

# Thermo-Mechanical Behaviour of Schizostachyum Grande Bamboo Fibre, Epoxy and Vinyl Resin Thermoset for Potential in Composite Application

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DOI: <https://doi.org/10.30880/jaita.2025.06.02.007>

## Article Info

Received: 10 October 2025  
Accepted: 18 November 2025  
Available online: 31 December 2025

## Keywords

Schizostachyum grande bamboo, epoxy resin, vinyl resin, natural fibre composite, morphology properties, mechanical properties of composite

## Abstract

This study was conducted to investigate bamboo fibre and thermoset resin's thermophology and thermoset resin for composite applications and to delve into the morphology, behaviour, and mechanical properties of bamboo fibres from the species Schizostachyum grande, as well as thermoset resins such as vinyl and epoxy. Besides, fibre and thermoset resins were incorporated to achieve the desired mechanical properties, specifically for tensile strength and elongation characteristics. Additionally, this study was also conducted to determine physical and chemical composition properties, where Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) tests were executed on bamboo fibre and epoxy and vinyl resins. Furthermore, Thermogravimetric Analysis (TGA) and Fourier Transform Infrared Spectroscopy (FTIR) tests were performed to determine the physical performance of the material in terms of mass loss over time. The data obtained for bamboo fibre, epoxy, and vinyl resin were then compared for the factors of maximum stress, stiffness, deflection, and maximum load. Hence, this research contributes to the understanding of bamboo fibres and thermoset suitability for sustainable engineering applications by providing comprehensive data on morphology, behavior, and tensile properties. The results of this research are useful in terms of design and materials selection processes, enabling the creation of more robust and ecologically friendly engineering solutions for the chosen fibre and thermoset resin towards sustainable structures, such as modular houses.

### 1. Introduction

This paper investigates the thermo-mechanical behaviour of *Schizostachyum grande* bamboo fibre reinforced epoxy and vinyl thermoset resins to evaluate their potential for sustainable composite applications. Bamboo fibre is chosen for its renewability, low density, and strength, and is combined with epoxy and vinyl, which are widely used for their durability and structural performance. The key challenge addressed is the poor interfacial bonding between hydrophilic bamboo fibre and hydrophobic thermoset matrices, which often limit mechanical efficiency. By comparing the performance of these materials, the study aims to highlight the suitability of bamboo fibre as reinforcement in thermoset composites and its potential to deliver lightweight, durable, and eco-friendly alternatives for future engineering and construction needs.

### 2. Natural Fibre

Natural fibres have gained recognition as renewable, eco-friendly substitutes for non-biodegradable materials, thereby reducing the impacts of global warming and promoting the development of green products [1]. They are categorised into plant, animal, and mineral sources, with plant fibres further divided into bast, seed, leaf, straw, grass, and wood [2] as shown in Fig. 1.

Fig. 1 Type of natural fibre [3]

Their appeal lies in low cost, biodegradability, lightweight structure, and excellent mechanical performance, including high specific strength, vibration absorption, fracture toughness, and flexibility [3], [4], making them widely applied in composites, automotive, construction, and packaging [5]. Global consumption continues to grow, projected at  $817.6 \times 10^3$  tonnes in 2025 and  $883.2 \times 10^3$  tonnes in 2026, with North America as the largest consumer shown in Fig. 2 [6] and production data in Table 1 highlights wood fibre as the most abundant at  $1,750.00 \times 10^3$  tonnes annually, while bamboo, a major stem-derived fibre, contributes  $10,000\text{--}30,000 \times 10^3$  tonnes per year [7].

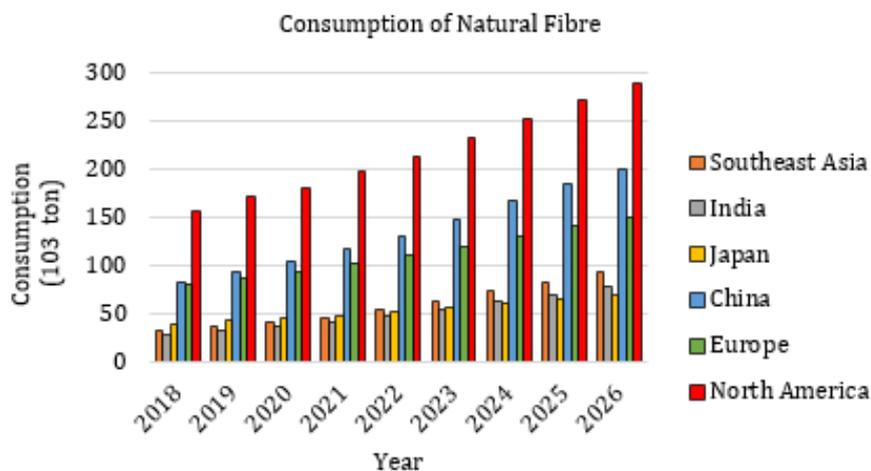


Fig. 2 Statistics on consumption of natural fibre [6]

**Table 1** Annual production of natural fibre [7]

Type of Fibre	Origin	Annual production (10 <sup>3</sup> tons)
Abaca	Leaf	70
Bamboo	Stem	10,000 – 30,000
Banana	Stem	200
Coir	Fruit	100
Cotton Lint	Stem	18,500
Flax	Stem	810 – 830
Hemp	Stem	215
Jute	Stem	2300 - 2500
Kenaf	Stem	770 - 970
Ramie	Stem	100
Wood	Stem	1,750,000

## 2.1 Bamboo Fiber

Bamboo, comprising approximately 1,250 species across 90 genera, is one of the fastest-growing natural resources, producing an estimated 20 million tons globally [8]. As giant woody grass, it offers versatility, a high strength-to-weight ratio, and ease of handling, making it valuable for both technical and non-technical applications, including construction, where it has been used since ancient times. Found abundantly in Asian countries such as Malaysia, Indonesia, and China, bamboo is categorized as a green fibre that matures in five years and can be harvested repeatedly without harming growth cycles [9], [10]. Its strength has established it as a promising sustainable biomass resource[2]. Table 3 highlights the details of bamboo's chemical composition, while Table 4 compares its mechanical performance to cotton, sisal, and kenaf, highlighting bamboo's balance of 700 MPa tensile strength and moderate 10 MPa modulus, making it a strong yet flexible reinforcement material.

**Table 2** The chemical composition of natural fibre [3], [11]

Natural Fibre	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Fat and wax (%)
Abaca	60.8 – 68.0	17.5 – 21	5 – 15.1	<1	<1
Bagasse	55.2	16.8	25.3	10	-
Bamboo	36.1 - 54.6	11.4 – 16.6	20.5 – 28.5	<1	1 – 4
Banana	63-64	-	5-11	4	-
Coir	32.0 – 43.4	0.3	40 – 45.8	3	0 – 6
Cotton	82.7 – 98.0	4.5 – 5.7	0.7	4	2 – 3
Curaua	7.36	9.9	7.5	-	-
Flax	71	18.6 – 20.6	2.2 – 20.6	0.9	-
Hemp	55 – 90	12	2 – 5	3	1.7
Jute	58.0 – 71.5	13.6 – 24.0	11.8 – 16	2	<1
Kenaf	45 – 72	20.3 – 21.5	8 – 13	2	-
Pineapple	80.5	17.5	8.3	4	-
Ramie	60 – 91	5 – 15	0.4 – 0.7	1.9	0.3
Sisal	65 – 78	10 – 14	9.9 – 14	1.2	-

**Table 3** Comparison of the mechanical properties of fibres [12]

Fibre	Density (g/cm <sup>3</sup> )	Tensile Strength (Mpa)	Elastic Modulus (Mpa)
Bamboo	1.5	700	10
Sisal	1.5	600	10
Kenaf	1.5	900	50
Cotton	1.5	400	10

### 3. Thermoset

Thermosets are polymers formed through irreversible curing, where liquid matrices undergo heat- or radiation-activated polymerization with hardeners, producing cross-linked, insoluble, and high-performance composites with excellent mechanical and thermal properties [5], [13]. Common types include unsaturated polyester, epoxy, and condensation resins. Epoxy resin is widely applied in coatings, adhesives, corrosion protection, and fibre-reinforced composites due to its strong adhesion, chemical resistance, and load-bearing capacity [14], [15]. The network structure of epoxy resin forms through the reaction of epoxide groups with curing agents, such as amines, anhydrides, or thiols, as illustrated in Figure 3 [16], [17]. Various mechanical properties of this resin, such as durability, toughness, and thermal stability, depend strongly on the curing agent and degree of cross-linking, which transform the resin into a rigid, solid matrix [16], [18].

Meanwhile, Vinyl ester resin is a robust thermosetting polymer valued for its strength and resistance to harsh environments, featuring unsaturated oligomer bonds that react with styrene to form a dense, cross-linked network [10], [19]. Its processing ease, high strength, and chemical resistance make it popular in marine, automotive, and chemical industries [20]. Compared to unsaturated polyesters, their terminal double bonds enable tighter crosslinking, producing a less permeable structure with superior resistance to water, chemicals, and corrosion [19], [20]. Mechanically, vinyl esters show tensile strengths of 80-120 MPa and elastic moduli of 2.9-11.9 GPa, ensuring high stiffness and reliable performance under static and dynamic loading [3], [21], [22]. Although less flexible, with 3-5% elongation at break [3], [23], they strike a balance between ductility and integrity. With a density of 1.2–1.4 g/cm<sup>3</sup>, vinyl esters remain lightweight yet strong, making them ideal for composite applications where strength, durability, and reduced weight are critical [3], [21], [24].

### 4. Materials and Methods

This research examines three materials: bamboo fibre, epoxy resin, and vinyl resin, which are evaluated using both physical-chemical characterization and mechanical performance testing. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) were used to evaluate the morphology and structural properties of each material. Thermal stability and functional group composition were further investigated using Thermogravimetric Analysis (TGA) and Fourier Transform Infrared Spectroscopy (FTIR). Tensile testing was carried out using standardized procedures to determine tensile strength and elongation at break. The main natural material used is Schizostachyum Grande bamboo fibre, which was chosen for its rapid growth, renewability, and sustainability potential. Epoxy and vinyl resins, both thermosetting polymers, were made with a resin-to-hardener ratio of 1:1. Both resins were cured for 24 to 48 hours at room temperature, and bamboo fibres were allowed to air dry naturally to eliminate moisture. Prior to testing, every specimen was prepared in the lab. Table 4 summarises the procedures used for each tensile strength and chemical analysis test.

**Table 4** *The laboratory testing*

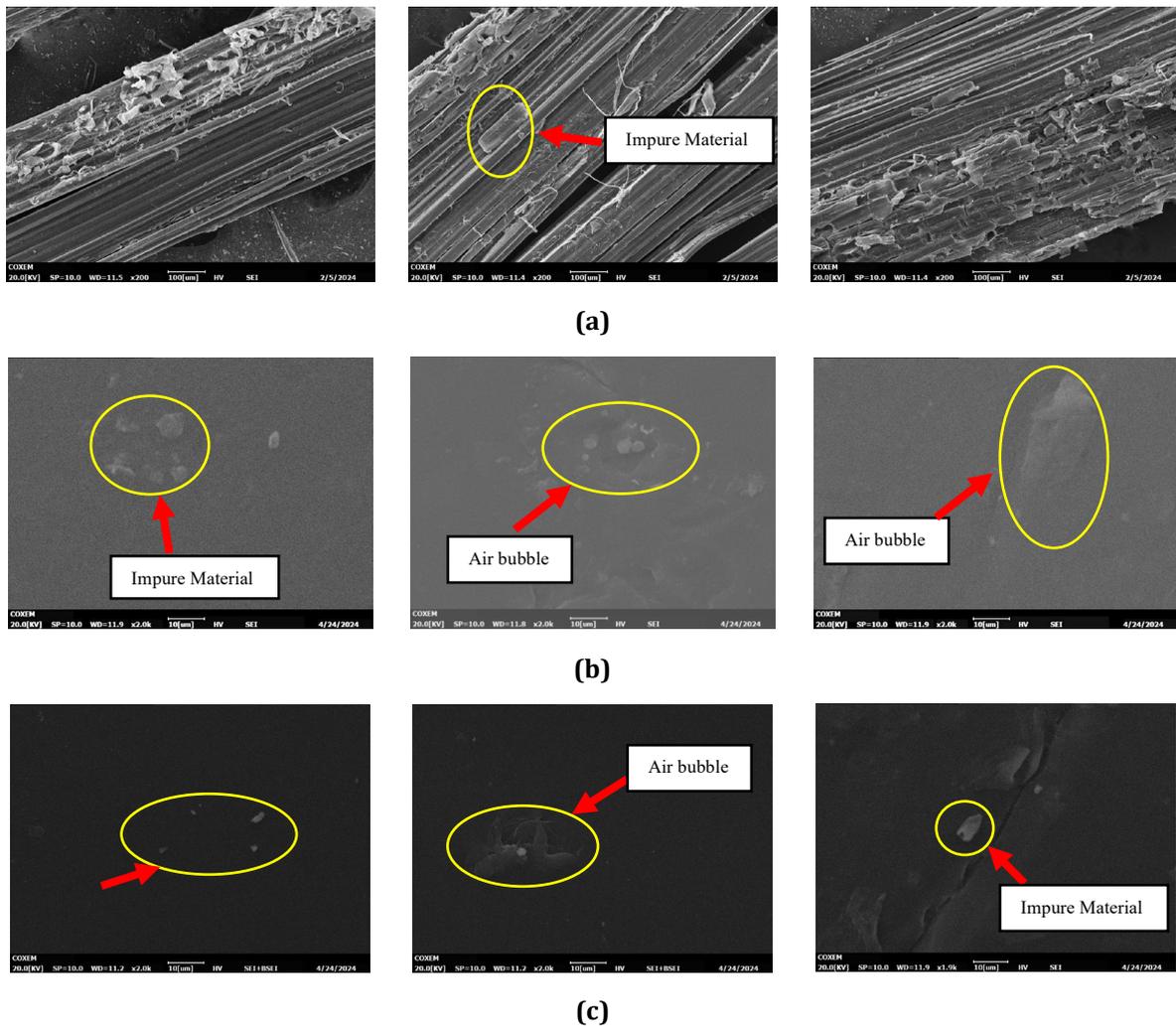
Type of test	Laboratory work
Scanning Electron Microscopy (SEM)	Scanning Electron Microscopy or SEM is used to analyse the morphology, surface, and fibre-matrix interface of the materials in this study, which was done based on the ASTM E2809-22 and conducted at the Physics Nanotechnology Lab at UTHM Pagoh.
Thermogravimetric Analysis (TGA)	Thermogravimetric Analysis (TGA) is a technique used to measure changes in a material's mass as it is subjected to controlled temperature variations over time. TGA testing was carried out at the Process Instrumentation Laboratory, UTHM Campus Pagoh, and conducted in accordance with ASTM E2105.
Fourier Transform Infrared Spectroscopy (FTIR)	Fourier Transform Infrared Spectroscopy (FTIR) is a technique for identifying and characterising chemical compounds based on their molecular structures. FTIR testing is carried out at the Analytical Laboratory at UTHM Campus Pagoh according to ASTM D7653-18.
Tensile Testing	The tensile test in this study was conducted to evaluate the tensile strength of polymer composite samples. Testing was performed using a Universal Testing Machine (UTM) at the Material Science Laboratory, Block C, UTHM Pagoh Campus according to ASTM D790.

### 5. Data Analysis

#### 5.1 Scanning Electron Microscopy (SEM)

The morphology of the material in this research is shown in Fig. 3, where (a) shows the SEM image for bamboo fibre at 200 magnifications. A rough surface can be observed on the bamboo fibre with the presence of impure material, indicating that the bamboo fibre doesn't have a smooth surface and may act as one of the contributing

factors affecting the bonding with other materials for composite applications. Meanwhile, (b) and (c) show the SEM images for Epoxy and Vinyl Resin at 2000 magnification. The data indicate that both materials exhibit smooth surfaces; however, certain handling procedures during sample preparation may influence the overall structure. The presence of impure material and air bubbles was detected in both resins in the SEM images. The formation of air bubbles in thermoset structures can potentially affect the overall strength and performance in composite applications. This observation indicates that both thermoset resins exhibit similar surface characteristics and are affected by poorly controlled sample preparation. In contrast, bamboo fibre indicates a rough surface, which can enhance the mechanical interlocking with other materials, especially resin. A rough surface morphology suggests potential strong bonding, where a rough surface provides and promotes interface interaction, while the resin's liquid form enables it to fill the surface effectively, leading to enhanced and improved strength for composite applications.



**Fig. 3** Scanning Electron Microscopy (SEM) of (a) Bamboo fibre; (b) Epoxy resin; and (c) Vinyl resin

## 5.2 Energy Dispersive X-ray (EDX)

The element composition content for bamboo fibre, epoxy, and vinyl resin was confirmed through EDX analysis, with the findings summarised in Table 5, where the highest elements are Carbon (C) and Oxygen (O). Bamboo fibre demonstrated a nearly equal distribution value of Oxygen (48.53 wt%) and Carbon (49.36 wt%). Other minor element presences such as Potassium (0.93 wt%), Silicon (0.31 wt%) and Copper (0.87 wt%) indicate the prove from the previous study of its organic and cellulose-based nature, with the hydrophilic nature of bamboo and its tendency to absorb moisture in fibre matrix bonding [25], [26]. Meanwhile, Epoxy and vinyl resin exhibit the consistent characteristics of thermoset polymers, with significantly higher Carbon (74.52 wt% and 74.06 wt%) and Oxygen content (23.92 wt% and 25.65 wt%), respectively.

**Table 5** Chemical element (EDX) of bamboo fibre, epoxy resin and vinyl resin

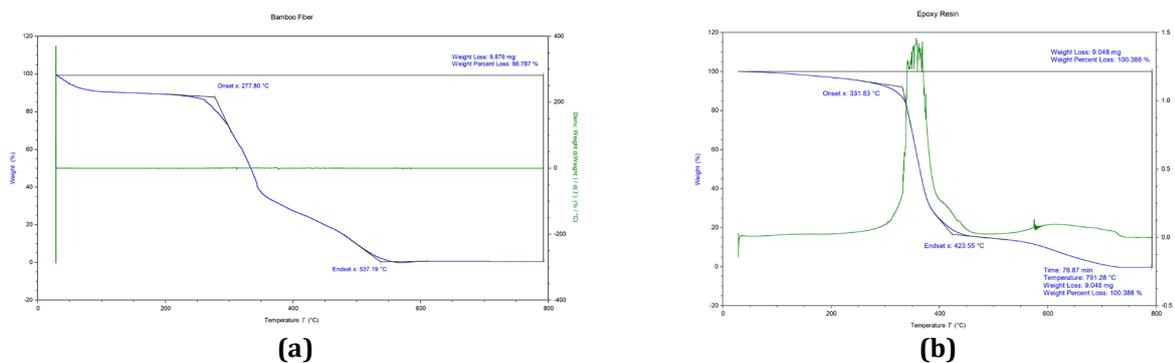
Element		O	K	C	Si	Na	Al	Cu	Mg	Cl	Ca
Bamboo Fibre	Weight (%)	48.53	0.93	49.36	0.31	-	-	0.87	-	-	-
	Weight (%) Sigma	1.96	0.15	1.99	0.12	0.26	0.13	0.41	-	-	-
	Atomic (%)	42.18	0.33	57.15	0.15	-	-	0.19	-	-	-
Epoxy Resin	Weight (%)	23.92	-	74.52	0.15	-	0.67	-	0.48	0.16	0.11
	Weight (%) Sigma	4.77	-	4.81	0.40	-	0.39	-	0.44	0.40	0.34
	Atomic (%)	19.28	-	79.99	0.07	-	0.32	-	0.25	0.06	0.04
Vinyl Resin	Weight (%)	25.65	-	74.06	0.05	-	0.11	-	-	0.07	0.06
	Weight (%) Sigma	3.21	-	3.22	0.23	-	0.24	-	-	0.22	0.23
	Atomic (%)	20.61	-	79.27	0.02	-	0.05	-	-	0.03	0.02

This finding shows that the thermoset matrix with low polarity and concentration, where a small presence of trace elements such as Aluminium, Magnesium, and Calcium in both resins, suggests the inclusion of additive agents in their formulation. A previous study [13] demonstrates that a high carbon-to-oxygen ratio in both resins correlates well with their thermally stable, non-polar nature and the inherent polarity mismatch with natural fibres. The chemical composition of each material in the results supported that the bamboo fibre exhibits a hydrophilic character, and both thermosets demonstrate non-polar and carbon-dominant structures.

### 5.3 Thermogravimetric Analysis (TGA)

The thermal degradation behaviour trend in thermal stability of bamboo fibre and thermoset matrices, specifically Epoxy and Vinyl Resin, was evaluated by TGA analysis, and the graph of weight loss over temperature is shown in Fig. 4. Bambo fibre displayed early degradation with significant mass loss initiating at approximately 275 °C and peaking near 331 °C, which corresponds to the decomposition of hemicellulose and cellulose, followed by partial lignin degradation. This proves that the limitation for thermal resistance of this fibre is lower, with a total loss of 84%. Bamboo fibre major thermal breakdown is recorded by [27], between 250 and 350 °C. This is affected by its lingo-cellulosic composition and lack of chemical modification [28]. Meanwhile, thermoset matrices exhibit better thermal stability, as their liquid form cures into a rigid and cross-linked network, which acts as a significant contributor.

The observation trend indicates that delayed degradation occurs near 350 °C, with a sharp decomposition peak at around 376 °C. These observations align with [13], who reported similar high-temperature behaviour for epoxy and vinyl composites in structural applications. The total mass loss shows a similar value of 84°C to 85°C, but the extended thermal resistance of these thermosets is attributed to their high cross-link density. The prevention of melting and instead results in a one-step decomposition mechanism once the thermal threshold is exceeded. This mechanical behaviour is supported by [29], where a cross-linked network of thermoset matrices offers excellent thermal resistance with degradation beyond 340°C. The combination of thermosetting matrices, such as epoxy or vinyl resin, with treated bamboo fibres can improve overall thermal performance and extend composite usability in environments requiring heat resistance [26].



**Fig. 4** TGA analysis for (a) Bamboo fibre; (b) Epoxy resin

## 5.4 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectrum of bamboo fibre, epoxy resin and vinyl resin, as shown in Fig. 5, reveals several characteristic absorption bands typical of lignocellulosic materials. A broad peak around  $3300\text{--}3400\text{ cm}^{-1}$  corresponds to O-H stretching, indicating the presence of hydroxyl groups from cellulose and hemicellulose. Peaks near  $2900\text{ cm}^{-1}$  are attributed to C-H stretching, while the  $1730\text{ cm}^{-1}$  and  $1640\text{ cm}^{-1}$  bands suggest C=O stretching from ester and carboxylic acid groups. Vibrations in the  $1050\text{--}1150\text{ cm}^{-1}$  region confirm C-O and C-O-C stretching, reinforcing the natural biopolymeric structure of bamboo. These results confirm that bamboo fibre is rich in polar functional groups, which are responsible for its hydrophilic nature and tendency to absorb moisture as a key factor in fibre-matrix compatibility [25], [26].

Meanwhile, both thermoset materials show more chemically stable and less polar structures. Epoxy resin shows prominent peaks around  $3050\text{--}3080\text{ cm}^{-1}$  (aromatic C-H),  $1600\text{ cm}^{-1}$  and  $1500\text{ cm}^{-1}$  (C=C stretching), and a sharp signal at  $\sim 910\text{ cm}^{-1}$ , corresponding to epoxide ring vibrations. Vinyl resin exhibits peaks at  $2950\text{ cm}^{-1}$  (C-H stretching),  $1720\text{--}1740\text{ cm}^{-1}$  (C=O from ester groups), and strong C-O stretching between  $1000\text{--}1300\text{ cm}^{-1}$ . These spectra confirm the presence of unsaturated and cross-linked polymer networks in both resins, giving them their characteristic rigidity, thermal stability, and water resistance [13]. However, the chemical mismatch between hydrophilic bamboo and hydrophobic thermosets suggests that surface modification of the fibre is crucial to improve adhesion in composite applications [26].

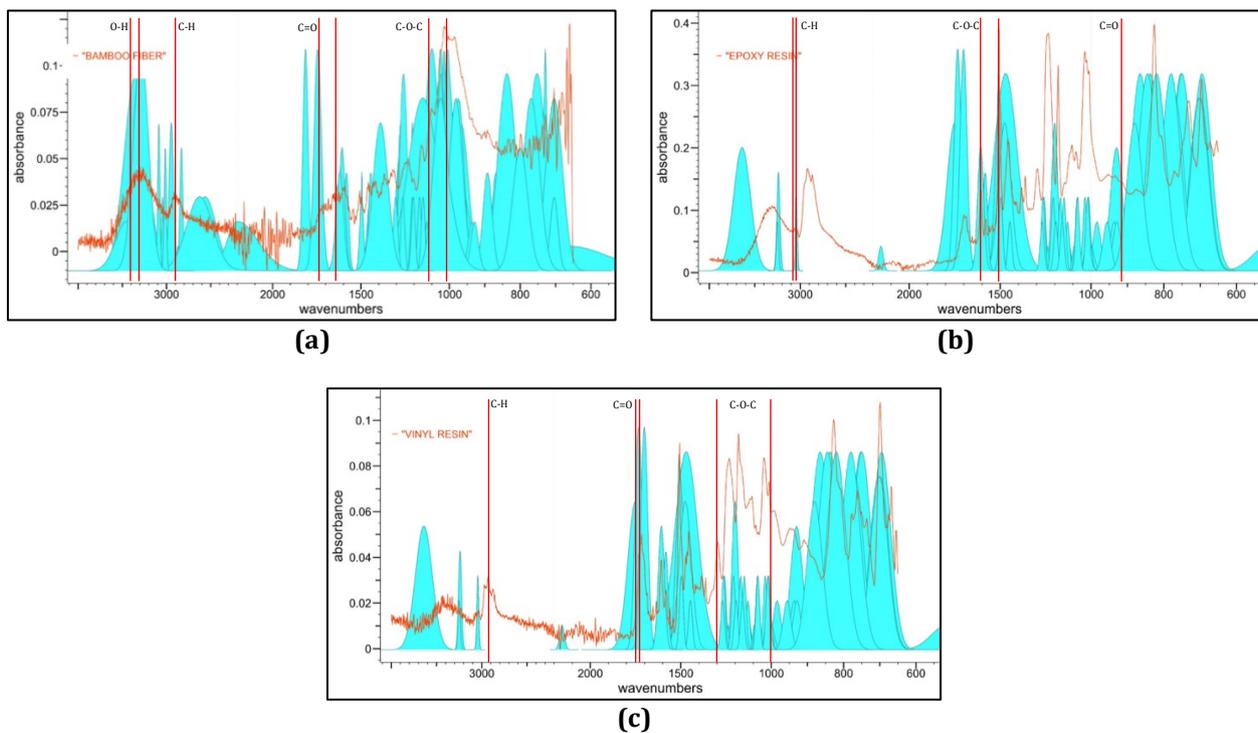


Fig. 5 FTIR analysis for (a) Bamboo fibre; (b) Epoxy resin and (c) Vinyl resin

## 5.5 Tensile Testing

The tensile test results in Table 6 clearly differentiate the mechanical behaviour of bamboo fibre, epoxy, and vinyl resin in this research. Epoxy resin exhibits a moderate tensile strength, ranging from 21.11 MPa to 24.37 MPa, while displaying high strain values of 40.8% to 67.8%. This indicates the material's ability to undergo significant deformation before failure. This observation aligns with the discussion in the previous study [30], which found the toughness and energy of the epoxy resin composite to be acceptable. Unlike vinyl resin, these characteristics indicate a higher tensile strength of 103.7 MPa to 147.7 MPa, along with low strain values of 3.2 MPa to 3.9 MPa. These results prove its mechanical behaviour, such as brittle and stiff.

This reflects its rigid and fragile nature, resulting from tight molecular cross-linking, and is supported by previous research, which has shown that the vinyl composite matrix enhances mechanical performance [30]. Additional support from previous research reveals that vinyl resin is prone to brittleness, but becomes stronger with the addition of natural fibre, which can enhance tensile strength and improve stress distribution [31]. Meanwhile, Bamboo Fibre show the minimal tensile strength of 2.13 MPa to 3.27 MPa and a lower strain value of

0.6% to 0.8%. This result highlights the limitations of Bamboo Fibre in terms of standalone mechanical performance, as confirmed by previous research on bamboo fibre with alkaline treatment [32].

**Table 6** Mechanical properties of epoxy resin, vinyl resin and bamboo fibre

Sample	Tensile strength (MPa)	Strain (%)	Stress (MPa)
Epoxy Resin	23.6227	40.8095	21.6873
	21.6873	43.7555	23.6227
	22.0149	46.0942	24.3683
	21.1072	67.7864	22.0149
Vinyl Resin	147.7196	3.2372	95.6013
	132.0234	3.3631	108.8255
	103.7401	3.6732	132.0234
	108.8255	3.8939	103.7401
Bamboo Fiber	3.2730	0.6633	2.1457
	2.9416	0.6069	2.1338
	2.1457	0.7658	2.9416
	2.1338	0.7916	1.7220

However, [33] proves that the significant improvement in bamboo fibre tensile properties and its potential in hybrid composites with thermoset materials enhances the performance of the composite structure. Additionally, [34] noted that this approach develops fibre-thermoset composite matrices for a desirable balance between mechanical properties and sustainability in composite structures, highlighting the development of hybrid matrices in sustainable structures that balance ductility and stiffness [35].

The trend in the mechanical properties of bamboo fibre, epoxy, and vinyl resin is clearly demonstrated in Fig. 6, where the structural behaviour differs for each material. The vinyl resin value for stiffness shows the highest values between 520 N/mm and 670 N/mm, and Young's modulus ranges from 5400 MPa to 6800 MPa. This trend demonstrates that its behaviour provides a highly rigid matrix and is suitable for high load-bearing applications, compared to epoxy resin, where minimal deformation is desired. Proven by [36], where vinyl strength is higher among thermosets in hybrid composites. It also indicates that this can result in high stiffness under flexural loads. Meanwhile, the Epoxy Resin value is recorded as moderate stiffness, with a value of 140 N/mm to 180 N/mm and a Young's modulus value of 1500 MPa to 1790 MPa.

This indicates that the mechanical characteristics demonstrate a balance between rigidity and flexibility, aligning with the previous observation trend in natural fibre-reinforced epoxy composites by [30] and [37]. The balance stiffness can enhance or contribute to higher impact resistance and strain value. Compared to thermoset, bamboo fibre exhibits the lowest stiffness, with values ranging from 37 N/mm to 44 N/mm and a Young's modulus of 388 MPa to 452 MPa. This trend in mechanical properties suggests that bamboo fibre can act as a reinforcement for the structure. By nature, it has low mechanical properties and can be used to improve and support the interfacial bonding in composite structures. These lower values also reflect its natural variability and porous structure [38]. Hybrid matrices with thermoset material can hold the potential to achieve a balanced mechanical behaviour between both materials, making them a choice for sustainable composite structures.

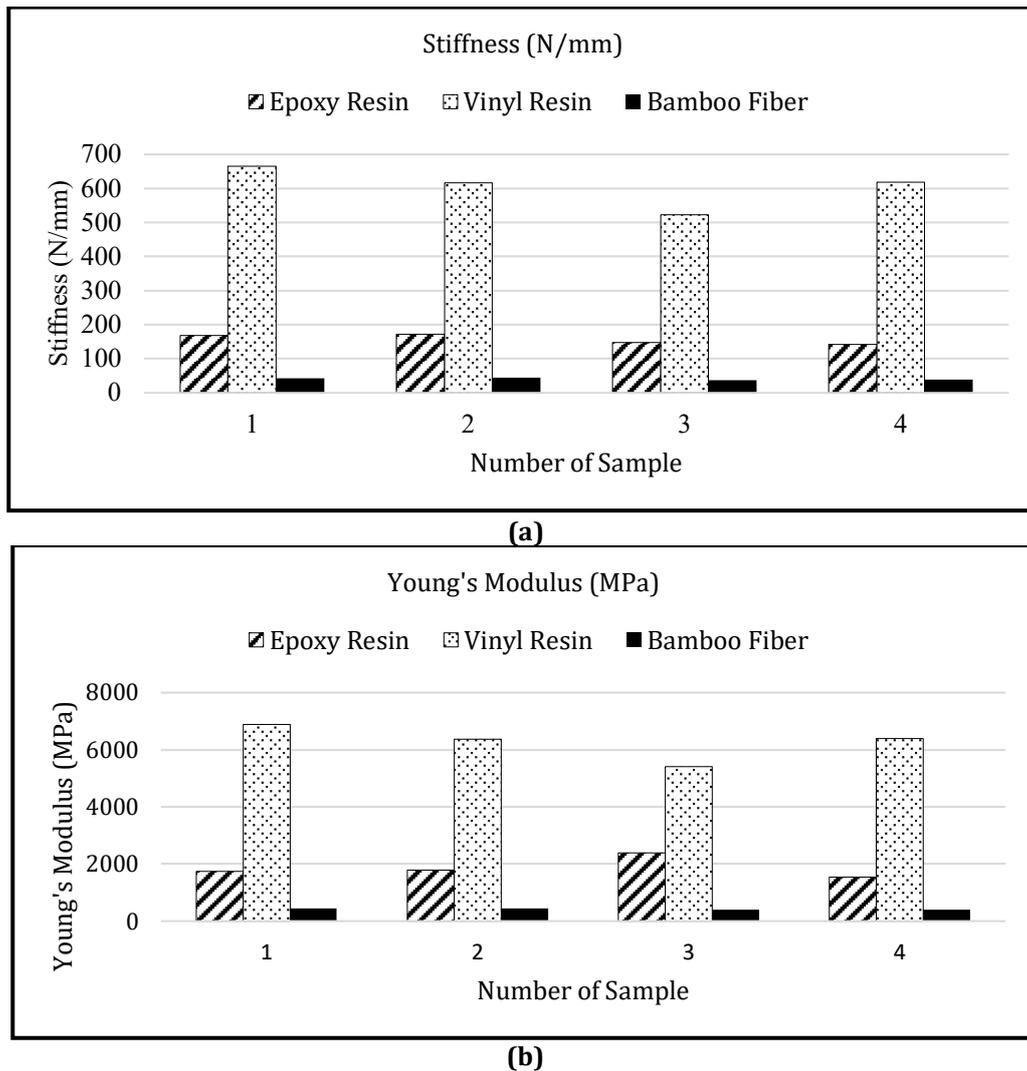


Fig. 6 (a) Stiffness analysis; (b) Young's modulus for bamboo fibre, epoxy resin and vinyl resin

## 6. Conclusion

In conclusion, this research highlights the thermopology and mechanical properties of bamboo fibre, epoxy, and vinyl resin as thermoset matrices for potential application in composite structures. Morphology properties demonstrate the rough and impure surface of bamboo fibre, which is potentially limiting in terms of cleanliness, but offers favourable mechanical interlocking for improved fibre-thermoset composites. Meanwhile, both thermosetting resins (epoxy and vinyl resins) exhibit smooth, rigid morphologies but are susceptible to defects, such as air bubbles, during preparation, which can impact their structural performance. For the chemical composition, EDX and FTIR analyses confirmed the organic, hydrophilic nature of bamboo fibre, with a high oxygen content and polar functional groups. In contrast, epoxy and vinyl resins showed a dominant carbon content and low polarity, indicating strong thermal and chemical stability. Additionally, TGA results further prove that bamboo fibre degrades earlier (peak 331 °C), while both thermoset matrices resist degradation until 376 °C due to their high cross-linking densities. Mechanical behaviour also proves that epoxy resin displayed moderate tensile strength (21 MPa - 24 MPa) and high strain (up to 67%), indicating ductile performance, while vinyl resin shows higher tensile strength (104 MPa - 148 MPa) but lower strain (3% - 4%), reflecting stiffness and brittleness. Bamboo fibre, although weak alone (2 MPa - 3 MPa), demonstrated potential as a reinforcement material. Stiffness and Young's modulus trends also show that vinyl resin is the most rigid, epoxy balances strength and flexibility, and bamboo fibre is the least stiff but suitable for interface support. Overall, the integration of Bamboo Fibre with Epoxy or Vinyl Resin is strongly recommended to create sustainable hybrid composites that optimise the balance between stiffness, toughness, and environmental performance, making them ideal for lightweight, impact-resistant, and eco-conscious structural applications.

## Acknowledgement

This research was supported by the Minister of Higher Education (MOHE) through the Fundamental Research Grant Scheme (FRGS/1/2024/TK01/UTHM/03/3) and Universiti Tun Hussein Onn Malaysia (UTHM) through GPPS (vot J047).

### **Conflict of Interest**

Authors declare that there is no conflict of interest regarding the publication of the paper.

### **Author Contribution**

*The authors confirm contribution to the paper as follows: **study conception and design:** Mohd Shaffiq Md Desa, Wan Amizah Wan Jusoh; **data collection:** Mohd Shaffiq Md Desa; **analysis and interpretation of results:** Mohd Shaffiq Md Desa, Wan Amizah Wan Jusoh, Noor Ain Najihah Che Rosely; **draft manuscript preparation:** Mohd Shaffiq Md Desa, Wan Amizah Wan Jusoh, Syed Mohd Fareed Syed Zin, Loke Kok Foong. All authors reviewed the results and approved the final version of the manuscript.*

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