



Influence of Saltwater and Distilled Water on the Mechanical Properties of Natural Fiber–reinforced Polyester Composites Enhanced with SiC Nanoparticles

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ABSTRACT

This study examines the mechanics of polyester composites reinforced with *Cyperus* fiber (CF) and *Calotropis gigantea* fiber (CGF), together with their moisture absorption characteristics. The ability of distilled water and salt water to absorb moisture was studied. The composites, one reinforced with pure *Calotropis gigantea* fiber, one with pure *Cyperus* fiber, and one with a hybrid of both fibers, were subjected to tensile and flexural testing. The alterations in mechanical properties resulting from varying moisture conditions were also examined. The impact of silicon carbide (SiC) nanoparticles on these composites was also assessed. The results indicate that SiC nanoparticles enhance the mechanical properties, particularly in damp conditions. Studying fracture behavior facilitates the understanding of the interactions of natural fibers, the matrix, and nano-reinforcement. The CF composite exhibits a moisture absorption of 8.19% in distilled water and 9.50% in saltwater at a maximum natural fiber weight fraction of 40%, while the CGF composite demonstrates maximum absorptions of 6.57% and 8.26%, respectively. Comparable conditions showed moisture absorptions of 4.19% (distilled water) and 6.54% (salt water) for the hybrid composite. The incorporation of silicon carbide into the polymer matrix significantly diminishes the moisture absorption capacity of the *Cyperus* composite to 35.2% for distilled water and 31.7% for saltwater. Overall, the study demonstrates that SiC nanoparticles effectively mitigate moisture-induced degradation in natural fiber composites, making them promising candidates for outdoor, marine, and structural applications.

Keywords: Natural fiber; Silicon carbide; Moisture absorption; Flexural modulus; Tensile modulus.

1. INTRODUCTION

Due to their versatility, durability, and cost-effectiveness, polymer materials, both synthetic and natural, have been extensively utilized throughout several industries. *Cyperus* fibers were removed using water retting and alkaline techniques and subsequently tested for their characteristics. Alkaline and benzoyl chloride treatment produced a greater cellulose yield and

a reduced lignin content in comparison to water retting (Sheferaw *et al.* 2023), (Babu, 2020). *Cyperus* fibers were integrated into epoxy composites with graphene oxide (GO) for mechanical enhancement. (Neuba *et al.* 2023a). *Calotropis gigantea* fiber (CGF) enhanced tensile characteristics, simultaneously decreasing water absorption. (Zaman and Khan, 2022), (Jeyapragash *et al.* 2022). *Cyperus* fiber reinforced epoxy nanocomposites have been synthesized and their viscoelastic

characteristics have been examined using Dynamic Mechanical Analysis (DMA) (Neuba *et al.* 2025). Epoxy composites reinforced with Cyperus fibers were assessed for tensile, impact, and thermal characteristics. (Neuba *et al.* 2020). *Calotropis gigantea* fiber was incorporated into polymer composites with varying fiber lengths (25–150 mm) and weight percentages (10–50%) using compression molding (Ramesh *et al.* 2020). *Calotropis gigantea* fiber-epoxy composites were fabricated with diverse fiber orientations ranging from 0° to 90°. The 0° orientation demonstrated 142.46 MPa of flexural and 93.13 MPa tensile strengths (Ramesh *et al.* 2022).

Hybrid biocomposites composed CG and palmyra fibers, reinforced with phenol–formaldehyde resin, were produced using the hand layup technique (Sekar *et al.* 2020). The use of 2 wt.% fly ash nanofiller with CG fiber/epoxy raised tensile strength by 29.83%, markedly improved mechanical characteristics. The moisture resistance was enhanced, rendering these composites appropriate for sustainable brake materials (KG *et al.* 2023). Epoxy composites reinforced with CG fibers (10–30 mm, 5–30 vol.%) were produced by compression molding. Optimal mechanical performance was noted at 25% fiber volume, whereas 30%/30 mm fibers exhibited the highest water absorption (Velusamy *et al.* 2019). Nano-SiO₂ enhanced interlaminar shear strength (ILSS), water absorption, particularly at 4.5 wt% concentration with 30 wt% CG fiber (Velmurugan *et al.* 2023). Composites containing 6% SiC with woven bamboo/epoxy exhibited ideal enhancements in tensile strength (+30.7%) (Kumar *et al.* 2025b). Optimum tensile strength (221.3 MPa, +25.7%) was attained at 7.5 wt% SiC /Basalt fiber/epoxy, while hardness peaked at 10 wt% (Pithalis *et al.* 2022). Hybrid natural composites comprising kenaf and bamboo fibers bonded with silicon carbide and polyester were produced using the hand layup method. Mechanical evaluations validated enhanced performance with the incorporation of fibers and fillers (Marappan *et al.* 2025).

Roystonea regia fiber and glass fiber epoxy composites were evaluated with and without silicon carbide fillers. Equal fiber proportions without SiC produced the highest tensile and hardness results; however, the inclusion of SiC enhanced flexural strength (Balaji and Goud, 2022). Ramie–jute/epoxy hybrid composites with SiC and cellulose fillers were examined for their mechanical and thermal properties (Mohanavel *et al.* 2022). The mechanical results indicated that the 45° orientation basalt fiber and aluminum mesh with SiC-filled epoxy provided optimal strength due to

interlocking effects, whereas SEM analysis demonstrated fiber fracture and pull-out (Thooyavan *et al.* 2022). Hybrid composites of Kevlar, Ramie, and nano-SiC were produced by hand lay-up and evaluated against single-fiber composites. Mechanical evaluations indicated satisfactory density, tensile, and flexural characteristics, with hybridization enhancing strength (Vedanarayanan *et al.* 2022). Optimized combinations Basalt fiber/vinyl ester composites with micro- and nano-SiC attained a tensile strength of 204.33 MPa, a flexural strength of 525.33 MPa. Scanning Electron Microscopy identified failure mechanisms, including matrix cracking, delamination, and fiber fracture (Thooyavan *et al.* 2022). The hybrid composites including CGF and abaca fiber (AF) inside an epoxy matrix surpassed single-fiber composites, with one of the samples attaining a tensile strength of 36.19 MPa, a compressive strength of 94.45 MPa, and an impact energy of 53.88 kJ/m (Pandi *et al.* 2024).

Although natural fiber composites have been widely investigated, Cyperus and *Calotropis gigantea* fibers remain relatively less explored, particularly regarding their mechanical reliability and moisture absorption behavior. Most existing studies focus on dry conditions or traditional fillers, with limited attention to their performance in realistic environments such as distilled and saltwater. Furthermore, the potential of silicon carbide (SiC) nanoparticles to mitigate moisture-induced degradation in these specific fiber composites has not been systematically addressed, and very few studies integrate experimental evaluation with computational validation to predict long-term performance. To bridge this gap, the present work introduces SiC nanoparticles into Cyperus/*Calotropis gigantea*-based polyester composites, assesses their tensile and flexural behavior under moisture exposure, investigates fracture morphology using SEM, and validates the results through finite element analysis (FEA). This integrated approach provides novel insights into enhancing the durability and mechanical dependability of less-explored natural fiber composites for outdoor and marine applications.

2. MATERIALS AND METHODS

The Cyperus and *Calotropis gigantea* fibers were collected from various places in Coimbatore, Tamil Nadu, India. Cyperus fiber had a density of around 0.95 g/cm³ with 57-98% cellulose, 13.55% hemicellulose, and 25.42% lignin. The fiber of *Calotropis gigantea* exhibits a density of 1.360 g/cm³, comprising around 73.8% cellulose, 20.5% hemicellulose, and 2.7% lignin. This

study employs polyester resin as the matrix phase. A suitable catalyst (MEAP) and hardener are employed to produce composite specimens. Silicon carbide nanoparticles (purity 99%) were used in this study. Polyester resin was employed as the matrix.

2.1 Extraction of Fibers

2.1.1 Extraction of *Cyperus* Fibers

The primary source of *Cyperus* fibers is the stem. The stems were immersed in tanks for a duration of 21 days to facilitate microbial degradation of the fiber-binding pectin and hemicellulose. Then, the fibers were manually extracted, thoroughly cleansed, and air dried in sunlight. Sodium hydroxide solution (5%) was used for alkali retting. *Cyperus* fibers underwent alkali treatment with NaOH at concentrations of 3%, 5%, and 10% for durations of 24 to 72 hours to enhance fiber-matrix interaction. Fibers subjected to 3% NaOH treatment for 24–48 hours were selected. Similar NaOH treatments have been reported to improve fiber quality and matrix adhesion (Neuba *et al.* 2023b). This technique yields cleaner, softer fibers with enhanced mechanical performance by eliminating wax, lignin, and hemicellulose.

2.1.2 Extraction of *Calotropis gigantea* Fibers

The stems of the *Calotropis gigantea* tree were collected for extracting the fibers. The stems were immersed in water for 10 to 15 days to soften the fibrous bundles, followed by physical separation, washing, and drying of the fibers. Then, the stems were subjected to alkali retting using sodium hydroxide solution (5-10%) at 80-90 °C for 2 hours, followed by washing and neutralizing with diluted acetic acid.

2.2 Fabrication of the Composites

Composites were fabricated using the hand lay-up method. The mold was cleaned and coated with a release agent. Fibers were washed, treated with 5% NaOH, and dried before use. Polyester resin, accelerator, and catalyst were mixed in the ratio 100:1.5:1, and fibers were introduced to obtain a 40% fiber weight fraction. The mixture was cured for 24 hours at room temperature under a 20 kg load.

A composite of *Cyperus* fiber (S1), *Calotropis gigantea* fiber (S2), and a composite of *Cyperus* and *Calotropis gigantea* (S3) were produced by the previously described procedure. The study evaluated the

performance of composite specimens in both dry and wet situations. Wet conditions indicate exposure to moisture, whereas dry conditions simulate standard usage conditions.

After fabrication, the composites underwent oven drying at 100°C to remove residual moisture and ensure uniform curing of the resin matrix. Upon attaining room temperature, they were allowed to stabilize. To precisely assess changes in weight and dimensional stability throughout curing, the specimens were weighed to the nearest 0.0001 g immediately after 24 hours and subsequently dried with a cloth.

Table 1. Composition details of fiber–filler reinforced epoxy composites

Specimen Code	Reinforcement (Fiber + Filler)	Fiber wt%	Filler wt%	Epoxy wt%
S1	CF/P	40	-	60
S2	CGF/P	40	-	60
S3	CF/CGF/P	40	-	60
S4	CF/SiC/P	40	2	58
S5	CGF/SiC/P	40	4	56
S6	CF/CGF/SiC/P	40	6	54

Furthermore, hybrid composites (Table 1) were produced by using silicon carbide (SiC). These nano fillers were included to enhance the rigidity and strength of the polyester resin matrix. Ultrasonication was employed to uniformly disperse SiC nanoparticles inside the resin matrix, hence enhancing the mechanical characteristics of the composite and optimizing reinforcing efficiency.

2.3 Moisture Absorption (MA)

The moisture absorption behaviour of the composites was evaluated following ASTM D570-98. The fabricated specimens were first dried in an oven at 100 °C to remove residual moisture and ensure a uniform initial condition. After drying, they were cooled to ambient temperature and acclimatised before testing. The specimens were then immersed in distilled water and saltwater for 24 hours. After each immersion period, they were removed, the surface moisture was wiped off with a cloth, and the specimens were weighed immediately to the nearest 0.0001 g. This procedure was repeated at regular intervals up to 240 hours or until no further change in mass was observed. The moisture uptake at each interval was calculated using the percentage weight-gain equation.

$$MA(\%) = \frac{W_w - W_o}{W_o} * 100 \quad \dots (1)$$

The specimen's weight at a specific immersion period is denoted as W_w , and the oven-dried weight is denoted as W_o .

The moisture uptake kinetics were analyzed using a power-law model (Eq. 2), which relates fractional absorption to time.

$$\frac{\log(M_t)}{\log(M_\infty)} = \log(k) + n \log(t) \quad \dots (2),$$

where M_t/M_∞ is the fractional water uptake at time t , k is the diffusion rate constant, and n is the diffusion exponent.

2.4 Testing of the Composites

Samples were fabricated in accordance with ASTM D638 criteria, pertinent for evaluating polymers and polymer-reinforced composites. Specimens were subsequently evaluated for elongation, tensile strength, and tensile modulus utilizing an Instron universal testing equipment. Flat flexural specimens fabricated in accordance with ASTM D790 requirements were utilized to evaluate the flexural modulus and flexural strength employing the identical UTM apparatus. The water-absorption characteristics of tensile and bending specimens by measuring their weight prior to immersion in water at room temperature were evaluated. The specimens that had absorbed moisture were reweighed and submerged until no further weight variation was observed. Subsequently, they underwent re-evaluation for tensile and flexural strength. The microstructural characteristics of the fractured surfaces were examined using scanning electron microscopy (SEM) at Bannari Amman Institute of Technology, Sathyamangalam.



Fig. 1: Specimens for tensile flexural strength

2.4.1 Tensile Testing

The tensile properties of the fabricated specimens were using a universal tensile testing apparatus with a load cell capacity of 20 KN. The specimens used for the tensile test measured 125 mm × 24 mm × 3 mm in compliance with ASTM D638 (Venkatesh *et al.* 2024). The tensile strength and elongation of the composite material were assessed during the testing process. Each test involved the examination of three specimens, and the mean value was considered to ascertain the result.

2.4.2 Flexural Tests

The tensile testing apparatus was employed to ascertain the bending strength, measured with a 20 KN load cell and a three-point bending load arrangement. Specimens measuring 127 mm × 12.7 mm × 3 mm were used in the flexural test conducted following ASTM D790 standards (Aruna *et al.* 2024).

2.4.3 SEM Examination

The fracture surface behavior of the natural composite was investigated using a scanning electron microscope (SEM) (Bhunia *et al.* 2023). The study employed GEMINI-ZEISS Field Emission Scanning Electron Microscopy with an acceleration voltage set between 0.02 kV and 30 kV, and a magnification capability ranging from 10x to 1,000,000x.

3. RESULTS AND DISCUSSION

3.1 Diffusivity and Kinetics of Water Absorption

The testing was performed with a fiber weight fraction of 40%, as this is the optimal fraction that yields favorable mechanical qualities. The mechanical properties deteriorate as the increments continue to increase. The specimens were submerged in both the water to replicate natural settings. A comprehensive understanding of the behavior of natural fibers under many conditions was attained by calculating the mean results of their absorption capacity.

Fig. 2 and 3 illustrate the moisture absorption behavior of composites (S1-S6) under distilled and saltwater immersion. Absorption increased steadily with time until reaching saturation at ~228 hours in distilled water and ~324 hours in saltwater. Among the fiber systems, *Cyperus* fiber composites absorbed the most moisture, *Calotropis gigantea* fiber composites absorbed less, and hybrid composites showed the lowest uptake.

This hierarchy reflects the higher hemicellulose and lignin content of *Cyperus*, which increases hydrophilicity, whereas CGF contain more cellulose and less lignin, making them less prone to swelling. The hybrid system benefits from a compensating effect, where reduced hydrophilicity from CGF offsets the higher uptake by *Cyperus*.

A consistent trend was that saltwater exposure caused greater absorption than distilled water. This can be attributed to the presence of chloride ions, which accelerate microcrack initiation at the fiber–matrix interface and increase permeability. Once microcracks form, water molecules diffuse more easily through the composite, leading to higher equilibrium uptake in saline conditions.

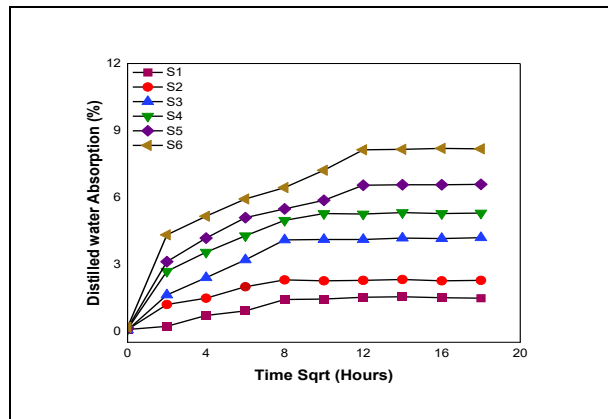


Fig. 2: Percentage of distilled water absorption

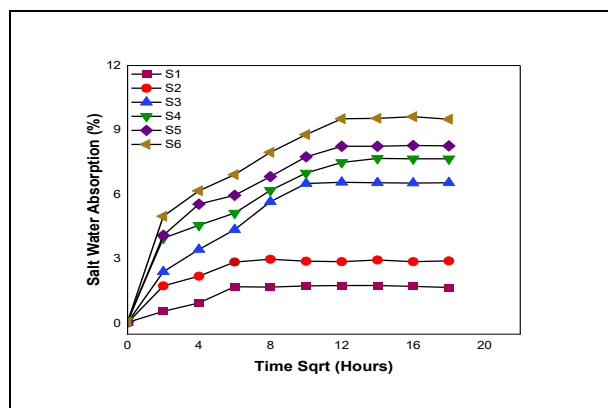


Fig. 3: Percentage of salt water absorption

The addition of SiC nanoparticles (S4–S6) significantly reduced absorption compared to unfilled composites (S1–S3). This improvement arises from two key mechanisms: (i) the nanoparticles occupy voids and micro-gaps at the fiber–matrix interface, reducing pathways for water ingress, and (ii) their inherent hydrophobicity and high aspect ratio create a barrier

effect, hindering diffusion of water molecules. Consequently, hybrid composites reinforced with both fibers and SiC showed the greatest resistance to moisture penetration, making them more suitable for long-term use in humid or marine environments.

The moisture absorption capacity of composites bound with natural fibers diminished following the infusion of silicon carbide. The *Cyperus* fiber-reinforced composite exhibited a moisture absorption capability of 5.29 % in distilled water (Fig. 2) and 7.65 % in saltwater (Fig. 3). In a previous study, a composite was developed using eco-friendly *Lablab purpureus* fiber and SiC particles in a vinyl ester matrix. A remarkably low water absorption rate of 0.0009% was achieved, confirming the composite's durability for structural applications as observed by Sudhakar *et al.* (2025).

The incorporation of SiC into the polymer matrix markedly diminished the moisture absorption capacity of the *Cyperus* composite in comparison to the unmodified *Cyperus* fiber-reinforced composite. Distilled water had a reduced moisture absorption capacity of 35.2%, whereas saltwater demonstrated a lowered capacity of 31.7%.

Natural fiber-reinforced composite samples exhibit a superior capacity for moisture absorption when immersed in saltwater, in contrast to pure water. The proliferation of holes and subsequent microcrack creation caused by the presence of salt in the water is the probable source of this phenomenon. The specimen absorbs more moisture due to the permeability created by these microcracks.

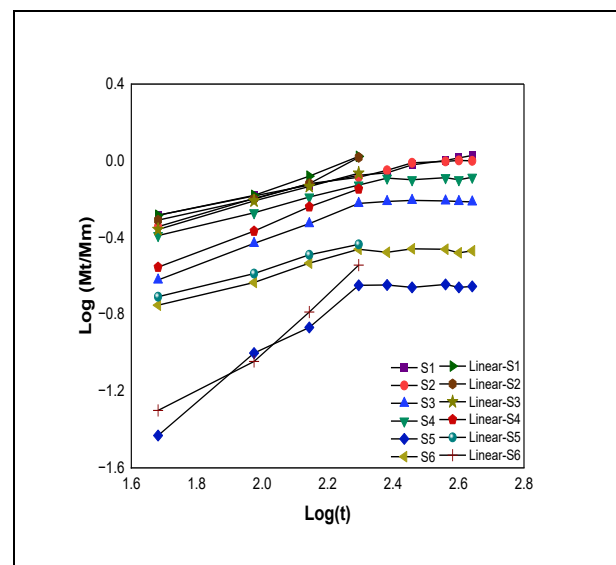


Fig. 4: Diffusion case fitting plots for distilled water

All available voids in the composite specimen are occupied by water that has permeated throughout. The random configuration of polymer molecules facilitates the void in the volume. Due to their hydrophilic properties, natural fibers absorb water molecules when immersed in a liquid medium, resulting in water infiltrating these gaps.

Water molecules cannot penetrate the composite because of the higher aspect ratio of SiC nanoparticles. The barrier effect hinders the diffusion of water molecules through the composite material. Another notable characteristic of SiC is its inherent hydrophobicity, which enables it to reject water naturally.

Moreover, the inclusion of SiC nanoparticles predominantly diminishes the water absorption rate in composites S4, S5, and S6. Consequently, the composite can absorb only a finite quantity of water before reaching saturation.

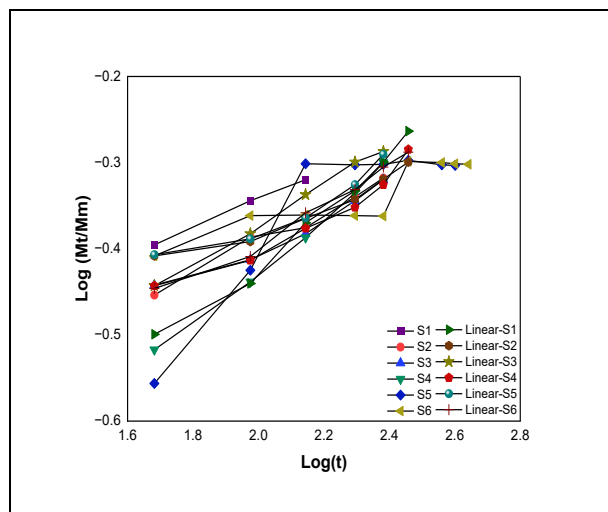


Fig. 5: Diffusion case fitting plots for salt water

Fig. 4 illustrates the diffusion parameter 'n' for various composites submerged in pure water, whereas Fig. 5 presents the corresponding data for saltwater. The diffusion parameter 'n' remains consistently below 0.2–0.4 throughout all cases, and the fitting plot indicates that all materials examined adhere to Fick's law. The composites have absorbed sufficient water to attain saturation.

Three distinct processes influence the rate of water diffusion into the composite material reinforced with natural fibers. Water molecules initially occupy the interstices between polyester resin molecules. The water molecules are subsequently transported to the cracks and voids inside the composite. The final phase is enlarging

the natural fiber by traversing minute cracks in the host material.

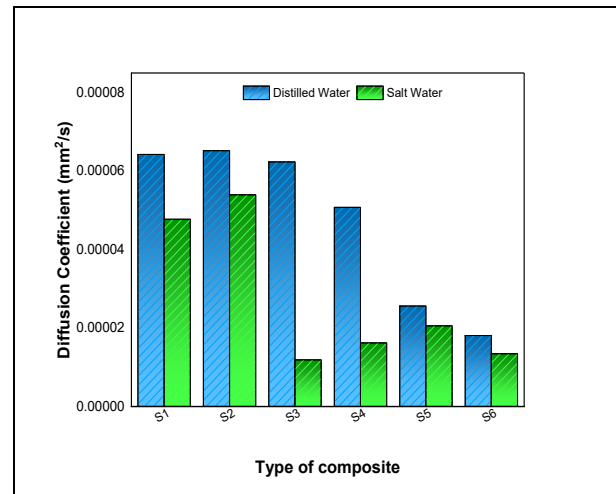


Fig. 6: Diffusion coefficient of natural composite under different fluid immersions

Submerging specimens in distilled water yields a higher diffusion coefficient for natural fibers than that observed in saltwater as illustrated in Fig. 6. The presence of salt molecules in saltwater hinders diffusion within the natural composite, therefore accounting for this difference. Consequently, natural fibers have a greater diffusion coefficient when submerged in pure water compared to saltwater.

Composites reinforced with many fibers have greater resistance to dispersion than those reinforced with a single strand. The incorporation of SiC nanoparticles in the matrix materials considerably diminishes the diffusion coefficient when employing a synthetic filler with a natural composite. The hybridization process and the use of SiC enhance resistance to water absorption and diffusion.

3.2 Tensile Strength and Tensile Modulus

Fig. 7 illustrates the tensile modulus and tensile strength of the composite material during the water absorption process. Tensile strength and modulus tests were conducted on specimens that have absorbed dry, distilled, and saltwater upon reaching the saturation stage of moisture absorption for natural composites.

The same specimens utilized for the moisture absorption test were employed in these experiments as well. Relative to the tensile strength of the dry specimen, the immersion of the S1, S2, S3, S4, S5, and S6 composites in distilled water leads to reductions of

34.56%, 39.31%, 26.79%, 25.75%, 28.57%, and 25.18%, respectively. The occurrence of swelling and porosity due to moisture absorption may impair these attributes.

Specimens submerged in saltwater exhibited a significant decline in mechanical characteristics relative to dry specimens. Notable reductions of 34.05%, 64.12%, 28.76%, 26.94%, 44.50%, and 36.42% were recorded for S1, S2, S3, S4, S5, and S6 composites, respectively, when submerged in a saltwater solution, in comparison to dry specimens. The CG fiber-reinforced composite demonstrated the most significant reduction in strength when immersed in seawater.

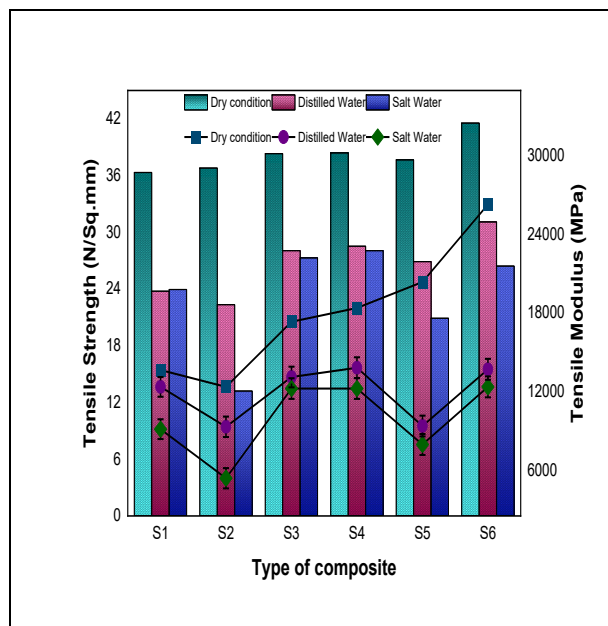


Fig. 7: Tensile strength and tensile modulus of the composites

In the same underwater settings, SiC-based composites (S4 and S6) exhibited minimal loss in tensile properties relative to pure natural composite materials (S1, S2, and S3). The benefits of the nano filler, particularly its elevated surface area, indicate that the introduction of synthetic filler diminished water absorption and improved tensile strength. Submersion in distilled water caused a smaller reduction in tensile strength compared to saltwater. The difference arises because saltwater contains alkali and alkaline earth metal ions (Na^+ , K^+ , Mg^{2+} , Ca^{2+}) that enhance water ingress at the fiber–matrix interface. These ions promote osmotic pressure gradients, accelerate fiber swelling, and weaken interfacial bonding, thereby facilitating microcrack formation in the polymer matrix. Similar observations have been reported in studies on natural fiber composites exposed to marine environments, where ionic species

were found to intensify degradation and reduce tensile performance (Velmurugan *et al.* 2023).

The tensile modulus of the S1, S2, S3, S4, and S6 composites exhibited reductions of 33.09%, 56.47%, 29.38%, 33.48%, and 60.95%, and 52.99%, respectively, when exposed to distilled water compared to the dry specimens. The identical composites exhibited decreases of 9.41%, 24.68%, 24.29%, 24.81%, 54.01%, and 47.91%, following immersion in seawater. This indicates that submerging the composites in distilled water leads to a less significant reduction in tensile modulus compared to immersion in saltwater. In a previous study, polypropylene composites reinforced with alkali- and silane-treated *Calotropis gigantea* fiber (10–40 wt%) exhibited optimal strength at 40 wt% reinforcement. The composite demonstrated superior mechanical exhibiting a tensile strength increase of 54.2% (Zaman and Khan, 2023).

3.3 Flexural Strength and Flexural Modulus

Fabricating materials with elevated flexural strength is crucial for various applications. This study compared specimens lacking moisture (dry) with those subjected to distilled water and saltwater to assess the effect of moisture on different natural fiber reinforced composites. Comparing the two reveals the impact of moisture exposure on the flexural strength properties of the composites. It further underscores how SiC nanoparticles improve flexural strength and flexural modulus properties in both instances of moisture exposure. The flexural modulus and flexural strength of the moisture-absorbed composites are presented in Fig. 8 and 9, respectively.

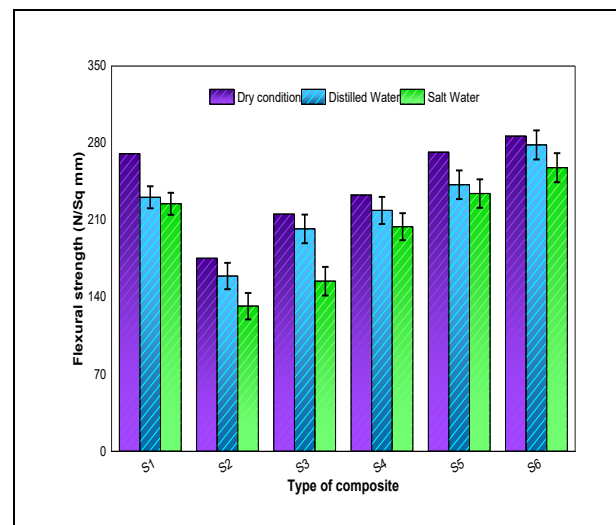


Fig. 8: Flexural strength of composites

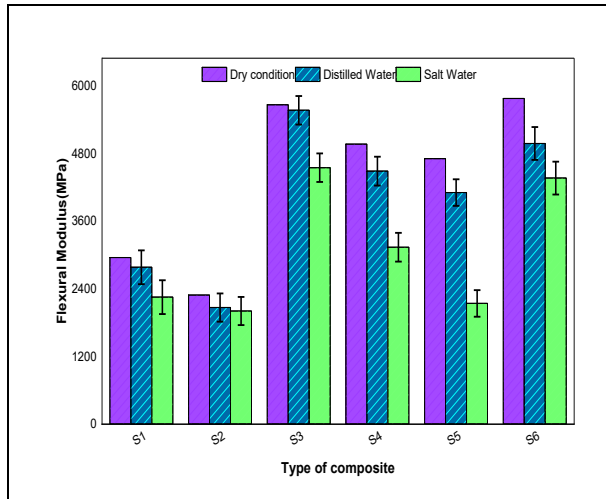


Fig. 9: Flexural modulus of composites

The flexural strengths of composites reinforced with S1, S2, S3, S4, and S6 decreased by 14.52%, 10.71%, 5.81%, 6.31%, 10.44%, and 3.79%, respectively, upon immersion in distilled water. In contrast, submerging the same composites in saltwater diminished their flexural strength to a greater extent than immersion in distilled water (16.80%, 26.08%, 27.98%, 12.31%, 13.41%, and 9.41%, respectively). Similarly, mechanical performance of bamboo fiber/epoxy composites enhanced with SiC particles was investigated. Incorporating 10 wt% SiC improved flexural strength by 13% (Saravana *et al.* 2025).

The reduction in flexural strength was less pronounced across all composite types with the inclusion of SiC nanoparticles. This reinforcement exhibited minimal deterioration, demonstrating that SiC nanoparticles enhance the mechanical characteristics of composites, even under moisture exposure.

The flexural modulus exhibited a more pronounced decrease in composites exposed to saltwater than in those subjected to pure water, indicating that environmental factors affecting mechanical properties are conditionally dependent. This can be attributed to the action of chloride and other ions in saltwater, which accelerate the formation of microcracks in the matrix and promote fiber–matrix debonding. Since flexural loading subjects the outer composite layers to maximum tensile and compressive stresses, even minor interfacial defects become critical failure initiation sites. In addition, osmotic pressure generated by dissolved ions enhances water ingress, further weakening the interfacial region. These combined effects explain why saltwater immersion has a stronger detrimental impact on flexural properties than distilled water.

3.4 Fracture Morphology

Fig. 10(a) depicts a fragmented surface characterized by a mixture of smooth matrix areas, voids, and regions of fiber-matrix adhesion for composite sample S1. The smooth sections denote areas of matrix failure and weak adhesion, whereas the observable joined fibers denote localized strong fiber-matrix contact that facilitated stress transfer. Voids are evident and have arisen from inadequate resin infiltration and air trapping during manufacturing, serving as stress concentrators under tensile loading. In a literature study, SEM examination demonstrated morphology, substantiating the importance of Cyperus fiber in tribological applications by revealing improved fiber–matrix adhesion, reduced surface damage, and enhanced resistance to material removal under sliding conditions (Rajini *et al.* 2021).

Fig. 10(b) displays significant fiber fracture and matrix failure, together with the presence of voids in S2 composite samples. This shows that stress transfer from the matrix to the fibers was efficient, leading to fiber rupture instead of total pull-out. Nonetheless, the matrix portions exhibit brittle cracking, a prevalent characteristic of epoxy subjected to tensile stress. The presence of fiber fracture and void-induced debonding indicates a heterogeneous fracture mechanism in the hybrid composite.

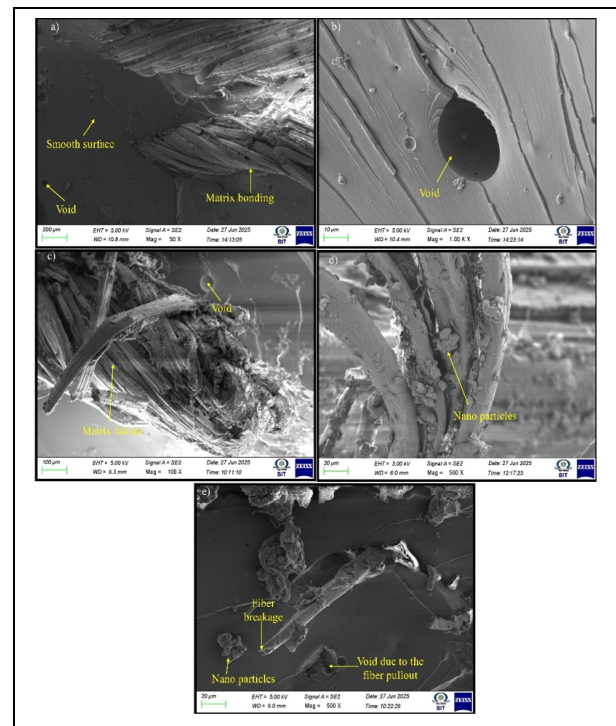


Fig. 10: SEM images of S1, S2, and S4 composites

Fig. 10(c) illustrates the SEM image of S4 composite. The presence of SiC nanoparticles in the fracture zone validates their function in filling interfacial voids and augmenting bonding strength. Nonetheless, the observable void indicates that, despite the incorporation of nanoparticles, certain vulnerable areas remained, potentially leading to fracture formation and expedited failure.

Fig. 10(d) illustrates fiber surfaces combined with SiC nanoparticles, which augment roughness and facilitate mechanical interaction between the fiber and matrix. This robust adhesion enhances tensile strength by restricting fiber slippage and promoting fiber breakage as the primary failure mechanism. The deposition of such nanoparticles illustrates their reinforcing impact by enhancing load transmission and crack resistance.

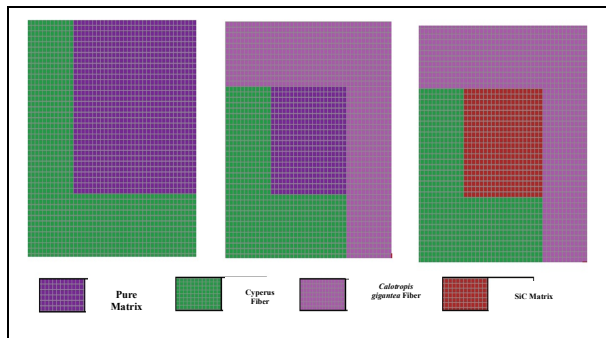


Fig. 11: Elastic properties of finite element models for matrix and fibers

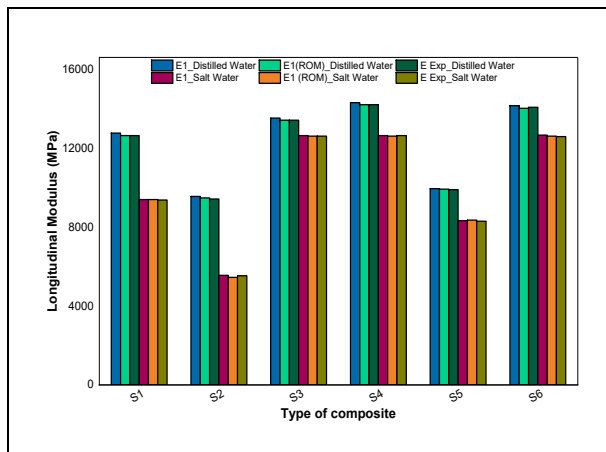


Fig. 12: Variation of longitudinal modulus

Fig. 10(e) illustrates fiber rupture, voids resulting from fiber pull-out, and the presence of nanoparticles along the fractured fibers of S5. The voids indicate localized weak zones; yet, the concurrent fiber fracture and nanoparticle dispersion imply that the interfacial adhesion was markedly enhanced by SiC reinforcement. The river

patterns and uneven surfaces in this area suggest brittle fracture development, which is impeded and diverted by the hybrid fiber–nanoparticle reinforcing system. These morphological improvements directly explain the reduced moisture uptake and the superior tensile and flexural properties observed in SiC-filled composites compared to unmodified systems.

4. Finite Element Analysis of Moisture Effect of Natural Composites

The finite element (FE) models simulate the behavior of composites reinforced with natural fibers under various stresses by implementing appropriate boundary conditions. Crucial elements for defining the mechanical properties of the material, these boundary conditions facilitate the computation of both major and minor Poisson's ratios, in addition to longitudinal and transverse Poisson's ratios.

The finite element model determines the longitudinal modulus by applying uniform pressure in the fiber-aligned direction and utilizing Hooke's law. Utilizing the identical finite element model, the transverse modulus was obtained by exerting a load in the transverse direction. This method allows for the assessment of the material's stiffness in a direction orthogonal to the fiber orientation.

To guarantee the accuracy of the FE model, the analytical and experimental results were used in conjunction with the rule of mixtures. The transverse modulus of the same composite utilizing the inverse rule of mixtures was evaluated. Fig. 12 illustrates the experimental data compared with the expected transverse modulus derived from the finite element model.

All composites subjected to saltwater exhibited a substantial reduction in transverse modulus relative to longitudinal modulus, and this reduction was statistically significant. Specifically, as illustrated in Fig. 13, the transverse modulus of the *Calotropis gigantea* fiber-reinforced polymer composite decreased by 6.64% when subjected to saltwater in comparison to pure water. The use of SiC mitigated this decline to 2.21% under identical experimental conditions. Integrating SiC into composites enhances their transverse modulus, an essential attribute for design, and alleviates the adverse effects of moisture exposure.

Fig. 14 and 15 illustrate the variations in both the major and minor Poisson's ratios of composite materials. The material's deformation under stress,

namely its lateral expansion or contraction relative to its axial elongation or compression, dictates these ratios. The primary and secondary Poisson's ratios of composite materials immersed in saltwater exceed those of those immersed in pure water. The nature of environmental exposure and its influence on the material's behavior are the determinants of this variance. Immersing the composite in saltwater results in greater transverse distortion than longitudinal displacement in the specimens. This indicates that under loading, the material will exhibit greater expansion or contraction laterally than axially. Consequently, specimens aged in saltwater demonstrate a significant elevation in the minor Poisson's ratio, which quantifies the relationship between axial elongation and lateral contraction.

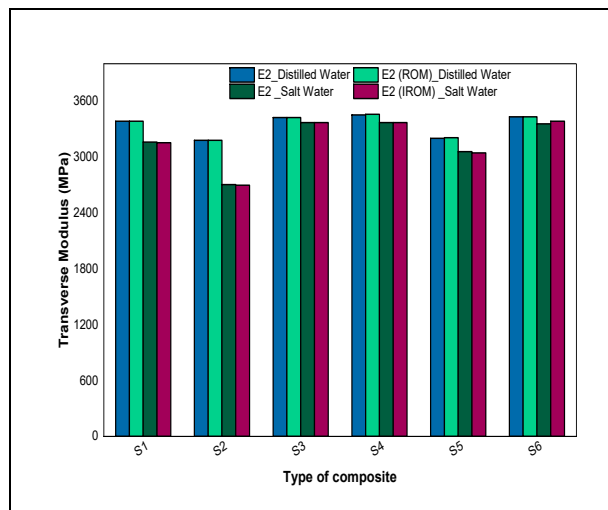


Fig. 13: Variation of transverse modulus

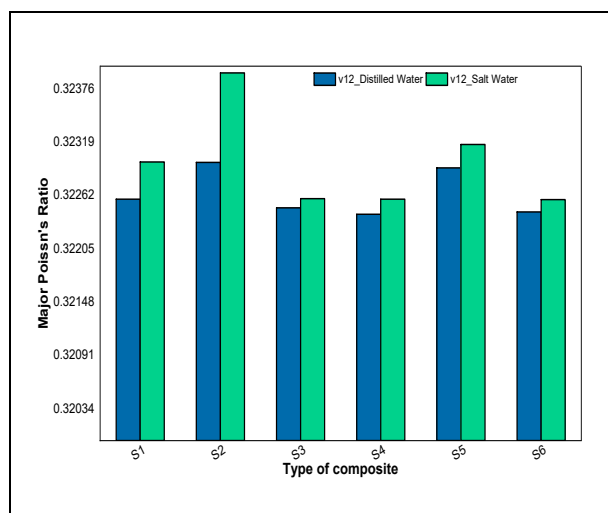


Fig. 14: Variation of major poisson's ratio

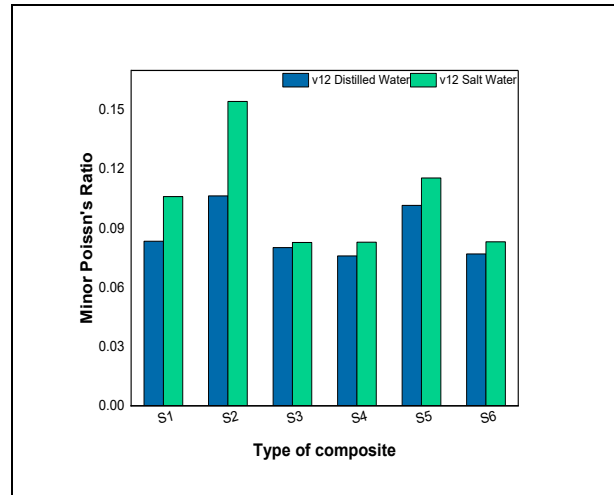


Fig. 15: Variation of minor poisson's ratio

5. CONCLUSIONS

This study showed that polyester composites reinforced with *Cyperus* and *Calotropis gigantea* fibers display distinct moisture absorption patterns, with *Cyperus* composites exhibiting the highest uptake (8–9%), *Calotropis* lower values, and hybrids the least (4–6%). Saltwater caused greater moisture absorption and more pronounced loss in mechanical properties than distilled water. Adding SiC nanoparticles reduced moisture uptake by about one-third and improved tensile and flexural strength retention. The SEM analysis confirmed fewer voids and improved fiber–matrix bonding in SiC-filled systems. Overall, SiC-modified hybrid natural fiber composites appear promising for outdoor and marine applications, with future work needed on long-term durability, additional nanofillers, and predictive modelling strategies.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization and Supervision - P. Satishkumar, Rajasekaran Saminathan, and Haitham M. Hadidi. Methodology and Experimental Design - M. Vadivel, and V. Y. Ganvir. Composite Fabrication and Mechanical / Moisture Absorption Testing - M. Vadivel, Vijayakumar Sivasundar, S. Mayakannan, and J. Sandhiya Jenifer. Data Analysis and Interpretation – P. Satishkumar, V. Y. Ganvir, and Haitham M. Hadidi. Original Draft Preparation - M. Vadivel, P. Satishkumar. Review and Editing - Rajasekaran Saminathan, Vijayakumar Sivasundar, J. Sandhiya Jenifer, and S. Mayakannan.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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