



Research article

Investigation of the effect of SiO₂ and melamine cyanurate fillers loading on the physical, mechanical, vibration, and flammability behaviors of hybrid waste mesocarp fiber/denim fabric epoxy composites

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ABSTRACT

The transition to a green economy is motivating industries to replace non-renewable materials with sustainable alternatives derived from agricultural and industrial waste. Therefore, this study aims to evaluate palm-oil mesocarp fiber (MF) and denim textile waste as reinforcing constituents for hybrid fiber-reinforced polymer composites (FRPC) to address performance limitations of natural-fiber composites in structural and safety-sensitive applications. Two separate sets of hybrid composites were fabricated: one modified with silicon dioxide (SiO₂, 1–3 wt%) and another modified with melamine cyanurate (MCA, 5–15 wt%). The characterization process included physical, mechanical (tensile, flexural, and buckling tests), vibration (natural frequency and damping ratio), and flammability (vertical and horizontal burning) tests. The experimental results showed that hybridization with denim improved load transfer, flexural or tensile response, and damping capacity. SiO₂ loading also increased density, stiffness, and strength but reduced ductility and damping, which are associated with matrix stiffening and particle agglomeration at higher filler loadings. Among the MCA-filled composites, 5 wt% MCA provided the highest tensile strength, while 10 wt% MCA resulted in the highest tensile modulus. The 15 wt% MCA formulation exhibited the greatest reduction in water absorption and the highest flame-retardant performance. The observations indicated that SiO₂-filled composites were more effective in enhancing stiffness-related properties, whereas MCA-filled composites provided greater improvements in moisture resistance and flame-retardant behavior. These findings highlight the importance of selecting appropriate filler types and loading levels according to the intended structural application.

1. Introduction

Oil palm (*Elaeis guineensis*) is a strategic tropical agricultural commodity with high economic and industrial importance, particularly in developing countries such as Indonesia. The vast plantation areas and favorable climatic conditions make Indonesia the largest palm oil producer in the world, with approximately 60% of global consumption, and the commodity also contributes an estimated 7.5% to national export earnings [1]. This large-scale production is supported by more than 1150 palm oil mills distributed across the archipelago [2]. However, the extensive processing of oil palm generates a considerable amount of lignocellulosic biomass waste, including empty fruit bunches (22%), kernel shells (7%), and mesocarp fibers (MF) (15%) from fresh fruit

bunch (FFB) [3]. This shows the need to ensure sustainable utilization of the biomass waste becomes an important component in the circular bioeconomy agenda of the country.

MF derived from the pulp residue of oil palm fruit after oil extraction is part of the most abundant lignocellulosic waste. The rich content of cellulose, hemicellulose, and lignin allows MF to possess a natural hierarchical structure suitable for reinforcement in composite materials. Currently, approximately 70% of MF is used as boiler fuel while the rest is discarded or left to decompose around processing facilities [4]. This underutilization represents a missed opportunity for value addition considering the fact that the chemical composition and morphology reflect excellent potential as reinforcement for natural fiber polymer composites. Moreover, the valorization of MF into composite materials

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is in line with global efforts toward sustainable materials, promoting resource efficiency, waste minimization, and carbon footprint reduction.

Natural fiber–reinforced polymer composites (NFRPCs) are currently identified as promising substitutes for synthetic composites over the past two decades in line with global sustainability goals. The mechanical strength is generally lower than those possessed by synthetic fibers such as glass or carbon but the vibration-damping, acoustic-insulation, and impact-resistance properties can be comparable or even superior in specific applications [5,6]. The composites also offer a combination of desirable attributes including low density, high specific strength, corrosion resistance, biodegradability, and recyclability [7]. Structurally, a composite consists of two or more distinct phases which are typically a polymeric matrix and a reinforcing fiber working synergistically to enhance overall performance [8]. This has led to the increasing adoption of NFRPCs in sectors such as automotive, aerospace, construction, and furniture manufacturing [9,10]. The context shows oil palm MF as a sustainable, low-cost, and locally available reinforcement candidate for next-generation green composites.

Several experimental studies have explored the incorporation of MF to improve the structural performance of polymer matrices. Olu-summade et al. [11] fabricated linear low-density polyethylene (LLDPE) composites reinforced with MF at 5–25% volume fractions and reported that excessive fiber content reduced tensile strength due to poor interfacial bonding. Huisken et al. [12] also showed that optimum mechanical performance was achieved at 5% fiber volume as a confirmation of weak matrix–fiber adhesion without surface modification. Another study by Eng et al. [13] improved flexural and impact strengths by 17% and 48% respectively through silane (5% methacrylate) treatment while Mahakur et al. [14] reported that alkaline (NaOH) treatment of jute fibers enhanced tensile strength by 11.3%. These results collectively suggested that surface modification improved interfacial adhesion, but mechanical improvements remain limited when only chemical treatments were adopted.

Nanoparticle addition has been identified as an effective route to enhance interfacial bonding and mechanical performance of fiber composites beyond surface treatment. Jotiram et al. [15] observed that adding 2% nano-SiO₂ to a kenaf-polymer composite increased tensile, flexural, and impact strengths by more than 20%. Velmurugan et al. [16] also reported a significant improvement in tensile strength from 72 MPa to 167 MPa by incorporating 3% CuO nanoparticles in a ramie composite. Another study by Sumesh and Kanthavel [17] showed that the addition of TiO₂ nanoparticles to pineapple/sisal hybrid composites enhanced both static and dynamic properties. However, excessive nanoparticle concentration can cause agglomeration which leads to non-uniform dispersion and reduced mechanical performance. An important observation from the results is that the synergistic role of nanoparticles in hybrid composites reinforced with agricultural waste fibers such as MF remains insufficiently explored.

Hybridization which is the combination of two or more fiber types has recently gained attention as another strategy to achieve balanced mechanical and functional properties in composites. Ikbali et al. [6] reported that a 40% ramie–glass hybrid composite exhibited the highest natural frequency and damping ratio. Masood et al. [18] also produced hybrid composites from cotton textile waste, jute, and glass fibers with competitive performance compared to pure glass fibers while Khalid et al. [19] showed that jute–carbon fiber hybrid achieved tensile strengths nearly equivalent to carbon fiber composites. Several other studies reported that hybridization with waste textile or animal fibers improved both strength and thermal insulation properties [20–22]. Textile waste shows promise as a reinforcement for structural composites: one review found that discarded denim provides adequate strength, comparable to that of natural fibers [23,24]. However, no prior study has investigated the integration of oil palm MF with textile waste and nanoparticle additives in a hybrid composite system, despite promising developments. This represents a key study gap that limits the broader utilization of MF-based composites for advanced structural or functional

applications.

The review shows that oil palm mesocarp fiber holds strong potential as reinforcement for sustainable composite materials. However, challenges remain in achieving adequate interfacial bonding, mechanical strength, and thermal stability. In addition, comprehensive studies examining the relationships among the mechanical, vibrational, and flame-retardant properties of MF-based hybrid composites remain limited. Previous studies have not simultaneously investigated the combined effects of fiber hybridization using MF and denim waste, nanoparticle reinforcement, and flame-retardant additives on the structural, vibration, and flammability performance of polymer composites. Although nanoparticle and flame-retardant modifications have individually been reported to improve composite performance, a systematic understanding of how filler type and concentration govern the interphase characteristics at the fiber–matrix interface in hybrid mesocarp fiber/textile waste composites is still lacking. Moreover, the compatibility between the hybrid reinforcement architecture and particulate modifiers, as well as the specific roles of each filler system in controlling stress-transfer efficiency, micro-void generation, crack propagation, and vibration energy dissipation, have not been clearly established. Consequently, a critical gap remains in elucidating the structure–property relationships between SiO₂ and MCA loading and the mechanical, dynamic, and flammability responses of MF/denim-based hybrid composites.

The specific contribution of this study is the comparative investigation of two distinct modification routes within the same MF/denim epoxy composite system. Therefore, this study aims to fabricate two sets of hybrid composites: one modified with silicon dioxide (SiO₂, 1–3 wt%) and another modified with melamine cyanurate (MCA, 5–15 wt%). The composites were systematically characterized in terms of physical (density and water absorption), mechanical (tensile, flexural, and buckling), vibration (natural frequency and damping ratio), flammability (UL–94 vertical and horizontal burning tests), and microstructural (SEM) properties to elucidate the influence of filler type and loading on the evolution of the fiber–matrix interphase and the associated structure–property relationships. The novelty of this study lies not only in integrating agricultural and textile waste streams with targeted nanoparticle and flame-retardant modifications, but also in establishing the role of SiO₂ and MCA loading in governing interfacial characteristics and their correlations with stiffness, damping behavior, moisture resistance, and fire performance in multifunctional green composite panels intended for structural applications.

2. Experimental methodology

2.1. Materials preparation

The waste of oil palm MF was obtained from residues of a local mill as a by-product of the pressed fruit during the extraction process. It accounts for approximately 11% of the total oil palm fruit mass and consists of a mixture of fruit fibers, shell fragments, and crushed kernels [25]. The fibers were thoroughly cleaned before use to remove surface contaminants and subsequently subjected to an alkali treatment with the aim of eliminating residual oil, wax, lignin, and hemicellulose. The purpose of the process was to improve the fiber–matrix interfacial adhesion. The treatment included immersing the fibers in a 5 wt% sodium hydroxide (NaOH) solution for 4 h followed by thorough washing and drying under ambient conditions to ensure the removal of excess alkali and moisture.

The denim fabric waste was collected from post-consumer domestic sources and prepared as an additional reinforcement material. Denim is a widely used twilled cotton fabric that possesses several favorable characteristics such as biodegradability, high mechanical durability, and cost-effective large-scale production potential. Chemically, cotton fibers consist primarily of 94% cellulose with minor constituents such as 1.2% proteins, pectic substances, and approximately 0.6% waxes which

contribute to the unique structural integrity of the fabric [26]. Denim fabrics were cut into rectangular sheets measuring 360 mm × 260 mm with a surface density of approximately 398 g/m². The detailed specifications of the denim fabric are presented in Table 1 [27].

The hybrid composite panels were fabricated using the hand-lay-up method, followed by compression molding in a closed mold. The total laminate thickness was approximately 5 mm, consisting of two layers of denim fabric at 1.2 mm and a randomly distributed MF mat at 3.8 mm. The overall reinforcement content was fixed at 25 wt% in the composite, comprising 12.5 wt% denim fabric and 12.5 wt% MF, resulting in an equal hybrid reinforcement ratio of 50:50 by weight. The remaining 75 wt% consisted of the epoxy matrix. The matrix material was a transparent, two-component epoxy system based on diglycidyl ether of bisphenol-A (DGEBA) with an aliphatic amine hardener (Rapid Resin, Indonesia). The viscosity of epoxy resin is approximately 2500 mPa·s at 25 °C and a cured-state glass transition temperature T_g of 80 ± 5 °C. The resin and hardener were mixed at a 4:1 mass ratio prior to impregnating the reinforcement. The laminates were produced with an overall dimension of 360 × 260 mm². Moreover, SiO₂ nanoparticles and MCA particles were incorporated into the epoxy matrix as additives. The MCA powder had an average particle size of approximately 25 µm and was used without any surface treatment. The SiO₂ nanoparticles were added at concentrations of 1%, 2%, and 3%, while the MCA particles were introduced at 5%, 10%, and 15% by weight. The SiO₂ content was limited to 1–3 wt% because previous studies have shown that low silica loadings are sufficient to enhance interfacial bonding and mechanical properties, while higher contents may lead to particle agglomeration [28]. In contrast, MCA was varied from 5 to 15 wt% because flame-retardant additives generally require higher loadings to achieve effective fire resistance, and this range has been widely reported as optimal for polymer composites [29]. No surface treatment was applied to filler particles prior to composite fabrication. Both fillers were used in their as-received condition. SiO₂ or MCA particles were gradually added to the epoxy resin and mechanically stirred for 30 min at room temperature to ensure uniform dispersion. Subsequently, the curing agent was added and mixed for an additional 3 min before the impregnation process. After the lay-up process, the mold was closed and secured using a clamping system to apply a constant compressive pressure during curing. The composite panels were then cured under ambient laboratory conditions. Upon completion of the curing process, the panels were demolded and machined into test specimens in accordance with the relevant testing standards. The experimental combinations of the MF/denim hybrid composites are summarized in Table 2.

2.2. Physical characterizations

2.2.1. Density measurement

The density of the composite specimens was determined using the geometrical method. This was achieved by measuring the mass (*m*) of each specimen using a high-precision digital balance with an accuracy of ±0.01 g. The volume (*V*) of the specimen was also calculated from the measured dimensions including length (*L*), width (*W*), and thickness (*T*) using a digital caliper. The density of a substance is the mass per unit

Table 1
Main physical and mechanical characteristics of denim fabric.

Material Properties	Unit	Value
Surface density	g/m ²	398
Thickness	mm	0.74
Weft density	picks/cm	22.0
Warp density	ends/cm	29.4
Ultimate tensile strength	N	810.3
Breaking work	J	9.8
Strain	%	24.3
Weft rigidity	N/m	41274

Table 2

Different types of composite combinations with varying SiO₂ and MCA filler proportions.

No. Exp.	Code	Combinations
1	MF/E	Mesocarp Fiber + Epoxy
2	MF/D/E	Mesocarp Fiber/Denim + Epoxy
3	MF/D/E/Si1	Mesocarp Fiber /Denim + Epoxy + SiO ₂ (1%)
4	MF/D/E/Si2	Mesocarp Fiber /Denim + Epoxy + SiO ₂ (2%)
5	MF/D/E/Si3	Mesocarp Fiber /Denim + Epoxy + SiO ₂ (3%)
6	MF/D/E/MC5	Mesocarp Fiber /Denim + Epoxy + MCA(5%)
7	MF/D/E/MC10	Mesocarp Fiber /Denim + Epoxy + MCA(10%)
8	MF/D/E/MC15	Mesocarp Fiber /Denim + Epoxy + MCA(15%)

volume as shown in the following equation:

$$\text{Density}, \rho (\text{g/cm}^3) = \frac{\text{mass}}{\text{Volume}} = \frac{m}{V} \quad (1)$$

Where, *m* is the specimen weight and *V* is the volume of the composite.

2.2.2. Water absorption test

The water absorption test was conducted to assess the hydrophilic tendency and porosity level of the denim/MF–MF-reinforced epoxy composites in line with the ASTM D570 standard. Rectangular specimens with dimensions of 25 mm × 25 mm were cut from the fabricated panels and were pre-conditioned in an oven at 50 °C for 6 h to remove residual moisture and achieve a stable dry mass (*w*₀). Each specimen was immersed in distilled water at room temperature after the condition and periodically removed from the water bath every 24 h, gently wiped with absorbent tissue to eliminate surface water, and weighed to obtain the wet mass (*w*₁). The immersion–weighing process continued until the mass difference between consecutive measurements became negligible to show that the water absorption equilibrium or saturation state had been achieved. The water absorption % was subsequently determined using the following equation:

$$\text{WA}(\%) = \frac{w_1 - w_0}{w_0} \times 100\% \quad (2)$$

Where, WA represents the percentage of water absorption, *w*₁ is the weight of the composite specimen after immersion, and *w*₀ is the initial weight before immersion.

2.3. Mechanical tests

The mechanical performance of the fabricated hybrid composites was evaluated through tensile, flexural, and buckling tests which were important for characterizing the strength and structural stability under different loading conditions. The experimental configurations for each test are presented in Fig. 1.

2.3.1. Tensile test

The tensile properties of the hybrid composite specimens were evaluated in accordance with the ASTM D3039 standard. The specimens were carefully cut from the fabricated laminate panels with dimensions of 250 mm in length and 25 mm in width and subjected to an MTS Landmark Servohydraulic Universal Testing Machine as shown in Fig. 1. The test was conducted under a cross-head speed of 3 mm/min with the load applied progressively until the failure of the specimen. The applied load and corresponding elongation were continuously recorded during the test to obtain the stress–strain characteristics. The values were subsequently used to determine the tensile strength, modulus of elasticity, and elongation at break. Moreover, each composite configuration was tested using three replicate specimens to ensure data reliability and repeatability.

2.3.2. Flexural test

The flexural behavior of the composites was evaluated using the

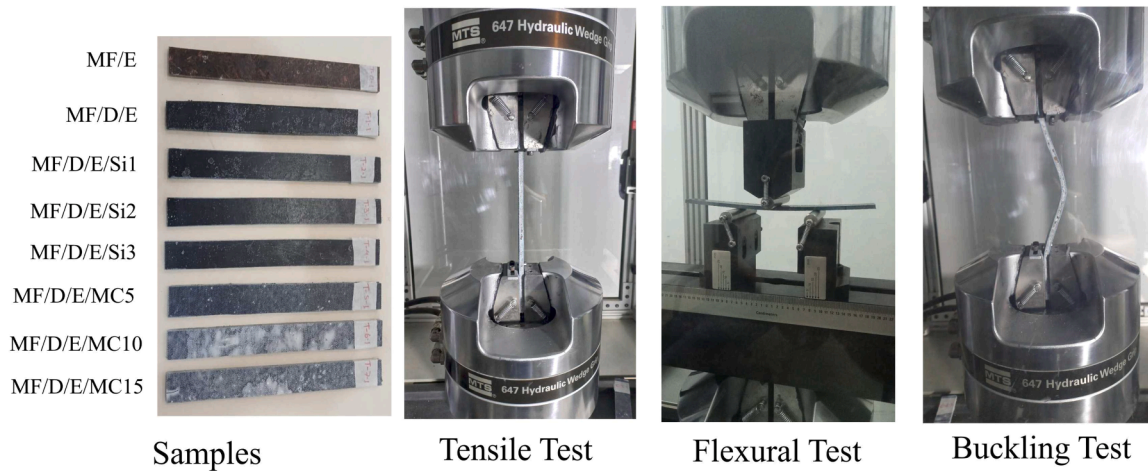


Fig. 1. Experimental setup for tensile, flexural, and buckling tests for each of the three specimens.

three-point bending method in accordance with ASTM D790–10 [30]. This test is important for determining the resistance of a material to bending loads in order to provide key insights into the stiffness, ductility, and load-bearing capability. Therefore, specimens with dimensions of 250 mm × 25 mm × 5 mm were prepared from the composite panels. The three-point bending tests were conducted using a support span of 75 mm, corresponding to a span-to-depth ratio of 15:1, in accordance with ASTM D790–10. Three specimens were tested for each composite configuration. The tests were conducted using a Universal Testing Machine (UTM) at a loading rate of 3 mm/min and the load was applied continuously until the failure of the specimen. The equation used to calculate the maximum flexural stress is presented as follows:

$$\sigma_{\max} = \frac{3P_{\max}L}{2bh^2} \quad (3)$$

Where, $P_{\max}$ represents the maximum load at failure (N), L is the span of two supports (mm) while b and h are the width and thickness of the specimen (mm) respectively. The flexural modulus was also determined from the starting section of the slope in the load-deflection curve and calculated using the following equation:

$$E = \frac{mL^3}{4bh^3} \quad (4)$$

Where, m is the gradient constant of the starting slope in the load-deflection curve.

2.3.3. Buckling test

The buckling test was used to assess the stability of structural materials under compressive loads by identifying the ability to resist sudden deformation or collapse. The process provided important insights into the buckling strength and structural integrity of slender components, aiding design optimization and material selection. The test was performed according to ASTM E2954 [31] using a 5 kN Universal Testing Machine. During the test, both ends of the specimen were rigidly clamped, corresponding to a fixed-fixed end condition, in order to prevent rotation and translational movement at the supports. The specimens measuring 250 mm × 25 mm × 5 mm were axially compressed at a crosshead speed of 3 mm/min. Three specimens were tested for each composite type, and the average values were used for further analysis.

2.3.4. Morphological analysis

The fractured surface morphology of the hybrid denim/MF with particle composite specimens was examined using a scanning electron microscope (SEM, Thermo-Scientific Prisma E SEM 16.0). This analysis

offered detailed microstructural visualization to enable clearer interpretation of the matrix–fiber interfacial behavior and bonding failure mechanisms. The high-resolution imaging further showed a more uniform fiber distribution across the composite surface.

2.4. Vibration analysis

The vibrational behavior of the fabricated composite structures was evaluated to determine their natural frequencies and damping ratios. These parameters are critical for preventing resonance and for assessing the material's ability to dissipate vibrational energy in dynamic applications. The vibration test was conducted in accordance with ASTM E756–05 by exciting a beam specimen using an impact hammer (PCB Model–086C03), while the response was measured using a Piezotronic accelerometer (PCB Model–352C33). The experimental setup for the vibration test on the composite panel is shown in Fig. 2. The signals were acquired using an NI–9250 data acquisition system and LabVIEW software at a sampling rate of 52 kHz. Subsequently, the acquired time-domain signals were transformed to the frequency domain using the Fast Fourier Transform (FFT) in MATLAB to obtain the frequency response and identify resonance peaks. The damping ratio was determined using the Half-Power Bandwidth (HPBW) method by measuring the bandwidth between the two half-power frequencies on either side of the resonance peak.

$$\zeta = \frac{f_2 - f_1}{2f_n} \quad (5)$$

where ζ is the damping ratio, f_n is the natural frequency corresponding to the resonance peak, and f_1 and f_2 are the lower and upper half-power frequencies, respectively.

2.5. Flame retardancy test

The flame retardancy test was conducted to evaluate the resistance and response of the composite materials under direct flame exposure. This was achieved using two standard methods which were the Vertical Burning Test (ASTM D3801 / UL 94) and the Horizontal Burning Test (ASTM D635 / UL 94HB). The evaluation parameters included ignition duration, burning length, and flame propagation rate which were measured over controlled exposure times. The overall experimental configuration for the flame retardancy test is shown in Fig. 3.

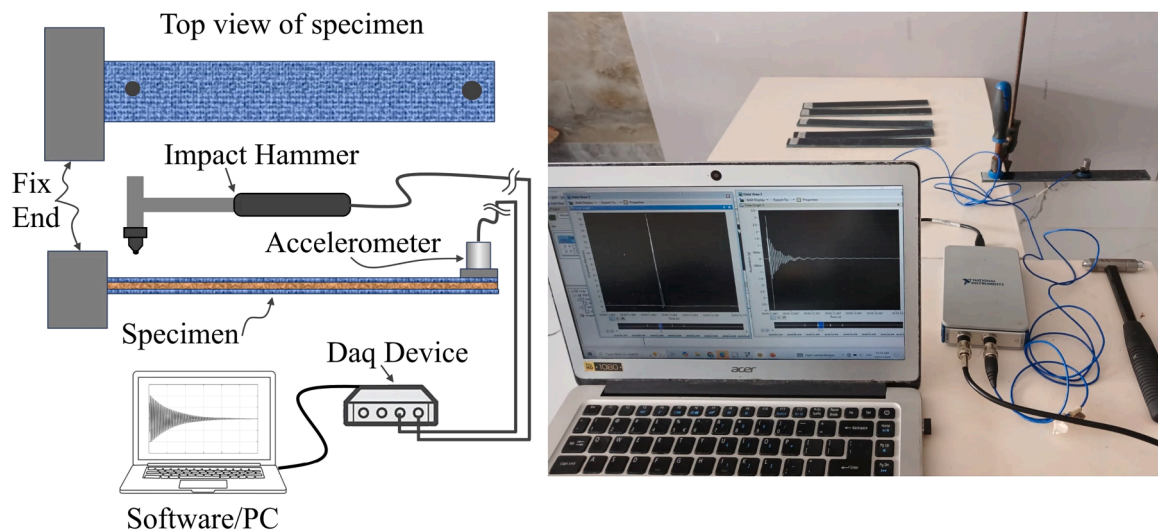


Fig. 2. Vibration test configuration of composite panel.

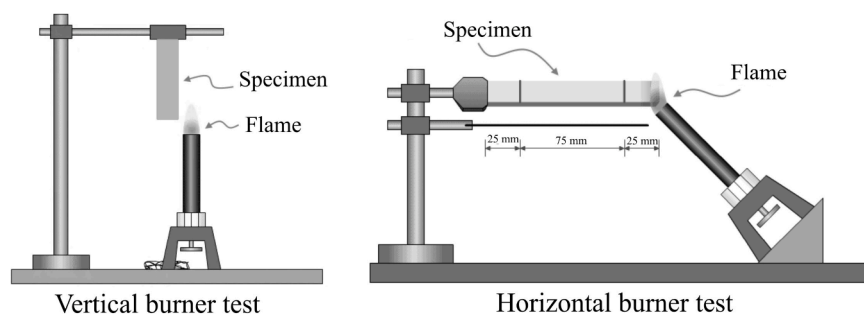


Fig. 3. Flame retardancy test configuration.

3. Results and discussion

3.1. Density and water absorption properties

The density value is the main indicator of mechanical performance in most studies related to natural fiber composite materials. Baghaei et al. [32] previously reported that the density range of the denim fabric-reinforced composite was 1.36–1.43 g/cm³. Meanwhile, the values for the hybrid composites developed in this study using MF and epoxy (MF/E), denim, and particle fillers ranged from 1.122 to 1.196 g/cm³. The trend reflects a consistent correlation between filler addition and matrix compactness even though the value is slightly lower than those in the MF/E composite.

The composite specimens have different density values depending on the types of fillers and the combination as summarize in Table 3. An increase in density was observed with the addition of SiO₂ particles in MF/D/E/Si1, MF/D/E/Si2, and MF/D/E/Si3, reaching values in the range of 1.163–1.189 g/cm³. The trend showed that the incorporation of

SiO₂ led to a denser microstructure. The inclusion of MCA also resulted in higher composite density compared to the unfilled counterparts, with the density increasing from 1.122 g/cm³ for MF/D/E to 1.196 g/cm³ for MF/D/E/MC15, representing a 6.6% increase. These results indicate that MCA addition contributed to improved compactness and overall structural integrity of the composite.

The water absorption behavior of the composite specimens with different filler additions is presented in Figs. 4(a) and 4(b). All the specimens generally exhibited a rapid increase in water absorption during the first 2–3 days of immersion followed by a gradual movement towards saturation after approximately 10–12 days. The final water absorption for the unfilled composites such as MF/E and MF/D/E reached 6.38% and 6.27% respectively. Meanwhile, the incorporation of SiO₂ particles into MF/D/E/Si1 to MF/D/E/Si3 caused a consistent reduction in the equilibrium water uptake. This was specifically observed from the decrease in the saturation water absorption from 6.04% to 4.48% as the SiO₂ content increased from 1% to 3%. The composite containing 3 wt% SiO₂ (MF/D/E/Si3) exhibited a 28.5% reduction in water absorption compared to MF/D/E. The trend confirmed that the hydrophobic SiO₂ particles effectively filled microvoids and strengthened the epoxy network to produce a more tortuous diffusion pathway for water molecules. This was consistent with the previous report of Gautam et al. [33] that the addition of nano-silica to epoxy composites decreased water absorption by approximately 30% mainly due to the improved cross-link density and reduced micro-porosity within the matrix.

The comparison to composite specimens containing 15 wt% MCA showed an equilibrium water absorption of 4.04% which corresponded to a 35.5% reduction relative to MF/D/E. This was a sign that the MCA-

Table 3
Density of hybrid MF/D/E with different particle fillers loading.

No. Exp.	Type of Composite	Density (g/cm ³)
1	MF/E	1.140
2	MF/D/E	1.122
3	MF/D/E/Si1	1.163
4	MF/D/E/Si2	1.166
5	MF/D/E/Si3	1.189
6	MF/D/E/MC5	1.166
7	MF/D/E/MC10	1.190
8	MF/D/E/MC15	1.196

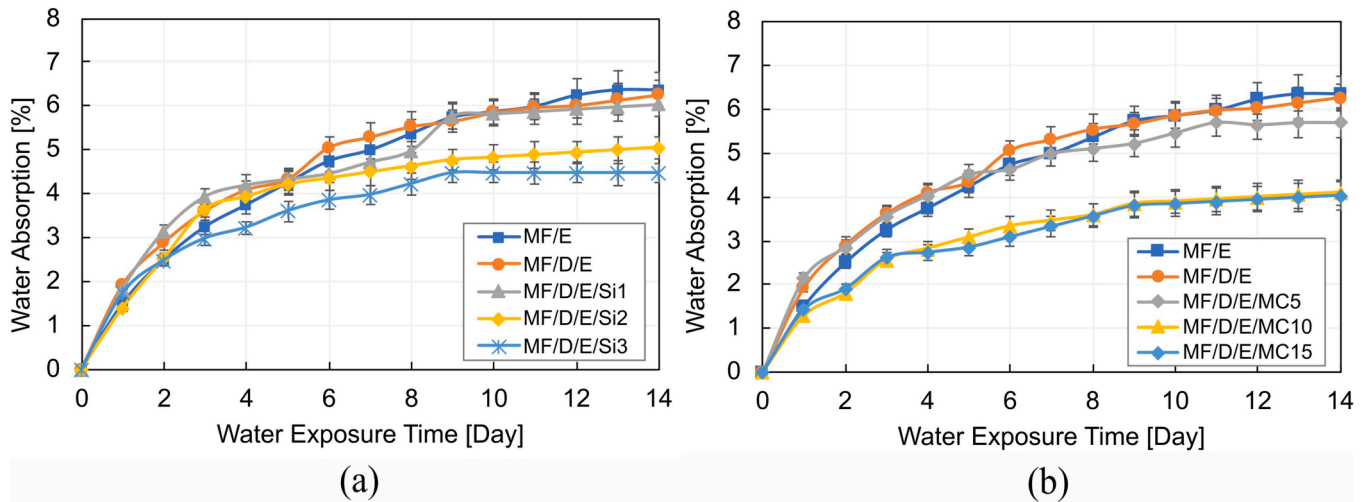


Fig. 4. Percentage water absorption of hybrid MF/D/E with particle fillers: (a) MF/D/E/SiO₂ and (b) MF/D/MCA.

modified composite exhibited even greater moisture resistance than the SiO₂-filled version under the present conditions. The improved performance of MCA was mainly due to the capability to provide a denser interfacial region and strengthen the bonding between the epoxy matrix and the fiber which assisted in minimizing the micro-void formation and preventing water penetration.

3.2. Mechanical properties

Fig. 5 shows the tensile behavior of hybrid MF and denim fabric composites containing SiO₂ (a) and MCA (b). All the specimens exhibited typical nonlinear stress–strain curves of fiber-reinforced polymers. This is because the stress–strain curves in both figures show an initial linear region up to approximately 0.2% strain followed by a gradual nonlinear increase until fracture. The linear segment represents the elastic deformation zone where the relationship between stress and strain follows Hooke's law to determine the modulus of elasticity for the composite. Beyond this region, the curves deviate from linearity to show the onset of plastic deformation as local debonding and micro-slipping occur between the fiber and the matrix.

The incorporation of denim fabric increased the elongation at break from 0.87% for MF/E to 1.19% for MF/D/E, as summarized in Table 4, indicating improved deformation capability. The SiO₂-filled composites

exhibited elongation values ranging from 0.93% to 1.17%. Although these values were slightly lower than those of MF/D/E at lower SiO₂ loadings, the elongation remained comparable to the hybrid composite without filler, particularly at 3 wt% SiO₂. At the same time, the SiO₂-filled composites exhibited improved tensile strength and modulus, suggesting that the incorporation of SiO₂ enhanced the mechanical performance without substantially compromising the deformation capability of the composites within the investigated filler range.

The MCA-filled composites exhibited the highest elongation values, reaching 1.24% for MF/D/E/MC5 and remaining above 1.10% for all MCA loadings. This indicates that MCA generally preserved the deformation capability of the composites. However, increasing the MCA content from 5 wt% to 15 wt% was accompanied by a gradual reduction in tensile strength. This behavior may be associated with particle accumulation at higher filler loadings, which can create localized stress concentration sites and reduce the effectiveness of stress transfer within the composite, thereby leading to a reduction in tensile strength [34,35].

The flexural stress–strain behavior in Fig. 6 shows that the hybrid MF/D/E composite exhibits improved flexural strength and strain compared to only MF/E. The trend is a reflection of enhanced load-bearing capacity and ductility due to denim reinforcement. Fig. 6(a) shows that the incorporation of SiO₂ fillers increased the flexural strength at lower loadings of 1 wt% and 2 wt%. However, at a higher

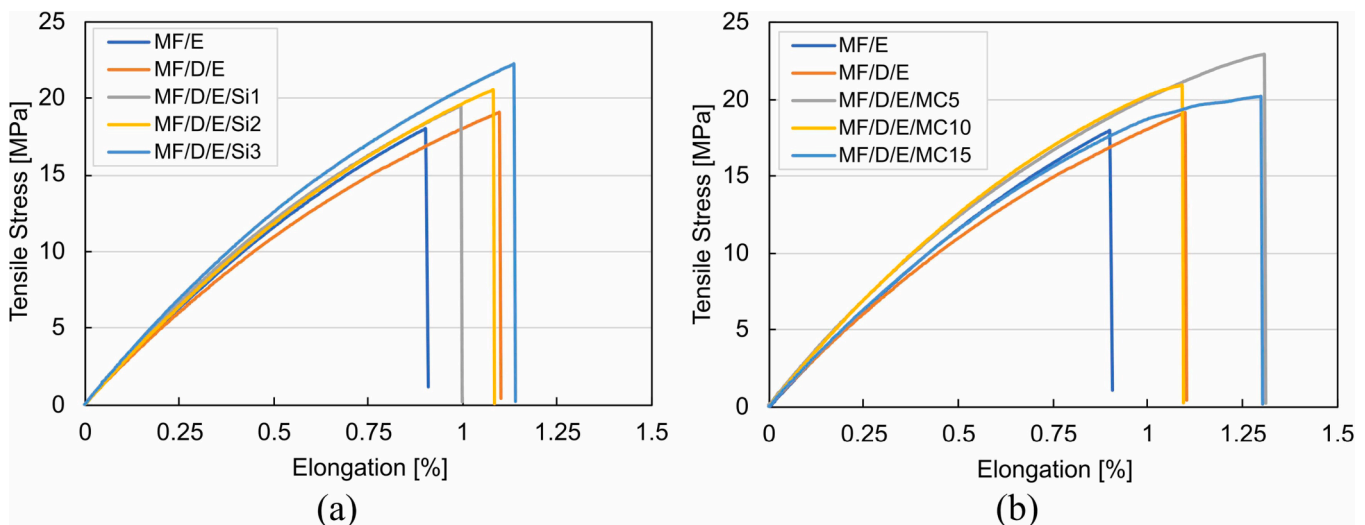
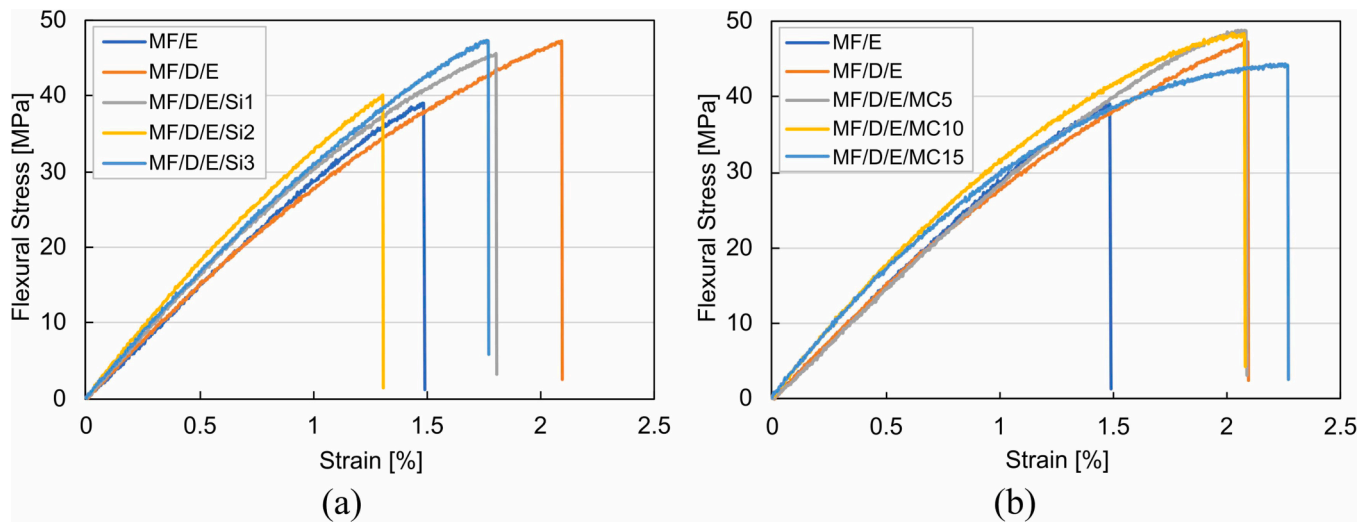


Fig. 5. Typical tensile stress-strain curve of hybrid MF/D/E with different particle fillers: (a) MF/D/E/SiO₂ and (b) MF/D/E/MCA.

Table 4

Summary of tensile, flexural and buckling properties of hybrid of MF/D epoxy composite with different particle fillers.

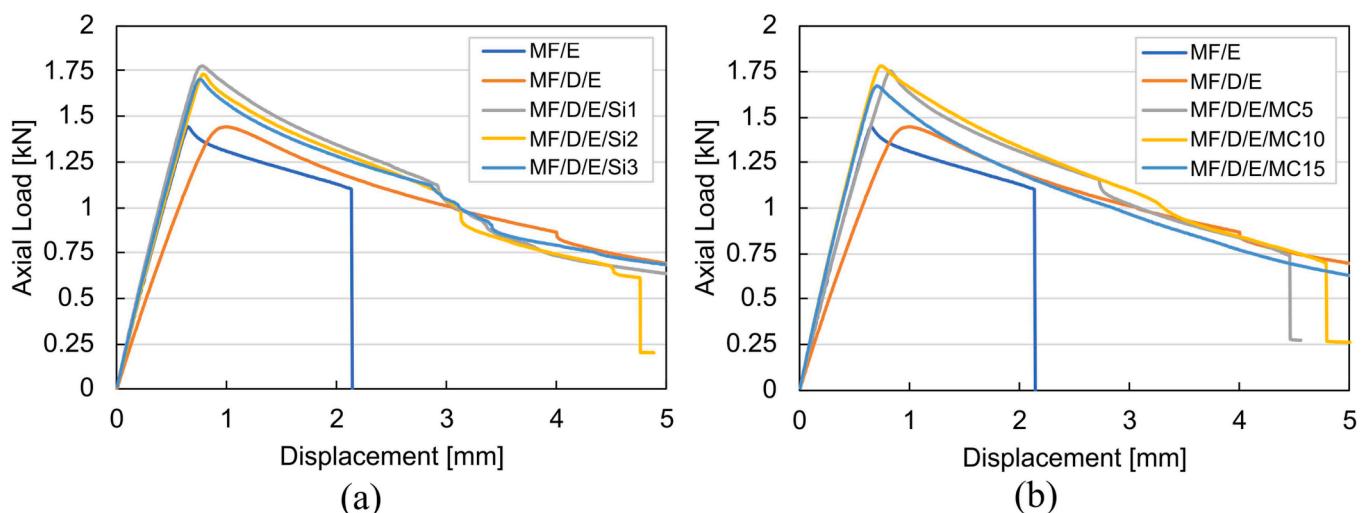
Type of Composite	Tensile Strength (MPa)	Elongation at break (%)	Tensile Modulus (MPa)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Buckling Critical Load (kN)
MF/E	17.3 ± 2.1	0.87 ± 0.084	2602.5 ± 53.1	35.4 ± 5.1	3273.7 ± 243.6	1.47 ± 0.15
MF/D/E	19.4 ± 0.5	1.19 ± 0.018	2467.5 ± 104.7	48.2 ± 4.3	2735.3 ± 257.5	1.45 ± 0.07
MF/D/E/Si1	18.8 ± 0.7	0.93 ± 0.068	2754.4 ± 30.3	47.4 ± 2.0	3285.9 ± 187.0	1.81 ± 0.15
MF/D/E/Si2	19.2 ± 1.1	1.03 ± 0.108	2733.0 ± 107.1	46.6 ± 5.0	3558.1 ± 294.7	1.76 ± 0.07
MF/D/E/Si3	21.6 ± 0.5	1.17 ± 0.013	2725.9 ± 51.5	44.1 ± 3.2	3485.2 ± 84.2	1.68 ± 0.12
MF/D/E/MC5	22.1 ± 1.1	1.24 ± 0.052	2727.9 ± 137	44.7 ± 5.2	3273.7 ± 243.6	1.68 ± 0.17
MF/D/E/MC10	21.0 ± 0.3	1.10 ± 0.007	2803.6 ± 54.6	43.2 ± 4.6	3559.2 ± 100.3	1.74 ± 0.13
MF/D/E/MC15	19.8 ± 0.4	1.20 ± 0.078	2615.2 ± 110.6	42.9 ± 1.7	3596.2 ± 136.2	1.63 ± 0.15

**Fig. 6.** Typical flexural stress-strain curve of hybrid MF/D/E with different particle fillers: (a) MF/D/E/SiO₂ and (b) MF/D/E/MCA.

loading of 3 wt%, a reduction in strength was observed, which may be associated with reduced particle dispersion uniformity within the epoxy matrix. This condition can disrupt matrix continuity and limit the effectiveness of stress transfer, thereby reducing the flexural performance. Fig. 6(b) signals that MCA-filled composite specimens exhibited smoother and more ductile curves with 10% MCA achieving a balanced combination of strength and flexibility [36].

Fig. 7 shows the axial load–displacement behavior of all composite variants. The results showed that all specimens exhibited a typical buckling response characterized by a rapid increase in load up to the

critical buckling load, followed by a reduction in load-carrying capacity during post-buckling deformation. The MF/E specimen exhibited an abrupt loss of load-carrying capacity after reaching its peak load, indicating limited post-buckling stability. In contrast, the hybrid and filler-modified composites showed a more gradual reduction in load with increasing displacement, suggesting an improved ability to sustain compressive loading after buckling initiation. Among the SiO₂-filled composites, the highest critical load was obtained for MF/D/E/Si1 rather than MF/D/E/Si3, despite the latter exhibiting superior tensile properties. This observation indicates that improvements in material

**Fig. 7.** Axial load–load-displacement curves of hybrid MF/D/E with different particle fillers: (a) MF/D/E/SiO₂ and (b) MF/D/E/MCA.

strength and stiffness do not necessarily translate into proportional gains in buckling resistance. A moderate SiO₂ loading appears to provide a more favorable balance between stiffness and structural stability under compressive loading. Similar behavior was observed for the MCA-filled composites, where the highest buckling load was achieved at 10 wt% MCA, while further filler addition produced only marginal improvements in post-buckling performance. These results suggest that the buckling behavior of the composites is governed not only by material stiffness but also by their ability to maintain structural integrity and redistribute stresses during post-buckling deformation.

The effect of hybrid MF/D with different particle fillers reinforced epoxy composite specimens on tensile, flexural, and buckling properties is summarized in Table 4. The tensile strength showed a clear improvement trend with the incorporation of denim fibers and filler materials. The reference composite (MF/E) exhibited a tensile strength of 17.27 MPa while the hybrid MF/D/E fibers without fillers increased the strength to 19.35 MPa as a representation of 12% improvement. This increase was attributed to the load transfer capability provided by the denim fiber reinforcement which effectively bridged stress between the polymer chains and delayed crack propagation during tensile loading.

The introduction of SiO₂ nanoparticles at concentrations of 1–3% further increased the tensile strength to 21.61 MPa at the highest concentration on specimen MF/D/E/Si3. This represented a 25.1% improvement compared to MF/E and approximately 11.6% relative to the hybrid MF/D/E. The increase is attributed to the strong interfacial bonding and efficient stress transfer between the SiO₂ particles and the epoxy matrix. SiO₂ particles formed via sol-gel dispersed in epoxy act as interlocking pins at the interphase, which increases the friction between the fiber and the matrix and strengthens the interfacial adhesion [37]. The trend was consistent with the reports of previous studies that the addition of 2–4% silica nanoparticles enhanced the tensile strength of fiber-reinforced composites by approximately 20–30% [15,38].

Composite specimens containing MCA as a flame-retardant filler showed a different trend by exhibiting a less consistent improvement. The highest strength was observed in MF/D/E/MC5 at 22.05 MPa which represented a 27.6% increase compared to MF/E but the strength slightly decreased at higher concentrations with 19.82 MPa at MF/D/E/MC15. This behavior showed that a moderate amount of MCA could improve interfacial cohesion due to the fine dispersion and possible hydrogen bonding with the polymer matrix. However, higher MCA loadings such as 15 wt% may be associated with filler accumulation at higher loadings, resulting in a less uniform matrix structure and reduced interfacial compatibility, which can promote localized stress concentration sites [35,39].

The tensile modulus results showed that hybridization with denim fabric slightly reduced the composite stiffness from 2602 MPa for MF/E to 2467 MPa for MF/D/E. This behavior may be associated with the woven architecture of the denim reinforcement. The crimped yarn structure requires an initial realignment during tensile loading, causing part of the applied strain to be consumed in straightening the yarn undulations before effective fiber stretching occurs, thereby reducing the effective tensile modulus [40,41]. Moreover, the incorporation of SiO₂ particles successfully counteracted the effect by increasing the modulus up to 2754 MPa which was approximately 14% improvement compared to MF/D/E. These results showed that the rigid SiO₂ particles effectively enhanced matrix stiffness and promoted better stress transfer. This enhancement can be attributed to the ability of SiO₂ particles to increase the surface roughness of the fibers, thereby strengthening the mechanical interlocking between the fibers and the matrix [42]. However, a slight declination was observed at 3% concentration which reflected the onset of particle crowding limiting additional modulus gains.

A similar behavior was identified in the MCA-filled composite specimens where the modulus increased from 2728 MPa at MC5 to a maximum of 2804 MPa at MC10 as a reflection of an improved interfacial adhesion and uniform particle dispersion at moderate loading. Meanwhile, the modulus decreased to 2615 MPa at MC15, which may be

associated with a less uniform particle distribution at higher filler concentrations that disrupted matrix continuity and reduced reinforcement efficiency. Both SiO₂ and MCA successfully restored and enhanced the stiffness lost during composite hybridization. SiO₂ provided steadier improvements across concentrations while MCA exhibited a more pronounced optimum effect at intermediate loading. These results showed the importance of balancing filler content and dispersion quality to optimize the tensile modulus of hybrid reinforced composites [15,43].

The hybridization of MF/E with MF/D/E increased flexural strength from 35.4 MPa to 48.2 MPa, corresponding to a 36% increase. This increase is attributed to the reinforcing role of denim fabric which improves load-bearing capacity through structural contribution. However, the enhancement is accompanied by a decrease in flexural modulus to 2735.3 MPa due to the inherent stretchability and compliant nature of denim fabric, which tends to deform more under flexural stress. The woven structure of denim allows for internal sliding and fabric realignment during bending [44].

The incorporation of SiO₂ particle fillers restored and further improved the modulus to a peak of 3558 MPa at a filler content of 3% (MF/D/E/Si3). This enhancement reflected the stiffening capability of rigid SiO₂ particles which limited polymer chain mobility and reinforced the matrix structure [45]. However, the flexural strength shows a slight downward trend with increasing SiO₂ content from 1% to 3%, ranging from 47.4 MPa to 44.1 MPa respectively. This decrease, which may be associated with reduced dispersion uniformity at higher filler loadings and localized stress concentrations that act as failure initiation sites [46].

The MCA-filled composite specimens had a more stable mechanical performance where the flexural modulus increased progressively from 3273 MPa at 5% MCA to 3596 MPa at 15% MCA to reflect a 31.5% gain over the unfilled hybrid. The flexural strength decreased slightly with increasing MCA content from 44.7 MPa to 42.9 MPa but the trend was less drastic compared to the SiO₂ particle. This showed better compatibility and dispersion of MCA within the matrix particularly at an intermediate loading (10% MCA) which achieved a favorable balance between modulus with 3559 MPa and strength with 43.2 MPa.

Table 4 shows that the addition of SiO₂ particles to the MF/D/E matrix improves the critical axial load. The MF/D/E/Si1 specimen reached the highest peak at 1.807 kN, which was approximately a 23% increase over the MF/E reference. The specimens with 2% and 3% SiO₂ also showed enhanced performance of 20% and 14%, respectively, reflecting increased stiffness and good dispersion of SiO₂ fillers, which contributed to improved load transfer and local rigidity. However, the slight reduction from 1 wt% to 3 wt% suggests that further increases in filler content may result in excessive matrix stiffening and reduced strain accommodation, thereby reducing the composite's ability to effectively redistribute compressive stresses during buckling. MCA-filled composite specimens exhibit improved critical loads compared to MF/E, with 10% MCA achieving the highest value of 1.739 kN, which was an 18% increase. The increases of 14% and 11% observed for MCA 5 wt% and 15 wt%, respectively, suggest that particle reinforcement was more effective at intermediate filler concentrations. The bar chart emphasizes that the hybrid composite without filler (MF/D/E) performs slightly lower than MF/E, confirming that only denim fabric cannot improve axial stability. Meanwhile, both SiO₂ and MCA fillers enhanced buckling resistance most effectively at controlled loadings to emphasize the role of filler dispersion and interfacial bonding in axial load-bearing capacity [47].

3.3. SEM morphology

Fig. 8 shows the surface morphology of tensile-tested specimens as observed under SEM to study the failure mechanism. The SEM observations showed apparent variations in damage mechanisms and interfacial bonding quality in different composite types. The MF/E analysis showed fiber pull-out and a relatively smooth epoxy matrix as dominant

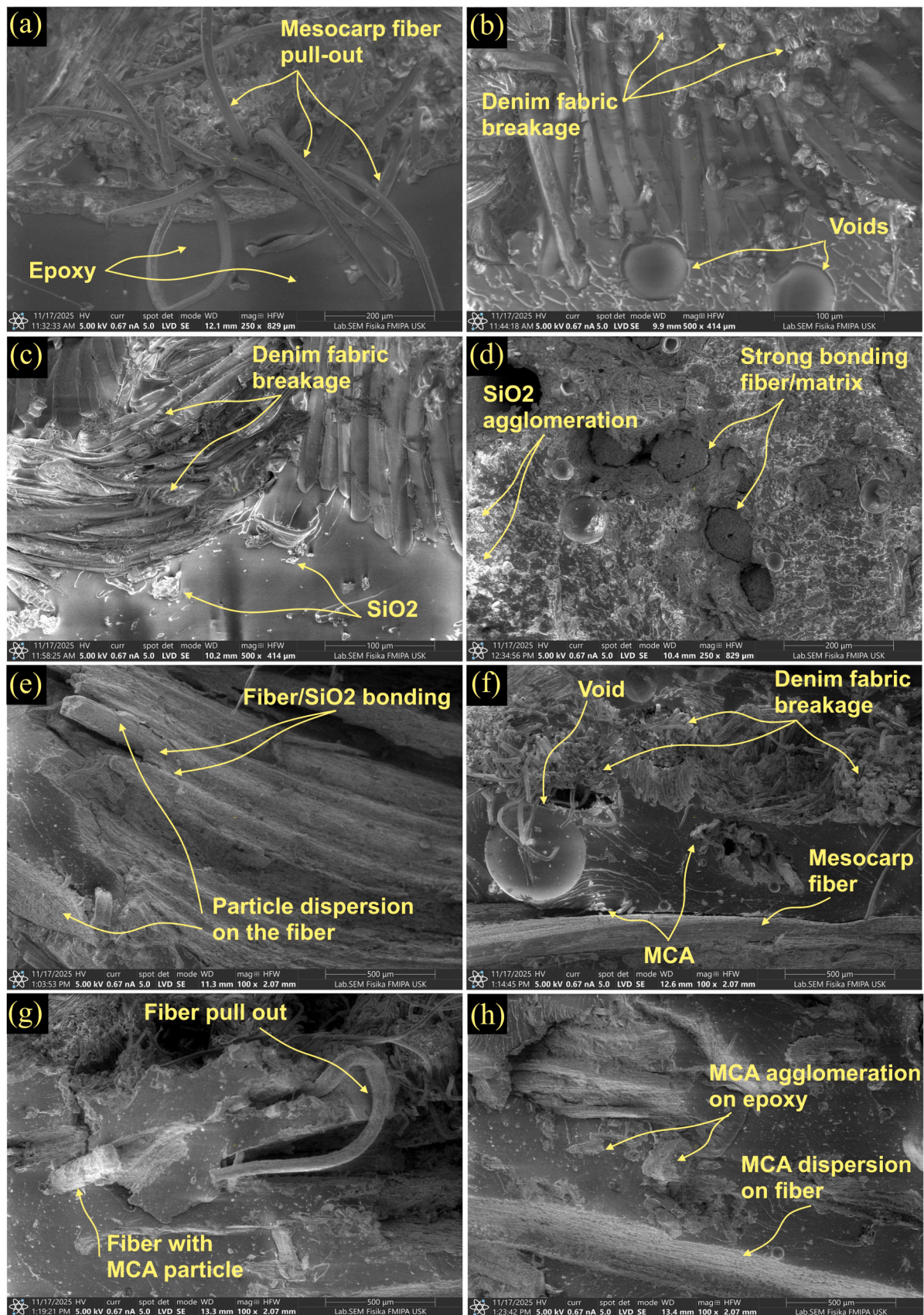


Fig. 8. SEM result of fractured hybrid MF/D/E and different particle filler: (a) MF/E, (b) MF/D/E, (c) MF/D/E/Si1, (d) MF/D/E/Si2, (e) MF/D/E/Si3, (f) MF/D/E/MC5, (g) MF/D/E/MC10, and (h) MF/D/E/MC15.

features, reflecting weak interfacial adhesion between the MF and the resin in Fig. 8(a). Such extensive fiber pull-out indicates that the applied tensile load could not be efficiently transferred from the matrix to the reinforcement, which is consistent with the relatively low tensile and flexural strengths of the MF/E composite. The fracture surfaces of the hybrid MF/D/E showed a shift toward dominant denim fiber breakage, accompanied by the presence of voids in Fig. 8(b). This morphology indicates improved load transfer compared to MF/E, despite some inconsistencies in resin impregnation. The increased tensile strength of MF/D/E relative to MF/E is consistent with SEM evidence of denim fabric breakage, which shows the denim fabric's ability to enhance load distribution. The improved fiber breakage behavior also suggests stronger interfacial interactions between the reinforcement and the epoxy matrix, contributing to the observed enhancement in flexural strength of the hybrid composite. The trend was consistent with the observation by Arshad et al. [48] that hybridizing weak fibers with stronger fibers effectively redistributed mechanical loads.

More pronounced improvements were evident in the SiO₂-filled composites in Fig. 8(c) to (e), where the fracture surfaces display finer particle dispersion, enhanced fiber–matrix interlocking, and fewer voids. These microstructural features are consistent with the improved tensile modulus and flexural strength, where the SiO₂ particles distributed around the fiber–matrix interface may have enhanced interfacial adhesion. Nevertheless, even with mechanical stirring, partial nanoparticle agglomeration persisted at 2 wt% SiO₂, underscoring the limited dispersion efficiency in the epoxy matrix. The overall fracture morphology remained comparatively uniform at 3 wt% SiO₂, indicating a sustained interfacial-strengthening contribution from the filler, although agglomerated regions likely diminished stress-transfer pathways and reinforcement efficiency by introducing localized stress concentrations. This limitation could be mitigated by combining mechanical mixing with subsequent ultrasonication to promote more homogeneous nanoparticle dispersion [49]. Meanwhile, the MCA-filled composites exhibited a less uniform fracture morphology, particularly in specimens containing 10 wt% and 15 wt% MCA. This condition coincided with more extensive fiber pull-out and a less cohesive fracture surface compared to the lower MCA loading. In contrast, the specimen containing 5 wt% MCA exhibited a more homogeneous fracture surface and improved fiber–matrix interaction, consistent with its superior tensile strength. The results generally indicated that each particle filler exhibited distinct characteristics. Increasing SiO₂ concentrations tended to enhance interfacial bonding and mechanical integrity, whereas higher MCA concentrations were associated with a less pronounced improvement in mechanical performance. However, the reduction in strength at higher MCA loadings was relatively moderate, indicating

that MCA remains a viable additive when used within an appropriate loading range.

3.4. Vibration behavior

Fig. 9 presents the vibration response curves of the composite panels as a function of SiO₂ and MCA content. The dominant vibration mode was observed at the second mode. The pure MF/E and hybrid MF/D/E composites exhibited the same natural frequency of 174.1 Hz. However, the hybrid composite showed a slightly lower spectral amplitude than the pure MF/E composite, indicating a greater damping capability. This behavior can be attributed to the inherent viscoelastic nature of the denim fabric, which enhances internal energy dissipation and absorbs a portion of the vibration energy during resonance [50,51]. The natural frequencies of all hybrid composite specimens with filler particles also decreased by approximately 3–11% compared to the panel without fillers. This reduction in natural frequency may be associated with changes in the composite's dynamic characteristics following filler incorporation. In addition to increasing the composite mass, the fillers may have enhanced internal energy dissipation and modified the matrix's viscoelastic response, resulting in a lower natural frequency. This result is consistent with previous studies reporting that particulate fillers can modify the mass–stiffness balance and damping characteristics of polymer composites, thereby influencing their vibration response and natural frequency [52].

Fig. 10 compares the damping ratio (ζ) of the MF/E, the hybrid MF/D/E, MF/D/E/SiO₂, and MF/D/E/MCA. The filler-free hybrid had the

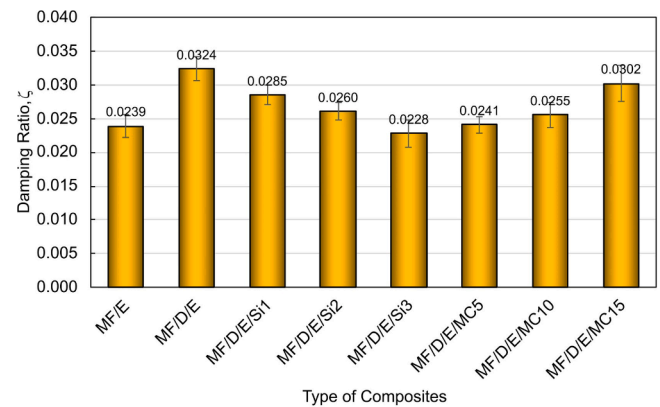


Fig. 10. Damping ratio of hybrid MF/D/E with different particle fillers.

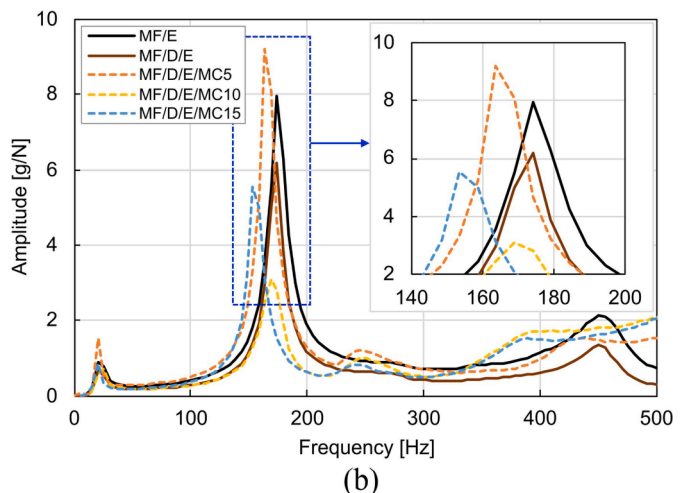
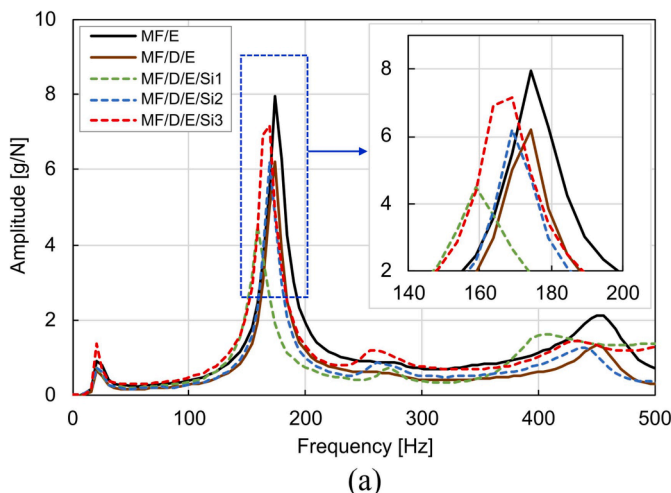


Fig. 9. Typical natural frequency of hybrid MF/D/E with different particle fillers: (a) MF/D/E/SiO₂ and (b) MF/D/E/MCA.

highest damping ratio (ζ) of 0.0324 which represented an increase of 35.6% relative to the neat MF/E with 0.0239. This improvement suggested that hybridizing MF with denim fabric promoted greater energy dissipation possibly due to increased internal interfaces and interfacial friction with mechanisms consistently identified in hybrid and other plant-fiber composite systems [53].

The hybrids filled with SiO₂ particles had a progressive reduction in damping ratio due to the increase in the filler content. The reduction compared to the 0.0324 recorded for the filler-free hybrid was approximately 12%, 20%, and 30% at 1%, 2% and 3% concentration respectively. These results were consistent with the observation of Bozkurt et al. [28] that the addition of SiO₂ particles enhanced the damping ratio at low concentrations of 0.5–1% but the effect was reversed at 1.5–2%. The downward trend suggested that SiO₂ nanoparticles tended to agglomerate and stiffen the matrix at higher loadings with subsequent reduction in the ability of the composite to dissipate vibrational energy via interfacial sliding and viscoelastic loss [54].

The damping ratios of 0.024, 0.0255, and 0.0302 recorded for MCA-filled hybrids at 5, 10, and 15% respectively showed an initial decrease of approximately 26% relative to the filler-free hybrid followed by a substantial recovery at the highest loading which reached 25% from the minimum point. This trend suggested that low to moderate MCA contents tended to limit viscoelastic energy dissipation while higher concentrations restored and partially enhanced the damping ratio. The hybridization generally increased damping performance compared to the MF composite while the filler effect depended strongly on the type and concentration. This was because SiO₂ tended to reduce damping at higher loadings while MCA improved the value at higher concentrations.

3.5. Flame retardancy properties

The flame retardation of the composite was evaluated using vertical and horizontal burning tests (UL–94 VB and HB) with the conditions of the specimens during the test presented in Figs. 11 and 12. The vertical test results showed that all the specimens ignited within the first 10 s of flame exposure but no flaming drips were observed. The trend was a reflection that the molten polymer remained stable and did not trigger secondary ignition. The after-flame time also showed that all specimens were in the non-rated UL–94 category even though the flame intensity and propagation rate differed among different composite specimens. The neat MF had the most aggressive flame spread with the burning zone extending nearly across the entire specimen by 40 s while the addition of fillers slowed the flame front progression.

The reduction in flame propagation observed for the SiO₂-filled

composites may primarily be attributed to the barrier effect of the inorganic particles, which restricts heat transfer and suppresses the diffusion of volatile combustible products from the matrix to the combustion zone, as reported by Thenmozhi and Murugavel [55]. However, increasing the SiO₂ content beyond 2 wt% provided only a limited additional benefit, suggesting that the barrier layer's effectiveness reached a relatively stable level within the investigated loading range. Meanwhile, the MCA-filled composites exhibited a progressive reduction in flame propagation with increasing filler content.

The horizontal burning results further supported the behavior with the neat MF/E specimen having the highest burning rate of 20.45 mm/min as a confirmation of its low resistance to horizontal flame propagation. The incorporation of denim fibers reduced the burning rate to 15.79 mm/min which was a 22.8% improvement associated with the char-forming ability of cellulose to enhance thermal insulation and limit lateral heat diffusion. SiO₂-filled hybrids showed only modest variations in burning rate (14.75–15.63 mm/min), with the lowest value observed at 2 wt% SiO₂, corresponding to a 27.9% reduction relative to MF/E. The slight increase at 3 wt% suggested that excessively rigid particulates could disrupt char continuity and reduce the shielding efficiency.

MCA provided the most substantial improvement with the burning rates decreasing to 15.10 mm/min (5 wt%), 13.55 mm/min (10 wt%), and 10.98 mm/min (15 wt%) which represented 26.2–46.3% enhancement compared to neat MF/E. The results were consistent with the flame-retardant mechanism of MCA which required endothermic decomposition, the release of inert nitrogen gases, and the formation of an expanded intumescent char layer effectively hindering heat transfer and flame propagation [56]. The thicker and more cohesive char observed at higher MCA loadings was very important in reducing the horizontal burning rate. Despite the reduced burning rate achieved with MCA, all specimens remained non-rated in the UL–94 test due to the highly combustible nature of the mesocarp fiber and cotton-based denim reinforcement. Although MCA enhanced char formation, the maximum loading of 15 wt% was insufficient to achieve self-extinguishing behavior. Future studies should explore higher MCA loadings or synergistic flame-retardant systems to further improve fire performance.

4. Conclusion

In conclusion, this study showed that hybridizing MF composite with denim fabric and incorporating SiO₂ and MCA particulate fillers led to improvements in the physical, mechanical, vibration, and flame-retardant performance. The density of all hybrids increased with filler addition to confirm enhanced matrix compactness. Water absorption

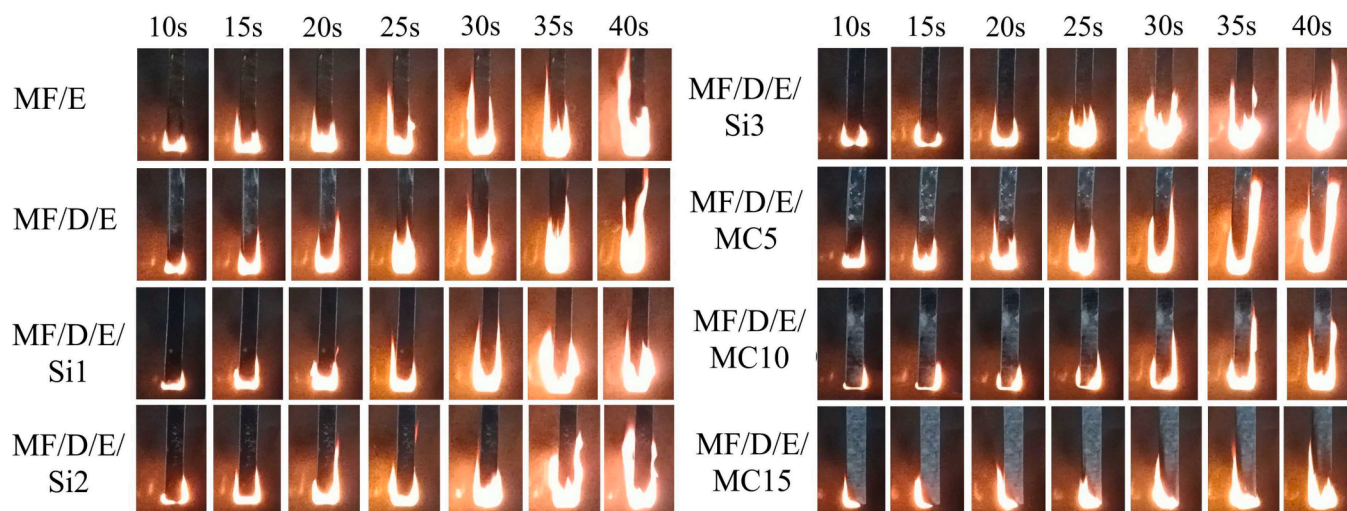


Fig. 11. Image captured from the UL–94 vertical burning test.

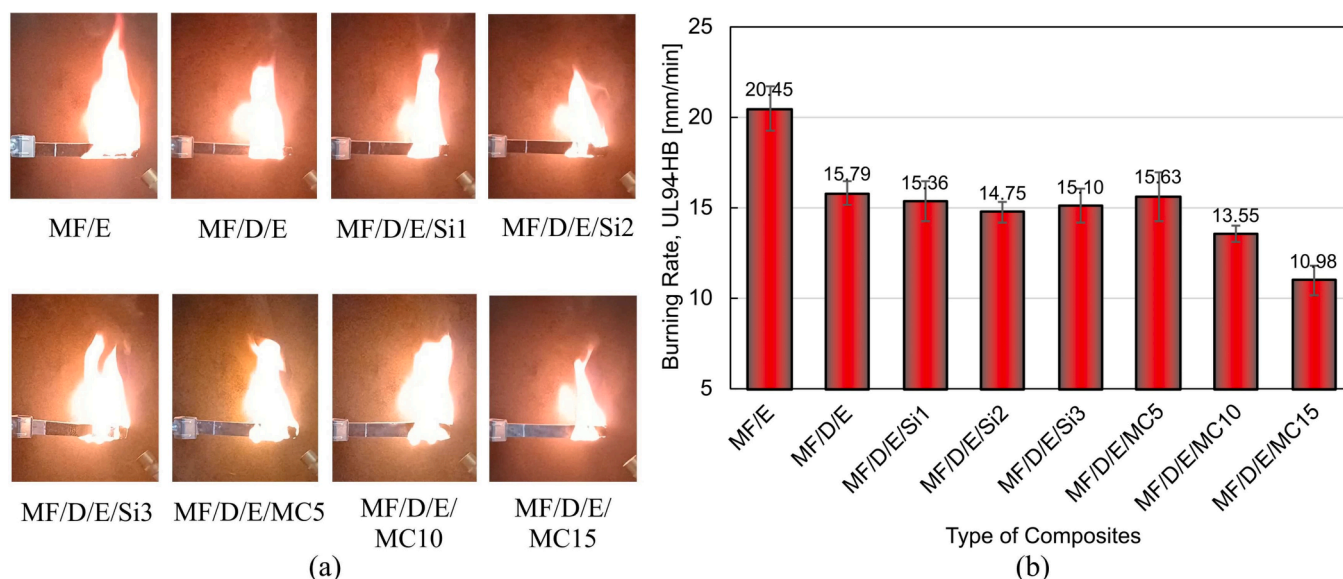


Fig. 12. Burning behavior of mesocarp/denim/particle composite in UL-94 HB test: (a) image captured after 2 min and (b) burning rate.

also decreased by up to 28.5% for SiO₂ and 35.5% for MCA due to reduced micro porosity and improved interfacial sealing. Moreover, the mechanical characterization of the hybrid MF/D/E composite showed improved tensile and flexural strength compared to the pure MF/E composite as a reflection of more efficient load transfer enabled by denim reinforcement. An increase in SiO₂ content at 1–3 wt% steadily led to an improvement in the density, reduction in water absorption by up to 28.5%, as well as an enhancement of tensile and flexural modulus due to the rigid, well-dispersed nanoparticle structure. SiO₂ particles also improved buckling resistance and provided moderate flame-retardant benefits. However, higher SiO₂ loading tended to reduce ductility and damping ratio, which was consistent with increased matrix stiffening at elevated filler contents. Moderate MCA contents of 5–10 wt % enhanced tensile strength, modulus, and buckling load through improved reinforcement efficiency. The 15 wt% MCA formulation increased density, reduced water absorption by 35.5%, enhanced damping ratio, and provided the greatest improvement in flame retardancy. However, excessive MCA loading may promote particle agglomeration, resulting in lower tensile and flexural strengths than with intermediate filler contents. MCA particles in MF/D/E composites at 10–15 wt% reduced the horizontal burning rate by up to 46.3%; however, all specimens remained in the UL-94 non-rated category during vertical burning tests. Although the results exhibited clear and consistent trends, the present study was limited to three replicate specimens per testing condition. These results confirmed that hybridization and appropriate filler selection can effectively tailor the multifunctional properties of natural fiber composites for indoor structural applications requiring moderate flame-retardant performance.

CRedit authorship contribution statement

Muhammad Rizal: Supervision, Funding acquisition, Conceptualization. **Nurdin Ali:** Formal analysis, Data curation. **Muhammad Haikal Khadafi:** Project administration. **Husni Usman:** Investigation. **Muhibul Jamal:** Investigation. **Fauzan Abdi:** Visualization.

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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References

- [1] R. Nabila, W. Hidayat, A. Haryanto, U. Hasanudin, D.A. Iryani, S. Lee, S. Kim, S. Kim, D. Chun, H. Choi, H. Im, J. Lim, K. Kim, D. Jun, J. Moon, J. Yoo, Oil palm biomass in Indonesia: thermochemical upgrading and its utilization, *Renew. Sustain. Energy Rev.* 176 (2023) 113193, <https://doi.org/10.1016/j.rser.2023.113193>.
- [2] S. Kraus, R. Heilmayr, N. Koch, Spillovers to manufacturing plants from multimillion dollar plantations: evidence from the Indonesian Palm Oil Boom, *J. Assoc. Environ. Resour. Econ.* 11 (2024) 613–656, <https://doi.org/10.1086/727196>.
- [3] T.A. Kurniawan, M. Ali, A. Mohyuddin, A. Haider, M.H.D. Othman, A. Anouzla, H. H. Goh, D. Zhang, W. Dai, F. Aziz, M.I. Khan, I. Ali, M. Mahmoud, S.A. A. Alkhadher, G.A. Alsultan, Innovative transformation of palm oil biomass waste into sustainable biofuel: Technological breakthroughs and future prospects, *Process. Saf. Environ. Prot.* 193 (2025) 643–664, <https://doi.org/10.1016/j.psep.2024.11.073>.
- [4] N.I.A.A. Nordin, H. Ariffin, Y. Andou, M.A. Hassan, Y. Shirai, H. Nishida, W.M.Z. W. Yunus, S. Karuppachamy, N.A. Ibrahim, Modification of oil palm mesocarp fiber characteristics using superheated steam treatment, *Molecules* 18 (2013) 9132–9146, <https://doi.org/10.3390/molecules18089132>.
- [5] M. Rizal, A.Z. Mubarak, T.R. Alhaidar, A Comparative Study of the Static and Dynamic Characteristics of Jute and Glass Fiber-Reinforced Polyester Composites, *Exp. Tech.* 48 (2023) 229–237, <https://doi.org/10.1007/s40799-023-00655-z>.
- [6] M. Ikbal, M. Rizal, N. Ali, T.E. Putra, Effect of Hybridization of Ramie Fibers on the Vibrational and Damping Responses of Ramie/Glass/Epoxy Resin Composite Laminates, *Key Eng. Mater.* 951 (2023) 65–71, <https://doi.org/10.4028/p-vhk2WE>.
- [7] J. Qureshi, A review of fibre reinforced polymer structures, *Fibers* 10 (2022) 27, <https://doi.org/10.3390/fib11050040>.
- [8] S. Waghmare, S. Shelare, K. Aglawe, P. Khope, A mini review on fibre reinforced polymer composites, *Mater. Today Proc.* 54 (2022) 682–689, <https://doi.org/10.1016/j.matpr.2021.10.379>.
- [9] M. Ramesh, C. Deepa, L.R. Kumar, M.R. Sanjay, S. Siengchin, Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: a critical review, *J. Ind. Text.* 51 (2022) 5518S–5542S, <https://doi.org/10.1177/1528083720924730>.
- [10] M. Ichim, E.I. Muresan, E. Codau, Natural-Fiber-reinforced polymer composites for furniture applications, *Polym. (Basel)* 16 (2024) 3113, <https://doi.org/10.3390/polym16223113>.
- [11] O.F. Olusunmade, D.A. Adetan, C.O. Ogunnigbo, A study on the mechanical properties of oil palm mesocarp fibre-reinforced, *J. Compos.* (2016) 3137243, <https://doi.org/10.1155/2016/3137243Research>.
- [12] P.W.M. Huisken, G. Tchémou, N.R.S. Tagne, D. Ndapeu, E. Njeugna, Effect of the addition of oil palm mesocarp fibers on the physical and mechanical properties of a

- polyester matrix composite, *Int. J. Polym. Sci.* 2022 (2022) 3399986, <https://doi.org/10.1155/2022/3399986>.
- [13] C.C. Eng, N.A. Ibrahim, N. Zainuddin, H. Ariffin, W.M.Z.W. Yunus, Impact strength and flexural properties enhancement of methacrylate silane treated oil palm mesocarp fiber reinforced biodegradable hybrid composites, *Sci. World J.* 2014 (2014) 1–8, <https://doi.org/10.1155/2014/213180>.
 - [14] V.K. Mahakur, S. Bhowmik, P.K. Patowari, S. Kumar, Effect of alkaline treatment on physical, mechanical, and thermal characteristics of jute filler reinforced epoxy composites, *J. Vinyl Addit. Technol.* 29 (2023) 330–342, <https://doi.org/10.1002/vnl.21963>.
 - [15] G.A. Jotiram, B.K. Palai, S. Bhattacharya, S. Aravindh, G. Gnanakumar, R. Subbiah, M. Chandrasu, Investigating mechanical strength of a natural fibre polymer composite using SiO₂ nano-filler, *Mater. Today Proc.* 56 (2022) 1522–1526, <https://doi.org/10.1016/j.matpr.2022.01.176>.
 - [16] G. Velmurugan, S.S. Kumar, J.S. Chohan, A.J.P. Kumar, T. Manikandan, D.E. Raja, K. Saranya, M. Nagaraj, P. Barmavatu, Experimental investigations of mechanical and dynamic mechanical analysis of bio-synthesized CuO/Ramie Fiber-Based Hybrid Biocomposite, *Fibers Polym.* 25 (2024) 587–606, <https://doi.org/10.1007/s12221-023-00432-0>.
 - [17] K.R. Sumesh, K. Kanthavel, Effect of TiO₂ nano-filler in mechanical and free vibration damping behavior of hybrid natural fiber composites, *J. Braz. Soc. Mech. Sci. Eng.* 42 (2020) 211, <https://doi.org/10.1007/s40430-020-02308-3>.
 - [18] Z. Masood, S. Ahmad, M. Umair, K. Shaker, Y. Nawab, M. Karahan, Mechanical behaviour of hybrid composites developed from textile waste, *Fibres Text. East. Eur.* 26 (2018) 46–52, <https://doi.org/10.5604/01.3001.0010.7796>.
 - [19] M.Y. Khalid, M.A. Nasir, A. Ali, A. Al Rashid, M.R. Khan, Experimental and numerical characterization of tensile property of jute/carbon fabric reinforced epoxy hybrid composites, *SN Appl. Sci.* 2 (2020) 1–10, <https://doi.org/10.1007/s42452-020-2403-2>.
 - [20] B.T. Wondmagegnehu, V. Paramasivam, S.K. Selvaraj, Fabricated and analyzed the mechanical properties of textile waste/glass fiber hybrid composite material, *Mater. Today Proc.* 46 (2021) 7297–7303, <https://doi.org/10.1016/j.matpr.2020.12.984>.
 - [21] B.I. Omer, Y.M. Ahmed, R.M. Abdalrahman, Impact of textile types and their hybrids on the mechanical properties and thermal insulation of mohair-reinforced polyester Composite laminates, *Results Mater.* 21 (2024) 100502, <https://doi.org/10.1016/j.rinma.2023.100502>.
 - [22] N. Fitriadi, M. Balkhaya, S. Rizal, Fonna, Physical and Thermal Characteristics of Coco Peat Fibre Reinforced Polyurethane Composite for Insulation Box in Marine Application, *J. Eng. Sci. Technol.* 17 (2022) 3787–3799.
 - [23] M. Rizal, N. Ali, H. Usman, M.L. Litusarfi, S. Kasim, Influence of Processing Techniques on the Performance of Outworn Denim Fabric-reinforced Polymer Composites, *J. Appl. Sci. Eng.* 30 (2026) 26030010, <https://doi.org/10.6180/jase.202607.30.010>.
 - [24] R.M.W.U. Khan, A.F.M. Seyam, M. Hussain, Y. Nawab, Valorizing denim and Polyethylene sheet waste to fiber-reinforced composites, *Polym. Compos.* 46 (2025) 12091–12111, <https://doi.org/10.1002/pc.29730>.
 - [25] M.R.M. Asyraf, M.R. Ishak, A. Syamsir, N.M. Nurazzi, F.A. Sabaruddin, S. Shazleen, M.N.F. Norrahim, M. Rafidah, R.A. Ilyas, M.Z.A. Rashid, M. R. Razman, Mechanical properties of oil palm fibre-reinforced polymer composites: a review, *J. Mater. Res. Technol.* 17 (2022) 33–65, <https://doi.org/10.1016/j.jmrt.2021.12.122>.
 - [26] J.T. Lee, M.W. Kim, Y.S. Song, T.J. Kang, J.R. Youn, Mechanical properties of denim fabric reinforced poly(lactic acid), *Fibers Polym.* 11 (2010) 60–66, <https://doi.org/10.1007/s12221-010-0060-6>.
 - [27] G. Mouna, J. Boubaker, S. Faouzi, Effect of Friction Parameters on the Residual Bagging Behavior of Denim Fabrics, *Int. J. Appl. Res. Text.* 3 (2015) 32–43.
 - [28] Y.T. Bozkurt, M. Bulut, A. Erklği, Ö. Özbeke, SiO₂ nanoparticle modified CFRP composites effecting on mechanical and vibration damping properties, *Polym. Compos.* 45 (2024) 169–180, <https://doi.org/10.1002/pc.27766>.
 - [29] Y. Li, Y. Lin, K. Sha, R. Xiao, Preparation and characterizations of flame retardant melamine cyanurate/polyamide 6 composite fibers via in situ polymerization, *Text. Res. J.* 87 (2017) 561–569, <https://doi.org/10.1177/0040517516632478>.
 - [30] ASTM D790, Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, ASTM International, West Conshohocken, 2010.
 - [31] ASTM E2954, Standard Test Method for Axial Compression Test of Reinforced Plastic and Polymer Matrix Composite Vertical Members, ASTM International, West Conshohocken, 2022.
 - [32] B. Baghaei, B. Johansson, M. Skrifvars, N. Kadi, All-Cellulose Composites Properties from Pre-and Post-Consumer Denim Wastes: Comparative Study, *J. Compos. Sci.* 6 (2022) 130, <https://doi.org/10.3390/JCS6050130>.
 - [33] B.R. Gautam, N.I. Khan, S. Kumar, Study of hardness, density, water absorption, tensile, and thermal properties of epoxy composite reinforced with functionalized nano-silica, *J. Eng. Appl. Sci.* 72 (2025) 175, <https://doi.org/10.1186/s44147-025-00732-7>.
 - [34] A. Šehić, J. Vasiljević, A. Demšar, M. Leskovšek, V. Bukošek, J. Medved, M. Colović, I. Jerman, B. Simončić, Polyamide 6 composite fibers with incorporated mixtures of melamine cyanurate, carbon nanotubes, and carbon black, *J. Appl. Polym. Sci.* 136 (2019) 47007, <https://doi.org/10.1002/app.47007>.
 - [35] H. Huang, K. Zhang, J. Jiang, J. Li, Y. Liu, Highly dispersed melamine cyanurate flame-retardant epoxy resin composites, *Polym. Int.* 66 (2016) 85–91, <https://doi.org/10.1002/pi.5244>.
 - [36] X.-J. Li, C. Liu, C.-Y. Zhang, Z.-B. Shao, B. Zhao, Self-assembly of triazoly-based cyclomatrix polyphosphazene and melamine cyanurate for flame-retardant, smoke-suppressing, and mechanically robust epoxy resin, *Polym. Degrad. Stab.* 235 (2025) 111268, <https://doi.org/10.1016/j.polymdegradstab.2025.111268>.
 - [37] Y. Tian, H. Zhang, Z. Zhang, Influence of nanoparticles on the interfacial properties of fiber-reinforced-epoxy composites, *Compos. Part. A* 98 (2017) 1–8, <https://doi.org/10.1016/j.compositesa.2017.03.007>.
 - [38] S.K. Singh, A. Kumar, A. Jain, Improving tensile and flexural properties of SiO₂-epoxy polymer nanocomposite, *Mater. Today Proc.* 5 (2018) 6339–6344, <https://doi.org/10.1016/j.matpr.2017.12.243>.
 - [39] W.K.P. Lim, M. Mariatti, W.S. Chow, K.T. Mar, Effect of intumescent ammonium polyphosphate (APP) and melamine cyanurate (MC) on the properties of epoxy/glass fiber composites, *Compos. Part. B Eng.* 43 (2012) 124–128, <https://doi.org/10.1016/j.compositesb.2011.11.013>.
 - [40] M.J. Avnani, A.A.A. Jeddi, A. Rastgoo, Theoretical Estimation of Initial Uniaxial Tensile Modulus in 2/2 Twill Woven Structures, *Fibers Polym.* 15 (2014) 1992–2000, <https://doi.org/10.1007/s12221-014-1992-z>.
 - [41] F. Stig, S. Hallström, Effects of Crimp and Textile Architecture on the Stiffness and Strength of Composites with 3D Reinforcement, *Adv. Mater. Sci. Eng.* 2019 (2019) 8439530.
 - [42] J. Zhou, C. Chen, S. Zhang, T. Zhong, Q. Xu, Z. Su, M. Jiang, Enhancing the interfacial adhesion between continuous basalt fibers and epoxy resin by depositing silicon dioxide nanoparticles, *J. Ind. Text.* 51 (2022) 3309–3329, <https://doi.org/10.1177/15280837221099661>.
 - [43] T. Sathish, R. Saravanan, S.J. Arunachalam, Glass fiber influence on PP/Sisal/SiO₂ nanofillers/glass hybrid nanocomposites/plain nanocomposite for mechanical property improvement, *Interactions* 246 (2025) 25, <https://doi.org/10.1007/s10751-025-02252-5>.
 - [44] I.R. Chowdhury, J. Summerscales, Woven Fabrics for Composite Reinforcement: A Review (<https://doi.org/>), *J. Compos. Sci.* 8 (2024) 280, <https://doi.org/10.3390/jcs8070280>.
 - [45] R.K. Sinha, K. Sridhar, R. Purohit, R.K. Malviya, Effect of nano SiO₂ on properties of natural fiber reinforced epoxy hybrid composite: A review, *Mater. Today Proc.* 26 (2020) 3183–3186, <https://doi.org/10.1016/j.matpr.2020.02.657>.
 - [46] B. Suresha, G.S. Divya, G. Hemanth, H.M. Somashekar, Physico-Mechanical Properties of Nano Silica-Filled Epoxy-Based Mono and Hybrid Composites for Structural Applications, *Silicon* 13 (2020) 2319–2335, <https://doi.org/10.1007/s12633-020-00812-8>.
 - [47] L. Fang, X. Lu, J. Zeng, Y. Chen, Q. Tang, Investigation of the Flame-Retardant and Mechanical Properties of Bamboo Fiber-Reinforced Polypropylene Composites with Melamine Pyrophosphate and Aluminum, *Mater. (Basel)* 13 (2020) 479, <https://doi.org/10.3390/ma13020479>.
 - [48] M.N. Arshad, H. Mohit, M.R. Sanjay, S. Siengchin, A. Khan, M.M. Alotaibi, A. M. Asiri, M.A. Rub, Effect of coir fiber and TiC nanoparticles on basalt fiber reinforced epoxy hybrid composites: physico – mechanical characteristics, *Cellulose* 28 (2021) 3451–3471, <https://doi.org/10.1007/s10570-021-03752-7>.
 - [49] V.U. Siddiqui, S.M. Sapuan, M.R. Hassan, Innovative dispersion techniques of graphene nanoplatelets (GNPs) through mechanical stirring and ultrasonication: Impact on morphological, mechanical, and thermal properties of epoxy nanocomposites, *Def. Technol.* 43 (2025) 13–25, <https://doi.org/10.1016/j.dt.2024.04.018>.
 - [50] K.S. Kumar, I. Siva, P. Jeyaraj, J.T.W. Jappes, S.C. Amico, N. Rajini, Synergy of fiber length and content on free vibration and damping behavior of natural fiber reinforced polyester composite beams, *Mater. Des.* 56 (2014) 379–386, <https://doi.org/10.1016/j.matdes.2013.11.039>.
 - [51] L. Lu, W. Fan, X. Meng, T. Liu, L. Han, T. Zhang, J. Dong, L. Yuan, H. Tian, Modal analysis of 3D needled waste cotton fiber/epoxy composites with experimental and numerical methods, *Text. Res. J.* 91 (2021) 358–372, <https://doi.org/10.1177/0040517520944477>.
 - [52] Z. Muřinková, P. Postawa, J. Winczek, Parameters influence on the dynamic properties of polymer-matrix composites reinforced by fibres, particles, and hybrids, *Polym. (Basel)* 14 (2022) 3060.
 - [53] T. Liu, P. Butaud, V. Placet, M. Ouisse, Damping behavior of plant fiber composites: a review, *Compos. Struct.* 275 (2021) 114392, <https://doi.org/10.1016/j.compstruct.2021.114392>.
 - [54] A.C. Kandemir, Mechanical Characterization of Polymer Nanocomposite Films: Influence of Force Regimes and Nano Silica Reinforcement, *Polym. Compos.* 46 (2025) 14447–14460, <https://doi.org/10.1002/pc.30072>.
 - [55] S. Thenmozhi, Investigation on mechanical, thermal, and flame retardant properties of particulate SiO₂ reinforced cardanol based composites, *Polym. Compos.* 41 (2020) 1118–1134, <https://doi.org/10.1002/pc.25443>.
 - [56] X. Wu, X. Zhang, H. Jiang, X. Li, X. Su, M. Zhen, J. Shang, M. Zou, Thermal degradation, flame retardance and mechanical properties of polyurethane composite elastomers based on expandable graphite/aluminum hypophosphite/melamine cyanurate, *Thermochim. Acta* 751 (2025) 180057, <https://doi.org/10.1016/j.tca.2025.180057>.