elastomeric components are added. Strong fiber-resin connections are created when polyester resin chemically binds with lignocellulosic reinforcement. Bio-fibers and polymers offer excellent system compatibility as a result. Natural fiber-reinforced polymer composites have grown in popularity due to their advantages in production, low cost, and great strength [12–14].

Natural fibers may be harvested from different plant sections. This work extracts fiber from *Ficus benjamina* L. plant stem for potential reinforcement in composite materials. *Ficus benjamina* L., a member of the moraceae family in the angiosperm division, is one of several fibrous plants that are common in tropical regions. This plant is a perennial, terrestrial shrub or tree that may reach a height of 30 m. It is extensively found in India, Taiwan, Malaysia, China, Indonesia, and the Philippines. This plant is native to Asia and Australia [15, 16]. The monoecious plant produces spherical inflorescences that are 1.5 cm in diameter and

Table 3 Listing the chemical properties of some investigated natural fiber

Fiber	Cellulose (Wt.%)	Hemi celluloses (Wt.%)	Lignin (Wt.%)	Wax (Wt.%)	Moisture content (Wt.%)	Ash (Wt.%)	Reference
FBSF	68.71	10.15	11.31	0.91	9.83	3.97	This work
Phoenix dactylifera L.0 (trunk)	35	15.40	20.13	-	15.6	12.6	[46]
Borassus fruit	68.94	14.03	5.37	0.64	6.83	-	[47]
Root of *Ficus religiosa* tree	55.58	13.86	10.13	0.72	9.33	4.86	[48]
Althaea officinalis L.	44.6	13.5	2.7	-	-	2.3	[49]
Arundo donax	43.2	20.5	17.2	-	-	1.9	[50]
Aerial roots of banyan tree	67.32	13.46	15.62	0.81	10.21	3.96	[51]
*Phoenix dactylifer*a L. (stalk)	44	26	11.45	-	9.6	1.85	[46]
Phoenix dactylifera L. (leaf sheath)	43.50	24	18	-	6.8	7.73	[46]
Dracaena reflexa	70.32	11.02	11.35	0.23	5.19	6.23	[52]
Pergularia daemi	53±2	26±1	15±0.8	4	10	1.2	[53]
Coccinia grandis	62.35	13.42	15.61	0.79	5.6	4.388	[54]
Pergularia tomentosa L. seed fiber	43.8	16	8.6	1.88	8.5	2.74	[55]
Coccinia grandis stem	63.22	-	24.42	0.32	9.14	-	[42]
Areca palm leaf stalk	57.49 ± 0.66	18.34 ± 0.24	7.26 ± 0.12	0.71 ± 0.024	9.35 ± 0.15	1.43 ± 0.01	[56]
Tridax procumbens	32	6.8	3	0.71	11.2	-	[57]

have leaves that are 6–13 cm long. The plant contains latex, certain allergic reactions have been associated and eating any plant parts may cause nausea, vomiting, and diarrhea [17, 18]. Therefore to increases the value of this plant, fibers from this plant can be used in manufacturing composite for industries. They have no defined fiber harvesting season and have always access to this fiber source. Using *F. benjamina* L. stem fiber (FBSF) composite manufacturing will produce economic value to agriculturist. In order to explore the *F. benjamina* L. stem fiber's potential for composite reinforcement, it was reinforced in polyester composite specifically the impact of varying fiber length and weight percentage. Stem fiber from *F. benjamina* L. plant has not been studied yet in composites. The composite was created using hand lay-up techniques. According to ASTM standards, measurements of tensile, flexural, impact, hardness, and water absorption were made. Measurements of composite's heat stability were made using a TGA analyzer. SEM was used to examine the processes of failure occur in the composites under tensile testing [19].

Various investigations carried out on new natural fibers in polymer composites, in order to determine the optimal

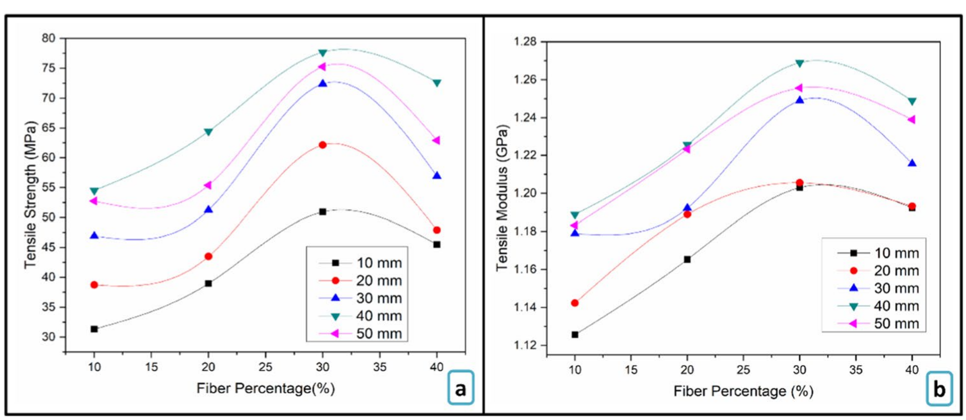

Fig. 2 **a**, **b** The effect of varying fiber length and weight percentage with respect to tensile and Young's modulus

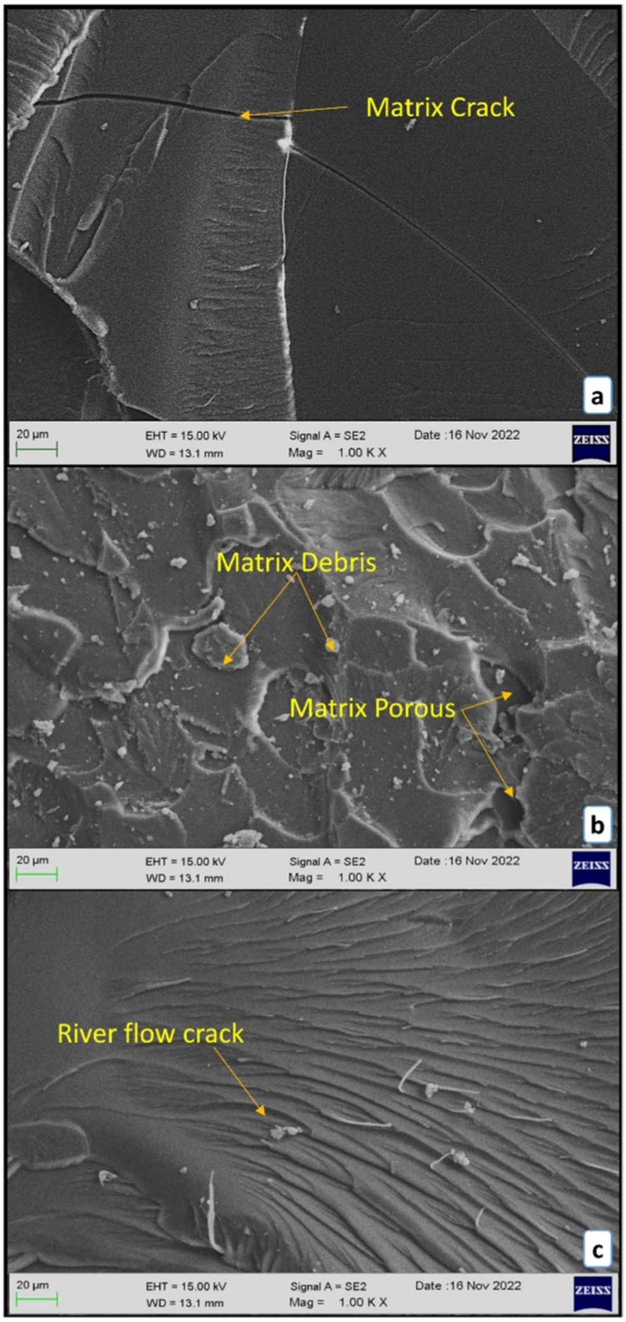

Fig. 3 **a**, **b**, **c** Different fracture pattern observation in pure polyester matrix at 500X magnification

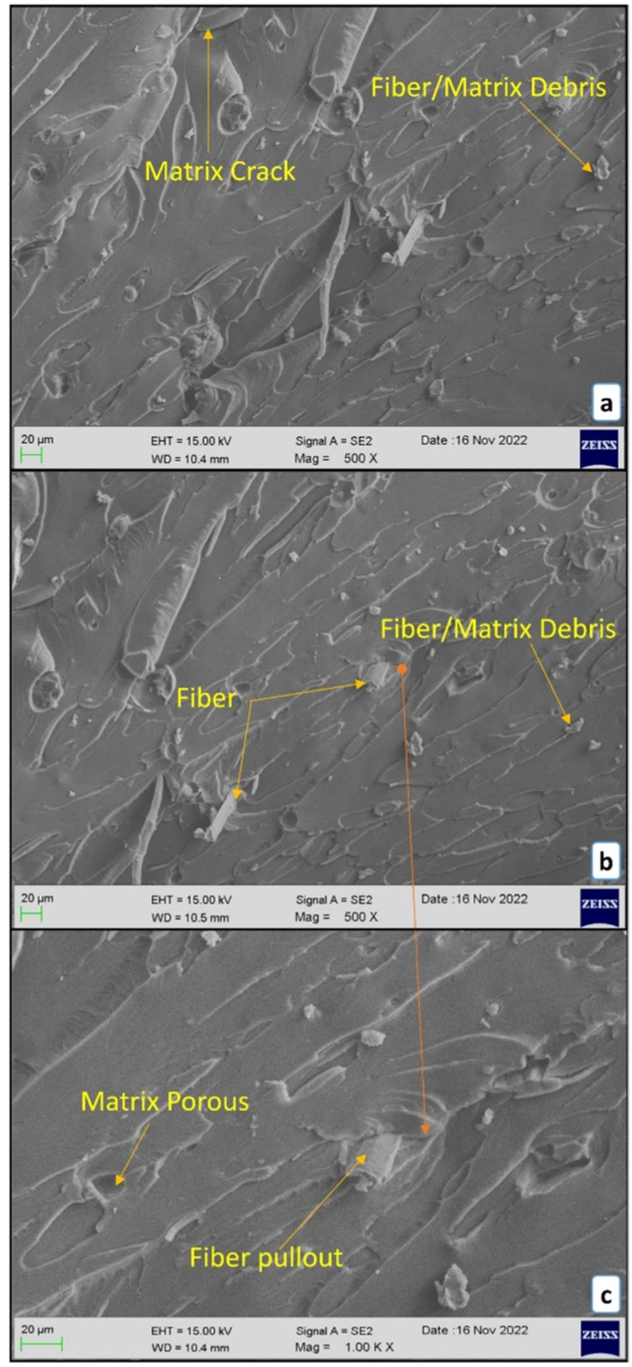

Fig. 4 (**a**, **b**, **c**) Tensile property tested 30 wt.% reinforcement of FBSF sample SEM fractography at various magnification

weight and critical length of the fibers, were presented in Table 1.

2 Materials and methods

The water retting process was used to separate the fibers from the plant's bark stem (Fig. 1a–c). After extraction of fiber, it is sundried for two days and kept in oven in 60 °C to remove the moisture for composite preparation. The unsaturated polyester, methyl ethyl ketone peroxide [MEKP], and cobalt naphthenate were used as a resin, curing catalyst and accelerator. Resin, catalyst, and the hardener used for the composite were provided by M/s. Covai Seenu and Co., Tamil Nadu, India. The matrix

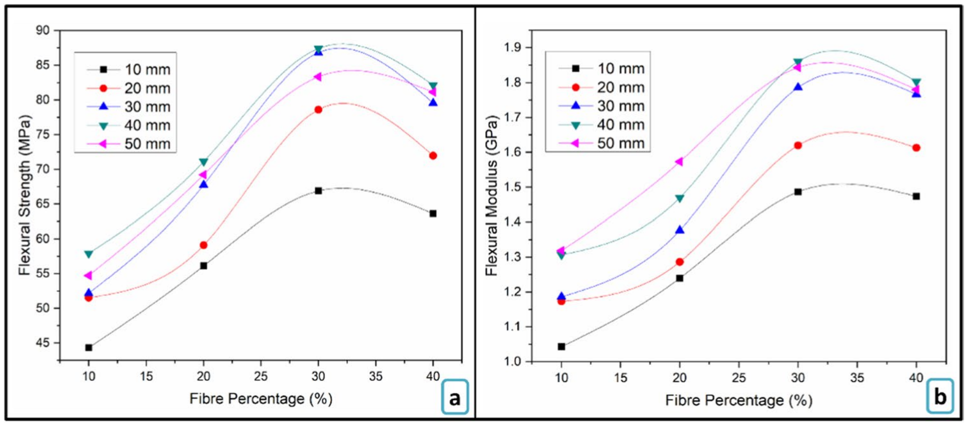

Fig. 5 **a**, **b** The effect of varying fiber length and weight percentage with respect to flexural strength and flexural modulus

resin was examined at Saint-Gobain Vetrotex India Ltd. in Thimmapur, Andhra Pradesh, India. Tests on the hardened resin were carried out by the Composites Technology Center at the Indian Institute of Technology-Madras in Chennai, Tamil Nadu, India. The experiments were conducted under ambient conditions of 21 °C and 65% relative humidity. The matrix resin test results are shown in Table 2.

In the beginning, the *F. benjamina* L. stem fibers were sliced in lengths of 10, 20, 30, 40, and 50 mm. At each gauge, length fibers were evenly dispersed, and prepressed from 10 to 50% weight percentage. The 2% MEKP (catalyst), 0.5% cobalt naphthenate, and 97.5% unsaturated polyester resin were mixed (accelerator) in a container. A mild steel mold (300 mm by 125 mm by 3 mm) surface was completely cleaned, and wax coating was formed inside the mold's interior to serve as a releasing agent. This makes it possible to remove the molded components from the cavity quickly. Fibers and matrix material were then added one layer at a time. To provide a superior surface finish and prevent the layers from sticking to the mold surface, polyethylene sheets were positioned beneath the bottom layer and on top of the top layer. Matrix solution was degassed prior to pouring. With degassed matrix solution, the compressed sheet was created, and air bubbles were eliminated with a grooved roller. The composite laminates were then compressed for three hours at a holding pressure of 35 MPa and a temperature of 60 °C. The closed mold was pressurized for the full 24 h. Total of 20 flat plates (Fig. 1d) were made by altering fiber length and fiber weight percentage [32].

2.1 Chemical testing

The chopped fibers were aged in 95% ethanol and oven-dried at 700 °C. Then, Kurshner and Hoffer's approach used to measure cellulose [33]. The fibers were heated with hydrobromic acid, as per NFT 12-008 standard to determine hemicellulose [34, 35]. Klason's approach used to assess lignin content [36]. The dichloromethane-extracted fibers were crushed and hydrolyzed in sulfuric acid. Soxhlet extraction using the Conrad technique was used to assess fiber wax content [37].

2.2 Mechanical testing

A universal testing machine (S-Series H25K-S; Instron, UK) of 400 kN capacity was used to conduct tensile and three-point flexural testing. For tensile testing, 100 mm gauge length, and 1 mm/min cross head speed in accordance with ASTM Standards D 3039M-95 were used [5, 38]. With a 5 metric tonne capacity, gauge length of 50 mm, and a cross head speed of 1 mm/min, flexural test comprising three points (two supports and one load) was carried out accordance to ASTM Standards D 790-10 [39]. A Zwick R5LB041 digital Shore hardness tester (Zwick Roell, Ulm, Germany) was used to evaluate the composite's Rockwell hardness in accordance with ASTM D 785–98 [40]. According to ASTM D256, the Unnotched composite impact energy were assessed using a Coesfeld-Material impact tester (Dortmund, Germany) [41]. The results represent an average with standard deviations across the samples. At least six samples from each event were evaluated, and the average was given. The conditions for all experiments were 21 °C and 65% humidity. With the use of a pycnometer and toluene solution, the density of the composite material was determined [42].

2.3 Fractography analysis

Using a JEOL 6390 scanning electron microscope with a 142-eV acceleration voltage, composite failure surfaces was investigated. Using a vacuum sputter coater, the samples were coated with platinum at ten nano meter thickness to make the surface conductive and the samples were then

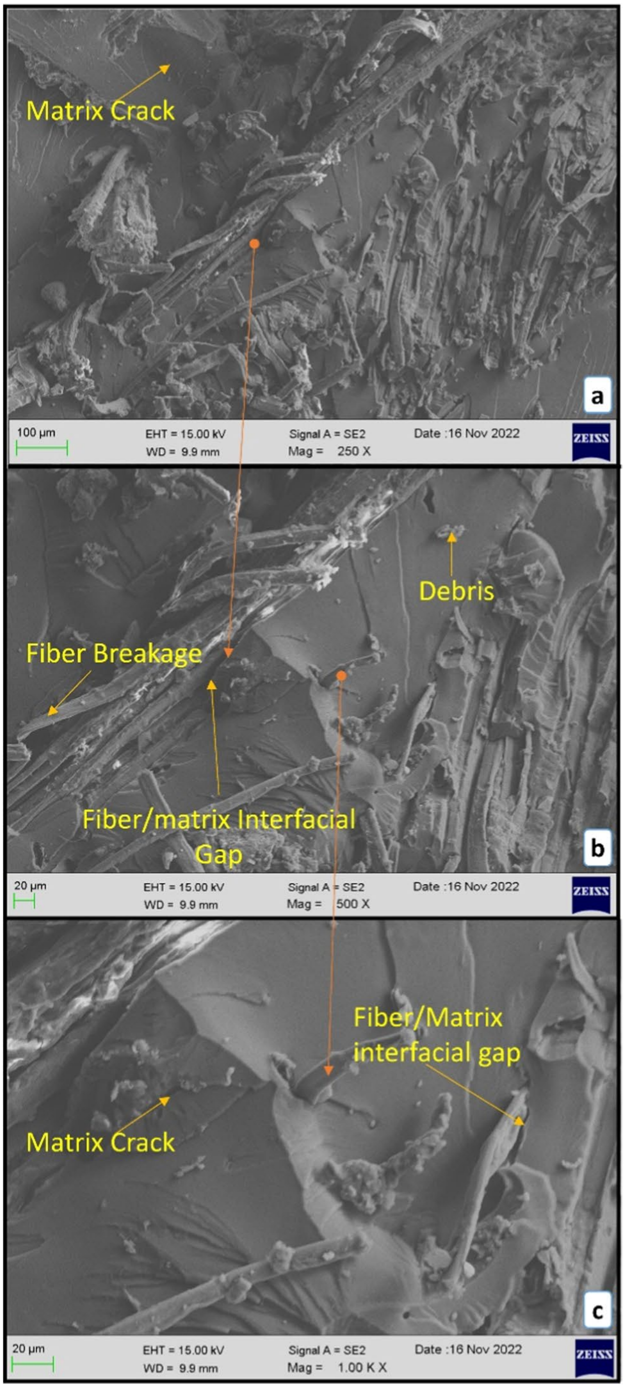

Fig. 6 **a**, **b**, **c** Flexural property tested 30 wt.% reinforcement of FBSF sample SEM fractography at various magnification

examined under a microscope [43]. Tensile broken specimens were examined at various magnifications.

2.4 Thermal behavior

For diverse applications, the composites reinforced with varying weight percentage of fibers are very important to examine the thermal decomposition behavior [44]. Thermogravimetric analysis was performed in EXSTAR TG/DTA6300 RT (RT Instruments Inc. Woodland, CA, USA). TGA tests were conducted from room temperature to 600 °C with a heating rate of 10 °C min^{-1} in a nitrogen environment at a constant flow rate of 200 ml/min.

2.5 Water uptake behavior analysis

Based on ASTM-D 570, the water absorption test was carried out [30]. In this, 60-mm square specimens were submerged in saltwater and distilled water for around 48 h. They were routinely taken out, cleaned with tissue paper, weighed, and then returned to the water. Samples were weighed using an electronic mass balancer of accuracy 0.0001 g (AUX220; Shimadzu, Japan), and the percentage of water absorption was calculated with equation 1 as follows:

$$\text{Water adsorption\%} = \frac{\text{Final weight} - \text{Initial weight}}{\text{Initial weight}} \times 100 \tag{1}$$

3 Results and discussion

3.1 Chemical and physical analysis

The FBSF density was determined to be 886 kg/m^3 which are comparable to other natural fibers [45]. Low weight composites can be produced with lower density fiber. Cellulose is the strongest element that gives mechanical strength in fiber. The FBSF had a higher cellulose content of 68.71% which is comparable to widely used fiber listed in the Table 3. Additionally, the hemicelluloses, lignin content, and wax content were assessed as 10.15, 11.31, and 0.91%. The minor amount of this component observed helps the FBSF bind better with the polymer matrix.

3.2 Analysis of FBSF reinforced composite properties

Addition of fibers in the polyester matrix makes the composite ductile and exhibits higher elongation at break. Properties of the composite are maximized or reduced by varying fiber length and weight ratio for a particular matrix system. Low length fiber reinforced composites fracture easily because load transfer becomes difficult [58]. So, the optimization fiber length and fiber content in wt.% reinforcement is need. A larger fiber length consequence in curling and obtaining straightness in them becomes a challenging. The fiber length must be at least equal to the critical fiber length in order to reach the fiber's fracture

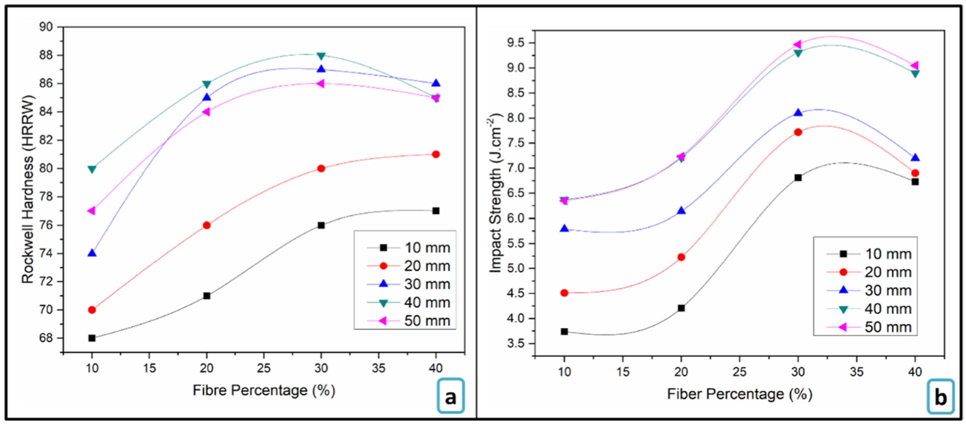

Fig. 7 **a**, **b** The effect of varying fiber length and weight percentage with respect to hardness and impact strength

stress [25]. The optimal fiber weight % also influences the composite. When the optimal fiber weight percentage was used, the composites showed strong mechanical characteristics. The fiber aspect ratio, matrix, fiber type, and interfacial bonding between the fiber and matrix all affect the optimal fiber weight percentage [59].

3.3 Tensile behavior

Tensile strength and Young's modulus of the composite rise for FBSF length 40 mm and weight percent up to 30%, then decrease for any given strain level (Fig. 2a, b). The inclusion of fiber decreased the brittleness of polyester resin and increased the elongation value. Longer-length fiber entanglements lessen stress levels [25]. In comparison to other combinations, the tensile strength and Young's modulus of the composite were greater for FBSF 30 weight percent (optimum weight) and 40 mm fiber length (critical length) [11]. At this combination, the load transmittance from the fiber to matrix was higher. The maximum tensile strength and modulus were determined to be 77.71 MPa and 1.26 GPa at 30 mm and 40% FBSF.

The results of the fractography examination of the pure sample as well as the sample that represented 30 weight percent were given in Figs. 3 and 4, respectively. The pure polyester matrix fracture can be seen with more fracture debris (Fig. 3a, b), as well as a failure in the river flow pattern (Fig. 3c). Figure 4 depicts the tensile property tested using 30 weight percent reinforcement of FBSF sample SEM fractography at various magnifications. In the ideal reinforcement of FBSF, the fiber pull out and a reduced amount of matrix failure are seen. The fiber matrix bonding was observed through this analysis.

3.4 Flexural behavior

The polyester matrix is plasticized by fibers [60]. Due to their excellent extensibility, they can withstand stress and prevent catastrophic composite failure. The results for flexural strength and modulus of FBSF composites with various fiber lengths and weight percentages are shown in Fig. 5a and b. In comparison to plain resin, increasing FBSF (40 mm long with a weight percentage of 30%) enhanced flexural strength from 44.67 to 87.40 MPa and modulus from 1.63 to 1.85 GPa, respectively. The modulus is increased when a transcrystalline layer develops at the fiber/matrix contact. Maximum flexural performance was seen in composites with 30 mm (critical fiber length) fiber and 40% (optimum fiber weight percent) fiber weight. Flexural strength and modulus were reduced when FBSF length and weight were increased above 50 mm and 40%. At this point, the uniform distribution of fiber in composites becomes challenging, which decreases the interaction of the fiber matrix under compressive bending stress. Flexural testing revealed a 1.85-GPa flexural modulus and an 87.40-MPa flexural strength for this FBSF 40 mm with 30 wt.% reinforcement.

The results of a fractography test on the flexural property of an FBSF sample with 30 weight percent reinforcement were taken using a scanning electron microscope (SEM) and displayed in Fig. 6a–c. The flexural property was investigated using 30 weight percent reinforcement of FBSF sample SEM fractography at various magnifications, and the results showed clearly that fiber pull and more fiber cracks were detected in the ideal reinforcement of FBSF. After conducting the tests, an observable fiber/matrix interfacial gap was found. It is recommended that the surface be treated in order to get the best possible flexural result from the FBSF reinforced polyester composites.

3.5 Hardness

The composite's resistance to abrasion and scratching was evaluated using hardness testing [61]. Figure 7a illustrates how hardness value varies with respect to FBSF fiber weight and length. The results show a maximum hardness of 88 HRRW at 30% and 40 mm length. The dispersion of fibers in the matrix evenly prevents matrix deformation during indentation and raises the hardness. Sharp decrease in hardness on increase of length and weight percentage above critical length and weight percentage is due to the local phase inversion brought on by fiber aggregation.

3.6 Impact behavior

The impact characteristics of the composites are shown in Fig. 7b. The strongest impact resistance was found in FBSF composites with a 30% fiber weight at a 40 mm length found to be around 9.31 J/cm^2. Longer fibers disperse impact energy more rapidly and absorb more energy [62, 63]. The number of fiber ends diminishes as fiber length grows, and the number of defects caused by fiber ends in the composite similarly goes down. As a result, as the fiber length in the composite grows, the quantity of pull-out during failure reduces [21]. As a result, the impact strength of composites grows with fiber length. However, compared to shorter lengths where fiber pull-out is the active fracture process, a high percentage of fiber will be pulled out of the matrix owing to fiber entanglements after an optimal length of fiber, which will cause a little loss in impact strength as a result. When compared to other fiber loading and length combinations, fiber loading of 30 weight percent with a fiber length of 50 mm has the highest impact strength. But since it is extremely close to 30 weight percent of fiber loading with 40 mm of fiber length, the impact strength of 30 weight percent of fiber loading with 40 mm of fiber length is selected as the ideal level. The impact strength of the FBSF composite with 30%, 40-mm long fiber is 16 times greater than that of hardened polyester resin. Frictional losses have a role in the impact strength of FBSF composites when fiber is pulled out. A slight fall of impact strength fell seen when the percentage of fiber weight in FBSF composites was raised beyond 40%. This is because the matrix's fibers provide a site for fractures to begin and grow. Additionally, linked composites stiffen the polymer chains due to the tight connection between the fiber and the polymer, which results in a rapid rupture and a reduction in impact strength.

Figure 8a–c depicts the fractography analysis of impact strength analysis with 30% reinforcement of FBSF sample SEM fractography at different magnifications. The 30 percent reinforcement of FBSF sample SEM fractography at various magnifications revealed fiber pull out, fracture debris, and higher matrix failure when impact characteristics were evaluated. The composite's porous matrix was observed following testing. For FBSF-reinforced polymer matrix composites to achieve maximum impact strength, surface treatment is recommended. The explanation for the improvement in mechanical characteristics was identified by the fractography of an impact-tested sample. Matrix was packed into the fiber lumens. These events may boost the correct adhesion between fiber and matrix, as well as the overall property improvement.

3.7 Thermogravimetric analysis

The thermogravimetric analysis (TGA) observations of FBSF composites with different weight percentages are shown in Fig. 9a. Three phases of heat degradation were visible in the TG curves of all composite samples. At temperatures between 50 and 245 °C, moisture loss from

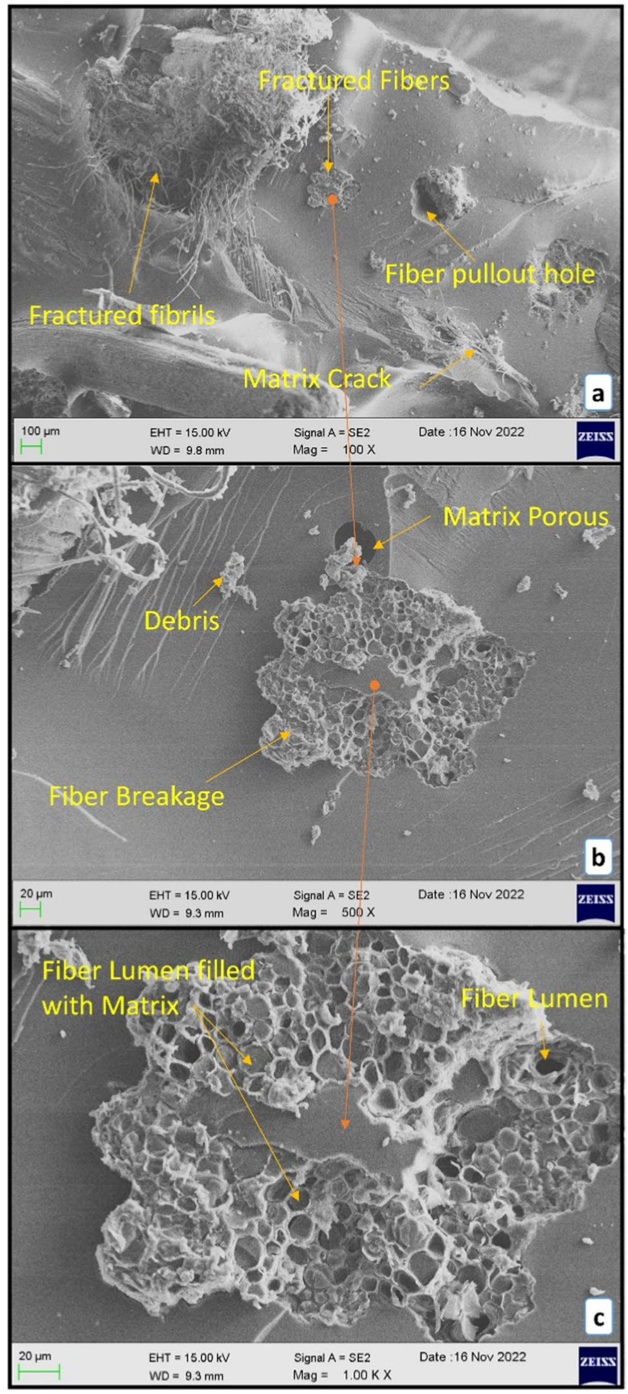

Fig. 8 **a**, **b**, **c** Impact strength property tested 30 wt.% reinforcement of FBSF sample SEM fractography at various magnification

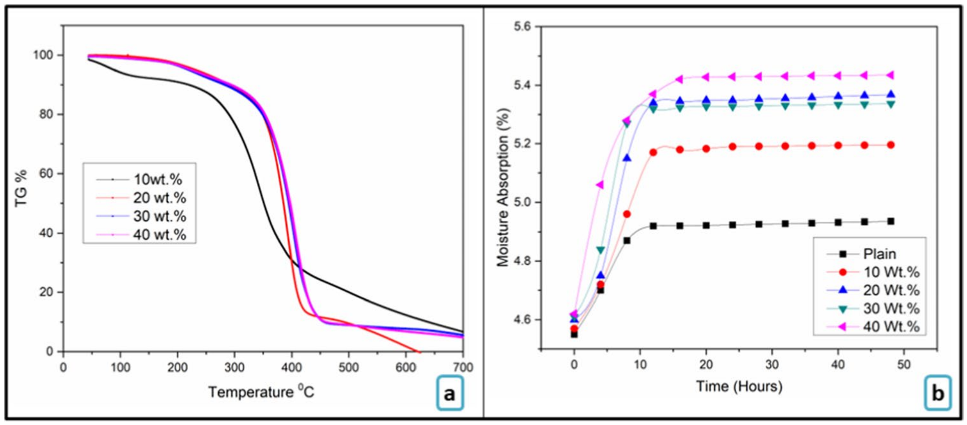

Fig. 9 **a** TGA of varying fiber weight percentage and (**b**) water absorption behavior

the composite caused the first stage of degradation [32]. The breakdown of cellulose and hemicellulose was linked to the second stage of degradation, which was observed to occur between 245 and 470 °C [33]. The third stage (470 to 660 °C) saw the degradation of the composites' soft segments and volatilization [34]. The increase in fiber weight % as shown by the TGA curves had improved the degradation temperatures. The maximum degradation temperature of FBSF 40wt.% reinforced composite is around 483 °C. Additionally, compared to a 10% fiber composite, a 30% fiber composite has less residual mass (11.3%). These findings proved that FBSF composites are a suitable material for applications requiring high-temperature composites.

3.8 Water absorption analysis

For outdoor water resistance applications, it is essential to characterize the water absorption of the composite [64]. Composite water absorption leads to dimensional instability as a result of fiber swelling. The 48-h water absorption behavior of the composite in distilled water and saltwater was tested and shown in Fig. 9b. The hydrophilic characteristic of FBSF enhances the composite's water absorption behavior. Fiber content enhances the behavior of water absorption. Thirty weight percentages of the FBSF reinforced composite exhibit less aggressive uptake behavior as compared to the 40 weight %. Due to greater adhesion between the polymer matrix and lignocellulosic, there are less microvoids in the composite at this specific weight percentage. The water absorption percentages in seawater and distilled water were 5.827 and 6.403, respectively. The 30 weight % FBSF composite roughly fits the unfilled polyester matrix water uptake graph. The permissible limit for the total weight percentage of FBSF reinforced composite water absorption is 5%-6% in two solutions.

3.9 Fractography of 50 wt.% FBSF reinforced composite

The tensile fractography of FBSF composites with maximal weight percent (50 percent) and fiber lengths of 30 millimeters is depicted in Fig. 10a–c. The fractography reveals that, when subjected to tensile stress, composites had a greater degree of fiber pull-out and debonding. Matrix wetting is caused by the presence of wax, hemicellulose, and pectin on the surfaces of FBSF. Hence FBSF deboned from matrix under tensile strain. Both the fibers and the matrix are broken as a result of the tensile force that was applied. Fragmentation of the fibers and fiber pull-out were the primary mechanisms of failure in this composite material. Fiber pull-out generated cavities on composite failure surfaces. There is seen to be less gap in the composite fiber to fiber surface, which results in poor bonding with the matrix. In addition to this, they demonstrated the maximal void, which results in a fiber-to-matrix stress transmission that is less effective. Entanglements of the composite fibers occurred if their length was greater than 30 mm, which led to flaws. Therefore, composites with a fiber length of 40 mm or 50 mm have a greater number of voids with maximum fiber pull-out. It was found that a fiber length of 30 mm was the key fiber length for FBSF composites, and it is suitable for both structural and semi-structural applications. Properties comparison of *Ficus benjamina* L. stem fiber/polyester composite in comparison with other natural fiber reinforced composite is listed in Table 4.

3.10 Composite EDS spectroscopy analysis

The use of EDX allowed for the determination of the elemental composition of the FBSF-reinforced composite. The confirmation that carbon and oxygen are present in the composite binding energies can be shown in Fig. 11(b).

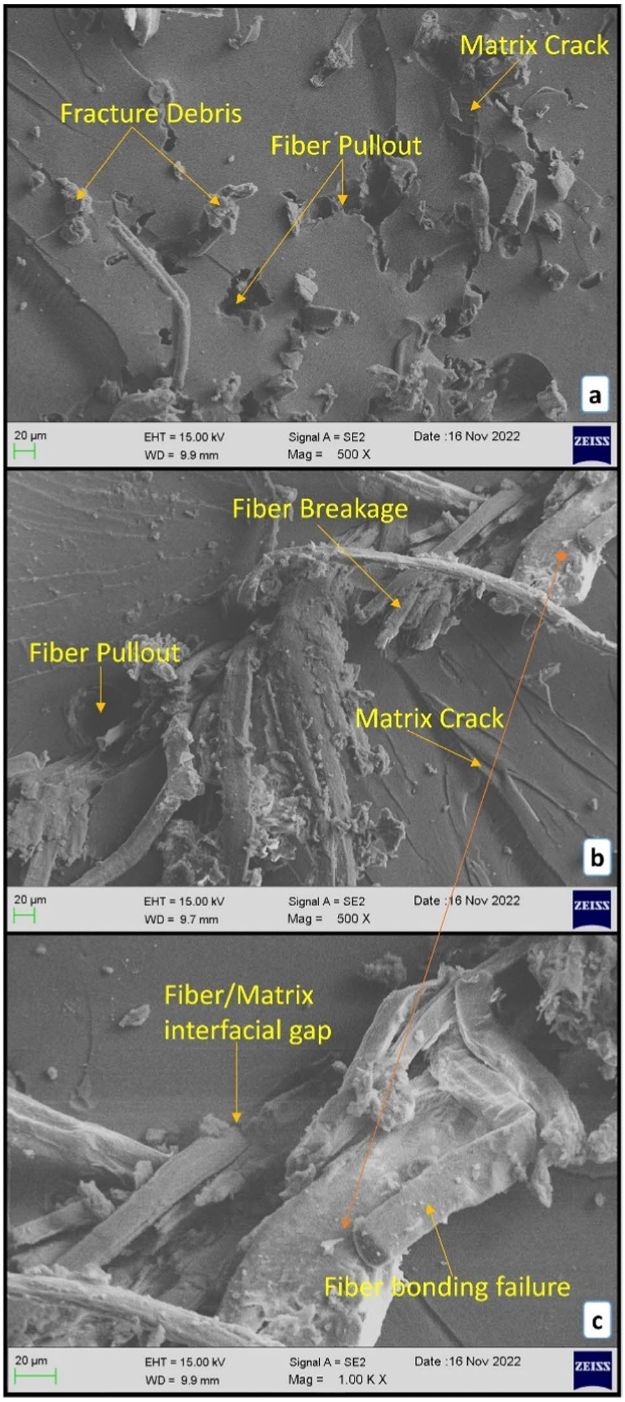

Fig. 10 **a**, **b**, **c** 50 wt.% reinforcement of FBSF sample SEM fractography at various magnification

Oxygen accounts for 29.24 weight percent of the total composite material that is FBSF reinforced, while carbon is the other major component (70.76 wt.%). In the EDX spectra of cellulose isolated from plants that are not trees, traces of potassium, salt, sulfur, and chlorine have been found in a number of different investigations. This suggests that the

Table 4 Properties comparison of *Ficus benjamina* L. stem fiber/polyester composite in comparison with other natural fiber reinforced composite [9, 11, 18, 21, 30, 34–43, 50–57, 59]

Fiber	Matrix	Method	Optimum fiber		Tensile strength MPa	Tensile modulus GPa,	Flexural strength MPa	Flexural modulus GPa,	Impact strength J/cm^2	Hardness (HRRW)
			Length mm	Loading %						
Ficus benjamina L. stem fiber	Polyester	Hand layup	150	40	77.71	1.26	87.40	1.85	9.31	88
Bamboo fiber	Polyester	Hand layup	160	40	126.2	2.48	128.5	3.70	-	-
Calotropis gigantea	Epoxy	Hand layup	0.149-0.100	10	48.73		195.19		6.34	67
Calotropis procera fiber	Epoxy	Hand layup	30	30	11.43 ± 0.06	-	26.38 ± 0.47	-	0.167	-
Cissus quadrangularis stem	Polyester	Hand layup	40	30	90.200	1.400	103.040	2.250	10.7	92
Dichrostachys cinerea bark fibers	Epoxy	Hand layup	0.07	30	46.69	0.484	68.89	4.456	7.577	-
Jowar fiber	Polyester	Hand layup	160	40	124	2.75	134	7.87	-	-
Jute fiber	Epoxy	Hand layup	30	20	75.15	0.638	124.01	2.61	3.25	-
Musa paradisiac banana fiber	Polypropylene	Compression molding	70	20	47	2.642	73.24	-	2.656	75
Sansevieria cylindrica fiber	Polyester	Compression molding	30	40	75.75	1.102	84	3	9.5	-
Sisal fiber	Epoxy	Hand layup	10	30	40.25	0.187	104.78	11.896	1.366	-
Tamarind fruit fiber	Polyester	Compression molding	50-100	40	77.4	1.4	88.5	1.5	7.3	90

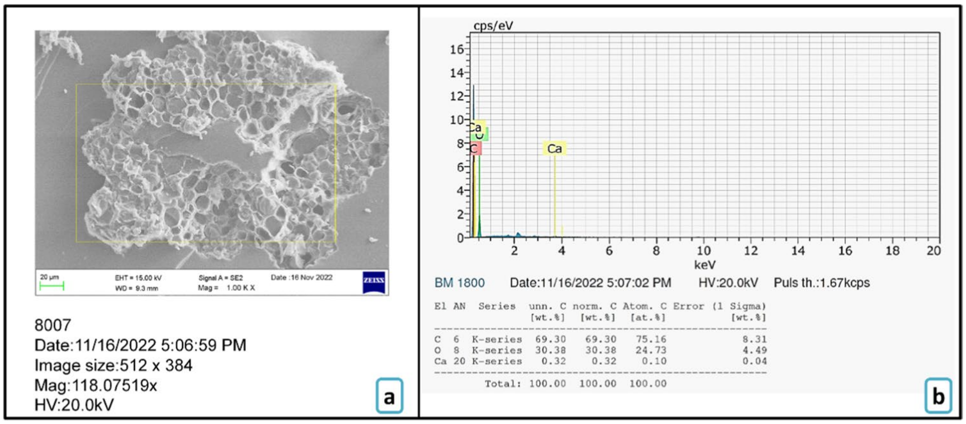

Fig. 11 **a**, **b** Energy-dispersive X-ray Spectroscopy analysis of FBSF composite

elements that led to the production of an exceptionally pure biofiber reinforced composite did not change when natural cellulosic fiber was used as reinforcement for the composite.

4 Conclusion

Ficus benjamina L. are typically found along roadsides and in forests. Planned production, extraction, processing, and use of these fibers create opportunities for farmers and enterprises to generate income. A unique natural lignocellulosic stem fiber of *Ficus benjamina* L. is extracted by water retting. Comparable cellulose contents of this fiber (68.71%) enhance its mechanical strength. The critical length and optimum weight percentage of the fibers were discovered to be 30 mm and 40%, respectively. The maximum tensile strength and modulus were determined to be 77.71 MPa and 1.26 GPa at 30 mm and 40% FBSF. Flexural testing revealed a 1.85 GPa flexural modulus and an 87.40 MPa flexural strength. At this specific proportion, the impact strength was found to be around 9.31 J/cm^2. Even after 48 h of immersion in water, the maximum water absorbency of *Ficus benjamina* L. stem fiber reinforced composites was determined to be 5.54 percent. TGA reveals the degradation temperature (430 °C) and char production (13.8%) are highest for 40 wt.% *Ficus benjamina* L. composite. *Ficus benjamina* L. enhances the heat resistance of the composite. These characteristics demonstrated that the fibers had a high potential for usage as reinforcement in external structural composites. Due to the fiber's high tensile strength and low extensibility, it has the potential to be a unique option for the creation of high-performance lightweight composite applications and other technical textile goods such as ropes, sacks, packaging materials, cords, yarns, and industrial textiles.

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Author contributions All authors are equally contributed to conceptualization, methodology, writing - original draft, writing - review & editing.

Data availability The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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