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Effect of Fibre Loading on the Physical, Mechanical and Flammability Properties of Sugarcane Bagasse/Epoxy Composites

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Abstract. *Sugarcane bagasse is a readily available lignocellulosic waste material with potential for use as a renewable reinforcement in polymer composites. However, excessive fibre loading can adversely affect composite performance. Therefore, this study systematically evaluated the effects of sugarcane bagasse fibre loading (10, 20, 30, 40, and 50 wt.%) on the physical (water absorption behaviour), mechanical (tensile, flexural and impact testing), flammability (horizontal and vertical burning test) and morphological properties (digital microscopy) of epoxy-based composites fabricated using the hand lay-up method. The results demonstrated that water absorption increased with fibre loading due to the hydrophilic nature of sugarcane bagasse. Moreover, mechanical properties generally improved with increasing fibre content up to an optimum level which is 40wt.%, and show low properties at 50wt% loading of fibre. These improvements were attributed to enhanced stress transfer efficiency and effective fibre-matrix interfacial bonding. Furthermore, increases in fibre loading resulted in reduced mechanical performance because of fibre agglomeration and insufficient matrix impregnation. All composites attained the UL-94 HB classification and but did not satisfy the UL-94 vertical rating criteria. 40wt.% shows lowest horizontal burning rate at 20.08 mm/min with. Overall, composites containing 40 wt.% sugarcane bagasse fibre exhibited the most favourable balance properties highlighting their potential as sustainable lightweight non-structural or in fire-safety application.*
Keywords: *sugarcane bagasse; epoxy composite; fibre loading; water absorption; flammability test.*

Type of the Paper: Regular Article.

1. Introduction

Typically, a composite consists of a continuous phase known as the matrix and a discontinuous phase referred to as the reinforcement. The matrix binds the reinforcement to transfers applied loads and protects the reinforcement from environmental degradation, while the reinforcement contributes strength, stiffness and provide resistance to crack propagation exerted

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to the matrix [1]. Composite materials had been identified as one of the most important classes of engineering materials due to their ability to provide superior performance compared to conventional materials. Moreover, it can be classified through the type of matrix such as polymer matrix composites (PMCs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs) [2]. Among these categories, PMCs such as epoxy, polyester and vinyl ester resins are the extensively utilized polymer in composite design due to their low density, ease of processing, cost-effectiveness and excellent mechanical properties and also attracted significant attention in recent times for its uses in automotive, aerospace, marine and civil engineering applications [3].

There are various type of reinforcements such as synthetic fibres such as glass [4], carbon [5], Kevlar or natural fibres derived from renewable resources which have been extensively employed in various engineering sectors due to the excellent mechanical strength, dimensional stability and durability. However, manufacturing and disposal of synthetic fibre composites present several environmental challenges such as non-biodegradable, require high energy consumption during production, high generation of waste and difficult to recycle at the end of their service life [6]. Such concerns have prompted researchers and industries to explore renewable and environmentally sustainable alternatives capable of reducing the dependence on synthetic materials while maintaining acceptable mechanical performance and processing characteristics. Therefore, the growing awareness of environmental sustainability and the increasing demand for eco-friendly materials have accelerated the development of natural fibre reinforced polymer composites (NFRPCs) [7]. Recent studies have highlighted NFRPCs are becoming increasingly attractive because they contribute to carbon footprint reduction, support the circular economy, lightweight and utilise renewable resources that are widely available in many countries [6,8].

Natural fibres are generally derived from plants, mineral, animal and agricultural residues and they offer several advantages such as lower density, production costs, biodegradability, less abrasive to processing equipment, less health hazards and good specific mechanical properties and thermal properties over synthetic fibre [9]. Due to these numerous advantages, natural fibres have been heavily researched as reinforcing materials in polymer composites for applications in automotive components, packaging materials, construction products, consumer goods and furniture industries [10]. The various natural fibres including jute, kenaf, flax, hemp, sisal, coir and sugarcane bagasse have been incorporated into thermoplastic and thermosetting polymer matrices to improve the physical and mechanical performance of composite materials while simultaneously reducing environmental impact [11,12].

Among the natural fibres which have been investigated sugarcane bagasse has emerged as one of the most promising reinforcements for polymer composites due to its low abundance, low cost and renewable nature [13]. Globally, millions of tonnes of sugarcane bagasse are generated

annually, particularly in major sugarcane-producing countries such as Brazil, India, China, Thailand and Malaysia. The generation of bagasse is closely associated with sugar production, as bagasse is the fibrous residue obtained after extracting juice from sugarcane during sugar processing. With global sugar production projected to increase from 178 million tonnes during the base period to 205 million tonnes by 2034, representing an increase of approximately 15.2%, the amount of sugarcane bagasse generated is also expected to increase, particularly in major sugar-producing regions such as Asia and Latin America [14]. In its traditional use sugarcane bagasse is usually either burned as fuel [15] or disposed as agricultural waste which can contribute to greenhouse gas emissions and air pollution [16]. Therefore, it is necessary to utilized sugarcane bagasse to tackle disposal challenges and environmental concerns as well as providing solution for waste valorisation while contributing to the development of sustainable and value-added products.

However, NFRPCs still face several challenges which restrict their broader industrial applications. The physical challenges mainly related to presence of hydroxyl groups (-OH) makes natural fibres inherently hydrophilic, allowing them to absorb moisture from the surrounding environment. This excessive moisture absorption can result in fibre swelling dimensional instability, deterioration of fibre–matrix interfacial adhesion and reduction of mechanical properties [17–20]. Furthermore, the fibre loading into the polymer matrix is an important processing parameter that influences the physical characteristics of the composite [21]. An inappropriate fibre loading can lead to non-uniform fibre distribution and difficulties in achieving a homogeneous composite structure. Another significant challenge associated with the use of natural fibres in polymer composites is their relatively poor fire resistance and high flammability [22]. Therefore, the development of effective flame-retardant strategies is necessary to enhance the fire safety and broaden the potential applications of natural-fibre-reinforced polymer composites. Based on the review by Alsuwait *et al.* [23] mention that the mechanical properties such as tensile strength, flexural strength, impact strength are rely on the strength of the interfacial adhesion between the fibre and the matrix whereas, thermal properties, electrical properties, water absorption and acoustic performance all vary with natural fibre loadings. This indicating that the fibre loading is an important parameter that can effect properties of the polymer composite [24–26].

The combined effects of sugarcane bagasse fibre loading reinforced epoxy composites that fabricated though hand lay-up technique on water absorption measurements, tensile testing, flexural testing, impact testing, flammability and morphological analysis have not yet been sufficiently clarified. To address this gap, the present study aims to investigate the effect of sugarcane bagasse fibre loading reinforced epoxy composites at different fibre loadings of 10, 20, 30, 40 and 50 wt.%.

2. Materials and Methods

2.1 Materials

Sugarcane bagasse, with a density of 1.3 g/cm^3 was used as the reinforcement material in the epoxy polymer composite. The density of sugarcane fibre can be determined experimentally by measuring its mass using an analytical balance and its volume using a suitable volume-displacement method. The density is then calculated using mass per volume. The sugarcane bagasse used in this study was collected from a sugarcane juice stall located at Jelutong Market Penang, Malaysia. The matrix material consists of E182 epoxy resin (density of 1.3751 g/cm^3) and H192 hardener (density 0.9721 g/cm^3), which were purchased from Zeegen Enterprise Sdn. Bhd, located in Taman Temusu, Sungai Petani, Kedah, Malaysia.

2.1.1 Preparation of sugarcane bagasse

The collected sugarcane bagasse fibre was pre-treated by immersing in distilled water (DI water) to remove dirt, dust or any other contaminants and neutralize the pH as shown in Fig. 1 (a). The hard outer rind of the bagasse was manually separated from the soft interior pitch [27].Then, the fibre is washed with clean water for several time to further remove contaminants as shown in Fig. 1 (b). The cleaned fibre is then dried in an oven at 90°C for 24 hours (h) to remove moisture before being kept in room temperature (RT) as shown in Fig. 1 (c).

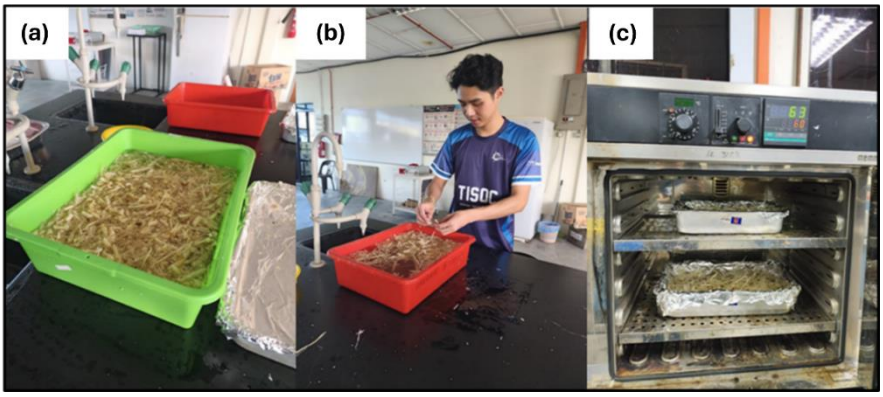


Fig. 1. The preparation of sugarcane bagasse fibre. (a) Immersing of bagasse fibres, (b) Removing the rind and pith fibres and (c) Drying of fibres in the oven.

2.2. Fabrication of Reinforced Epoxy Composites

The sugarcane bagasse fibre reinforced polymer composite was fabricated though hand lay-up technique. A square steel mould with dimension 200 mm in length, 200 mm in width and 3mm in thickness (200 mm x 200 mm x 3 mm) was used to prepare the composite board. The mould was prepared by placing the bottom plate and a Teflon sheet and spraying the mould frame with a silicone release agent. The fibres, epoxy resin and hardener were weighed according to the formulations as shown in Table 1.

Table 1. Weight of raw material used.

Fibre loading (wt.%)	Epoxy loading (wt.%)
0 (control)	100
10	90
20	80
30	70
40	60
50	50

A control sample consisting of a 100 wt.% epoxy-hardener matrix without fibre reinforcement was fabricated for comparison purposes. The low-temperature curing epoxy resin and hardener were mixed at a weight ratio of 2:1 using a wooden stirring stick until a homogeneous mixture was obtained. The fibre content was formulated according to fibre loadings ranging from 10 to 50 wt.%. As illustrated in Fig. 2(a), the fibres were first separated and arranged in the mould. Subsequently, a layer of the epoxy-hardener mixture was poured onto the Teflon sheet placed at the bottom of the mould, followed by the insertion of the pre-pressed fibre mat. The remaining epoxy-hardener mixture was then evenly distributed over the fibre mat to ensure adequate fibre impregnation and minimise air entrapment. A second Teflon sheet was placed on top of the lay-up before securing the upper mould frame. The mould was compressed at 60 psi using a cold press, as shown in Fig. 2(b), to eliminate any remaining air bubbles and improve composite consolidation. The composite laminates were then left to cure at RT for 24 h. After curing, the composite panels were cut into the required specimen dimensions according to the relevant ASTM standards for mechanical testing, as illustrated in Fig. 2(c). For each mechanical test, five specimens were evaluated, and the average value was reported. The error bars presented in the figures represent the standard deviation of the experimental results.

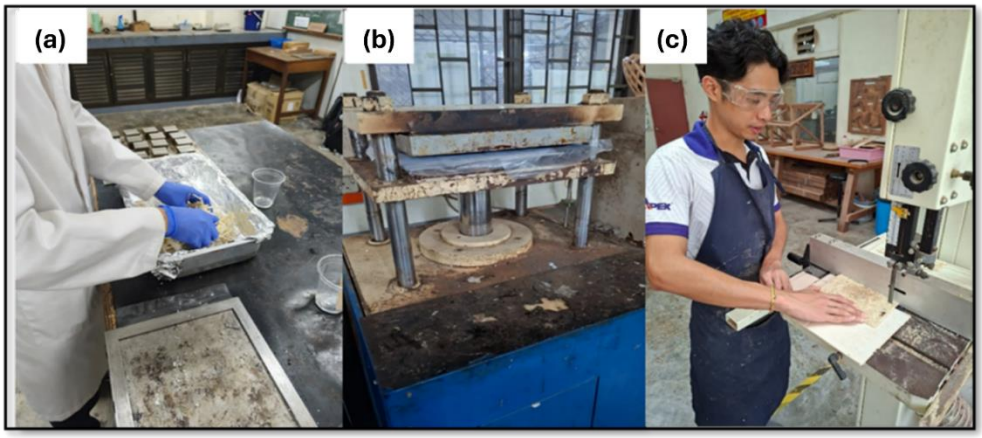


Fig. 2. Fabrication process of the composite. (a) Preparation of fibres before pre-pressing according to mould thickness, (b) Cold press of the mould filled with the composite materials and (c) Cutting of the composite board for characterization.

2.3. Characterizations

2.3.1 Water Absorption Test

The water absorption test was conducted based on ASTM D570. Prior to immersion, the specimens were dried in an oven and cooled in desiccator to remove moisture and then weighed to determine their initial mass (W_i). The specimens were then immersed completely in DI water at RT for 24 h intervals until a constant mass was achieved. At each interval, the specimens were removed from the water, gently wiped with a dry cloth to remove excess surface water and immediately weighed to determine their mass (W_f). The percentage of water absorption was calculated using Eq. (1) [28].

Water absorption, WA (%) = $[(W_f - W_i) / W_i]$ x 100%	(1)

where WA is the water absorption percentage (%), W_i is the initial dry mass of the specimen (g), and W_f is the mass of the specimen after water immersion (g).

2.3.2. Tensile Test

The tensile test of sugarcane bagasse fibre reinforced epoxy composites was evaluated and carried out using Instron GT-A1-7000L universal testing machine with a crosshead speed of 2 mm/min in accordance with ASTM D638. Rectangular specimens were prepared in the dimension of **150mm (length) × 150 mm (width) × thickness** and the gauge length (L_0) was 50 mm. Dimensions were measured using a vernier calliper prior to testing which is to ensure accuracy in determining the stress calculations.

2.3.3. Flexural Test

The flexural properties of sugarcane bagasse fibre-reinforced epoxy composites were evaluated using an Instron Universal Testing Machine (UTM) (Model 3366). This test was conducted to determine the flexural strength, flexural modulus and deformation behaviour of the composites under bending load. Rectangular specimens measuring **127 mm (length) × 12.7 mm (width) × thickness** were prepared for flexural testing in accordance with ASTM D790. The specimens were tested using a three-point bending configuration, with the support span set according to the standard span-to-depth ratio of 16:1. During testing, each specimen was positioned horizontally on the support rollers, while a loading nose applied force at the midpoint of the specimen. A constant crosshead speed with 5 mm/min was maintained throughout the test until specimen fracture occurred or the maximum allowable deflection specified by the standard was reached. The test results recorded provide an indication of the material stiffness and resistance to bending deformation.

2.3.4. Impact Test

The impact strength of sugarcane bagasse fibre-reinforced epoxy composites was evaluated

using an Instron GOTECH impact testing machine (Model GT-7045-MDL, Taiwan) equipped with pendulum**.** Rectangular specimens measuring **63.5 mm (length) × 12.7 mm (width) thickness** with V-notch depth 2.5mm using notching machine to facilitate controlled crack initiation and consistent fracture behaviour during testing. The specimens were mounted vertically in the Izod configuration and subjected to pendulum impact testing based on ASTM D256. The energy absorbed during fracture was recorded by the testing machine.

2.3.5. UL-94 Horizontal and Vertical Burning Test

UL-94 Horizontal Burning Test was conducted using three rectangular bar specimens of sugarcane bagasse reinforced epoxy composites with dimensions of 125 mm × 13 mm. Bunsen burner was ignited and adjusted to have a blue flame of 20 mm high. The flame was applied to the free end of the bottom edge of the specimen with the flame adjusted to a 45º angle. The horizontal bar sample was also tilted at a 45º angle during the flaming of the sample. The flame was held for 30 seconds or until the flame front passed the 25 mm mark. The schematic diagram shown in Fig. 3. (a) shows the experimental set-up of the test in the laboratory [29].



Fig. 3. The experimental set-up of (a) horizontal and (b) vertical burning test

Moreover, for the UL-94 Vertical Burning Test five rectangular bar specimens of sugarcane bagasse reinforced epoxy composites with dimensions of 125 mm × 13 mm × 3 mm were used. The Bunsen burner was ignited and adjusted to have a blue flame of 20 mm high. The flame was applied centrally to the middle point of the bottom edge of the specimen. The flame was held for 10 seconds and retracted at a rate of 300 mm/s. If there are any flaming particles dripping from the sample, the Bunsen burner may be tilted at an angle to avoid the nozzle being clogged by the flaming particles. Once the flame self- extinguishes, the flame is reapplied onto the sample for another 10 seconds. If the flame does not self-extinguish for 60 seconds after the flame source has been removed, the second flaming of the sample was not required. The schematic diagram shown in Fig 3. (b) shows the experimental set-up of the test in the laboratory [29].

2.3.6. Morphological Analysis

The fracture surfaces of the tensile-tested specimens were examined using a Digital Microscope (Leica Emspira 3) to investigate the fibre–matrix interfacial bonding, fibre pull-out, fibre agglomeration and dominant failure mechanisms across the different fibre loadings. Representative specimens from the 10 wt.%, 40 wt.%, and 50 wt.% fibre loadings were selected for detailed morphological examination.

3. Results and Discussion

3.1. Water Absorption Properties

Water absorption demonstrated an increasing trend with immersion time for all samples. However, the percentage of water absorption is progressively higher as the fibre loading increased. This indicates that the incorporation of sugarcane bagasse fibre reduced the moisture resistance of the epoxy composite system. The control (0 wt.%) exhibited the lowest water absorption throughout the testing, which is mainly due to its hydrophobic nature, dense cross-linked network structure and lower porosity of epoxy resin which limits moisture penetration and diffusion into the material [29,30]. As the fibre loading increased from 10 wt.% to 30 wt.%, absorption generally increased but remained comparatively low which is below 15%. In contrast, a more significant increase in water absorption can be observed for the composite with 40 wt.% (30-40% range) and 50 wt.% fibre loading, with the 50 wt.% specimen exhibited the highest percentage of water absorption (range 50-82%) as shown in Fig. 4. The increase in moisture uptake is due to the hydrophilic characteristics of sugarcane bagasse, which mainly consists of cellulose, hemicellulose and lignin containing hydroxyl (–OH) groups that attract water molecules through hydrogen bonding and also due to the fibre-matrix interaction [11,31]. Moreover, at higher fibre loadings, insufficient resin distribution may occur which reduce the matrix continuity and creating micro voids, fibre agglomeration and interfacial defects [19]. From the water absorption behaviour, there is a clear tendency of equilibrium behaviour, in which the specimens absorbed water rapidly during the initial immersion period and then exhibited a slower absorption rate after several days. This pattern is also observed in a study conducted Lee and Mariatti [32] reported that water initially penetrates available pores and void spaces in the interface of the composite before approaching saturation as the concentration gradient decreases.

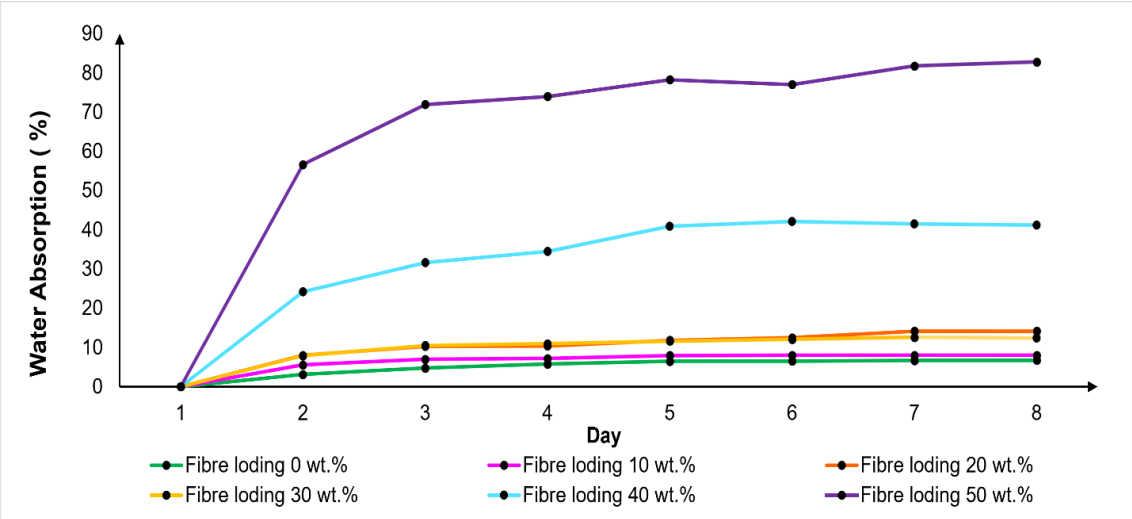


Fig. 4. Water absorption percentage against number of days.

3.2 Tensile Test

On the other hand, the tensile strength of the developed sugarcane bagasse/epoxy composites exhibited a non-monotonic trend with increasing fibre loading. The neat epoxy exhibited the highest tensile strength of 42.13 MPa, whereas the incorporation of 10 wt.% fibre resulted in a sharp decrease to 4.57 MPa, corresponding to an 89.15% decrease compared with the neat epoxy matrix. As the fibre loading increased from 10 to 40 wt.%, the tensile strength gradually improved, reaching a maximum of 14.84 MPa at 40 wt.%. However, a further increase in fibre loading to 50 wt.% resulted in a decrease in tensile strength to 10.11 MPa as shown in Fig. 5. The initial decline in tensile strength following fibre incorporation may be associated with inadequate interfacial adhesion between the fibres and the epoxy matrix, which could limit effective stress transfer [5,33]. The subsequent improvement at higher fibre loadings may indicate an increased contribution of the fibres to load bearing. In other word, at higher fibre loadings, the fibres may become more widely distributed throughout the matrix, forming an interconnected network that facilitates stress transfer within the composite. The applied mechanical load is shown to be able to transfer more effectively from a polymer matrix to a stiffer load-bearing cellulose structure of sugarcane bagasse fibres [34]. Nevertheless, the decline at 50 wt.% may be attributed to insufficient matrix coverage, fibre agglomeration or increased interfacial defects, which can adversely affect stress transfer and promote premature failure [25,30]. Besides that, the recent studies on natural fibre-reinforced epoxy composites have consistently reported that fibre orientation is one of the most dominant factors influencing tensile properties and often have a greater impact than fibre volume and fraction alone [8,29,35]. For this instance, the orientation distribution will significantly affect the elastic modulus, tensile strength and failure strain due to its control overload transfer efficiency and crack propagation pathways in short fibre composites [36]. Studies has shown that the long, continuous or well-aligned fibres provide better stress transfer, leading to higher tensile modulus

and strength, especially in the fibre direction, compared to short or randomly oriented fibres [19,37].

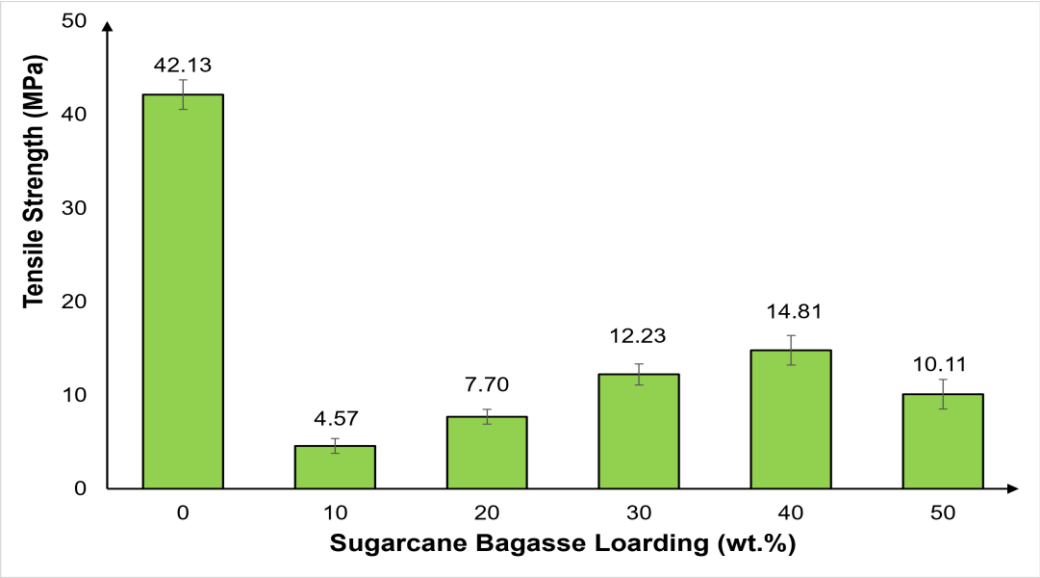


Fig. 5. Tensile Strength of Sugarcane Bagasse Composites by Loading Percentage.

Next, Fig. 6 shows the trend of the tensile modulus of the developed sugarcane bagasse-reinforced epoxy composites which also exhibits a clear non-linear trend with increasing fibre loading. The control epoxy matrix at 0 wt.% fibre loading recorded the highest tensile modulus of 746.12 MPa, which can be attributed to the inherent stiffness of the highly cross-linked molecular which restricts molecular chain mobility during tensile deformation, resulting in a higher modulus compared with the fibre reinforced composite. However, the incorporation of 10 wt.% sugarcane bagasse fibre into the epoxy matrix resulted in a substantial decrease in tensile modulus, from 746.12 MPa to 433.77 MPa, corresponding to a reduction of approximately 41.9%. As the sugarcane bagasse fibre loading increased from 10 wt.% to 20 wt.%, the tensile modulus decreased further from 433.77 MPa to 409.03 MPa, representing reduction of approximately 5.7%. This behaviour may be attributed to the poor compatibility between the hydrophilic sugarcane bagasse fibres and the hydrophobic epoxy matrix, which can result in inadequate fibre–matrix adhesion and inefficient stress transfer. In contrast, a notable increase in tensile modulus was observed at 30% fibre loading, reaching 564.17 MPa. This increase suggests that, at this fibre concentration, the sugarcane bagasse fibres may have provided more effective load-bearing reinforcement within the epoxy matrix. However, increasing the fibre loading to 40% resulted in a slight reduction in tensile modulus to 531.90 MPa. A more pronounced decrease was subsequently observed at 50% fibre loading, where the tensile modulus declined to 350.60 MPa. The fluctuations in tensile modulus with increasing fibre content may be associated insufficient resin available to fully encapsulate all fibre surfaces which leads to partial fibre exposure and reduced interfacial bonding

efficiency. The weakened fibre-matrix interface limits effective stress transfer and reduces overall stiffness improvement. There are additionally increased fibre-fibre interactions at higher loading promote microstructural irregularities that includes localized clustering and void formation, which act as soft zones within the composite structure and reduce the elastic modulus response.

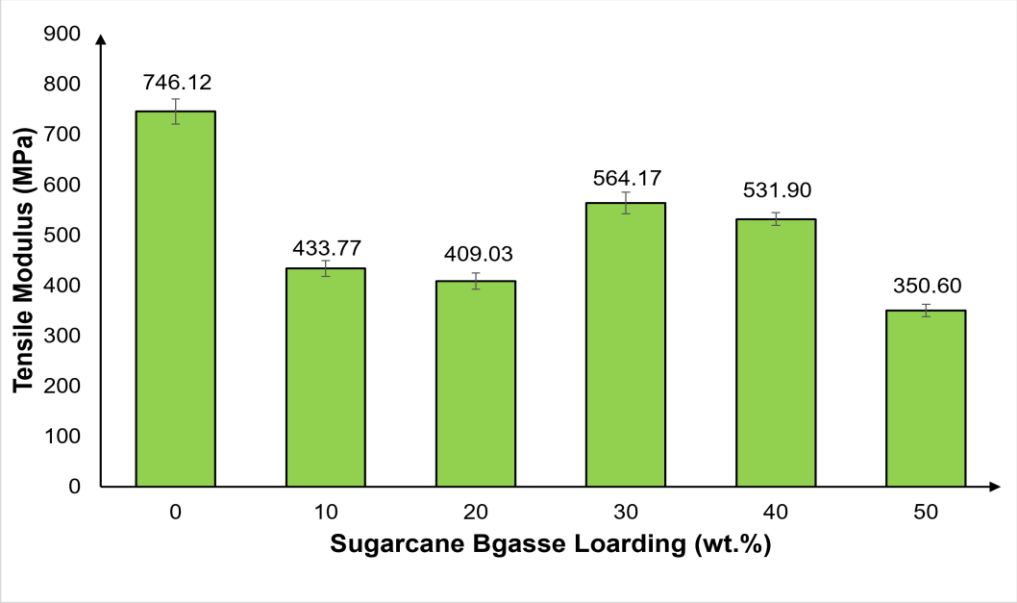


Fig. 6. Tensile Modulus of Sugarcane Bagasse Composites by Loading Percentage

Fig. 7 Illustrates a decreasing trend in elongation at break following the incorporation of sugarcane bagasse fibres into the epoxy matrix. The neat epoxy sample exhibited the highest elongation at break of 6.0%, indicating it had the highest ductility or greatest ability to undergo deformation before fracture.

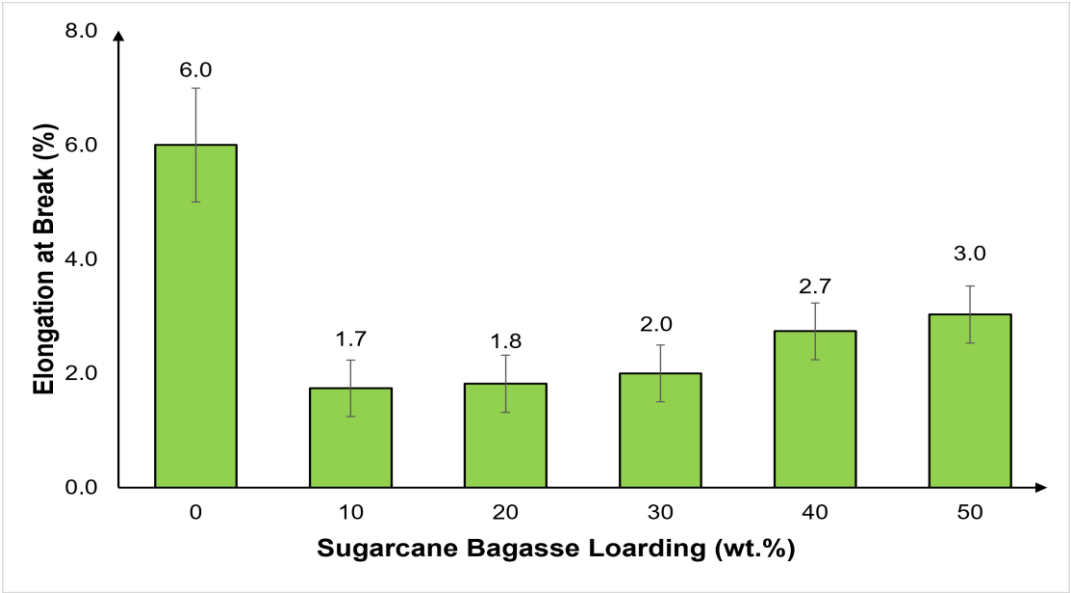


Fig. 7. Elongation at Break of Sugarcane Bagasse Composites by Loading Percentage.

Following the incorporation of 10% sugarcane bagasse fibre, the elongation at break decreased to 1.7%, representing a drop of 71.7 % compared with the neat epoxy. The decrease in elongation at break also indicates there is an increase in brittleness of the sugarcane bagasse-reinforced epoxy composites after fibre incorporation which suggest that the rigid fibres restricted the mobility of the epoxy polymer chains and consequently reduced the deformability and ductility of the composite. The brittle materials exhibited limited plastic deformation before fracture because they are unable to redistribute stress effectively once cracks have been initiated [36]. In other word, it indicating that the material becomes stiffer and fractures at lower strain values. As the sugarcane bagasse loading increase from 20 to 50 wt.%, the elongation at break gradually increased from 1.8% to 3.0%. This gradual recovery suggests that although the fibres continue to restrict matrix mobility the increasing fibre loading improves stress distribution and delays localized deformation which allows the composite to sustain higher strain before fracture occurs [19].

At low fibre loading the stress distribution within the composite has been highly localized which is due to the fibres being sparsely distributed. Under tensile loading the deformation becomes concentrated in the matrix regions between the fibres which leads to premature crack formation and lower elongation. As the fibre loading increases the stress is then distributed over a large number of reinforcing fibres. These fibres will act as stress-transfer bridges that can delay the localization of strain as well as slow down crack propagation [38]. This will result in the composite being able to withstand a larger deformation before failure and allows for a gradual increase in elongation at break. The maximum elongation at break at 50 wt.% loading (3.0%) remains approximately half of that of control epoxy which indicates that the reinforcing effect of sugarcane bagasse is still accompanied by reduced ductility. The elongation at break trend is consistent with previous studies on sugarcane bagasse-reinforced polymer composites. It was reported that the addition of sugarcane bagasse fibres will cause a reduction at break due to poor fibre wetting, increased porosity and weak interfacial bonding between hydrophilic fibres and the polymer matrix. The research observed that control polymer matrix had exhibited the highest elongation while the reinforced composites had showed a lower ductility due to the fibres restricted deformation and promoted brittle fracture.

3.3 Flexural Test

Next, the incorporation of sugarcane bagasse into the epoxy matrix resulted in variations in both flexural strength and flexural modulus, indicating that the bagasse loading influenced the bending performance of the composites as shown in Fig 8.

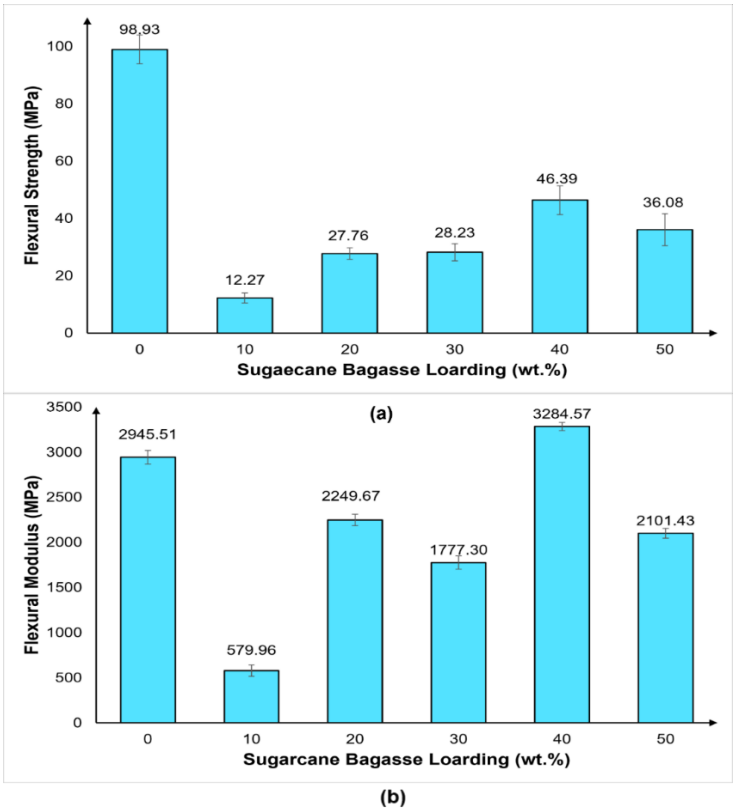


Fig. 8. Flexural strength (a) and flexural modulus (b) of sugarcane bagasse composites by loading percentage.

Flexural strength measures the maximum stress a sample can withstand before failure under bending, whereas flexural modulus indicates the sample's stiffness and resistance to bending deformation. The neat epoxy sample (0 wt.%) exhibited a flexural strength of 98.93 MPa and a flexural modulus of 2945.51 MPa which reflects the intrinsic ability of crosslinked epoxy networks to resist bending deformation through strong intermolecular bonding and high structural rigidity. At 10 wt.% sugarcane bagasse fibre loading, the flexural strength decreased substantially from 98.93 MPa to 12.27 MPa, reflecting decrease of 87.6%, while the flexural modulus decreased from 2945.51 MPa to 579.96 MPa, reflecting decrease of approximately 80.3% compared to neat epoxy. This gradual improvement suggests that the increasing number of bagasse fibres began to contribute more to load bearing. However, when the bagasse loading increased to 20 wt.%, both flexural strength and modulus improved to 27.76 MPa and 2249.67 MPa, respectively. This improvement suggests that increasing the sugarcane bagasse fibre content contributed to better load distribution within the composite. However, at 30 wt. % loading, the flexural strength increased slightly to 28.23 MPa, while the modulus decreased to 1777.30 MPa. This contrasting behaviour indicates that the factors affecting the maximum stress sustained before failure may differ from those governing stiffness, such as changes in fibre distribution or interfacial bonding may influence the two properties differently. On the other hand, at 40 wt.% sugarcane bagasse fibre loading, both properties reached their highest values among the bagasse-filled composites,

with flexural strength and modulus increasing to 46.39 MPa and 3284.57, respectively. This result suggests that the 40 wt. % formulation provide a more favourable balance between bagasse content and epoxy matrix distribution, allowing more effective stress transfer and improved resistance to bending deformation. Fibres here act as effective barriers against crack propagation by increasing the tortuosity of crack paths and improves the energy absorption capacity [39,40]. Nevertheless, at 50 wt. % loading, both flexural strength and modulus decreased to 36.08 MPa and 2101.43, respectively. This decline may be associated with a higher likelihood of fibre agglomeration, insufficient resin wetting or void formation at the higher bagasse loading, potentially weakening the composite structure.

3.4 Impact Test

Besides that, impact strength of a composite material is closely associated to its ability to absorb and dissipate energy [41]. Based on the data collected, the control epoxy matrix at 0 wt.% sugarcane bagasse loading has exhibited the highest impact strength of 2592 J/m as shown in Fig. 9.

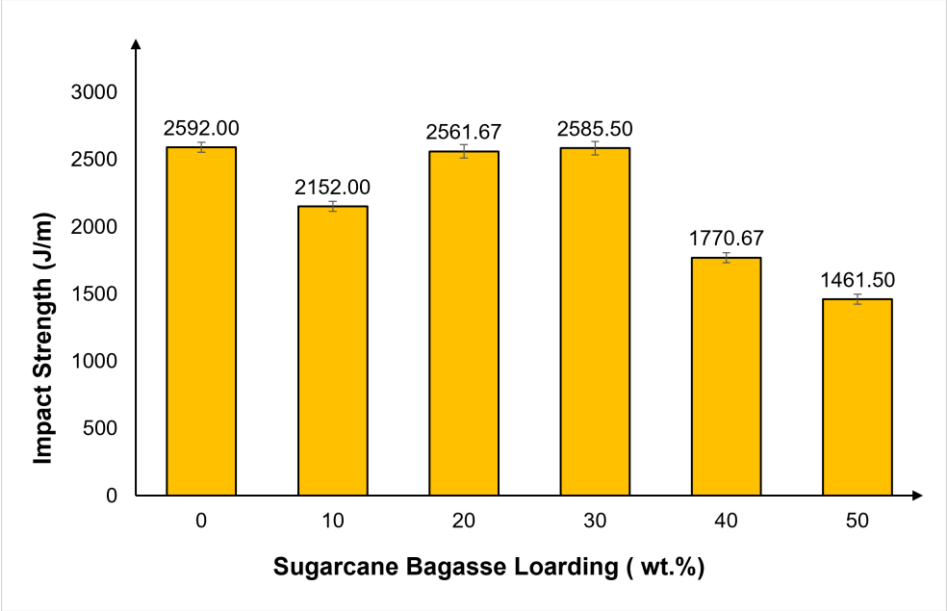


Fig. 9. Impact Strength of Sugarcane Bagasse Composites by Loading Percentage

After the addition of 10 wt.% sugarcane bagasse the impact strength decreased to 2152 J/m, representing a reduction of approximately 16.98%. Such a decline suggests that the initial addition of fibres has interrupted the continuity of the epoxy matrix and introduced stress concentration regions which promote crack initiation instead of energy absorption. Moreover, the fibres here are sparsely distributed and the energy absorbed during fracture is primarily governed by the epoxy matrix. The limited number of fibres cannot be enough to provide sufficient crack-bridging or pull-out resistance to dissipate the impact energy efficiently. Next, as the sugarcane bagasse loading was increased from 20wt.% and 30 wt.%, the impact strength recovered to 2561.67 J/m and

2585.50 J/m respectively which was approaching the value of control epoxy. These values can be attributed to the development of fibre bridging mechanisms and has entered a transition region where both matrix and fibres contribute to energy absorption. The fibres act as obstacles that force the advancing crack to deviate from its original path. This crack deflection increases the fracture surface area and requires more energy for crack growth which results in improved impact strength. Reviews on epoxy-based natural fibre composites have emphasized that crack deflection and increased fracture path tortuosity are among the main mechanisms responsible for improving impact resistance in natural fibre composites [23]. In addition, at the higher loadings of sugarcane bagasse fibre 40–50 wt.%, the failure mechanisms shift towards fibre-dominated behaviour, lead to low impact strength. As the fibre content increases, the reduced spacing between adjacent fibres can restrict resin flow during fabrication, resulting in incomplete wetting and the formation of weak interfacial regions [42,43]. Moreover, excessive fibre–fibre interactions can promote agglomeration and uneven stress distribution, limit the effectiveness of energy-dissipation mechanisms and increasing the likelihood of premature fracture. Fibre pull-out also plays an important role in determining the impact resistance of fibre-reinforced composites [44,45]. During impact fracture, energy can be dissipated through fibre breakage, fibre pull-out, interfacial friction and crack bridging. In addition, fibre pull-out, in particular, requires energy to overcome the frictional resistance between the fibre surface and the surrounding matrix. At intermediate bagasse loadings (20–30 wt.%), a more favourable balance between fibre content and matrix availability may promote effective stress transfer and energy dissipation through these mechanisms. However, the extent of fibre pull-out and its contribution to impact resistance depend on the quality of interfacial bonding and the distribution of fibres within the matrix.

Fibre bridging, crack defection and pull-out mechanism have become more effective which allows the impact strength to recover close to that of control epoxy. During impact loading the fibres spanning across crack surfaces are able to resist crack opening and force the crack to follow a more tortuous path. The crack defection process consumes additional energy and delays catastrophic failure. In addition, the increased number of fibres at intermediate loading provides multiple crack-arresting sites which is able to enhance the energy absorption capability of the composite. Studies have reported that natural fibre-reinforced epoxy composites exhibit improved impact resistance at moderate fibre loading due to crack deflection, fibre bridging, and fibre pull-out mechanisms, all of which contribute to enhanced energy dissipation during fracture [25].

3.5 Fire Properties UL-94 flammability test

3.5.1 Horizontal burning test (HB)

Next, UL-94 HB test was carried to determine the flammability of the composite in the horizontal position [22,29]. A material can be classed as HB when the material have a burning rate

not exceeding 40 mm per minute over a 75 mm span for specimens having a thickness of 3.0 – 13 mm, or have a burning rate not exceeding 75 mm per minute over a 75 mm span for specimens having thickness less than 3.0 mm, or the specimen cease to burn before the 100 mm reference mark. Based on the results in Table 2, all of the sugarcane bagasse reinforced epoxy composites had achieved a UL-94 HB rating, this shows that although the specimens were combustible, the burning rates remained within the allowable limits specified by the UL-94 HB standard.

Table 2. Average Burn Length, Average Burn Time, Average Linear Burning Rate and UL-94 Rating of the composite

Fibre Loading (%)	**Number of samples where flames passed the**		**Average Burn Length, L (mm)**	**Average Burn Time, t (s)**	**Average Linear Burning Rate,V (mm/min)**	**UL-94 Rating**
	25 mm Mark	100 mm Mark				
0	3	3	75.00± 0.00	204.08 ± 56.69	23.16 ± 6.04	HB
10	3	3	75.00± 0.00	174.58 ± 0.54	25.78 ± 0.08	HB
20	3	3	75.00± 0.00	198.65 ± 14.43	22.77 ± 1.59	HB
30	3	3	75.00± 0.00	148.15 ± 2.03	30.38 ± 0.42	HB
40	3	3	75.00± 0.00	227.29 ± 26.01	20.08 ± 2.50	HB
50	3	2	66.67±11.78	166.56 ± 2.16	24.07 ± 4.51	HB

*HB: Horizontal Burn

The average linear burning rates varied from 20.08 to 30.38 mm/min, with the 40 wt.% bagasse composites exhibiting the lowest burning rate (20.08 ± 2.50 mm/min), while the 30 wt.% composite exhibited the highest burning rate (30.38 ± 0.42 mm/min). All specimens except the 50 wt.% fibre loading composite exhibited complete flame propagation beyond the 100 mm reference mark, while only two out of three specimens for the 50 wt.% composite reached the 100 mm mark, resulting in a lower average burn length of 66.67 ± 11.78 mm. This observation suggests that a high fibre loading may contribute to partial self-extinguishing behaviour or reduced flame propagation in certain specimens.

This variation in burning behaviour can be explained by the competing effects of the lignocellulosic bagasse fibres and the epoxy matrix. Natural fibres such as sugarcane bagasse contain cellulose, hemicellulose and lignin which thermally decompose when exposed to flame, releasing volatile combustible gases that sustain combustion. Thus, increasing the fibre loading will generally increase the amount of combustible biomass available within the composite, which can accelerate flame spread and increase burning rates [46]. This phenomenon can be used to explain the high burning rate of the 30 wt.% fibre loading composites, where sufficient fibre content was present to promote combustion while the fibre network remained evenly dispersed within the epoxy matrix. However, the results indicated that further increasing the fibre loading to 40 wt.% reduced the burning rate considerably. Studies on the natural fibre reinforced epoxy

composites had reported that increased char formation can reduce burning rates and improve flame resistance by insulating the polymer matrix from direct exposure to heat [22]. This supports the longer burning time for the 40 wt.% composite (227.29 ± 26.01 s), as flame takes longer time to propagate along the specimen length despite being continuously sustained.

For the highest fibre loading which is 50 wt.%, the composite exhibited a shorter average burn length and incomplete flame propagation in one specimen. This behaviour may be related to insufficient epoxy content and the formation of a densely packed fibre structure. As fibre loading increases, the continuity of the polymer matrix decreases, limiting the availability of combustible epoxy resin that generally contributes significant heat release during burning. A study by Ao et al., [47] suggested that poor wetting and high void formation can negatively impact the combustion behaviour by effecting heat transfer pathways and oxygen accessibility within the composite structure, as well as acting as a channel for heat and mass transfer.

3.5.2 Vertical burning test

Furthermore, UL-94 vertical burning test was carried out to determine the flammability of the composite in vertical position. The composite is rated V-0, V-1 or V-2 if they achieve specific criteria (Table 3). If none of the criteria is achieved, then the composite is rated as "Not Rated" (NR).

Table 3. Material classifications according to UL-94 vertical test.

Criteria conditions	V-0	V-1	V-2
Afterflame time for each individual specimen t_1 or t_2	≤10s	≤30s	≤30s
Total afterflame time for any condition set (t_1 plus t_2 for the 5 specimens)	≤50s	≤250s	≤250s
Afterflame plus afterglow time for each individual specimen after the second flame application ($t_1 + t_2$)	≤30s	≤60s	≤60s
Afterflame or afterglow of any specimen up to the holding clamp	No	No	No
Cotton indicator ignited by flaming particles or drops	No	No	Yes

Based on the test results in Table 4, the sugarcane bagasse reinforced epoxy composite did not achieve any UL-94 vertical classifications (V-0, V-1 or V-2) and are all rated as NR. It is observed that all specimens continued burning for prolonged periods after flame removal, with average afterflame times ranging from 126.06 to 201.74 s, exceeding the maximum UL-94 requirement of 30 s for V-1 and V-2 classifications and 10 s for V-0 classification. The total afterflame times for all formulations ranged from 630.28 to 1008.72 s, which are significantly higher than the UL-94 limits of 50 s (V-0) and 250 s (V-1/V-2). Thus, none of the composites satisfied the fundamental criteria for vertical flame-retardant performance.

Table 4. Average Afterflame Time, Total Afterflame Time and UL-94 Rating of the composite.

Fibre loading (%)	Number of Samples where the Specimens		Average Afterflame Time, t_1 (1st fire application) (s)	Total Afterflame Time (s)	UL-94 Rating
	Burn the holding clamp	Dripped flaming particles			
0	5	5	201.74 ± 18.97	1008.72	NR
10	5	5	154.64 ± 20.66	773.21	NR
20	5	0	144.66 ± 10.22	723.30	NR
30	5	0	126.06 ± 8.87	630.28	NR
40	5	0	173.66 ± 28.98	868.30	NR
50	5	0	179.36 ± 33.63	896.82	NR

*NR: No Rating
*The afterflame time after 2nd fire application, t_2 and afterglow time after 2nd flame application, t_3 is not included.

The poor vertical burning performance can be attributed by the combustion nature of both epoxy matrix and sugarcane bagasse fibre reinforcement. Epoxy resin undergoes thermal decomposition when exposed to high temperatures which generates flammable volatile compounds that sustain combustion. Meanwhile, sugarcane bagasse contains significant amounts of cellulose, hemicellulose and lignin which thermally degrade within the temperature range of approximately 200–500 °C. The decomposition of cellulose and hemicellulose produces combustible gases such as levoglucosan, carbon monoxide, methane and other hydrocarbons that contribute to flame propagation [48]. A study by Rajeshkumar *et al.* [22] had also pointed that untreated natural fibre-reinforced epoxy composites generally exhibit poor UL-94 vertical performance because the lignocellulosic fibres provide an additional fuel source that accelerates combustion once ignition occurs. Lignin is known to possess a relatively high char yield compared to cellulose and hemicellulose due to its aromatic structure. During burning, lignin-rich materials form a carbonaceous layer that acts as a thermal barrier can effectively reduce heat transfer to the underlying material and slowing down the releasing of volatile components. This statement is supported by a research done by Liu *et al.* [49] who found that increasing biomass content in bio-based epoxy composites can enhance condensed-phase char formation, resulting in a lower flame intensity and reduced combustion rates. The lowest afterflame time obtained at 30 wt.% fibre loading indicates that the char-forming effect of the bagasse fibres had partially compensated for their inherent combustibility.

However, further increasing of the fibre loading from 40 wt.% to 50 wt.% had resulted in an increasing afterflame time to 173.66 s and 179.36s, respectively. This indicates that excessive fibre loading can negatively affect the fire performance of the composites. At higher fibre loading often leads to poor resin impregnation and increase void formation particularly in composites fabricated using hand lay-up techniques. Voids act as pathways for oxygen diffusion and facilitate heat transfer within the composite structure which promotes sustained combustion [47]. This is

supported by a study conducted by Sampathkumar *et al.* [22], which stated that excessive natural fibre loading can reduce flame resistance due to increased porosity and the availability of combustible biomass despite improvements in char formation. For the observation on the dripping of flaming particles, there is a reduction in the dripped flaming particle with increasing fibre loading. The control (0 wt.%) and 10 wt.% composites produced flaming drips in all specimens, whereas composites containing 20–50 wt.% bagasse fibres exhibited no flaming particle dripping. This phenomenon may be attributed by the reinforcing effect of the fibre network which improves structural integrity during thermal degradation and restricts molten epoxy flow. The absence of flaming drips suggested that the bagasse fibres improved the dimensional stability of the composite during burning. All of the specimens display a continued burning until the holding clamp, which indicated the poor flame-retardant capability of the composites. According to the UL-94 requirements, a specimen must not burn to the holding clamp to qualify for V-0, V-1, or V-2 classifications. This continued burning trend of the composites demonstrated that the heat release rate of the composite is sufficiently high to sustain combustion throughout the specimen length, where rapid flame spread occurs due to synergistic combustion between the polymer matrix and lignocellulosic fibre reinforcement.

3.6 Morphological Properties

Based on Fig. 10(a) 10 wt.% fibre loading reveals a highly non-homogeneous microstructure. The white circle outlines a dense accumulation or agglomeration of sugarcane bagasse fibres. This configuration indicates that during processing, the high aspect ratio and surface energy of the raw lignocellulosic material resulted in mechanical entanglement. Because liquid epoxy resin cannot fully penetrate these tightly bound fibre bundles, the interior core remains resin-starved. When subjected to flexural compression and tension, this dry bundle functions as an internal void pocket, acting as a stress concentration site that triggers localized micro-cracking rather than retarding it. For 40 wt.% and 50 wt.% fibre loading (Fig. 10(b) and (c)) track the morphological boundaries at higher localized fibre volumes. The red callouts highlight clear boundaries separating the smooth, translucent epoxy resin matrix from the textured, fibrous strands of the sugarcane bagasse. The sharp and un-bonded nature of these boundaries is an indication of chemical incompatibility between the hydrophilic plant fibres and the hydrophobic polymer matrix.

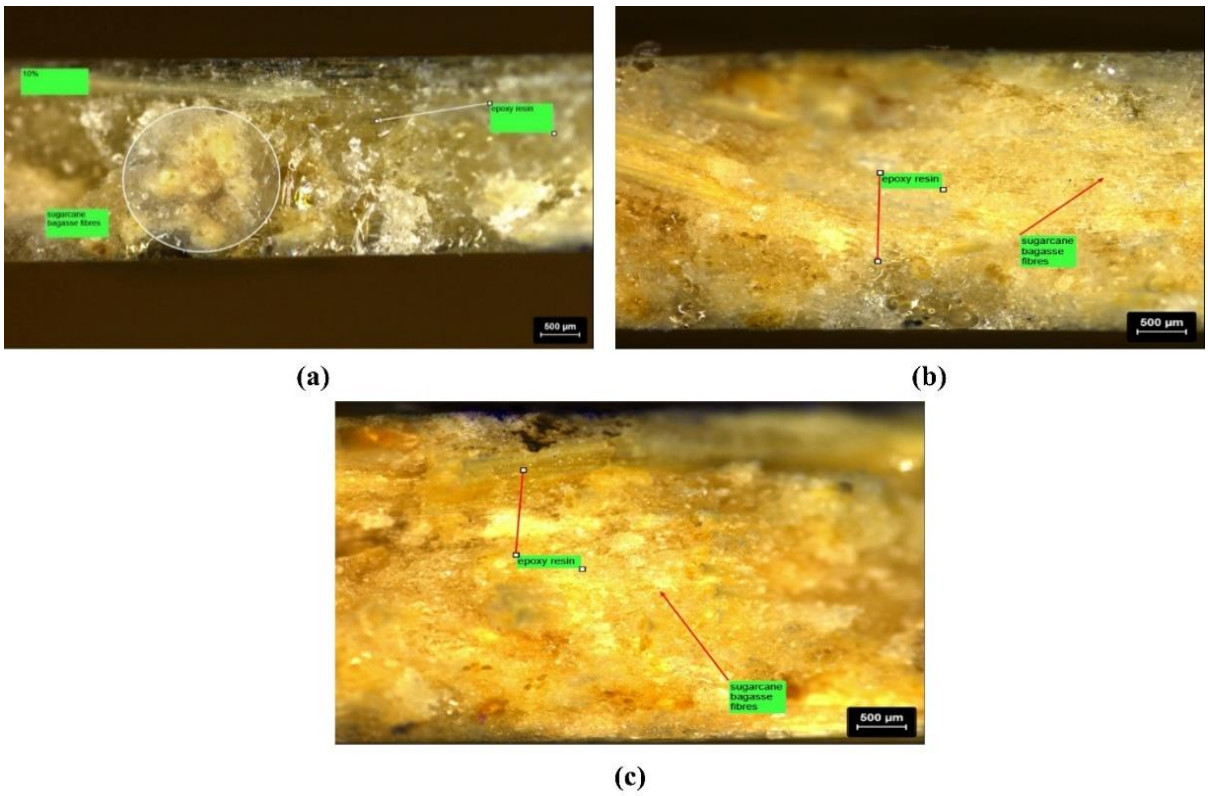


Fig. 10. The morphology of 10 wt.% fibre loading (a), 40 wt.% fibre loading (b), and 50 wt.% fibre loading.

4. Conclusions

In conclusion, this study systematically evaluated the influence of sugarcane bagasse fibre loading (0, 10, 20, 30, 40 and 50 wt.%) on the physical, mechanical, flammability and morphological characteristics of epoxy-based bio composites. The results demonstrated that fibre loading significantly influenced the overall performance of the composites. Water absorption increased considerably at higher fibre loadings. Among the sample, 10–30 wt.% fibre-reinforced composites exhibited comparatively lower water absorption, remaining below 15%, 50 wt.% composite showed the highest water absorption, ranging from 50% to 82%, while the 40 wt.% composite exhibited an intermediate absorption level of approximately 30–40%. Next, regarding mechanical performance, 40 wt.% composite demonstrated the highest tensile strength (14.81 MPa), flexural strength (46.39 MPa) and flexural modulus (3284.57 MPa) compared to other sample. Conversely, 30 wt.% composite exhibited the highest tensile modulus (564.17 MPa) and an impact strength of 2585.50 J/m, approaching that of neat epoxy. However, the neat epoxy control retained the highest tensile strength, tensile modulus, elongation at break and impact strength overall. Besides that, the decline in mechanical properties at 50 wt.% suggests that excessive fibre loading, which adversely affect stress transfer and composite integrity. In terms of flammability, all formulations achieved an HB rating in the horizontal burning test, while none obtained a recognised UL-94 classification in the vertical test. The 40 wt.% composite exhibited

the lowest HB rate (20.08 mm/min), whereas the 30 wt.% composite recorded the shortest average afterflame time (126.06 s). Overall, 40 wt.% sugarcane bagasse fibre is the most promising formulation for maximising flexural performance and selected tensile properties, with moderate water absorption rate less than 40%. However, its relatively high-water absorption remains a significant limitation which can be overcome through surface modification to improve fibre-matrix adhesion and reduce moisture penetration. Potential applications include non-structural interior panels, decorative components and selected moulded products, subject to further durability, fire-safety and application-specific testing. These findings support the potential utilisation of sugarcane bagasse as a renewable reinforcement in epoxy composites while highlighting the importance of optimising fibre loading for the intended application.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Jason Chow Zherui and **Kelvin Lee Kai Siang**: investigation, validation, visualization, writing. **Zahran Hafiraj** and **Mageswari Manimaran**: writing, editing. **Mageswari Manimaran**: writing. **Mohd Nurazzi Norizan:** research concept, writing, methodology, investigation, validation, visualization, funding acquisition, supervision. **Che Ku Abdullah**: methodology, visualization. **Anton Kuzmin:** research concept, methodology.

Declaration of Competing Interest

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

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