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Impact of Dual-Fiber Reinforcement on the Mechanical and Thermal Properties of Vinylester Composites

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Abstract: Rising ecological concerns over synthetic fibers and petrochemical polymers have accelerated the search for sustainable alternatives in composite development. This study investigates a novel hybrid vinyl ester (VIE) composite reinforced with Borassus flabellifer and Cocos nucifera fibers at varying loadings (10–30 wt%). The composites were fabricated and systematically characterized for their mechanical, thermal, and moisture resistance properties. Results revealed that the 30 wt% hybrid composite exhibited the highest property enhancements, with tensile strength improving from 6 MPa (neat VIE) to 24 MPa, flexural strength from 238 MPa to 566 MPa, impact resistance from 6 kJ/m² to 34 kJ/m², and hardness from 9 HRB to 67 HRB. Thermogravimetric analysis demonstrated enhanced thermal stability, indicating better resistance to thermal degradation. Water absorption studies confirmed reduced moisture uptake compared to neat VIE, highlighting the improved interfacial bonding between fibers and matrix. These findings demonstrate that Borassus flabellifer and Cocos nucifera fibers effectively enhance the physico-chemical performance of VIE, making the hybrid composites suitable for diverse structural and functional applications in aerospace, automotive, marine, and sports equipment industries.

Key words: Borassus flabellifer, Cocos nucifera, Vinylester (VIE), Thermal and Mechanical Properties, Applications.

INTRODUCTION

Composite materials are engineered by combining two or more different materials, each retaining its own chemical and physical properties, to form a superior material with enhanced characteristics. These materials are increasingly used in modern engineering due to their exceptional strength-to-weight ratio, high thermal resistance, and excellent corrosion and wear resistance. As a result, composites are gradually replacing conventional materials in industries such as automotive, aerospace, marine, renewable energy, and sports equipment manufacturing. Based on the matrix material, composites can be broadly categorized into PMCs, MMCs and CMCs. In recent years, the use of polymer matrix composites (PMCs) has increased dramatically, creating new markets (Chia & Chen 2021).

Composite materials utilize various types of fibers as reinforcement, which can be either natural or synthetic. Artificial fibers don't break down in the environment because they are made of chemicals or petroleum. Over the past 20 years, there has been a sharp rise in the utilization of cellulosic fiber materials as reinforcing fillers in polymer composites. The composites made of cellulosic fibers decompose spontaneously in soil after usage and are biodegradable. Consequently, cellulosic fiber reinforced plastics have gained popularity. When compared to synthetic fibers like glass, these fibers have better mechanical qualities like flexibility, stiffness, and modulus. Coir, sisal, hemp, jute, wood, sawdust, palm, kenaf, pineapple leaf fiber, banana, abaca, bamboo, and wheat straw are some of the materials that can be used to make cellulosic fibers. Cellulosic fibers have several advantages, such as low cost, wide availability, low density, little wear on processing equipment, and healthier working conditions as stated by Arpitha et al. (2021).

The matrix material used in this research was vinylester (VIE). The vinylester was selected because of its outstanding properties of strength, stability, durability, and corrosion resistance. Moreover, VIE is less expensive than epoxy resins. The mechanical properties of VIE are similar to those of epoxy resins in comparison. Further, when compared to epoxy resin, the vinyl ester can be easily handled at room temperature and provides greater control over cure time and reaction conditions. However, one of the drawbacks was the brittle nature of VIE resin, which limits their suitability in certain applications. One interesting method for strengthening composite materials is fiber hybridization. Compared to non-hybrid composites, these hybrid composites provide a superior balance of mechanical properties by integrating two or more fiber types. Research on fiber hybrid composites started a few decades ago. To state, Akash et al. (2018) investigated the mechanical properties of hybrid composites comprising epoxy polymer loaded with sisal and hemp. It has been reported that the hybridization effect of sisal and hemp enhanced the mechanical properties of vinyl ester. Further, their report concluded that sisal and hemp fibers show promise as reinforcement for low-cost bio-composites with good strength-to-weight ratios. The tensile and flexural characteristics of hybrid composites made of flax, jute, and sisal fibers loaded with epoxy polymer were investigated by Benkhelladi et al. (2020) It has been said that the developed hybrid composite exhibited superior mechanical properties compared to the individual fiber composites. Nasimudeen et al. (2021) investigated the mechanical characteristics of natural fiber hybrid composites based on vinyl ester in a different study. In this study, natural fibers such as banana, jute, and kenaf were hybridized in different stacking sequences in vinyl ester. It was concluded that the hybrid composites demonstrated the highest mechanical properties and it was concluded that the hybridized fiber is a potential candidate for the light weight structural applications. The research on fiber hybrid composites clearly indicates that combining different natural fibers within a polymer matrix significantly enhances the mechanical properties of the resulting materials. Hence, this study aims to develop a hybrid composite comprising natural fibers embedded in a polymer matrix.

Hence, in this study, Borassus flabellifer and Cocos nucifera were selected to enhance the physical and chemical properties of VIE. Borassus flabellifer, commonly known as the Palmyra palm, is a tall and robust tree belonging to the Arecaceae family, widely found in South and Southeast Asia. It holds significant cultural, economic, and medicinal importance in many tropical regions. The tree is highly valued for its versatility, as nearly every part of it can be utilized. The applications of Borassus flabellifer were in the Food and beverage Industry, craft and construction, agriculture and traditional medicine (Yogaraj et al. 2022). Coir fiber is a natural lignocellulosic fiber obtained from the outer husk of coconuts (Cocos nucifera) and is recognized for its durability, stiffness, and environmental sustainability. Thermally, coir fiber offers moderate stability and is suitable for low to medium-temperature applications (Bhardwaj et al. 2021). Its natural resistance to rot and degradation under humid conditions makes it ideal for long-term applications such as geotextiles, erosion control, and soil stabilization. The applications of Cocos nucifera fiber include automotive industry, construction and packaging sectors, geotextile industry, agriculture and horticulture, and furnishing and household industry. The synergistic effect of the fibers from Cocos nucifera and Borassus flabellifer on VIE has not yet been reported. Tensile, flexural, impact, and hardness properties of the VIE-based laminates made using Borassus flabellifer and Cocos nucifera fibers were mechanically analyzed. To confirm the composites viability for industrial applications, tests were also conducted on their swelling and thermal absorption characteristics.

Recent advancements in natural fiber composites have demonstrated their growing potential in structural and semi-structural applications, especially when hybridization techniques are employed to balance mechanical and environmental performance (Tayfun et al. 2023; Ojha A & Ahire, 2023). Studies also emphasize the compatibility and interfacial adhesion improvements achieved by hybridizing lignocellulosic fibers in thermoset matrices like vinyl ester and epoxy (Yuan et al. 2024). Furthermore, hybrid fiber composites have been extensively investigated for automotive, marine, and construction applications due to their tailored strength-to-weight ratios and sustainability advantages (Ali et al. 2022a).

MATERIALS AND METHODS

Materials

General purpose vinylester resin was provided by Covai Seenu Pvt. Ltd., Coimbatore, Tamil Nadu. Table I provides the characteristics of VIE. The same supplier provided the methyl ethyl ketone peroxide (catalyst), cobalt naphthenate (accelerator), and N, N-dimethylaniline (promoter). The grade of vinyl ester used in this study was general-purpose vinyl ester resin (VE 411), widely used in polymer composite manufacturing due to its excellent thermal stability, chemical resistance, and compatibility with natural fibers (Shanmugam et al. 2023).

Extraction of Borassus flabellifer and cocos nucifera fiber

The fruit of Borassus flabellifer was submerged in water for three days, and then it was repeatedly flushed with tap water to get rid of any greasy residue. The fibers were removed from the water and allowed to dry in the shade for a few days. Further, it was dried in the sun once more to eliminate any remaining moisture. To get rid of the undesirable short and tiny fibers, dried fibers were rammed. (Rathore et al. 2022).

In order to obtain Cocos nucifera, mature coir must first be dehusked and then retted, which involves soaking the husks in water to remove the fibers. After the husks have been

Table I. **The Properties of Borassus flabellifer and Cocos nucifera.**

Properties	Borassus flabellifer	Cocos nucifera
Density (g/cm3)	0.7-1.2	1.15-1.45
Tensile Strength (Mpa)	180-320	100-250
Elongation at break (%)	1.5-2.5	15-40
Youngs Modulus (Gpa)	4.5-12.5	4-6

softened, the fibers are separated by beating and then they are thoroughly cleaned and dried. For making membranes, the dried fibers are sorted and graded according to their length and strength (Sahu et al. 2023). The extracted Borassus flabellifer and Cocos nucifera fiber are shown in Figure 1a and their properties are indicated in Table II.

Manufacture of composites

The pure VIE and VIE composite samples reinforced with Borassus flabellifer and Cocos nucifera fibers were created using a conventional hand-lay molding technique (216 mm × 101 mm × 35 mm) as shown in Figure 1b. In the hand lay-up process used for composite fabrication, the fibers were carefully aligned in a unidirectional manner along the length of the mold cavity to promote consistent mechanical behavior and efficient load transfer. To maintain uniformity, the fibers were manually laid in layers, ensuring minimal entanglement and avoiding cross-orientation. While complete automation was not employed, consistent placement and visual inspection were used throughout the lay-up to reduce variation and promote structural uniformity. This alignment strategy supports better tensile and flexural performance and is in line with recent studies that emphasize the role of fiber orientation in the performance of natural fiber composites (Singh et al. 2024).

The selection of 10%, 20%, and 30% fiber loadings was based on both preliminary experimental trials and supporting evidence from literature. Initially, composites were fabricated with fiber contents of 10%, 20%, 30%, and 40% by weight. However, the 40% fiber-loaded samples exhibited poor resin wettability, higher void content, and reduced mechanical integrity, likely due to fiber agglomeration and insufficient matrix encapsulation. This made the 40% composition mechanically and structurally infeasible for further consideration. As a result, only the 10–30% fiber loading range was selected for detailed characterization. These levels provided a balance between improved mechanical properties and acceptable processability. Similar findings have been

a b

Figure 1. **a) Representation of utilized handlay molding, extracted Borassus flabellifer and Cocos nucifera fiber b) Representation of developed VIE composites.**

Table II. **The characteristics of Vinyl Ester.**

Characteristics	Value
Density (g/cm3)	80
Tensile Strength (Mpa)	5
Viscosity (mPas)	570
Potlife (minutes)	19

reported in prior studies where optimal performance was observed below 35 wt% fiber content in hand lay-up composites (Patil et al. 2024).

The various weight concentrations used to fabricate VIE composites are shown in Table III. Initially, the mold cavity was filled with the fiber's known weight following weighing. The catalyst, promoter, and accelerator (2% of the resin weight) were then added to the liquid resin in line with the weight ratio. The aligned fibers were then put in the mold cavity and covered with the premixed resin. The closing die was put on top of the fibers after the resin flow was complete. A 5 kg weight was applied during the compression process after the upper die was closed. For comparison, all composite fabrications used a weight of 5 kg. The curing procedure was carried out at room temperature for the whole day to improve bonding. The developed VIE composites comprising Borassus flabellifer and Cocos nucifera fiber are indicated in Figure 2.

Characterisation

Mechanical Testing Analysis

According to ASTM standard D 638-10, the universal testing apparatus was used to measure the composite's tensile characteristics. For unidirectional fiber-oriented composites, rectangular specimens of 165 × 17 × 3 mm were examined for tensile pull with a span length of 20 mm and a crosshead speed of 2 mm/min. According to ASTM D-790 standards, the three-point bending method was used to assess the flexural qualities of composites utilizing the same universal testing apparatus. Test specimens (100 × 10 × 3 mm) are subjected to testing with a 10 kN load cell and a crosshead speed of 2 mm/min. Additionally, low velocity impact tests were conducted in an impact tester in accordance with ASTM A370 to evaluate the impact strength of the composites. The specimen with dimensions of 55 mm × 10 mm × 10 mm was put into the testing device and left there to be broken or fractured by the pendulum. By doing the impact test, we can determine the energy needed for the material to shatter, revealing the material's toughness. The correlation between strain rate, fracture rate, and material ductility can also be investigated using the impact test. For every evaluation, a minimum of three samples are examined.

Table III. **VIE composites are made using different range of weight concentrations.**

S.NO	Sample Notation	Vinylester Weight Concentration (%)	Borassus flabellifer Weight Concentration (%)	Cocos nucifera fiber Weight Concentration (%)
1	VIE	100	-	-
2	VIE10	90	5	5
3	VIE20	80	10	10
4	VIE30	70	10	10

SEM Investigation

Following mechanical testing, the cracked surfaces were inspected at different magnifications using a scanning electron microscope (JEOL JSM-6480LV). All samples were covered with a 4 nm thick layer of gold before being analyzed using a scanning electron microscope. The gold coating was accomplished to obtain clear images. The scanning and imaging were carried out at an acceleration voltage between 10 and 30 kV.

Hardness Test

By applying a steady load of 50 grams of force for 30 seconds of dwell time, a Leitz micro-hardness tester was used to measure the hardness of all the manufactured VIE composites in accordance with the ASTM E384 standard. Made of diamond,

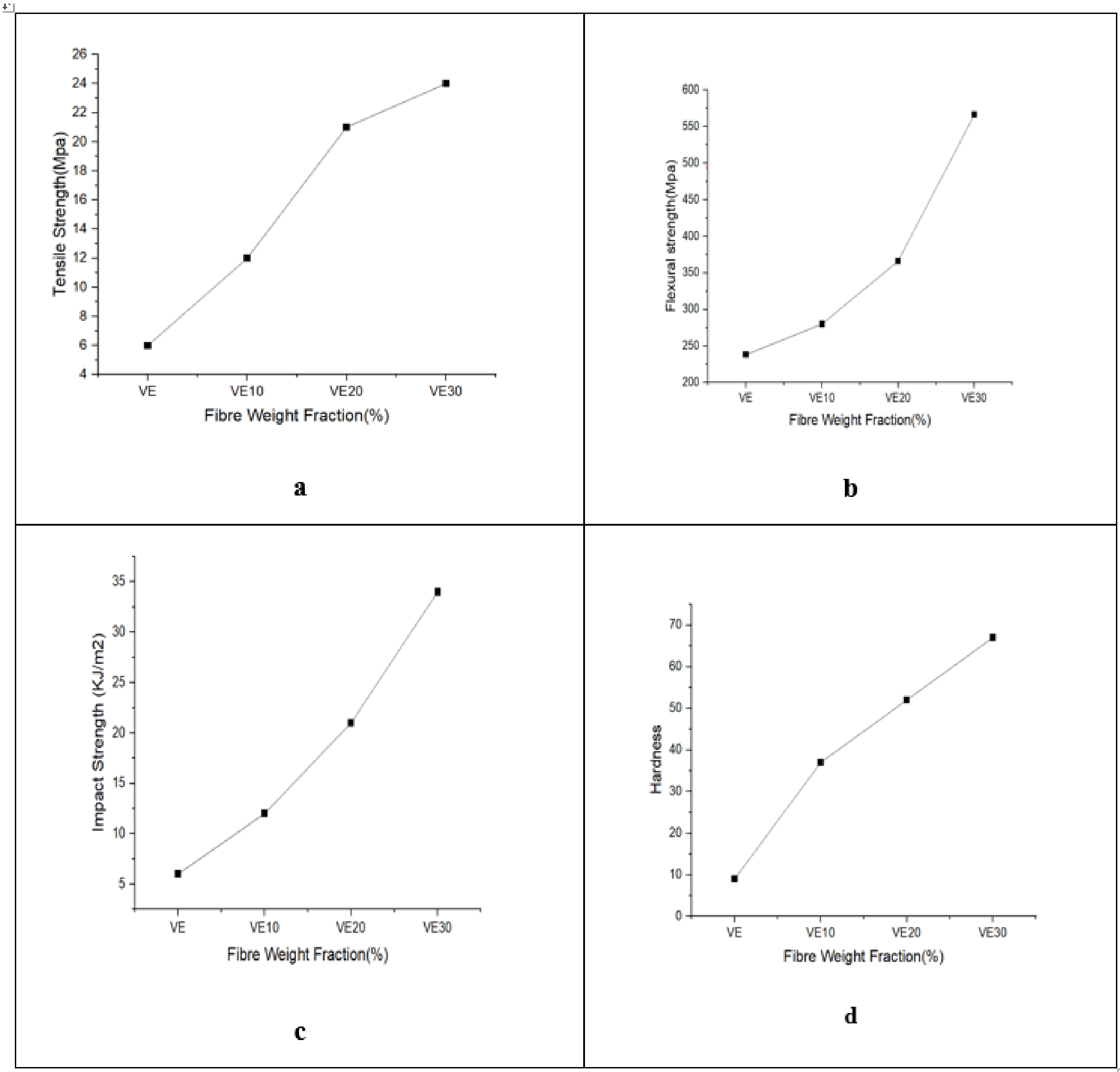

Figure 2. **a) Tensile strength, b) Flexural strength, c) Impact strength and d) Hardness of VIE and VIE loaded 10, 20 and 30 wt% of Borassus flabellifer and Cocos nucifera fiber.**

the indenter had a right pyramid shape, a square base, and an apex angle of 136°. The hardness of each prepared VE composite slab was measured using test specimens measuring 25 mm × 25 mm × 3.5 mm. After the test specimens were securely held in place and the lens was adjusted to obtain a sharp image at its focal length, the indentation was created using predetermined settings. Hardness tests were conducted on a minimum of three samples in order to achieve a statistically significant result for each condition. Prior to testing, samples are conditioned at 23 ± 2°C and 50 ± 5% relative humidity, under loads ranging from 100 to 500 gf.

Water Absorption Test

The water absorption investigation was carried out in compliance with ASTM D570-98 guidelines. In different containers, three samples of each developed membrane were initially weighed and immersed in distilled water at room temperature. The water absorption test was performed for 1, 4 and 7 days. At a particular time period, the immersed samples were taken out, water was wiped off and they were weighed. The water absorption test was calculated according to previously reported literature (Razak et al. 2022).

Thermogravimetric Analysis

The thermal stability of VIE based composites was examined using TGA equipment attached with DTA. In a controlled environment, the rate of change in weight and quantity as a function of temperature or time was ascertained using TGA. About 3 mg of the prepared samples were deposited in an alumina crucible for this examination using a precision balance. The heating was done at ambient temperature in a nitrogen environment. The samples were heated at a rate of 10°C/min from 0°C to 1000°C in order to achieve thermal stability. Each temperature point's weight residue was measured, and the results were exported into an Excel spreadsheet.

Statistical Analysis

Each experiment was conducted three times, and GraphPad Prism was used to analyze the statistical results. The mean ± SD indicates the results of each experiment. In the case of qualitative experiments, the pictures were shown as illustrations.

RESULTS AND DISCUSSION

Tensile Analysis

Using a universal tester, the stress-strain curves of pure VIE and VIE loaded with 10%, 20%, and 30% of Borassus flabellifer and Cocos nucifera fiber were acquired. The tensile strengths achieved for pure VIE, VIE loaded with 10%, 20%, and 30% of Borassus flabellifer and Cocos nucifera fiber are shown graphically in Figure 2a. Pure VE was reported to have an average tensile strength of 6 MPa, while VIE loaded with 10%, 20%, and 30% Borassus flabellifer and Cocos nucifera fiber had tensile strengths of 12 MPa, 21 MPa, and 24 MPa, respectively. The enhancement percentage for 10 wt%, 20 wt%, and 30 wt% loading of Borassus flabellifer and Cocos nucifera fiber was reported to be accordingly. The tensile findings clearly show that the addition of Borassus flabellifer and Cocos nucifera fiber enhanced the tensile strength of VE. Further, it has been observed that the increase in fiber content loading favors the increase in tensile strength of VIE. The improvement in tensile strength of the VIE was due to the presence of Borassus flabellifer and Cocos nucifera fiber. Stalin et al.(2020) investigated vinyl ester composites reinforced with Tamarind seed and observed an increase in tensile strength with its addition which resembles our results. They conclude the reason was due to improved fiber-matrix interaction. Hence, in our study, the Borassus flabellifer and Cocos nucifera fibers have formed a good interaction with the VIE matrix which might result in the increase in the tensile strength.

Flexural Analysis

The flexural properties of the fabricated hybrid composites were determined using a universal tester. The obtained data is presented graphically in Figure 2b. The pristine VIE showed a flexural strength of about 238 MPa, while VE loaded with 10 wt%, 20 wt%, and 30 wt% exhibited flexural strength of 566 MPa, 366 MPa, and 280 MPa, respectively. The enhancement percentage for 10 wt%, 20 wt%, and 30 wt% loading of Borassus flabellifer and Cocos nucifera fiber was reported accordingly. It can be seen that the addition of Borassus flabellifer and Cocos nucifera fiber improved the flexural properties of pure vinyl ester. Similar to the tensile analysis findings, the flexural strength increases with the content of Borassus flabellifer and Cocos nucifera fiber. The hybridization of Borassus flabellifer and Cocos nucifera fiber creates a synergistic effect, where the strengths VIE matrix leading to enhanced flexural strength. Subbarayalu et al. (2024) studied the mechanical properties of vinyl ester hybrid composite laminates reinforced by different weight content of screw pine and glass fiber. It was found that the addition of screw pine and glass fiber improved the flexural strength of vinylester. Further, it was revealed that the increase in weight of screw pine and glass fiber showed an increase in flexural strength which correlates with our discoveries. Hence, in our study, the increase in flexural strength was due to the presence of Borassus flabellifer and Cocos nucifera fiber in the VE matrix.

Impact Analysis

The impact properties of the fabricated hybrid composites were determined using an impact tester. The obtained data was presented graphically in Figure 2c. The pristine VIE showed an impact strength of about 6 kj/m² while VE loaded with 10 wt%, 20 wt%, and 30 wt% exhibited impact strengths of 12 kj/m², 21 kj/m², and 34 kj/m², respectively. The enhancement percentage for 10 wt%, 20 wt%, and 30 wt% loading of Borassus flabellifer and Cocos nucifera fiber was reported accordingly. It can be seen that the addition of Borassus flabellifer and Cocos nucifera fiber improved the impact properties of pure vinyl ester. The increase in impact strength was due to the presence of Borassus flabellifer and Cocos nucifera fibers that act as energy-absorbing reinforcements, effectively distributing the applied impact force throughout the material and minimizing sudden fracture. Razali et al. (2016) prepared composites comprising VE containing roselle fiber. In their study, different weight concentrations (10%, 20%, 30%, and 40%) of roselle fiber were added and investigated their impact performance. It has been reported that the addition of Roselle fiber improved the impact property of vinylester, which resembles our conclusions. Further, in their study, the impact energy was reduced with increasing concentration of roselle fiber and they concluded this reason was due to the decrease in bonding between the vinyl ester and roselle fiber. In our study, our composites showed higher impact properties even at higher weight concentrations, which might be due to the better interfacial bonding between the vinylester, Borassus flabellifer and Cocos nucifera fiber.

SEM Analysis

Following mechanical tests, SEM micrographic was performed for the tensile fractured

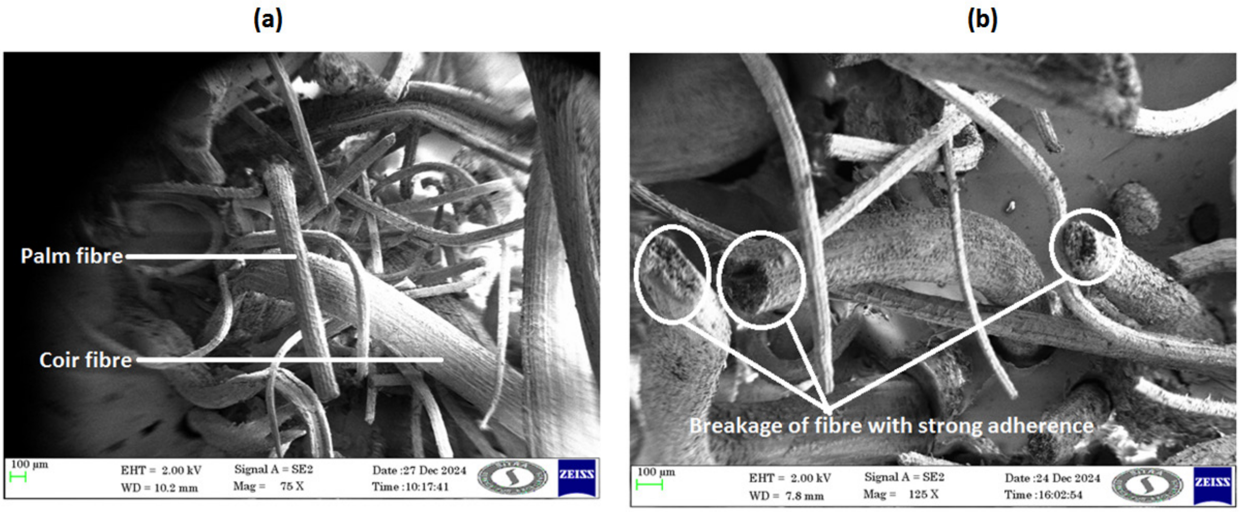

Figure 3. SEM image of VIE composites loaded with 30% Borassus flabellifer and Cocos nucifera fibre during tensile fracture.

samples of VIE composites loaded with 30% Borassus flabellifer and Cocos nucifera fiber and indicated in Figure 3. From the figure, it was evident that the VIE composites loaded with 30% Borassus flabellifer and Cocos nucifera fiber specimen surfaces did not experience filler pull-out or void cavity development and it was due to the presence of Borassus flabellifer and Cocos nucifera fiber. Vetrivel et al. (2025) developed VIE composites comprising sisal and abaca fibers. It has been reported that the added fibers were fully wetted into the matrix, promoting strong adhesion between the filler and the matrix. Consequently, the reason for the enhanced tensile strength of VIE composites loaded with 30 wt% of Borassus flabellifer and Cocos nucifera fiber specimens was due to the strong adhesion between filler and matrix. Moreover, the SEM micrograph of fractured VIE composite samples with 30 wt% of Borassus flabellifer and Cocos nucifera fiber after flexural strength testing was presented in Figure 4. The image reveals minimal voids and fiber pull-out, indicating improved bonding between the filler and the matrix at 30 wt% fiber loading (Vetrivel et al. 2025). These observations contribute to the composite's maximum flexural strength at this fiber concentration. Furthermore, the cross-sectional surfaces of VIE composites with 30 wt% of Borassus flabellifer and Cocos nucifera fiber were analyzed using SEM imaging after the impact test, as shown in Figure 5. The SEM micrographs show a good filler-vinyl ester resin interaction with minimal void formation (Vetrivel et al. 2025). These findings are directly related to the composite's increased impact strength at 30 wt% fiber loading.

Hardness Testing

The graphical representation of Figure 2d illustrates the hardness performance of pure VIE and VIE reinforced with 10, 20, and 30 wt% of Borassus flabellifer and Cocos nucifera fiber. It was found that the hardness value of pure VIE was recorded at 9 HRB, while the composites with 10, 20, and 30 wt% Borassus flabellifer and Cocos nucifera fiber exhibited hardness values of 37 HRB, 52 HRB, and 67 HRB, respectively. The enhancement percentage for 10 wt%, 20 wt%, and 30 wt% loading of Borassus flabellifer and Cocos nucifera fiber was reported accordingly. The average hardness test results indicate that incorporating Borassus flabellifer and

Figure 4. SEM image of VIE composites loaded with 30% Borassus flabellifer and Cocos nucifera fiber during flexural fracture.

Cocos nucifera fiber significantly enhances the hardness of pure VIE. Further, a clear trend was observed, where increasing the fiber content led to a significant improvement in hardness. Similar findings were reported by Stalin et al. (2020) who investigated vinyl ester composites reinforced with tamarind seed. Their study demonstrated an increase in hardness with reinforcement, attributing it to improved fiber-matrix interaction. In line with these findings, the enhanced hardness observed in our study, particularly at 30 wt% fiber loading, might be due to the strong interaction between the Borassus flabellifer and Cocos nucifera fiber with the VIE matrix.

Thermogravimetric Analysis

The thermal analysis of VIE composites containing 30 wt% Borassus flabellifer and Cocos nucifera fiber is shown in Figure 6. Appusamy & Dhanalakshmi (2025) reported an initial degradation temperature of pure VIE was around 407°C. In contrast, our study found that the initial degradation temperature of VIE composites loaded with 30 wt% Borassus flabellifer and Cocos nucifera fibers was found to be 377°C, indicating a reduction in initial degradation temperature compared to pure VIE. TGA analysis clearly indicated that the incorporation of Borassus flabellifer and Cocos nucifera fibers changed the thermal behavior of the VIE matrix. The decrease in initial degradation temperature was due to the degradation of volatile compounds found in the Borassus flabellifer and Cocos nucifera fibers. The term volatile compounds found in the Borassus flabellifer and Cocos nucifera fibers refers to low-molecular-weight organic substances such as waxes, oils, tannins, and hemicellulose derivatives naturally present in lignocellulosic fibers. During thermal decomposition, especially in TGA/DTG analysis, these compounds are typically the first to degrade, contributing to the initial weight loss observed at lower temperatures. The presence of such volatiles is a well-documented characteristic of natural fibers like Borassus flabellifer and Cocos nucifera fibers, and their decomposition behavior significantly influences the composite's thermal response (Ali et al. 2022b).

The alteration in thermal behavior confirms their presence in the composite, as noted by

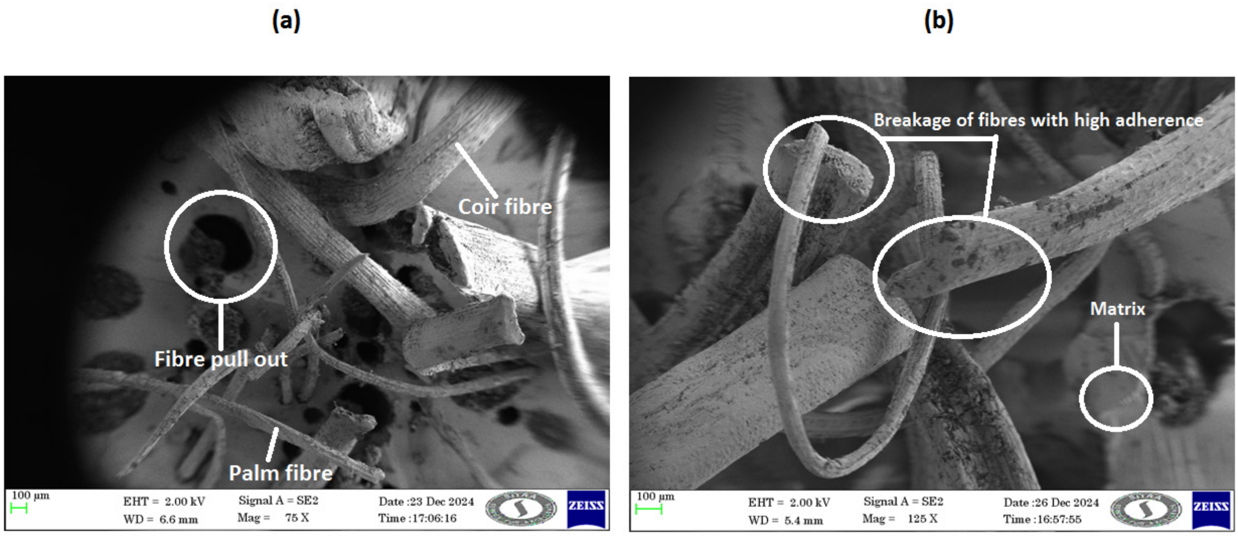

Figure 5. SEM image of VIE composites loaded with 30% Borassus flabellifer and Cocos nucifera fiber during impact fracture.

Mani & Jaganathan (2018). Further, the Tonset, T50, Tmax, Tend and Residue (wt%) data for the VIE composites containing 30 wt% Borassus flabellifer and Cocos nucifera fibers are indicated in Table IV. Residue analysis at the 30% composition level revealed a gradual decrease in residual mass across all thermal parameters. The residue percentage at T_{onset} was 2.6%, dropping to 1.6% at T_{50}, and further reducing to 0.655% and 0.629% at T_{max} and T_{end} respectively. The initial residue at Tonset (2.6%) implies early-stage decomposition, likely due to the degradation of hemicellulose and low-molecular-weight compounds. The reduction to 1.6% at T50 and further to 0.655% at Tmax and 0.629% at Tend highlights the gradual decomposition of cellulose and lignin components. This indicates a progressive breakdown of the organic constituents within the composite matrix, suggesting improved thermal stability. Razali et al. (2016) studied the thermal properties of developed composites comprising vinylester reinforced with roselle fiber. Their findings indicate that the inclusion of roselle fiber enhanced the thermal properties of vinylester. It was shown that an increase in the roselle fiber content in the VIE composites increased the formation of char residue, which resembles our findings. In our study, the demonstrated thermal properties of VIE were due to the reinforcement of Borassus flabellifer and Cocos nucifera fibers.

Further, the DTG analysis was also performed for VIE composites containing 30 wt% Borassus flabellifer and Cocos nucifera, as shown in Figure 10. The weight loss peaks of VIE composites containing 30 wt% Borassus flabellifer and Cocos nucifera fibers were shown in Table V. According to Appusamy & Dhanalakshmi (2025), it has been reported that the weight loss peak in pure VIE was two stages of degradation, one from 360°C and 480°C and another from 520°C and 580°C. In the composite VIE containing 30 wt% Borassus flabellifer and Cocos nucifera fibers, a two-step degradation one was a minor loss and another was a major weight loss. The minor loss occurs from 280°C to 350°C and the major weight loss starts from 385°C to 480°C. It was observed that the disappearance of the second major weight loss peak (520°C to 580°C) in the composite which was seen in the pure VIE. Hence, the disappearance of the second

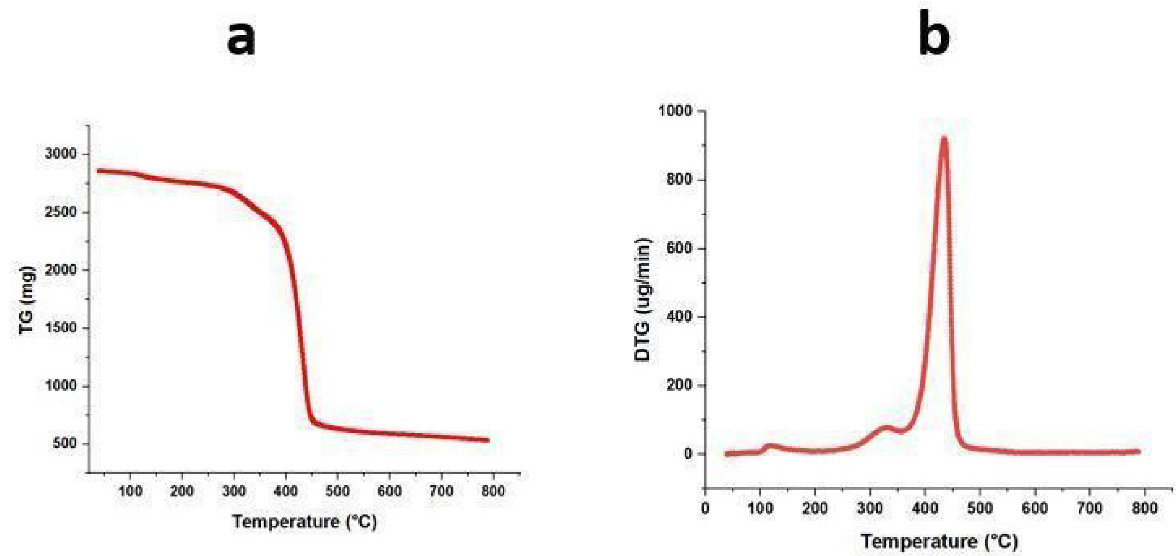

Figure 6. Thermo-gravimetric (TGA) and b) Differential thermal analyses (DTA) curves of VIE composites loaded with 30 wt% Borassus flabellifer and Cocos nucifera specimens.

peak clearly suggests the change in the thermal degradation behavior of pure VIE due to the presence of Borassus flabellifer and Cocos nucifera fibers (Niu et al. 2022). This phenomenon is similar to findings by Jaganathan et al. (2019), who developed polyurethane composites containing corn and neem oil. It was shown that the addition of corn and neem oil resulted in the disappearance of weight loss peaks of PU. Further, their DTG results confirm the presence of corn and neem oil in PU. Hence, in our study, the DTG findings showed a change in weight loss peaks indicating the presence of Borassus flabellifer and Cocos nucifera fiber in the VIE matrix.

Water Absorption Test

The water absorption characteristics of vinyl ester (VIE) composites reinforced with varying fiber contents (10%, 20%, and 30%) were evaluated as shown in figure 7 for 1, 4, and 7 day immersion periods. The results indicate a time-dependent increase in water uptake across all composite types. On Day 1, neat vinylester (VIE) exhibited the highest initial water absorption (8%), while VIE10, VIE20, and VIE30 showed less water absorption of about 7%, 6%, and 5.5%. The lower absorption in VIE30 can be attributed to denser fiber packing or improved interfacial bonding, which limits rapid absorption of moisture. By Day 4, all samples showed increased water absorption compared to Day 1. VIE30 exhibited a slower rate of water absorption (6%) compared to the others, while VIE, VIE10 and VIE20 demonstrated water absorption of 9%, 8%, and 7.5% respectively. On Day 7, the similar trend was observed as reported on Day 1 and Day 4. In summary, while the neat resin (VIE) absorbed more moisture early on, fiber-reinforced composites, especially VIE30, showed delayed water uptake. This behavior highlights the dual role of natural fibers acting as a barrier to the water absorption capability. Ramesh et al. (2022) demonstrates that hybrid composites incorporating natural fibers and specific fillers can achieve lower water absorption rates than standard resins, aligning with my experimental observations.

The dual role of natural fibers acting as a barrier to water absorption capability was due to different possible mechanisms. First, when

Table IV. **VIE composites loaded with 30 weight percent Borassus flabellifer and Cocos nucifera specimens: Tonset, Tmax, Tend, T50, and Residues (wt%).**

Sample	Tonset (°c)	Tmax (°c)	Tend (°c)	T50 (°c)
VIE30	376	504	473	421
Residues(30%)	2.6	0.655	0.629	1.6

Table V. **Weight loss peaks of VIE and VIE composites loaded with 30 wt% of Borassus flabellifer and Cocos nucifera specimens.**

Sample	First Loss curve (°c)	Second Loss curve (°c)
VIE	360 to 480	520 to 580
VIE30	280 to 350	385 to 480

well-dispersed and aligned within the vinyl ester matrix, natural fibers such as *Borassus flabellifer* and *Cocos nucifera* can physically obstruct the capillary pathways through which water typically diffuses. This creates a tortuous path, thereby reducing the rate and extent of water ingress. Second, the strong interfacial bonding between the fibers and the matrix, as evidenced by minimal voids and fiber pull-out in SEM images, limits the formation of micro-channels and interfacial gaps that often facilitate moisture uptake. Therefore, although natural fibers are themselves hydrophilic, their integration into a dense, well-cured matrix enhances the composite's resistance to water permeation by disrupting direct water transport routes and promoting cohesive structure (Tibin et al. 2023).

FTIR Analysis

Fourier Transform Infrared (FTIR) spectroscopy as shown in figure 8 was employed to analyze the chemical structure of both *Cocos nucifera* fiber and *Borassus flabellifer* fiber. In the *Cocos nucifera* fiber spectrum, characteristic absorption peaks were observed, including a broad O–H stretching vibration around 3300–3400 cm^{-1} indicating hydroxyl groups from cellulose and hemicellulose. A sharp peak at C–H stretching vibrations near 2900 cm^{-1} corresponds the to presence of cellulose and hemicellulose. Further, the region of 1600–1750 cm^{-1} was observed corresponding to C=O stretching from carbonyl groups indicates the presence of hemicellulose and lignin. Additionally, absorptions in the range of 1000–1200 cm^{-1} signified C–O–C and C–O functional groups due to presence of cellulose and hemicellulose. In the case of the FTIR spectrum of Borassus flabellifer fiber, similar characteristic peaks were observed as in Cocos nucifera fiber, confirming the presence of cellulose, hemicellulose, and lignin components (Kumar et al. 2022).

Synergistic Effect of Hybrid Fibers in Composite Performance

The improvement observed in the mechanical properties (tensile, flexural, impact, and hardness) of the VIE composites can be attributed to the synergistic reinforcement effect of Borassus flabellifer and Cocos nucifera fibers through several mechanisms. Firstly, both fibers act as load-bearing components, helping to share the applied stress with the vinyl ester matrix, which enhances overall strength and stiffness. The good interfacial bonding between

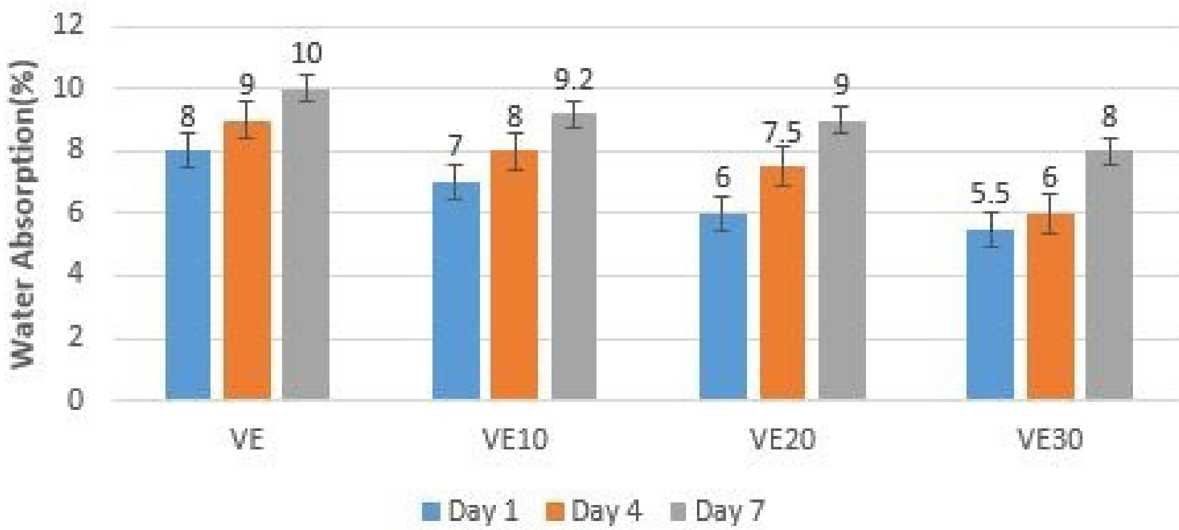

Figure 7. Water absorption test of VIE loaded with Cocos nucifera fiber and Borassus flabellifer fiber.

the fibers and the matrix ensures efficient stress transfer, reducing the chances of fiber pull-out and contributing to improved tensile and flexural strength. Additionally, the fibers play a crucial role in bridging and arresting cracks, which increases energy absorption and impact resistance. The combination of two different natural fibers allows the composite to benefit from the individual strengths of each one, where one may contribute more to stiffness, while the other adds toughness, leading to a balanced and improved mechanical performance. As the fiber content increases, the available surface area for bonding also grows, promoting better mechanical interlocking and enhancing hardness. Moreover, the uniform distribution of fibers within the matrix helps in spreading applied loads more evenly, reducing stress concentrations. Lastly, the natural microfibrillar structure of the fibers offers inherent strength and resistance to deformation. Altogether, these mechanisms work in combination to significantly enhance the mechanical properties of the fiber-reinforced VIE composites.

CONCLUSIONS

This study successfully developed a novel hybrid composite comprising vinylester (VIE) containing Borassus flabellifer and Cocos nucifera fibers. VIE-based composites were developed containing weights of Borassus flabellifer and Cocos nucifera fibers ranging from 10 to 30 wt%. The results showed that the dual-fiber-reinforced vinylester composite with 30 wt% fiber loading exhibited the highest mechanical strength (24 MPa) compared to the pure VIE (6 MPa). Similarly, the composite demonstrated enhanced flexural strength (566 MPa), impact strength (34 kJ/m^2), and hardness (67 HRB) compared to neat VIE, which recorded values of 238 MPa, 6 kJ/m^2, and 9 HRB, respectively. Thermogravimetric analysis (TGA) revealed that incorporating Borassus flabellifer and Cocos nucifera fibers improved the thermal stability of VIE. Furthermore, water absorption studies revealed reduced moisture uptake in the developed VIE composites reinforced with Borassus flabellifer and Cocos nucifera fibers than in pure VIE. Although the composites performed well up to 30 wt% fiber loading, higher loadings (e.g., 40 wt%) led to poor resin

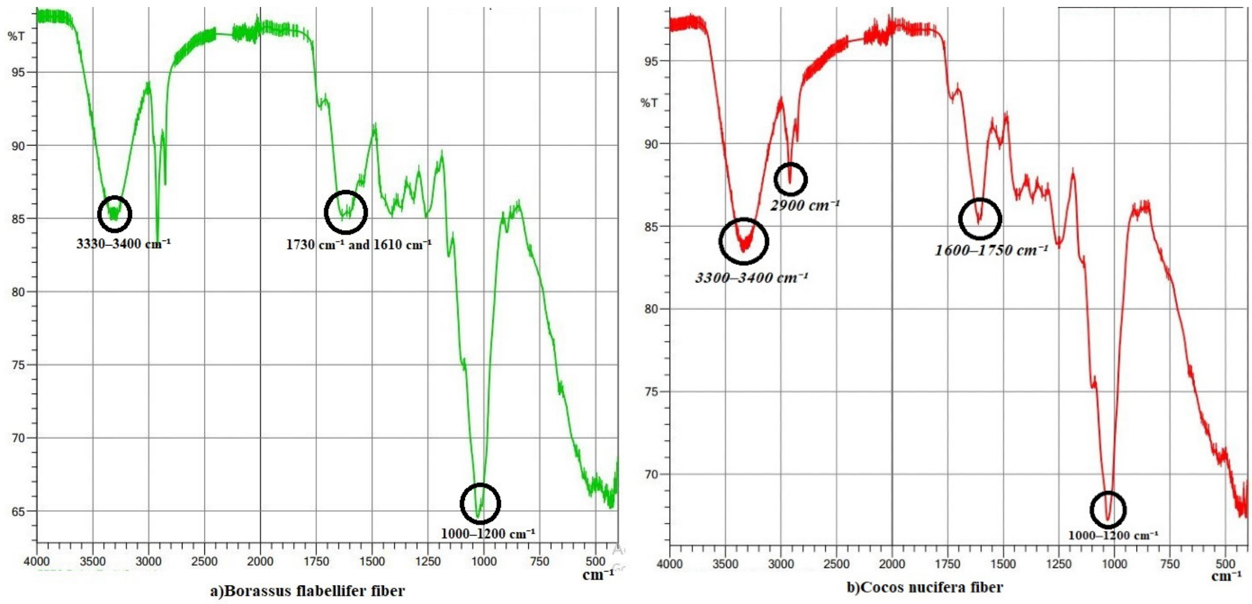

Figure 8. FTIR a) Borassus flabellifer b) Cocos nucifera.

wettability, increased void content, and reduced mechanical performance. This highlights the challenge of maintaining structural integrity at fiber loadings above 30 wt%. Future studies may focus on fiber surface modification, advanced characterization (e.g., XRD), and optimization of stacking/woven configurations to achieve higher durability and strength (Sasidharan et al. 2022, Yuan et al. 2024).

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Data availability

The authors confirmed that the data supporting the findings of this study are available within the article.