



Development of MUF-bonded Banyan Fiber Laminates Reinforced with Bio-synthesized CeO₂ Nanoparticles for Advanced Applications

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ABSTRACT

Research and innovation in natural fiber-reinforced composites have gained considerable interest due to the increasing demand for sustainable materials in automotive, construction, defense, aviation, and marine industries. Fiber lamination has become an effective reinforcement method for developing structural composites with thermosetting polymers. In this study, eco-friendly cerium oxide nanoparticles (CeO₂ NPs) were synthesized through a green in-situ method using peepal leaves (*Ficus religiosa*) as reducing and stabilizing agents. The synthesized nanoparticles were deposited on banyan (*Ficus benghalensis*) aerial root fiber textiles using precursor concentrations of 1, 2, and 3 mM. The treated and untreated fiber textiles were bonded using melamine-urea-formaldehyde (MUF) resin to fabricate laminated nanocomposite panels. ICP-OES analysis confirmed CeO₂ nanoparticle concentrations of up to 52 mg L⁻¹ on treated fibers. The synthesized composites were characterized using SEM, FTIR, TGA/DTG, and mechanical testing. Physical properties such as water absorption (2.63 ± 0.19%), moisture content, and thickness swelling were also evaluated. Mechanical analysis revealed improved composite performance, with tensile strength increasing from 6.2 MPa for the control sample to 8.4 MPa for the 2 mM CeO₂-treated composite, while flexural strength reached 18.9 MPa. Thermal degradation mainly occurred between 398 and 405°C, and nanoparticle incorporation slightly enhanced thermal stability. Colorimetric analysis showed a decrease in L values from approximately 76% to 53%, confirming effective nanoparticle deposition. Overall, CeO₂ nanoparticles significantly enhanced the mechanical, thermal, and functional performance of banyan fiber laminated composites for sustainable structural applications

Keywords: Green synthesis; Colorimetric analysis; Thermal behaviour; Mechanical properties; Sustainability.

1. INTRODUCTION

Natural fibers have gained significant attention in sustainable composite development due to their biodegradability, renewability, low density, and reduced environmental impact compared to synthetic reinforcements. Among various thermosetting resins, melamine-urea-formaldehyde (MUF) resin is widely used in composite applications because of its good mechanical strength, thermal stability, and water resistance (Ahmadi *et al.* 2024; Jorda *et al.* 2021). Recent studies have shown that MUF-based natural fiber composites exhibit improved structural and thermal performance, demonstrating their suitability for eco-friendly composite applications. Biodegradable mulch films reinforced with wheat straw fiber were fabricated through in situ polymerization. The modified films showed improved tensile strength, thermal stability, and crystallinity, and could biodegrade within about 50 days

for agricultural applications (Vigneshwaran *et al.* 2021). Alkali-treated coir fibers and fibrous chips were reinforced with different percentages of melamine-urea-formaldehyde (MUF) adhesive to make tri-layered composite panels. The composites demonstrated enhanced tensile, flexural, bonding, and thermal properties, indicating their potential as sustainable structural biocomposites (Hasan *et al.* 2021).

Among various natural reinforcements, banyan aerial root fiber has recently attracted attention due to its favorable cellulose content and potential for composite fabrication. Alkali treatment was applied to the banyan aerial root fiber by 10% NaOH solution to enhance its structural properties. The treatment increased the cellulose content and raised the crystallinity of the fiber, as confirmed by XRD analysis. The crystallinity index increased by 52% with a crystalline size of 51.2 nm, indicating improved suitability of banyan fiber for

composite applications (Thandavamoorthy *et al.* 2023). Graphene nanopowder was incorporated as filler in banyan aerial root fiber-reinforced epoxy composites to enhance performance. The hybrid composite exhibited improved tensile strength, flexural strength, hardness, and reduced water absorption compared to conventional composites. The optimum performance was achieved with 4% graphene filler in a composite containing 40% banyan fiber reinforcement (Ganapathy *et al.* 2021). Banyan aerial root fibers were chemically modified using citric acid through thermochemical treatment to enhance adsorption capacity. Characterization studies such as SEM, FTIR, and surface analysis confirmed structural modification and increased functional groups on the fiber surface. The modified fibers demonstrated improved adsorption efficiency for ciprofloxacin removal from aqueous solutions (Raja and Devarajan, 2025).

Natural fibers such as banyan aerial root fiber are increasingly used in composite materials due to their environmental advantages. However, their limited mechanical and thermal properties often require hybridization with other fibers or reinforcements (Baskar *et al.* 2025). Green synthesis of nanoparticles using plant extracts has emerged as an environmentally friendly approach for developing functional nanocomposites with improved performance characteristics. Zinc oxide nanoparticles were synthesized using both chemical and green synthesis approaches with *Ficus religiosa* leaf extract. The green-synthesized ZnO nanoparticles demonstrated enhanced fluorescence properties, suggesting their suitability for bio-imaging applications (Mehto and Shukla, 2025). Bio-based cellulose nanocomposite filters incorporating graphene oxide and graphite oxide were developed using *Ficus religiosa* leaf substrates for dye removal applications. Morphological and structural analyses using SEM and XRD confirmed uniform dispersion of nanofillers in the composite structure (Dogra *et al.* 2022).

Cerium oxide nanoparticles were green-synthesized by *Hemerocallis citrina* extract and incorporated into electrospun PCL/PLA nanofiber scaffolds for wound healing applications. Structural characterization confirmed spherical CeO₂ nanoparticles with a face-centered cubic crystalline structure and an average particle size of about 9.39 nm (Le and Su, 2025). CeO₂ nanoparticles were incorporated into chitosan/polyvinyl alcohol (CS/PVA) matrices to fabricate eco-friendly composite films using a solvent casting technique. Characterization through FTIR, SEM-EDX, XRD, UV-Vis, and contact angle analysis confirmed improved structural, mechanical, and thermal properties of the films (Ali *et al.* 2024). The incorporation of doped CeO₂ nanoparticles significantly improved the mechanical strength, hydrophobicity, and antibacterial performance of the packaging films (Adhika *et al.* 2025). Coir fibers were modified using natural latex with SiO₂ nanoparticles and KH550 with ZnO nanoparticles to

improve fiber-matrix bonding in composites. The modified fibers showed significantly enhanced tensile strength and interfacial shear strength, demonstrating improved compatibility and mechanical performance of natural fiber composites (Ru *et al.* 2024).

Despite the growing interest in green-synthesized metal oxide nanoparticles and natural fiber-reinforced polymer composites, limited studies have explored the in-situ green synthesis and deposition of CeO₂ nanoparticles on banyan textile reinforcements for sustainable laminated composite applications. Previous investigations have predominantly focused on chemically synthesized CeO₂ nanoparticles or conventional surface treatments involving toxic chemicals, high energy consumption, and environmentally hazardous processing routes. Therefore, this research presents a straightforward, environmentally benign, and cost-effective method for functionalizing banyan textiles with biosynthesized CeO₂ nanoparticles, followed by their incorporation with MUF resin to fabricate sustainable nanocomposite materials. The investigation includes quantitative assessment and colorimetric analysis to verify the effective deposition and distribution of CeO₂ nanoparticles on the fiber surface. The developed methodology reveals a novel approach for generating ecologically sustainable nanostructured reinforcements, with prospective applications in the automotive, marine, construction, aerospace, and defense industries, where the need for eco-friendly composite materials is swiftly escalating.

2. MATERIALS AND METHODS

2.1 Materials

This research utilized banyan aerial root fiber fabric as the natural cellulosic reinforcing material. Aerial roots of the banyan tree (*Ficus benghalensis*) were harvested from mature specimens in and around various places in Coimbatore, Tamil Nadu, and transformed into fiber fabric by traditional extraction and weaving methods. The plant extract used for the green production of nanoparticles was derived from peepal leaves (*Ficus religiosa*), collected from adjacent green spaces in Coimbatore. The chemical precursor cerium nitrate hexahydrate (Ce (NO₃)₃·6H₂O, analytical grade (≥99% purity) utilized for synthesizing cerium oxide nanoparticles was obtained from Sigma-Aldrich, whereas commercial-quality MUF resin is accessible by laboratory chemical vendors in Coimbatore.

2.2 In situ of CeO₂ NPs Over Banyan Fibers

In situ green production of cerium oxide nanoparticles (CeO₂ NPs) facilitates uniform deposition on cellulosic substrates. This study utilized banyan aerial root fiber fabric, a lignocellulosic substrate for nanoparticle coating, whereas peepal (*Ficus religiosa*)

leaf extract acted as the natural reducing and stabilizing agent for nanoparticle synthesis.

Initially, peepal leaves were rinsed with tap water to remove dust and contaminants, followed by drying at 100 °C for 15 minutes. The desiccated leaves were pulverized into fine powder utilizing a laboratory grinder. About 50 g of leaves was combined with 500 mL of DI water (10% w/v) and heated at 90 °C for 30 mins to extract bioactive chemicals. The extracted solution was filtered by filter paper and stored in a sealed container for use. A cerium precursor solution was prepared by dissolving cerium nitrate at varying concentrations (1, 2, and 3 mM) in distilled water, which was then placed in individual Erlenmeyer flasks with constant agitation to achieve uniform mixing (Govindasamy and Ponnusami, 2025).

Before the fabrication of the nanocomposite, the banyan aerial root fiber fabrics were chopped into 300 ×

300 mm² pieces to serve as the substrate for nanoparticle coating. The banyan fiber fabrics were immersed in the cerium precursor solution, followed by gradual addition of peepal leaf extract under magnetic stirring for 10 min. Throughout this process, phytochemicals in the plant extract promoted the reduction of cerium ions and the direct production of cerium oxide nanoparticles on the fiber surface (Yousefzadeh *et al.* 2023). The reaction mixture was maintained at 95 °C for 45 mins, facilitating the nucleation and development of CeO₂ nanoparticles on the fabric. The color change of the reaction media signified the effective synthesis and deposition of nanoparticles.

Subsequent to the reaction, the coated fabrics were finally dried in a hot air oven until the moisture content reached approximately 3–4%, yielding CeO₂ nanoparticle-coated banyan aerial root fiber fabrics with enhanced functional properties (Charti *et al.* 2025). A schematic illustration is presented in Fig. 1.

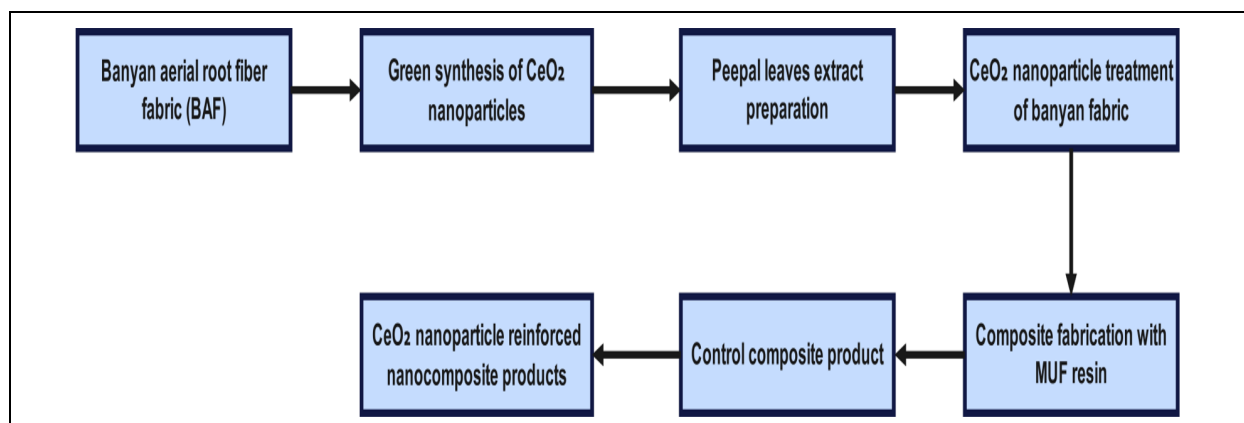


Fig. 1: Schematic view of CeO₂-treated banyan fiber MUF composites

2.3 Lamination of Developed Composites

Control and CeO₂ nanoparticle-coated fibers were bonded by MUF resin using the hand lay-up approach, by low-pressure application at a pressing machine (Dennison and Rajasekaran, 2023). The wax-coated Teflon sheet was initially positioned on a steel plate, followed by the arrangement of banyan fibers. Five layers of fabric were successively piled, with MUF resin placed between each layer. The laminated materials were subsequently compressed using a pressing machine and permitted to cure under ambient circumstances with relative humidity of 65 ± 5% and temperature of 20 ± 5 °C. The laminates were compressed under a pressure of 0.5 MPa for 30 min and cured for 8 h under ambient conditions. The identical manufacturing technique was employed for all laminate samples enumerated in Table 1. The untreated laminate was classified as S0, whilst the fabrics coated with CeO₂ nanoparticles were categorized as S1, S2, and S3, corresponding to CeO₂ concentrations of 1 mM, 2 mM, and 3 mM.

2.4 Characterizations of Nanocomposite and Control Products

Quantitative investigation of greenly produced CeO₂ nanoparticles at banyan reinforcements was conducted using ICP-OES in aqueous form, and the Ce concentration measured by ICP-OES was expressed in mg/L for all analyzed samples (Wei *et al.* 2025). The morphological analysis of synthesized composite materials was conducted by SEM apparatus (ZEISS, Gemini) at 15.0 kV. The colorimetric qualities were assessed using a spectrophotometer at standard daylight illuminant (D65) for wavelengths ranging from 400 to 700 nm (Kafashan *et al.* 2023). The mechanical characteristics of composites/nanocomposites was examined using Instron equipment for tensile and flexural characteristics (Raj *et al.* 2025). Tensile tests were performed at a crosshead speed of 2mm/min in accordance with the EN 310 standard, which was similarly employed for assessing flexural properties. The moisture content of the fabricated composites was

assessed in accordance with EN 322 following drying for 24 hours in a laboratory dryer. Six replicate specimens were prepared and tested for each characterization to ensure the repeatability and reliability of the experimental results. FTIR analysis was conducted utilizing a spectrophotometer (FT/IR-6300) at a wavenumber range of 4000–500 cm^{-1} , while thermal stability was assessed using a TGA/DTG analyzer inside a temperature range of 23–800 $^{\circ}\text{C}$.

Table 1. Physical properties of fabricated banyan fiber/MUF laminated composites

Composite	Reinforcement Type	Laminate Thickness	Composite Density
S0 (Control Sample)	100% control banyan	4.7 ± 0.04	664.2 ± 10.7
S1	1 mM $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ treated banyan	4.2 ± 0.02	722.3 ± 8.00
S2	2 mM $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ treated banyan	4.9 ± 0.12	1018.7 ± 11.00
S3	3mM $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ treated banyan	3.8 ± 0.01	736.5 ± 12.2

3. RESULTS AND DISCUSSIONS

3.1 Comparative Study of Control and CeO_2 Banyan Composites

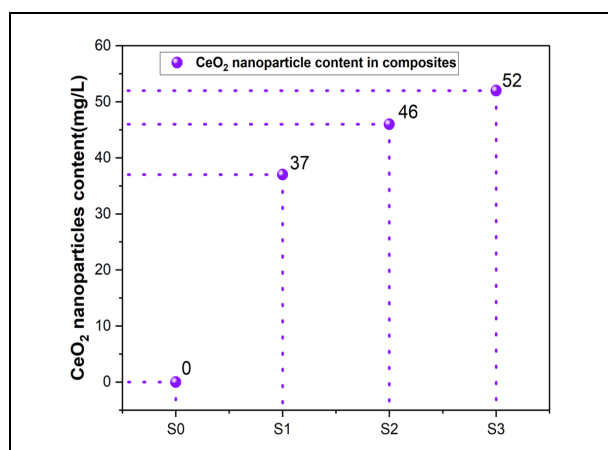


Fig. 2: ICP-OES analysis of CeO_2 banyan fibers

The concentration of in-situ biosynthesized CeO_2 nanoparticles deposited on banyan fiber reinforcements was quantitatively evaluated using ICP-OES analysis. The measured concentrations were 0, 37, 46, and 52 mg/L for untreated and treated banyan fibers, respectively, demonstrating a gradual increase in nanoparticle deposition with increasing cerium precursor concentration (Fig. 2). This trend confirms the effective reduction and stabilization capability of peepal leaf

extract during the green synthesis process. The higher concentration of CeO_2 nanoparticles on the fiber surface indicates successful in-situ functionalization of banyan fibers, which is expected to enhance interfacial adhesion and improve the overall performance of the laminated composites.

3.2 Morphological Analysis of Nanocomposites and Control

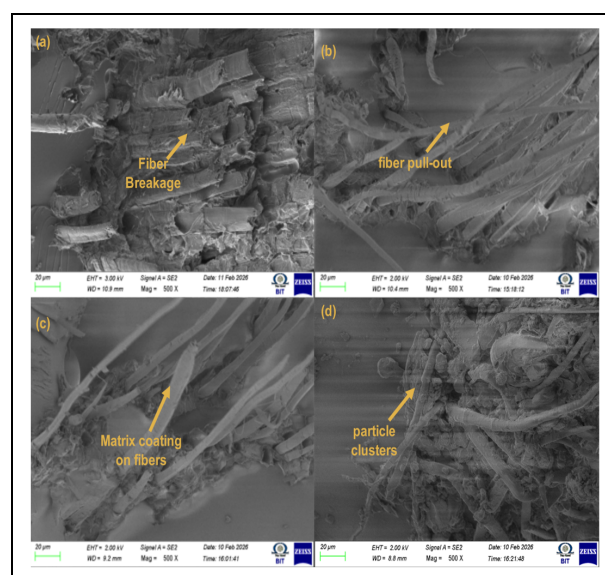


Fig. 3: SEM fractured surface for (a) S0, (b) S1, (c) S2 and (d) S3

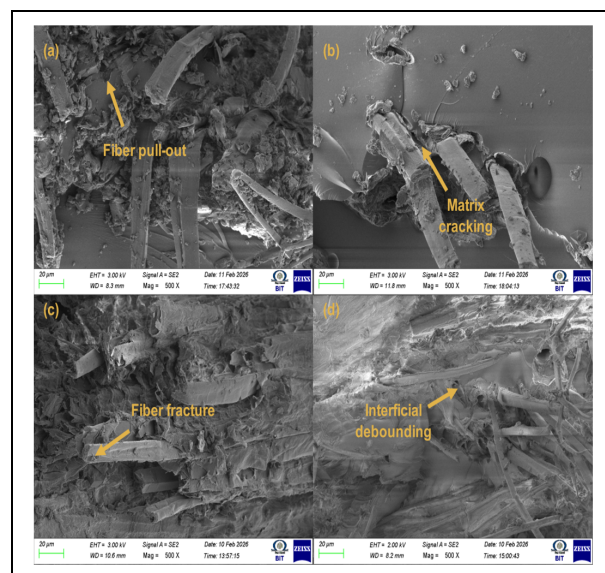


Fig. 4: SEM fractured surface for tensile test specimens (a) S0, (b) S1, (c) S2, and (d) S3

SEM micrographs of the fabricated composites was analyzed prior to and during tensile fracture. The fractured surface morphology clearly demonstrates the failure mechanisms occurring during tensile loading. The presence of matrix cracks and fiber pull-out indicates

stress concentration and crack propagation within the composite structure. In comparison, the treated composites exhibited relatively rougher fracture surfaces, suggesting higher energy absorption and improved stress transfer between the fiber and matrix phases. Figure 3 illustrates the tensile test specimens with figure 3a depicting the control sample and Figures 3c, e, and g representing CeO₂ NP-treated composites reinforced with MUF resin. SEM micrographs of the fractured composites exhibit fiber pull-out, matrix cracking, and interfacial debonding characteristics. The treated composites display relatively rougher fracture surfaces and better fiber–matrix adhesion, signifying improved interfacial bonding attributed to the presence of CeO₂ nanoparticles. Furthermore, the treated composites showed reduced fiber pull-out, fewer interfacial voids, and improved matrix coverage over the fiber surface compared to the untreated composite. These observations confirm that the incorporation of CeO₂ nanoparticles enhanced the interfacial compatibility and bonding efficiency between the banyan fibers and MUF resin matrix. Following tensile failure (Fig. 4), the fibers become more pronounced. Similar results were also observed in our prior research on nano graphene oxide-treated flax fiber reinforced polyester composites (Gupta *et al.* 2025). Although the present study primarily focused on qualitative morphological analysis, the improved interfacial characteristics observed in SEM images are consistent with the enhanced tensile performance of the CeO₂-treated composites. The improved stress transfer capability and reduced interfacial debonding indirectly indicate strengthened fiber–matrix interaction.

3.3 Mechanical Performance of Nanocomposites

The mechanical performance of CeO₂-modified laminates was assessed by tensile and flexural tests (Table 1). The findings demonstrate that both tensile strength and modulus increased with elevated CeO₂ precursor loading up to 2 mM, followed by a decline at 3 mM, presumably due to nanoparticle aggregation. The untreated composite demonstrated a tensile strength of 6.2MPa, whereas samples S1 and S2 displayed strengths of 7.6MPa and 8.4MPa, respectively, with a minor decline to 7.3MPa for S3. A comparable trend was noted for flexural strength and modulus. The Young's modulus raised from 1.4GPa for the control to 2.0GPa at 2 mM, subsequently shows a minor decline at 3 mM. Elevated R² results (≥ 0.79) signify a robust association between CeO₂ treatment and enhanced mechanical performance. Our prior investigations also revealed an enhancement in mechanical characteristics with the increased loading of graphene nanoparticles (Ganapathy *et al.* 2021). The present results are consistent with previous literature reports on CeO₂-modified composites. Earlier studies reported improvements of 95% and 67% in flexural strength and tensile strength, respectively, due to

enhanced interfacial bonding and stress transfer (Wu *et al.* 2026)

Table 2. Mechanical performance of CeO₂ nanocomposites

Composite ID	TS (MPa)	YM, E(GPa)	Modulus of Rupture (MPa)	Modulus of Elasticity (GPa)
S0	6.2 ± 0.3	1.4 ± 0.1	4.8 ± 0.2	1.5 ± 0.1
S1	7.6 ± 0.4	1.7 ± 0.1	13.4 ± 0.6	1.9 ± 0.1
S2	8.4 ± 0.2	2.0 ± 0.1	18.9 ± 0.5	2.6 ± 0.2
S3	7.3 ± 0.5	1.8 ± 0.1	15.6 ± 0.4	2.2 ± 0.1
Coefficient of determinations (R ²)	0.95	0.88	0.92	0.90

3.4 Colorimetric Analysis of Nanocomposites

The in-situ integration of CeO₂ nanoparticles boosted both the mechanical properties and aesthetic quality of the laminates. The colorimetric characteristics of the produced composites were assessed within the visible wavelength spectrum. The coloration mostly results from the localized surface plasmon resonance of CeO₂ nanoparticles, generating distinct color effects in the materials. Post-fabrication, the laminated composites had distinct color changes, as demonstrated in Fig.3 b, c, d in contrast to the control sample (Fig. 3a). The control composite had the greatest L* value (76.42), signifying a lighter hue, while CeO₂-treated samples displayed lower L* values (63.75, 58.21, and 52.64 for samples S1, S2, and S3), indicating darker shades with escalating nanoparticle concentration. Correspondingly, the color strength (K/S) values escalated from 0.24 for the control to 1.91 for the maximum loading, hence affirming enhanced coloration. Positive a* and b* values signify the existence of yellowish-red and brown hues. These colorimetric properties highlight the potential of CeO₂-integrated laminates for functional applications such as UV-protective textiles, decorative composites, and aesthetic surface coatings, where controlled color depth and uniformity are critically required. The colorimetric results are presented in Table 3.

Table 3. Colorimetric analysis of CeO₂ composites

Composite	L*	a*	b*	K/S
S0	76.42	2.11	11.38	0.24
S1	63.75	4.86	18.94	0.88
S2	58.21	6.42	21.17	1.36
S3	52.64	7.95	23.08	1.91

3.5 Moisture Content Investigation of Control and Nanocomposites

The study of moisture content in natural fiber reinforced composites is a significant characteristic, as natural cellulosic fibers absorb moisture from the atmosphere due to the presence of hydrophilic components such as $-OH$ and $-COOH$ in their polymeric structure (Vadivel *et al.* 2025). The moisture absorption characteristics of the composites are illustrated in Fig. 5. The control sample absorbed 3.18 (0.17)% moisture, but the composite treated with 1 mM $Ce(NO_3)_3 \cdot 6H_2O$ exhibited a reduced value of 2.63 (0.19)%. Moisture content marginally increased with elevated precursor loading, attaining 3.04 for 2 mM and 3.12 for 3 mM. A comparable pattern was noted following 24 hours of drying. The initial reduction in moisture absorption at lower CeO_2 loading (1 mM) can be attributed to the hydrophobic barrier formed by CeO_2 nanoparticles, which partially block the $-OH$ and $-COOH$ groups of the cellulose fibers, thereby limiting water molecule interaction. However, at higher nanoparticle concentrations (2 mM and 3 mM), agglomeration of CeO_2 nanoparticles may create microvoids within the composite matrix, facilitating moisture ingress and increasing hydrophilicity. However, samples with increased CeO_2 loading absorbed greater moisture after 24 hours, likely attributable to the hydrophilic characteristics of the cellulose banyan fibers inside the composite structure.

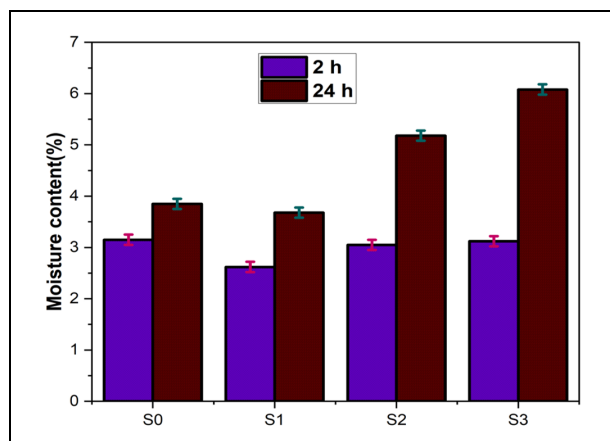


Fig. 5: Moisture absorption of CeO_2 composites

3.6 FTIR Analysis of Nanocomposites

Figure 6 displays the FTIR spectra of the control and CeO_2 NP-treated composites. A broad absorption band at 3402 cm^{-1} corresponds to $-OH$ stretching of hydroxyl groups from cellulose, lignin, and hemicellulose in banyan fibers (Manoharan *et al.* 2025). Peaks at 2912 cm^{-1} and 2856 cm^{-1} represent asymmetric and symmetric CH_2 stretching vibrations, respectively. The band at 1672 cm^{-1} is attributed to H_2O and $C=O$ stretching in conjugated systems, while 1132 cm^{-1}

corresponds to $C-O-C$ symmetric stretching and aromatic $C-H$ deformation. Following CeO_2 NP treatment, peak intensities increased; however, the overall chemical structure remained unaltered.

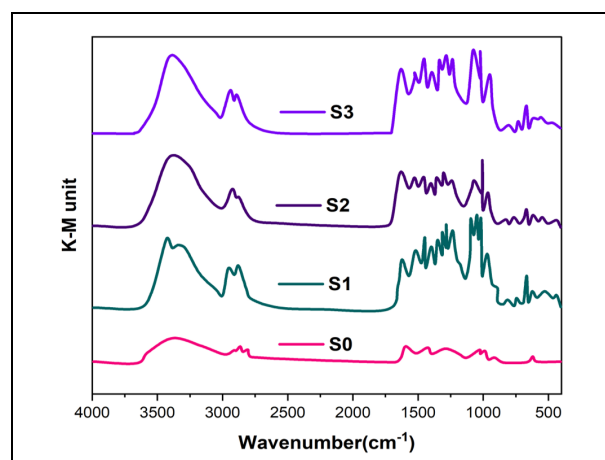


Fig. 6: FTIR spectra of CeO_2 composites

3.7 Thermal Testing

Thermal properties of CeO_2 NP banyan fiber composites was assessed using TGA analysis (Fig. 7). The nanocomposite samples exhibited marginally enhanced heat stability relative to the untreated composite. The thermogravimetric curves exhibited several deterioration phases. Initial weight reduction resulted from moisture evaporation from the fiber surfaces. The control sample exhibited significant degradation starting at $268\text{ }^{\circ}C$ and persisting until $368\text{ }^{\circ}C$, culminating in an approximate 75% weight loss by $800\text{ }^{\circ}C$. Conversely, CeO_2 -loaded composites demonstrated a comparable initial pattern but showed enhanced stability after $200\text{ }^{\circ}C$. The weight loss occurring between 398 and $405\text{ }^{\circ}C$ is indicative of cellulose degradation in the reinforcing fibers. Samples containing 1 mM and 2 mM precursor exhibited approximately 73% weight reduction, whilst the 3 mM sample demonstrated a 72% reduction. The improved stability is due to interactions between fibers and CeO_2 nanoparticles, which mitigate heat degradation and boost composite resistance. The improved thermal stability of the CeO_2 NP banyan fiber composites is comparable with previously reported CeO_2 -based epoxy nanocomposites. Earlier studies demonstrated that CeO_2 -GO/epoxy systems exhibited higher thermal stability and enhanced char yield compared to neat epoxy. Similarly, the present study showed reduced weight loss and improved thermal resistance in CeO_2 -treated composites relative to the untreated sample (Nassaj *et al.* 2021).

The collective findings from mechanical, colorimetric, moisture, FTIR, and thermal analyses consistently demonstrate that in-situ CeO_2 nanoparticle functionalization significantly enhances the

multifunctional performance of banyan fiber reinforced composites. The improved interfacial bonding observed in SEM, evidenced by reduced fiber pull-out and better matrix coverage, directly correlates with the enhanced tensile and flexural properties. The FTIR analysis confirmed that CeO₂ treatment did not alter the fundamental chemical structure but increased peak intensities, suggesting stronger fiber–matrix interactions. The partial blocking of –OH and –COOH groups by CeO₂ nanoparticles, as reflected in reduced moisture absorption at lower loadings, further supports the improved interfacial compatibility. Additionally, the thermal stability enhancement at higher CeO₂ concentrations aligns with the nanoparticle–fiber interaction mechanism, where CeO₂ acts as a thermal barrier delaying degradation. Collectively, these results establish CeO₂-functionalized banyan fiber composites as promising candidates for structural and functional applications requiring balanced mechanical, aesthetic, and durability performance.

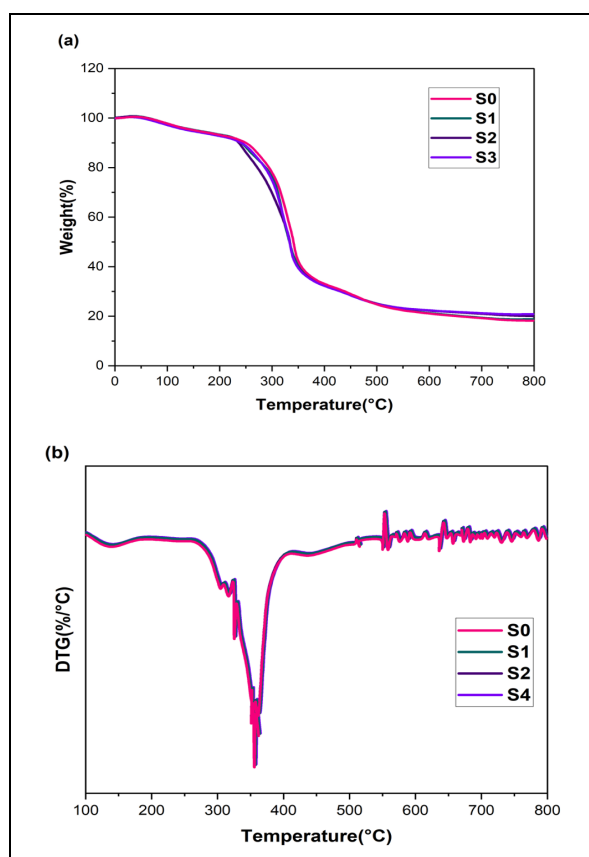


Fig. 7: TGA–DTG analysis of composites

4. CONCLUSIONS

This study illustrates a feasible, economical, and eco-friendly approach for developing nanocomposite materials utilizing banyan (*Ficus benghalensis*) aerial root fiber reinforced with melamine-urea-formaldehyde resin and green-synthesized cerium oxide (CeO₂) nanoparticles derived from peepal (*Ficus religiosa*)

leaves. The mechanical properties markedly improved with increased nanoparticle loading up to 2 mM, achieving a peak tensile strength of 8.4 (± 0.2) MPa compared to 6.2 (± 0.3) MPa for the control. The maximum flexural strength of 18.9 (± 0.5) MPa was recorded at 2 mM CeO₂ loading. The nanocomposites exhibited enhanced dimensional stability with a moisture absorption of 2.63 (± 0.19)%. Thermal analysis revealed improved thermal resistance, with significant degradation occurring between 398–405 °C and a weight loss of 72–73% up to 800 °C. Colorimetric analysis confirmed successful nanoparticle deposition, as the L value decreased from 76.42 for the control to 52.64 for the highest treated composite, signifying darker surface coloration. These findings demonstrate that CeO₂ nanoparticle incorporation significantly enhances the mechanical, thermal, and functional properties of banyan fiber-reinforced laminated composites. Future studies should explore the durability and long-term performance of these composites under varied environmental conditions, as well as their potential for industrial applications such as automotive interiors, construction panels, and sustainable packaging materials.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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