



Influence of Bio-extracted *Thespesia populnea* Fiber and Waste-derived CaO Nanoparticles on the Mechanical and Thermal Properties of Epoxy Composites

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Received: 13.05.2026 Accepted: 30.05.2026 Published: 30.06.2026

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ABSTRACT

Bio composite materials had gained significant attention in recent years because of their sustainability, lightweight nature, and favorable strength-to-weight characteristics. In the present study, epoxy-based composites reinforced with bio-extracted *Thespesia populnea* fiber and tuber waste-derived calcium oxide nanoparticles were developed using hand layup technique. The fabricated composites were evaluated for their mechanical and thermal performance in accordance with ASTM standards. Among the developed samples, the ETC2 composite containing 40 vol.% fiber and 4 vol.% CaO nanoparticles, exhibited superior mechanical properties with tensile, flexural, compressive and impact strengths of 139 MPa, 166 MPa, 151 MPa, and 6.5 J, respectively. The enhanced performance is attributed to improved efficient stress transfer and interfacial bonding among matrix, fiber and nanoparticles. Furthermore, ETC3 composite (6 vol.% CaO) showed the highest thermal stability with decomposition temperature of 382 °C and the lowest thermal conductivity of 0.26 W/m⁻¹K⁻¹, indicating its excellent thermal insulation capability. The progressive improvement in thermal behavior with increasing CaO content is associated with enhanced phonon scattering, increased interfacial thermal resistance, and disruption of heat conduction pathways within the matrix. Morphological analysis using scanning electron microscopy confirmed improved filler–matrix interaction and dispersion characteristics, which directly influenced the mechanical and thermal performance of the composites. The developed biocomposites exhibit strong potential for applications in automotive, aerospace, defense, sports, and thermal insulation systems.

Keywords: Phonon scattering; Thermal behavior; Stress transfer; Heat conductivity; Mechanical properties.

1. INTRODUCTION

The increasing environmental concerns associated with petroleum-based plastics and non-biodegradable materials have accelerated the development of sustainable and biodegradable composite systems for engineering and biomedical applications (Gupta *et al.* 2026). Natural plant-derived materials and green synthesized nanoparticles have attracted significant attention due to their eco-friendly nature, renewability, biocompatibility, and multifunctional performance characteristics (Krishnasamy *et al.* 2025). Among various bioresources, *Thespesia populnea* has emerged as a promising natural source for the synthesis of advanced functional materials because of its rich phytochemical composition and excellent biological

activities. *Thespesia populnea* extract-coated nano-zirconium particles deposited on cotton gauze fabrics exhibited strong antibacterial activity, demonstrating their suitability for antimicrobial wound dressing applications (Whangchai *et al.* 2023). Silver nanoparticles synthesized using *Thespesia populnea* bark extract showed excellent photocatalytic degradation of methylene blue along with remarkable antimicrobial performance (Yahya *et al.* 2022). Bioplasticizers developed from *Thespesia populnea* leaf powder demonstrated good crystallinity and thermal stability, highlighting their suitability for sustainable polymer and composite applications (Senthamaraikannan *et al.* 2025).

Fe-doped ZnO nanoparticles synthesized using *Thespesia populnea* flower extract exhibited reduced

band gap energy and enhanced biomedical interaction characteristics (Muhideen *et al.* 2021). Silver nanoparticles fabricated from *Thespesia populnea* fruit extract possessed strong antioxidant, antimicrobial, anti-inflammatory, and antidiabetic activities (Archana *et al.* 2026). Silver and gold nanoparticles synthesized using *Thespesia populnea* seed-kernel extract demonstrated high colloidal stability, strong antibacterial activity, and efficient catalytic reduction performance (George *et al.* 2025a). Silver nanoparticles synthesized from *Thespesia populnea* seed-kernel extract were also successfully utilized for selective colorimetric detection of gold ions with excellent sensitivity and stability (George *et al.* 2025b).

Green synthesized ZnO nanoparticles from *Thespesia populnea* leaf extract showed strong antibacterial and antibiofilm activity against multidrug-resistant pathogens (Kurien *et al.* 2025). Silver nanoparticles synthesized using *Thespesia populnea* leaf extract demonstrated potent antibacterial activity (Divya *et al.* 2020). Ag₂O, ZrO₂, and ZrO₂-Ag₂O nanocomposites synthesized using *Thespesia populnea* leaf extract exhibited excellent corrosion inhibition efficiency for dental alloy protection (Indumathy *et al.* 2026). Linezolid-conjugated silver nanoparticles synthesized from *Thespesia populnea* leaf extract showed antimicrobial performance against multidrug-resistant microorganisms (Puttaraju *et al.* 2025).

Biodegradable starch-based materials have also gained considerable importance for sustainable packaging applications. Pulsed electric field-modified elephant foot yam starch films exhibited enhanced tensile strength and moisture resistance suitable for biodegradable packaging systems (Singh *et al.* 2023). Elephant foot yam starch films reinforced with nanocrystal cellulose demonstrated improved crystallinity, mechanical strength, and biodegradability (Radiani *et al.* 2023). A pH-sensitive intelligent packaging film based on elephant foot yam starch exhibited effective freshness monitoring capability along with antimicrobial and antioxidant properties (Prakruthi *et al.* 2026a).

Sustainable geopolymer and low-carbon construction materials have received substantial attention due to their reduced environmental impact and improved durability performance. Geopolymer mortars containing slag, fly ash, and palm oil fuel ash showed improved compressive strength and dense microstructural characteristics at higher slag contents (Huseien *et al.* 2023). Coir fibre ash utilized as a sustainable replacement material enhanced compressive strength while reducing embodied carbon at optimum incorporation levels (Zada *et al.* 2025). Low-carbon concrete developed using recycled ceramic waste glass powder achieved improved durability and reduced carbon dioxide emissions (Hashim *et al.* 2025).

MgO-CaO composites reinforced using carbon nanofibers exhibited improved densification and flexural strength owing to reduced surface defects and effective reinforcement mechanisms (Shahraki *et al.* 2024). Reactive MgO-modified alkali-activated slag systems demonstrated enhanced compressive strength and chloride resistance through MgAl-layered double hydroxide formation (Zhou *et al.* 2025). MoO₃-doped SiO₂-CaO-P₂O₅ glass-ceramics exhibited improved fracture toughness, hydrophilicity, and hydroxyapatite formation suitable for regenerative medicine applications (Ali *et al.* 2024).

The novelty of this study lies in the integration of agro-waste-derived calcium oxide (CaO) nanoparticles with *Thespesia populnea* fiber in an epoxy matrix, enabling the simultaneous enhancement of mechanical strength and thermal insulation performance. Unlike conventional natural fiber composites, this work demonstrates a balanced optimization between load-bearing capability and thermal resistance through controlled nanoparticle loading, providing a sustainable and high-performance alternative for multifunctional engineering applications.

2. MATERIALS AND METHODOLOGY

2.1 Materials Used

Epoxy resin employed in this study was LY556 characterized by a viscosity of 100 cP and a density of 1.18 g/cm³. Curing of the resin was carried out using HY951- hardener with a density of 0.97 g/cm³. The epoxy resin and hardener were procured from Kovai Cheenu Enterprises, located in Coimbatore, Tamil Nadu, India. The reinforcement was provided in the form of *Thespesia populnea* fiber mats supplied by Fiber Source Enterprises, Chennai, India. Calcium oxide nanoparticles used as filler reinforcement, were synthesized from elephant foot yam peel as an agro-waste precursor by a controlled thermo-chemical route involving HCl and NaOH, procured from Star Scientific Enterprises, Erode, Tamil Nadu, India.

2.2 Synthesis of Calcium Oxide (CaO) Nanoparticles from Elephant Foot Yam Peel

Calcium oxide nanoparticles were synthesized from elephant foot yam peel through a controlled thermo-chemical route (Fig. 1). Initially, fresh elephant foot yam peels were collected from local agro-waste sources and thoroughly washed with distilled water to remove soil particles and impurities. The cleaned biomass was then dried in hot air oven at 105–120 °C for 2 hours to eliminate residual moisture (Zia *et al.* 2025).

The dried peels were mechanically ground into fine particles and subjected to thermal treatment in a muffle furnace at 500 °C for 3 hours to obtain mineral-

rich ash containing calcium compounds (primarily CaCO_3). The obtained ash was treated with 1 M HCl under continuous stirring to extract calcium ions into solution. The resulting mixture was filtered to remove insoluble residues, yielding a clear calcium-rich filtrate.

Subsequently, 1 M NaOH solution was added dropwise to the filtrate under constant stirring (until an alkaline pH was achieved), which resulted in the formation of calcium hydroxide precipitate. The

precipitate was aged at room temperature for 12–24 hours to ensure complete nucleation and growth.

The obtained precipitate was then washed repeatedly with distilled water until neutral pH and dried at 100 °C for 2 h. The dried material was calcined at 700–800 °C for 2 hours to convert Ca(OH)_2 into CaO nanoparticles. The final product was collected as fine white CaO nanopowder and stored in an airtight container to prevent moisture-induced degradation.

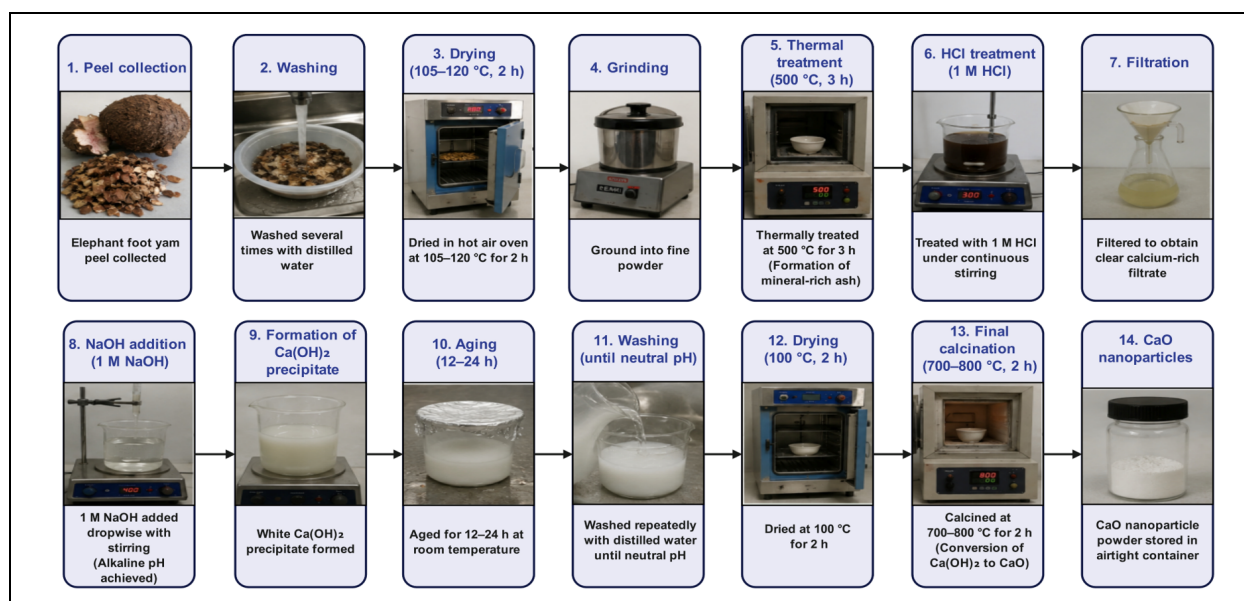


Fig. 1 Synthesis process of CaO nanoparticles derived from elephant foot yam peel waste

The crystallographic phase and structural characteristics of the prepared filler particles were investigated using X-ray diffraction (XRD) for detailed analysis of their behavior (Fig. 2).

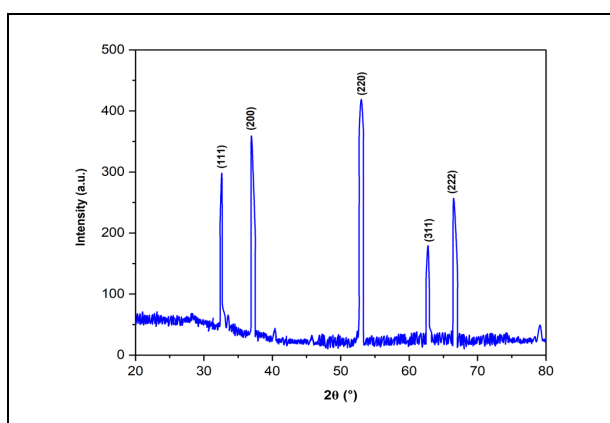


Fig. 2: XRD plot of calcium oxide nanoparticles

The diffraction peaks observed at 32.2°, 37.4°, 53.9°, 64.2°, and 67.3° correspond to the crystalline cubic phase of CaO nanoparticles, confirming the successful synthesis with good crystallinity. The purity of the synthesized calcium oxide particles was determined

using a chemical titration method, yielding a value of 97.1%. The XRD analysis indicated a highly crystalline cubic CaO structure, characterized by broad peaks and the presence of multiple minor diffraction features with a calculated crystallinity index of 41.7%.

2.3 Preparation of Composites

Epoxy-based composites with *Thespesia populnea* and CaO NPs were developed through a hand layup fabrication technique (Barve *et al.* 2025). Prior to composite fabrication, mold surfaces were carefully cleaned, dried and coated with suitable release agent to enable smooth demolding. Epoxy resin system was prepared by blending the resin and hardener in 10:1 weight ratio. Subsequently, CaO nanoparticles were introduced into the resin matrix and dispersed using magnetic stirring to achieve uniform distribution.

The nanoparticle-modified resin was then cast into the prepared mold, over which a layer of *Thespesia populnea* fiber mat was placed. Additional layers of CaO-filled resin were applied sequentially, followed by fiber placement to build a multilayered structure. This stacking sequence was repeated until the laminate thickness reached approximately 3 mm. The fabricated laminates

were initially allowed to cure at ambient conditions to promote cross-linking, followed by post-curing (130 °C) to ensure polymerization and enhanced structural stability. The composition details of the developed composites including fiber and filler proportions along with sample designations are summarized in Table 1.

Table 1. Composition of epoxy-based composites reinforced with natural fiber and varying concentrations of filler nanoparticles

Sample Code	Polymer Matrix Fraction (Vol. %)	Fiber Reinforcement (Vol. %)	Nanofiller Loading (Vol. %)
E	100	–	–
ET0	60	40	–
ETC1	58	40	2
ETC2	56	40	4
ETC3	54	40	6

2.4 Characterization

The fabricated composites were trimmed to required dimensions in accordance with relevant ASTM specifications by the use of CNC Aqua Jet cutting machine. To assess their qualities, samples were subjected to a series of mechanical and physical testing. Fig. 3 shows the ASTM standard specimens. Thermal and mechanical performance of the fabricated composites were compared with the appropriate ASTM standards. The flexural and tensile properties were measured according to ASTM D790 and D3039 standards by an INSTRON 5969 Universal Testing Machine. In tensile testing, elongation and tensile strength characteristics were determined by subjecting the specimens to uniaxial loading until failure. Flexural behavior was measured by a three point bending set up where the specimen was held at two points and loaded at the center. Each condition had five samples tested to enhance repeatability and statistical reliability. The composites were measured as per ASTM D256 by QC-639 impact testing machine. The standard V-notched specimens with a width of 12.7 mm were placed on the apparatus and the pendulum was released at predetermined height. The amount of energy absorbed during fracture was measured and used to measure the impact strength. Surface hardness was measured based on the ASTM D2240 with the help of a Shore-D hardness tester. To reduce contribution of local variation, multiple indentations were made at ten various locations on all specimens, and the average hardness value was reported. The compressive properties were determined according to ASTM D695 using compression testing machine. Progressively increasing compressive loads until failure were applied to sample, and resultant modulus and compressive strength were calculated. The measurements of thermal conductivity were conducted in accordance with ASTM D3850 with the help of disk method developed by Lee. Circular specimens of 50 mm

were tested and their thermal conductivity was evaluated. Five specimens were analyzed in order to afford uniformity in the findings.

Thermogravimetric analysis (TGA) was performed in accordance with ASTM standards under an inert gas atmosphere using a PerkinElmer TGA 8000 thermogravimetric analyzer. The samples were heated from ambient temperature to 800 °C at a constant heating rate of 10 °C/min in alumina crucibles. This procedure was employed to evaluate the thermal stability, degradation profile, and mass loss behavior of the developed composite materials.

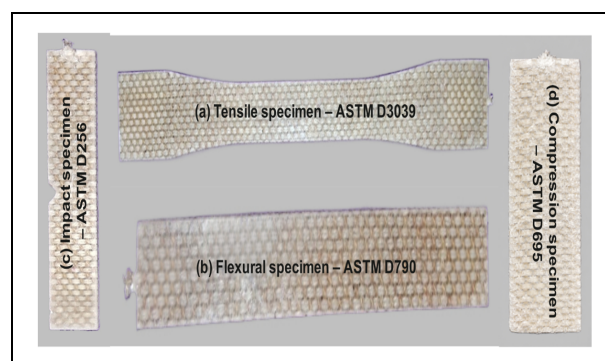


Fig. 3: ASTM-standard specimens for mechanical and thermal testing

3. RESULTS AND DISCUSSION

3.1 Mechanical Characteristics

Fig. 4 presents the mechanical performance of the fabricated composites. The combined incorporation of *Thespesia populnea* fiber and calcium oxide (CaO) nanoparticles results in a marked improvement in the mechanical strength of the epoxy matrix when compared to the neat epoxy.

The ETC3 composite showed slight decrease in performance, which could be explained by agglomeration of nanoparticles. Neat epoxy specimen had a relatively low tensile strength of 52 MPa because of its intrinsic brittle nature. The addition of 40 vol.% *Thespesia populnea* fiber in ET0 composite significantly increased the tensile strength to 108 MPa, which is about 116% increase. This has been mainly attributed to the good load bearing capacity and reinforcement efficiency of the natural fibers.

Additional improvement in tensile properties was made through the addition of calcium oxide nanoparticles. The tensile strength of ETC1 composite (2 vol.% CaO) was 121 MPa, and that of ETC2 (4 vol.% CaO) was 139 MPa. It is believed that the observed improvement occurs due to enhanced interfacial adhesion and effective stress transfer among matrix and reinforcement due to uniform dispersion of

nanoparticles. But, on further loading of 6 vol.% CaO (ETC3), the agglomeration of particles took place, which resulted in the appearance of regions of stress concentration in the matrix. This led to a small decrease in tensile strength to 131 MPa, and emphasized the crucial role of optimal nanoparticle dispersion in the achievement of excellent mechanical performance. A prior study states that the incorporation of *Bougainvillea glabra* extract significantly improved the tensile performance of the (dual-modified elephant foot yam starch) MEFYS–PVA blend films, owing to enhanced intermolecular hydrogen bonding within the polymer matrix. Among all formulations, the BGE6/MEFYS–PVA film exhibited the highest tensile strength of 16.72 MPa, indicating improved mechanical flexibility and structural stability (Prakruthi *et al.* 2026b).

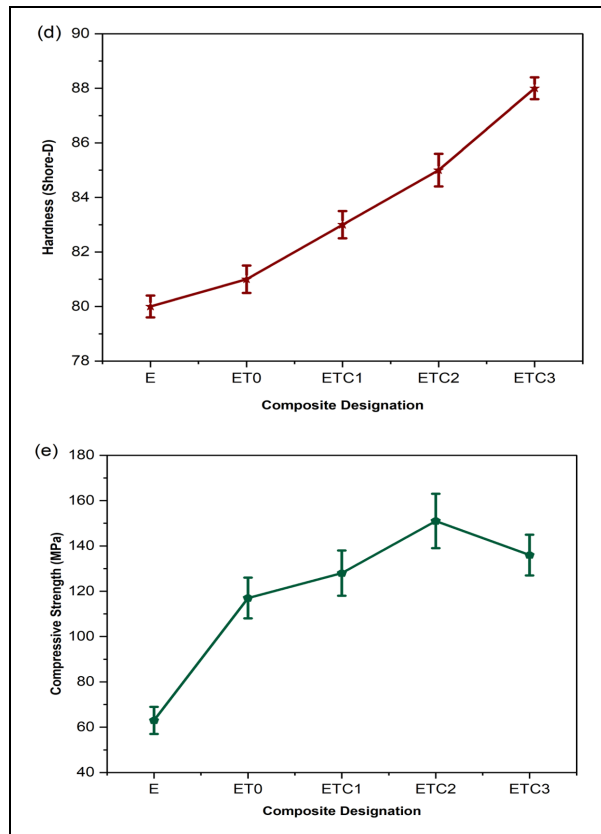
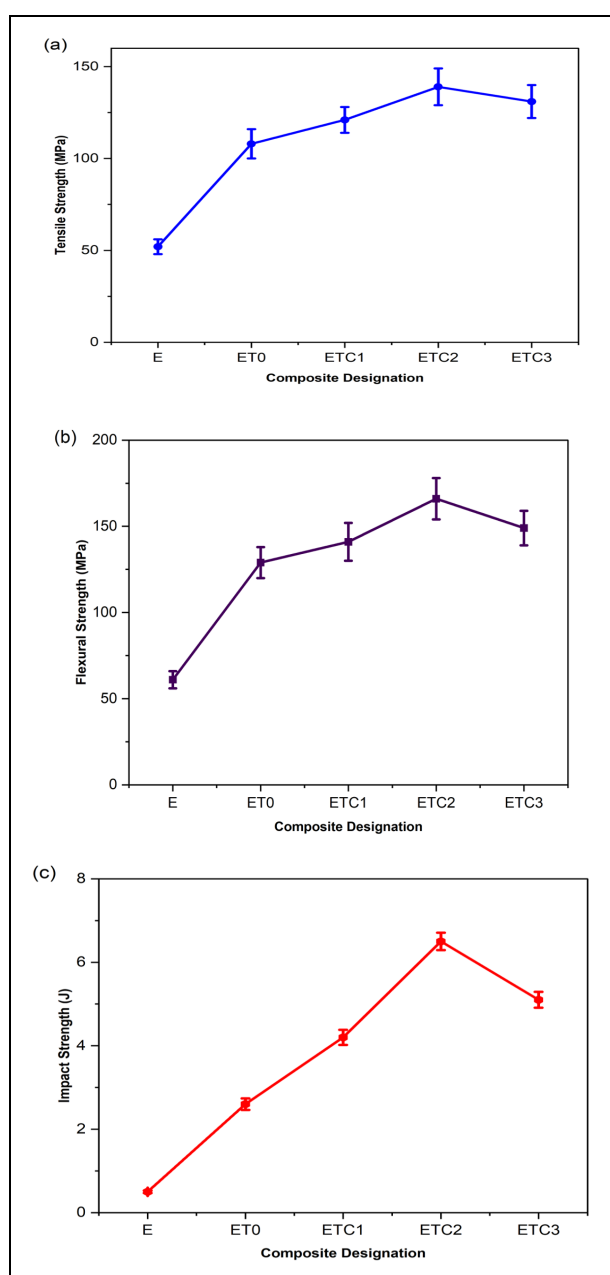


Fig. 4: Mechanical characteristics of various composite samples

The flexural behavior of the developed composites shows a clear enhancement with the addition of reinforcement and filler phases. The neat epoxy had a relatively low flexural strength of 61 MPa because of its brittle nature and low resistance to bending forces. Adding 40 vol.% of *Thespesia populnea* fiber to the ET0 composite resulted in a significant enhancement in flexural strength to 129 MPa which equates to an improvement of about 117%. This has been made possible by the fact that the fiber has a high level of stiffness and load carrying capacity, which effectively resists bending deformation and reinforces the matrix.

Further improvement was noted when CaO nanoparticles were added. Flexural strength of ETC1 composite (2 vol.% CaO) was 141 MPa, whereas ETC2 (4 vol.% CaO) reached the maximum value of 166 MPa. This enhancement is mainly because of increased interfacial adhesion and effective transfer of stress caused by uniform distribution of nanoparticles in epoxy matrix. But as filler loading increased (6 vol.% CaO in ETC3), flexural strength dropped to slightly lower levels of 149 MPa. This decrease is explained by agglomeration of nanoparticles, resulting in non-uniform distribution of stress and weak interfacial areas, thus impairing the bending performance. According to a prior research, the incorporation of 1.5% CaO-treated sisal fiber (SF) significantly enhanced the flexural performance due to

improved crack-bridging and load-transfer mechanisms within the matrix. The optimum SF content achieved an 88.83% increase in flexural strength demonstrating its suitability for sustainable structural applications (Muñoz *et al.* 2025).

The same trend was followed in compressive strength. The neat epoxy had a compressive strength of 63 MPa and the ET0 composite had a significant increase in compressive strength of 117 MPa (102% improvement). CaO nanoparticles further enhanced the compressive property of ETC1 and ETC2 to 128 MPa and 151 MPa, respectively. The highest improvement (141%) recorded in ETC2 can be explained by the increased densification of the matrix and the enhanced transfer of stress between the constituents. Nevertheless, nanoparticle clustering caused slight reduction of ETC3 to 136 MPa as this process disrupts uniform distribution of loads in the composite structure. A literature study demonstrated that the incorporation of snail shell powder enhanced the compressive strength due to its high CaO content (59.8%), which promoted dense microstructure formation and reduced voids and cracks (Rahman *et al.* 2025).

Impact resistance showed a significant increase in reinforcement. The clean epoxy specimen reflected extremely low impact strength (0.5 J), which means that the specimen has a low ability to absorb energy. The ET0 composite showed a significant boost to 2.6 J as a result of the capacity of natural fibers to dissipate and absorb impact energy through mechanisms like crack deflection and fiber pull-out. The addition of CaO nanoparticles also increased the impact strength of ETC1 and ETC2 to 4.2 J and 6.5 J, respectively. This improvement can be accredited to an increase in the energy dissipated and the enhancement of interfacial bonding. But, the impact strength of ETC3 was slightly reduced to 5.1 J as a result of agglomeration-induced defects, which are sources of crack initiation and are less efficient energy absorbers.

Measurement of hardness indicated that there was gradual increase with the addition of reinforcement and filler. The neat epoxy had a Shore-D hardness of 80, while ET0 exhibited a value of 81 due to the hardening effect of *Thespesia populnea* fibers. The hardness also increased to 83, 85, and 88 with the addition of CaO nanoparticles to ETC1, ETC2 and ETC3, respectively. This is due to the fact that CaO nanoparticles are characterized by the inherent rigidity of the material that contributes to the resistance of the composite surface to localized deformation. Contrary to other mechanical properties, hardness was found to progressively increase with filler content as a result of the localized reinforcing effect of the nanoparticles.

Fig. 5 presents the SEM images of fractured epoxy composites reinforced with *Thespesia populnea* fiber and varying concentrations of CaO nanoparticles,

illustrating the effect of nanoparticle dispersion and interfacial interaction on the composite morphology.

Fig. 5(a) corresponding to the ETC1 composite (2 vol.% CaO), shows moderate dispersion of CaO nanoparticles within the epoxy matrix along with a few microvoids and uneven surface regions. Certain localized interfacial gaps can be observed between the matrix and reinforcement phase, indicating incomplete stress transfer efficiency. The fractured morphology suggests that the incorporation of CaO nanoparticles improved the structural rigidity of the composite. However, the filler distribution was not completely homogeneous.

Fig. 5(b) representing the ETC2 composite (4 vol.% CaO) exhibits relatively uniform nanoparticle distribution and compact interfacial morphology with reduced void content. The reinforcement phase appears well embedded within the epoxy matrix, indicating improved interfacial adhesion and efficient stress transfer characteristics. The comparatively smoother and denser fractured surface confirms enhanced matrix–filler compatibility, which contributed to the superior mechanical performance of the ETC2 composite.

Fig. 5(c) corresponding to the ETC3 composite (6 vol.% CaO) reveals the formation of nanoparticle agglomeration regions and irregular clustered structures within the matrix. These agglomerated particles generated localized stress concentration sites and microstructural discontinuities. The presence of clustered filler regions and localized microcracks indicates deterioration in nanoparticle dispersion at higher filler loading, which slightly reduced the mechanical properties compared with the optimally reinforced ETC2 composite.

Thus, the SEM observations demonstrate that uniform CaO nanoparticle dispersion and improved matrix–fiber interfacial interaction play a critical role in enhancing the structural integrity and mechanical behavior of the developed composites.

3.2 Thermal Conductivity

Fig. 6(a) shows the change in the thermal conductivity (TC) of the fabricated composites. The maximum TC of $0.46 \text{ W/m}^{\circ}\text{K}^{-1}$ was found in neat epoxy specimen and this could be attributed to the continuous and homogeneous polymer network that allows effective heat transfer.

The TC of EC0 dropped to $0.39 \text{ W/m}^{\circ}\text{K}^{-1}$ or about 15.2% lower. This reduction is attributed to the low thermal conductivity of natural fibers and the presence of interfacial boundaries within the composite, which disrupt phonon transport and impede heat flow.

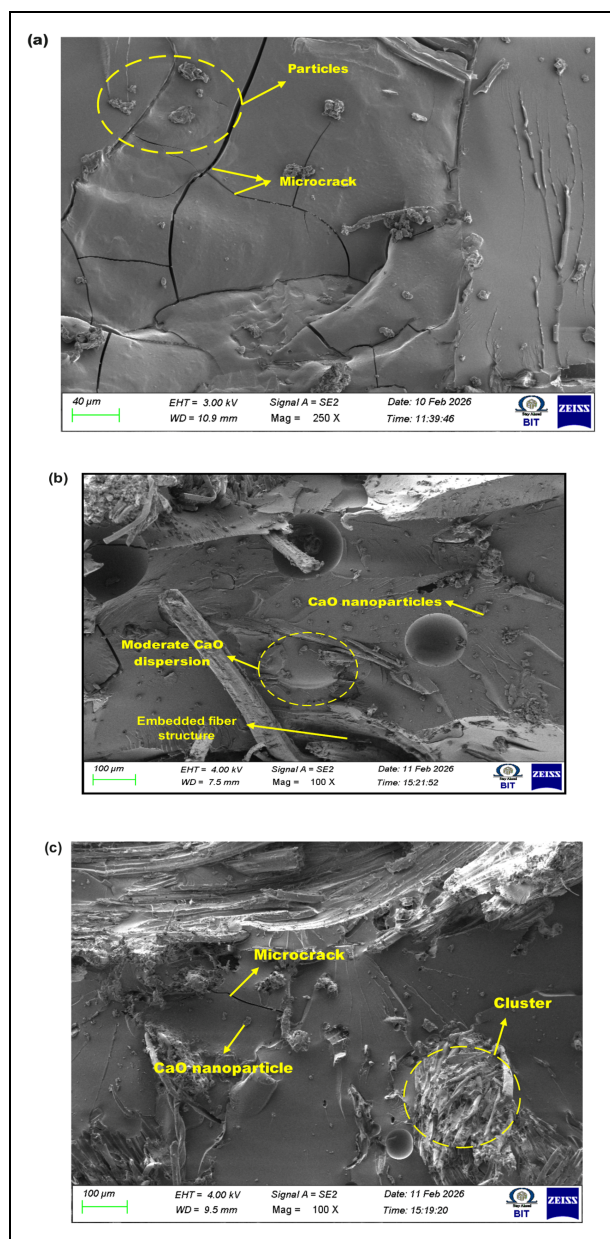


Fig. 5: SEM micrographs of (a) ETC1, (b) ETC2 and (c) ETC3 composite specimens

Fiber-matrix interfaces are known to enhance thermal resistance by scattering heat carriers and thereby reduces the overall capability of the composite to transfer heat. Moreover, the porous and lignocellulosic structure of *Thespesia populnea* fiber helps increase the thermal insulation property. This shows that the infusion of natural fiber is actually effective in converting the epoxy matrix into more thermally resistant system.

The decrease in thermal conductivity of ETO can be explained by the fact, that *Thespesia populnea* fiber has an intrinsically low thermal conductivity, which interferes with the continuity of the epoxy matrix, and hinders heat transfer. The formation of lignocellulosic fibers adds more interfaces that scatter the heat carriers,

thus increasing the overall thermal resistance of composite.

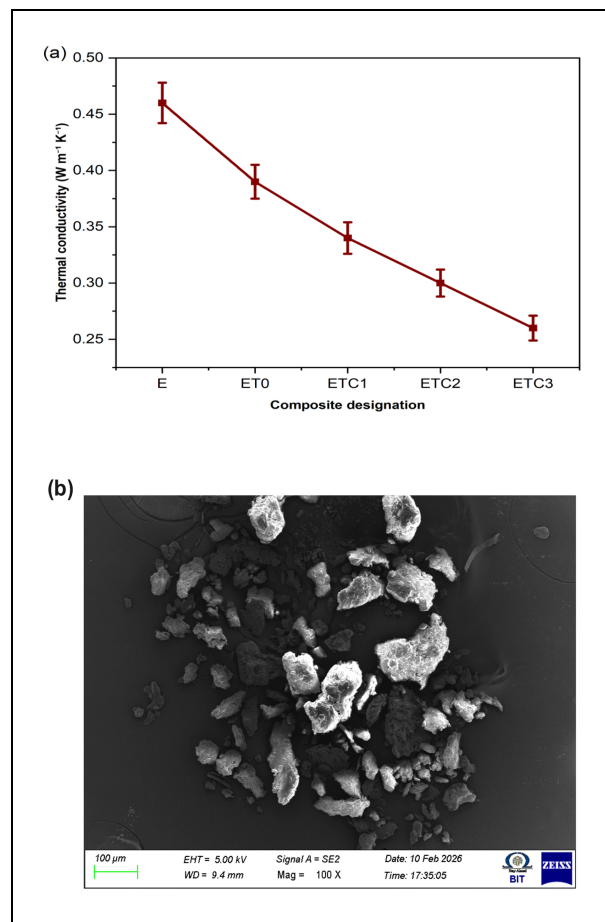


Fig. 6: (a) Thermal conductivity behavior and (b) nanoparticle dispersion

The decrease in thermal conductivity was observed with incorporation of CaO nanoparticles. The composite ETC1 (2 vol.% CaO) had a TC of $0.34 W m^{-1} K^{-1}$, which was 26.1% less relative to neat epoxy. In ETC2 (4 vol.% CaO), a further reduction (34.8%) in TC ($0.30 W m^{-1} K^{-1}$) was noted. This progressive deterioration is mainly caused by the increasing phonon scattering and the creation of new thermal resistance at the nanoparticle-matrix interfaces.

The thermal conductivity was lowest at a higher loading of 6 vol.% CaO (ETC3) with a minimum TC of $0.26 W m^{-1} K^{-1}$ (43.5% lower than the neat epoxy). The ceramic nature of CaO nanoparticles, coupled with their uniform distribution disrupts the pathways of heat conduction and inhibits the transfer of vibrational energy across the polymer chains. Moreover, a thick filler-matrix network enhances the interfacial thermal resistance, thus restricting the heat flow.

This behavior is supported by the FESEM micrograph (Fig. 6(b)) which reveals a well-distributed network of particles that effectively blocks heat transfer

routes. A combination of fiber reinforcement and the addition of CaO nanoparticle to the epoxy matrix changes the epoxy matrix into a thermally insulating system. As a result, the developed composites have a high potential of application in areas that need low thermal conductivity like thermal insulation components and thermal barrier coating. In a reported work, the FESEM analysis of *Thespesia populnea* leaf cellulose fibers revealed rough fibrillated surfaces and uniform microfibrillar morphology suitable for polymer composite reinforcement (Velmurugan *et al.* 2024).

3.3 Thermogravimetry Analysis (TGA)

Thermogravimetric analysis (TGA) was employed to evaluate thermal stability of developed epoxy composites by analyzing their decomposition temperature and weight loss behavior (TG%) (Fig. 7).

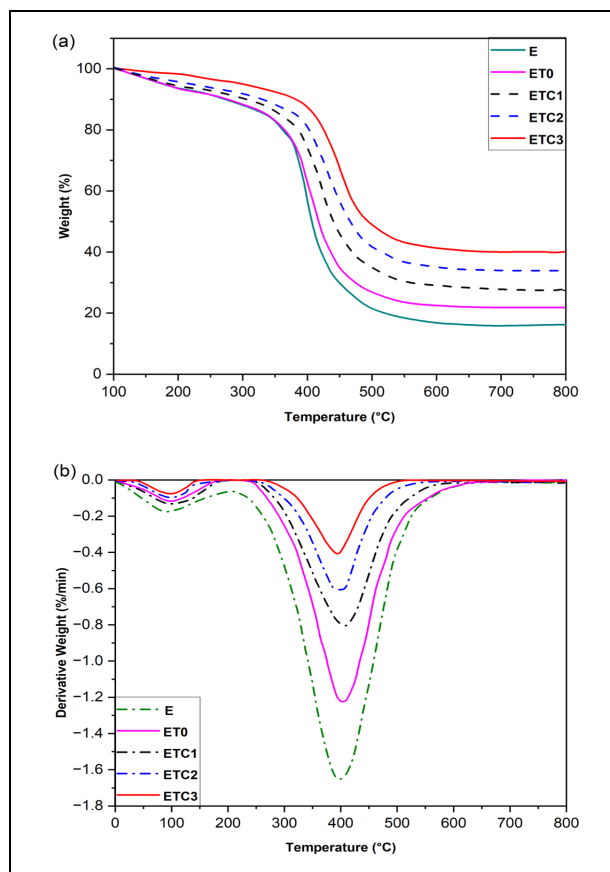


Fig. 7: Thermogravimetric profiles of various composite specimens

Thermal stability of the composites was evaluated through thermogravimetric analysis, where neat epoxy (E) exhibited stable thermal behavior with a decomposition temperature of 363 °C. This increased stability of the material is attributed to highly cross-linked three dimensional polymer network, which effectively resists thermal degradation and retards mass loss at high temperature.

Significant decrease in thermal stability was observed upon addition of 40 vol.% *Thespesia populnea* fiber (ET0). The TG% was lowered to 83% and the decomposition temperature was reduced to 331 °C. This is mainly attributed to the lignocellulosic nature of the fiber which contains thermally less stable constituents such as hemicellulose and cellulose which start to decompose at relatively lower temperatures with respect to epoxy matrix.

Existence of these thermally sensitive elements brings in early-stage deterioration in the composite, hence decreasing the overall heat-resistance of this composite. Moreover, the fiber matrix interface can serve as a preferential location in the process of thermal degradation, further enhancing mass loss. As a result, the use of natural fibers, being beneficial in terms of mechanical reinforcement, causes a slight sacrifice in thermal stability of their organic composition.

The addition of CaO nanoparticles has a significant impact on thermal stability of developed composites. The ETC1 composite (2 vol.% CaO) exhibited improved residual mass retention with a higher decomposition temperature of 343 °C, which showed a partial restoration of thermal stability as compared to ET0. The improvement is due to the presence of CaO nanoparticles, which are thermal barriers that inhibit heat transfer within the matrix.

Another improvement was observed in ETC2 (4 vol.% CaO), which exhibited a decomposition temperature of 371 °C along with enhanced residual mass retention behavior. This significant enhancement is mainly attributed to the homogenous distribution of CaO nanoparticles, which enhances interfacial bonding and gives rise to an effective barrier against heat propagation, thus delaying thermal degradation.

ETC3 (6 vol.% CaO) was found to have the highest overall thermal stability, at a decomposition temperature of 382 °C and enhanced residual mass retention due to the thermal barrier effect of CaO nanoparticles. The higher concentration of filler helps in better thermal insulation and structural rigidity, therefore, resistant to thermal bulk degradation in high temperatures. Nevertheless, an overloading of nanoparticles also facilitates agglomeration, which causes localized defects in the matrix.

The derivative thermogravimetric (DTG) analysis further explains the degradation pattern of the composites. The neat epoxy had a sharp DTG peak of 302 °C with a rate of 7.3%, which implies a rapid thermal degradation. Conversely, ET0 shows earlier degradation due to lignocellulosic fiber decomposition, while CaO-filled ETC2 and ETC3 shift degradation to higher temperatures due to thermal barrier effect.

The incorporation of CaO nanoparticles reduced the maximum degradation rate, where ETC1 and ETC2 exhibited DTG peak values of approximately 5.8 and 4.9 %/min, respectively. Furthermore, ETC2 showed a degradation peak around 367 °C, indicating improved thermal resistance due to enhanced heat shielding and stronger interfacial interaction. Nonetheless, ETC3 exhibited enhanced thermal resistance and delayed degradation behavior due to the thermal barrier effect of CaO nanoparticles. This behavior implies that, although nanoparticle agglomeration and non-uniform dispersion may lead to localized degradation earlier than possible under bulk thermal stability. These agglomerates serve as centres of stress concentration and promotes premature thermal decomposition in certain areas.

The overall findings suggest that CaO nanoparticles will increase the thermal stability to an

opportune loading amount, beyond which agglomeration effects will start to dominate the degradation behavior. A combination of *Thespesia populnea* fiber and CaO nanoparticles effectively enhances thermal resistance, and thus, the developed composites can be used in activities that require a high thermal insulation potential and resistance to instability. The schematic model (Fig. 8) further demonstrates how fiber and nanoparticle reinforcement can be used to resist heat degradation. In a previous work, TGA of the CaO/poly(lactic acid) nanoscaffolds demonstrated enhanced thermal stability with the composite maintaining structural integrity up to temperatures below 300 °C. The improved thermal resistance confirmed that the incorporation of CaO nanoparticles effectively reinforced the polylactic acid matrix, making the material suitable for composite applications (Ranjbar *et al.* 2019).

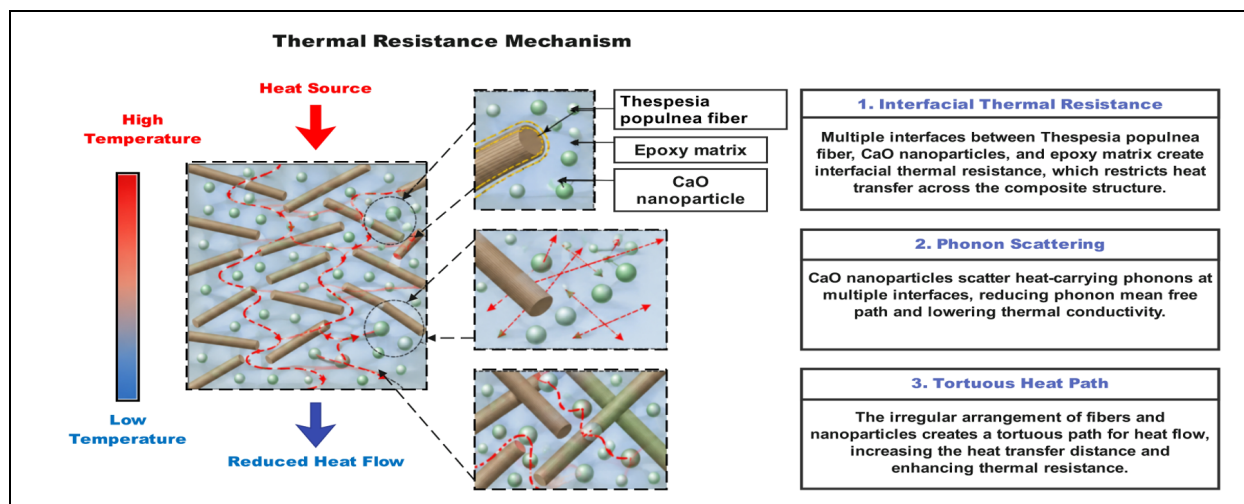


Fig. 8: Thermal barrier mechanism illustrating heat transfer resistance

4. CONCLUSION

The present study demonstrates that epoxy composites reinforced with *Thespesia populnea* fiber and biomass-derived CaO nanoparticles exhibit significantly enhanced mechanical performance and improved thermal stability, along with reduced thermal conductivity. The synergistic combination of lignocellulosic fiber and thermally stable inorganic filler resulted in superior tensile, flexural, compressive and impact strengths of 139 MPa, 166 MPa, 151 MPa, and 6.5 J for ETC2 composite containing 4 vol.% CaO. The ETC3 composite (6 vol.% CaO) showed highest thermal stability with the lowest thermal conductivity of 0.26 W/m²K⁻¹ and decomposition temperature of 382 °C showing its excellent thermal insulation capability. The progressive improvement in thermal behavior with increasing CaO content is attributed to enhanced phonon scattering, increased interfacial thermal resistance, and the formation of an effective barrier against heat transfer within the matrix. Morphological analysis using SEM

confirmed improved filler–matrix interaction and uniform dispersion at optimal loading. However, higher filler concentrations led to localized agglomeration, which adversely affected the composite performance. The results clearly indicate that the CaO nanoparticle content plays a critical role in balancing thermal stability and mechanical strength. The developed biocomposites show strong potential for advanced engineering applications, including automotive, aerospace, defense, and thermal insulation systems. The study further highlights that ETC2 is optimal for load-bearing applications due to its superior mechanical properties, whereas ETC3 is more suitable for thermal insulation applications owing to its enhanced thermal resistance.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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