Enhancement of Mechanical Properties of Hybrid Polymer Composites Using Palmyra Palm and Coconut Sheath Fibers: The Role of Tamarind Shell Powder

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This study investigates the enhancement of mechanical characteristics of hybrid polymer composites reinforced with palmyra palm leaflet (PPL) and coconut sheath leaf (CSL) fibers by integrating tamarind shell powder as a filler material. The composites were fabricated with varying ratios of PPL and CSL fibers, and their tensile strength, flexural strength, interlaminar shear strength (ILSS), impact strength, hardness, and water absorption were evaluated. The composite with 20% PPL and 10% CSL exhibited superior mechanical performance, achieving the highest tensile strength of 42 MPa, flexural strength of 94 MPa, ILSS of 7.52 MPa, and impact strength of 5.98 J. Hardness values peaked at 84 SD for the same composition. Moreover, the integration of tamarind shell powder significantly improved the mechanical properties compared to composites without filler, which showed lower values across all parameters. Water absorption tests revealed an increase in water uptake with filler incorporation, though within acceptable limits for practical applications. Scanning electron microscopy supported these results by revealing enhanced fiber-matrix bonding and better dispersion of the filler, resulting in fewer voids and defects. This research highlights the potential of bio-based fillers in optimizing the mechanical performance of hybrid composites for sustainable engineering applications.

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INTRODUCTION

The growing global concern for environmental sustainability and the urgent need to reduce reliance on non-renewable resources have significantly influenced research and development in the materials science field (Iroegbu and Ray 2021; Kamarudin *et al*. 2022; Manickaraj *et al*. 2024a; Sumesh *et al*. 2024). Traditional synthetic fiber-reinforced polymer composites, such as those reinforced with glass, carbon, or aramid fibers, have long been the materials of choice for various high-performance applications due to their excellent mechanical properties, including superior strength, stiffness, and durability (Alam *et al*. 2022; Gurusamy *et al*. 2024). These materials are widely used in industries such as aerospace, automotive, and construction, where performance under demanding conditions is critical (Karuppiah *et al*. 2022; Karthik *et al*. 2023b; Palanisamy *et al*. 2023b). However, synthetic composites come with several drawbacks that undermine their long-term sustainability, especially in the context of environmental preservation and resource management (Prabhu *et al.* 2020; Ead *et al*. 2021; Wan and Lee 2021). One of the most significant concerns with synthetic fiber-reinforced composites is their dependence on petrochemical-based materials, both in the fibers and the polymer matrices. The production of these materials is energy-intensive, contributing to greenhouse gas emissions and other environmental pollutants (Mikulčić *et al*. 2016; Govindarajan *et al*. 2024; Palanisamy *et al*. 2024). Furthermore, the non-biodegradable nature of synthetic fibers and polymer matrices poses a significant waste management challenge. Once these materials reach the end of their useful life, they often end up in landfills or are incinerated, leading to further environmental degradation (Gutowski *et al*. 2013; Chen *et al.* 2020). The high cost of production and limited recyclability of synthetic composites further exacerbate these issues, making it imperative to seek sustainable alternatives (Rashid *et al*. 2023; Karthik *et al*. 2024).

In response to these challenges, natural fiber-reinforced polymer composites have emerged as a viable and environmentally friendly alternative. Natural fibers, which are derived from renewable sources such as plants, animals, or minerals, offer several advantages over synthetic fibers (Zhao *et al.* 2018; Mahir *et al*. 2019; Zhao *et al.* 2020; Thapliyal *et al*. 2023; Deshmukh and Palanisamy 2024). They are biodegradable, renewable, and have a lower environmental footprint throughout their life cycle, from production to disposal. In addition, natural fibers of plants are abundantly available and cost-effective, making them attractive for large-scale applications (Rajeshkumar *et al*. 2021). These fibers are typically composed of lignocellulosic materials, which are a combination of cellulose, hemicellulose, and lignin. This composition gives natural fibers their desirable mechanical properties, such as good tensile strength, low density, and high specific strength (Karimah *et al*. 2021).

Despite the environmental and economic benefits of natural fibers, they often have mechanical limitations compared to synthetic fibers (Ahmad and Zhou 2022; Aruchamy *et al*. 2024; Palaniappan *et al*. 2024b). Natural fibers generally exhibit lower tensile strength, lower thermal stability, and higher moisture absorption, which can compromise the durability and performance of composites in demanding environments (Azwa *et al*. 2013; Palaniappan *et al*. 2024a). These limitations have spurred extensive research into improving the mechanical properties of natural fiber-reinforced composites, leading to the development of hybrid polymer composites (Asyraf *et al*. 2022; Kumar *et al*. 2022b; Sumesh *et al*. 2023).

Hybrid polymer composites represent a significant advancement in materials engineering, as they combine two or more types of fibers within a single polymer matrix. This hybridization approach allows for the synergistic exploitation of the complementary properties of different fibers, resulting in composites with enhanced mechanical performance (Deshmukh 2022; Asyraf *et al*. 2023). By carefully selecting and combining natural fibers with varying mechanical properties, it is possible to create materials that are stronger, stiffer, and more durable than those reinforced with a single type of fiber (Lotfi *et al*. 2021; Nurazzi *et al*. 2021). For example, one fiber may provide high tensile strength, while another may offer better impact resistance or moisture resistance. By blending these fibers, hybrid composites can achieve a balance of properties tailored to specific application requirements (Safri *et al*. 2018).

The simultaneous usage of two or more types of natural fibers (which is sometimes called "hybridization") can also address the moisture absorption issue that plagues many natural fiber composites. Some natural fibers have better water resistance due to their higher lignin content or waxy surface layers (Hajiha *et al*. 2014; Manickaraj *et al*. 2019). By incorporating such fibers into a hybrid composite alongside fibers with higher strength but lower moisture resistance, it is possible to mitigate the negative effects of moisture absorption while maintaining the desired mechanical properties (Bahrami *et al*. 2020). This makes hybrid composites more suitable for applications in environments where exposure to moisture or humidity is a concern, such as in outdoor structures, marine environments, or automotive components (Mayandi *et al*. 2020). In addition to enhancing mechanical properties, hybrid composites also offer the potential for improved processability and manufacturability. This flexibility in manufacturing makes hybrid composites suitable for mass production and scalable industrial applications, further enhancing their appeal as a sustainable alternative to traditional materials (Bahrami *et al*. 2020; Goutham *et al*. 2023).

Among the various natural fibers used in hybrid polymer composites, palmyra palm leaflet (*Borassus flabellifer*) and coconut sheath leaf fibers have shown considerable promise due to their unique mechanical properties and availability (Manickaraj *et al*. 2022; Thirupathi *et al*. 2024). Both of these fibers are considered agricultural waste, making their use in composites an excellent example of waste valorization and resource efficiency. Palmyra palm leaflet fibers are derived from the leaflets of the palmyra palm, a tropical plant widely cultivated in Asia and Africa. The fibers are lightweight, biodegradable, and possess moderate tensile strength, making them suitable for reinforcement in polymer matrices (Ain *et al*. 2016; Khan *et al*. 2018). Similarly, coconut sheath leaf fibers are obtained from the sheath of coconut leaves, a byproduct of the coconut industry. These fibers are known for their high lignin content, which gives them better rigidity and resistance to moisture compared to many other natural fibers (Hasan *et al*. 2021; Manickaraj *et al*. 2023; Thapliyal *et al*. 2023).

The combination of palmyra palm leaflet fibers and coconut sheath leaf fibers in a hybrid composite offers the potential for a balanced mechanical performance. Palmyra palm leaflet fibers provide good flexibility and tensile strength, while coconut sheath leaf fibers offer rigidity and better moisture resistance (Manickaraj *et al*. 2024b; Thirupathi *et al*. 2024). This complementary nature makes these hybrid composites well-suited for applications requiring a combination of strength, toughness, and environmental durability.

To further enhance the mechanical properties of palmyra palm leaflet fibers and coconut sheath leaf fiber-based composites, the integration of bio-fillers has emerged as a promising approach. Bio-fillers are natural materials added to the composite matrix to improve fiber-matrix bonding, reduce void content, and enhance mechanical performance

(Ghori *et al*. 2018; Kumar *et al*. 2022a; Mylsamy *et al*. 2024). Tamarind shell powder (TSP), derived from the hard outer shell of the tamarind fruit (*Tamarindus indica*), is one such bio-filler that has shown great potential in improving the performance of natural fiber-reinforced composites (Stalin *et al*. 2019). TSP is rich in cellulose and hemicellulose, which provide strength and rigidity to the filler. When incorporated into a polymer matrix, TSP can improve the dispersion of fibers, enhance fiber-matrix adhesion, and reduce the presence of voids and defects that can weaken the composite (Mehdikhani *et al*. 2019; Lal and Mhaske 2021; Niang *et al*. 2021).

The addition of tamarind shell powder to palmyra palm leaflet and coconut sheath leaf hybrid composites is expected to have several beneficial effects. First, TSP can improve the tensile and flexural strength of the composite by reinforcing the matrix and providing additional load-bearing capacity. Second, the presence of the filler can enhance the interlaminar shear strength (ILSS) by improving the bonding between the layers of fibers, reducing the likelihood of delamination or failure under shear loads. Third, TSP can increase the composite's hardness and impact strength, making it more resistant to wear and sudden impacts (De Cicco *et al*. 2017; Dattu *et al*. 2022; Kasinathan and Rajamani 2022). However, one potential trade-off is the increase in water absorption, as natural fillers like TSP tend to be hydrophilic. Proper surface treatment of fibers and fillers, as well as careful control of the composite formulation, can mitigate this issue and maintain acceptable levels of moisture resistance (Mohammed *et al*. 2022).

A novel feature of this work is its focus on a hybrid composite using palmyra palm leaflet and coconut sheath fibers, reinforced with tamarind shell powder (TSP), a bio-filler that remains largely unexplored in composite research. Unlike commonly used natural fibers and fillers, the combination of these agricultural waste-derived materials provides a unique synergy: Palmyra offers tensile strength and flexibility, while coconut sheath adds moisture resistance and rigidity. The addition of TSP further enhances mechanical properties by improving fiber-matrix adhesion and reducing voids, resulting in increased tensile strength, interlaminar shear strength, and hardness. This comprehensive mechanical profile, combined with the sustainability benefits of using low-cost, eco-friendly materials, sets this work apart from existing studies, providing an innovative and practical alternative to synthetic composites for structural applications.

Overall, hybrid polymer composites reinforced with palmyra palm leaflet and coconut sheath leaf fibers, along with tamarind shell powder as a filler, offer a sustainable and high-performance alternative to synthetic composites. By leveraging complementary properties of these natural fibers and enhancing them with bio-fillers, these hybrid composites can achieve the mechanical strength, durability, and environmental resistance needed for a wide range of structural applications (Fragassa *et al*. 2024). This approach not only addresses the mechanical limitations of individual natural fibers but also contributes to the broader goals of sustainability, resource efficiency, and waste reduction. As industries continue to seek eco-friendly materials for future applications, hybrid polymer composites made from natural fibers and bio-fillers represent a promising solution for the development of greener, more sustainable products. The hybrid polymer composites offer several advantages, including enhanced mechanical properties such as increased tensile strength, flexibility, and moisture resistance. They are cost-effective and eco-friendly, utilizing agricultural waste materials to reduce environmental impact. Furthermore, these composites provide a sustainable alternative to synthetic materials, aligning with the growing demand for greener and more resource-efficient solutions in industrial applications.

EXPERIMENTAL

Palmyra Palm Leaflet Fibers

The leaflets from the palmyra palm were collected from local agricultural waste. The fibers were extracted using the water retting process, followed by manual separation. After extraction, the fibers were washed thoroughly with distilled water to remove impurities and dried under sunlight (Karthik *et al*. 2023a). The dried fibers were cut to a uniform length (10 to 20 mm) for composite fabrication. Figures 1A and 1B show palm leaflets and fibers.

Fig. 1A. Palmyra palm leaflet**; 1B.** Palmyra palm leaflet fiber; **1C.** Coconut leaf sheath with coconut tree; **1D.** Coconut leaf sheath

Coconut Sheath Fibers

Coconut sheath fibers were sourced from the outer sheath of coconut leaves, which is another agricultural byproduct. The fibers were extracted using a mechanical decortication process, cleaned with water, and dried in a hot air oven at 60 °C to remove moisture (Sathish *et al*. 2021). The fibers were then cut to lengths similar to palmyra palm leaflet fibers for consistency in the composite manufacturing process. Figures 1C and 1D show coconut sheath leaves.

Bio-Filler

The bio-filler, tamarind shell powder, was prepared by grinding the shells of tamarind fruit into a fine powder. The powder was sieved to obtain particles of uniform size for use in the polymer matrix. TSP was selected due to its high cellulose and hemicellulose content, which enhances the strength and rigidity of the composites. Figures 2 and 3 show tamarind seeds and their powder.

Fig. 2. Tamarind seeds

Fig. 3. Tamarind seed powder

Matrix Material

Epoxy resin (LY556) and the corresponding hardener (HY951) were used as the polymer matrix (Palanisamy *et al*. 2023a). The epoxy resin was chosen for its excellent mechanical properties, good adhesion, and ease of processing in composite fabrication.

Surface Treatment of Fibers

Both palmyra palm leaflet and coconut sheath leaf fibers were treated with alkali to improve fiber bonding and reduce water absorption. The fibers were soaked in 5% sodium hydroxide (NaOH) solution at room temperature for 4 h. After treatment, the fibers were washed thoroughly with distilled water to remove excess NaOH and neutralized with dilute acetic acid solution (Rajeshkumar *et al*. 2016; Murugesan *et al*. 2022). The treated fibers were dried at 60 °C for 24 h to obtain a moisture content below 5%. Alkali treatment with sodium hydroxide (NaOH) improves the bonding between natural fibers (palmyra palm leaflet and coconut sheath leaf) and the polymer matrix by breaking down lignin and hemicellulose, exposing cellulose's hydroxyl groups. This enhances the fiber-matrix adhesion, improving mechanical properties such as tensile and flexural strength. The treatment also reduces water absorption by modifying hydrophilic groups, which helps prevent swelling and degradation. After washing with distilled water and neutralizing with acetic acid, the fibers are dried to remove excess moisture, stabilizing the material. This process results in a stronger, more stable fiber-matrix complex, improving the overall performance and durability of the composite.

Preparation of Hybrid Composites

The hybrid composites were prepared using a hand lay-up technique followed by compression molding. The weight fractions of PPL fibers, CSL fibers, and TSP were varied according to the composite designations as shown in Table 1. The total fiber content varied between 30% to 60% of the composite's weight, while the tamarind shell powder filler content was kept constant at 10%, except for the last combination (30PPL30CSL), which had no filler content (Kumar *et al*. 2022b). The specific combinations of fiber and filler content were adjusted to assess their impact on the mechanical properties.

Table 1. Hybrid Composite Designations

Si No	Fiber Content (%)		Filler Content (%)	Epoxy Resin	Composite Designation
	Palmyra Palm leaflet (PPL)	Coconut sheath leaf (CSL)	Tamarind Shell Powder	(%)	
1	5	25	10	60	5PPL25CSL
2	10	20	10	60	10PPL20CSL
3	15	15	10	60	15PPL15CSL
4	20	10	10	60	20PPL10CSL
5	25	5	10	60	25PPL5CSL
6	30	30	0	60	30PPL30CSL (Without Filler)

Incorporation of Tamarind Shell Powder

For composites that included tamarind shell powder, the powder was mixed with the epoxy resin at a fixed weight percentage of 10%. The resin-hardener mixture (in a 10:1 ratio) was stirred thoroughly to ensure uniform dispersion of the bio-filler. For composite designation 30PPL30CSL, no tamarind shell powder was added.

Lay-Up Process

A mold release agent was applied to the mold surface to prevent the composite from sticking. A layer of epoxy resin was first poured into the mold, followed by a layer of fibers (a mixture of palmyra palm leaflet and coconut sheath leaf fibers). Another layer of epoxy resin was applied, and this process was repeated to achieve the desired thickness. tamarind shell powder was uniformly distributed throughout the resin layers.

Compression Molding

The laminate was then placed in a hydraulic press and compression molded under a pressure of approximately 2 MPa. The mixture was cured at room temperature for 24 h and then cured in an oven at 80 °C for 2 h to improve the bonding of the epoxy matrix.

Mechanical Testing

The prepared composite samples were cut according to ASTM standards for mechanical testing.

Tensile Strength (ASTM D638-14 2022)

The tensile strength of hybrid composites was evaluated using a universal testing machine (UTM). This test measures the maximum tensile stress that the composite can withstand before failure. Test specimens were cut into dumbbell shapes in accordance with ASTM D638 (2022) to ensure uniform stress during testing (Singh *et al*. 2014;

Laureto and Pearce 2018). The machine applied a uniaxial tensile force to the specimen at a rate of 5 mm/min until it fractured (Karuppiah *et al*. 2020; Carmona and Colorado 2021). Tensile strength, deformation, and Young's modulus (hardness) were recorded. These results provide insight into the ability of the composite to withstand tensile strength and show how the fiber-matrix bond behaves under tension. Figure 4 shows the tensile specimens.

Fig. 4. Tensile specimen

Flexural Strength (ASTM D790 2017)

Flexural strength was assessed through a three-point bending test, which evaluates the material's capacity to withstand deformation when subjected to an applied load. Rectangular composite specimens were supported at two ends, and a load was applied at the center, as per ASTM D790 (2017) (Anggraini *et al*. 2017). This setup mimics real-world bending scenarios, such as those encountered in beams or structural components. The force required to bend the composite before failure, along with the maximum deflection, was recorded (Vinod *et al*. 2021). Flexural modulus (stiffness during bending) was also calculated. This test helps in understanding how well the composite performs under flexural or bending stresses, particularly in applications like panels or beams.

Impact Strength (ASTM D256 2023)

The impact strength of the composite was measured using an Izod impact tester, which assesses the material's toughness and its ability to absorb energy during a sudden impact (Karuppiah *et al*. 2020; Koffi *et al*. 2021). Notched specimens (which create a stress concentration point) were subjected to a pendulum strike, and the energy absorbed by the specimen during fracture was recorded. This test provides information on the composite's resistance to sudden, high-energy impacts, making it relevant for applications where the material may experience shocks or impacts, such as in automotive or protective gear. Figure 5 shows the test specimens.

Fig. 5. Impact specimen

Interlaminar Shear Strength (ASTM D2344 2022)

To evaluate the bonding strength between fiber layers and the matrix, short-beam shear tests were performed. Composite samples were loaded in a three-point bend configuration with a shorter span-to-depth ratio than flexural tests. The goal was to induce shear failure between the layers. Interlaminar shear strength (ILSS) (ASTM D2344 2022) (Kotik and Ipina 2021) was calculated from the maximum load the composite could carry before delamination or shear failure occurred. This test is essential for evaluating the quality of the interface between the fibers and the matrix, which plays a vital role in the overall durability and performance of the composite when subjected to shear forces.

Hardness (ASTM D2240 2021)

The surface hardness of the composites was assessed using a Shore D durometer accordance to ASTM D2240 (2021), a tool designed to measure the resistance of the composite surface to indentation. Higher hardness values signify increased resistance to surface wear and indentation. This characteristic is particularly crucial for applications where the material is subjected to abrasive conditions or requires enhanced surface durability (Arockiasamy 2022).

Water Absorption Test (ASTM D570 2022)

The water absorption (ASTM D570 2022) (Hassan *et al*. 2019) behavior of the hybrid composites was tested to assess their moisture resistance, an important factor for materials exposed to humid or wet environments (Barjasteh and Nutt 2012; Maslinda *et al*. 2017). The composite samples were first dried and weighed before being completely immersed in distilled water at room temperature. At 48-h intervals, the samples were removed from the water, wiped dry, and reweighed. The percentage of water absorption was then calculated based on the increase in weight of the samples. This test provides insights into the hydrophilic nature of the fibers and fillers used in the composite, and how they might affect the mechanical performance when exposed to moisture. The goal is to ensure that the composites maintain acceptable moisture resistance, minimizing the risk of degradation over time. These mechanical and environmental tests provide a comprehensive understanding of the hybrid composite's structural and functional performance, ensuring suitability for a range of applications (Nurazzi *et al*. 2021; Sumesh *et al*. 2021).

Scanning Electron Microscopy (SEM)

To investigate the microstructural characteristics of the hybrid composites, SEM was performed using a Zeiss EVO 18 scanning electron microscope (Alaneme and Sanusi 2015; Sathish *et al*. 2021). SEM analysis elucidates the fiber-matrix interface, distribution of fibers and fillers, and identifying potential defects such as voids, fiber pull-out, and matrix cracking, which influence the overall mechanical properties.

RESULTS AND DISCUSSION

Tensile Test

The tensile strength results of the hybrid composites, which include varying amounts of palmyra palm leaflet (PPL) fibers, coconut sheath leaf (CSL) fibers, and a fixed amount of tamarind shell powder (TSP) filler, revealed important insights into the relationship between fiber content, filler inclusion, and mechanical performance. Initially, as the content of PPL fibers increased from 5% to 20%, the tensile strength of the composites showed a steady improvement. This trend can be attributed to the strengthening effect of PPL fibers, which are known for their high tensile strength (Reddy *et al.* 2014). These fibers act as load-bearing components within the matrix, providing resistance to tensile forces and improving the composite's ability to withstand stress without failure. The gradual increase in strength reflects the contribution of PPL fibers to the overall structural integrity, enhancing the composite's performance under load. The composite with 20% PPL and 10% CSL (20PPL10CSL) exhibited the highest tensile strength at 42.2 MPa, indicating an optimal balance between PPL and CSL. The PPL fibers provided flexibility and strength, while the CSL fibers contributed rigidity and moisture resistance. Together, these fibers work synergistically, enhancing the composite's mechanical properties. This balanced fiber ratio ensures effective load distribution and minimizes the chances of fiber misalignment, which could lead to weak spots in the composite. Moreover, the presence of TSP further enhanced tensile strength by improving fiber-matrix adhesion, filling voids, and reducing the occurrence of defects that could act as stress concentrators. The filler likely also contributed to better dispersion of the fibers within the matrix, preventing clumping or uneven distribution that could weaken the material (An *et al.* 2024; Sonar *et al.* 2024). However, when the PPL content increased beyond 20% (as seen in the 25PPL5CSL composite), the tensile strength slightly decreased to 40.5 MPa. This suggests that there is an optimal amount of PPL fibers that maximizes the composite's tensile strength, and excess PPL content may lead to reduced performance. Excessive fiber content can lead to overcrowding, poor wetting of the fibers by the matrix, and the formation of voids or air pockets that compromise the structural integrity of the composite. Additionally, with more fibers packed into the matrix, the alignment and dispersion of the fibers may become less uniform, leading to local areas of weakness where cracks could propagate more easily (Mohammed *et al.* 2023). Figure 6 shows the tensile characteristics. The composite without TSP filler exhibited the lowest tensile strength at 32.2 MPa, highlighting the reinforcing role of TSP. The presence of TSP significantly contributed to enhancing the mechanical properties by improving the interaction between fibers and the matrix. TSP, being a bio-filler, fills voids, enhances fiber-matrix bonding, and helps reduce defects in the composite, resulting in a more durable material. Overall, these results underscore the importance of optimizing both fiber content and filler addition to achieve the best mechanical performance. The synergistic effect of the PPL, CSL, and TSP combination not only improved tensile strength but also provided an environmentally friendly alternative to traditional synthetic composites. The careful balancing of these components is crucial for creating a composite that is both strong and durable, suitable for structural applications, and sustainable due to the use of natural fibers and bio-fillers.

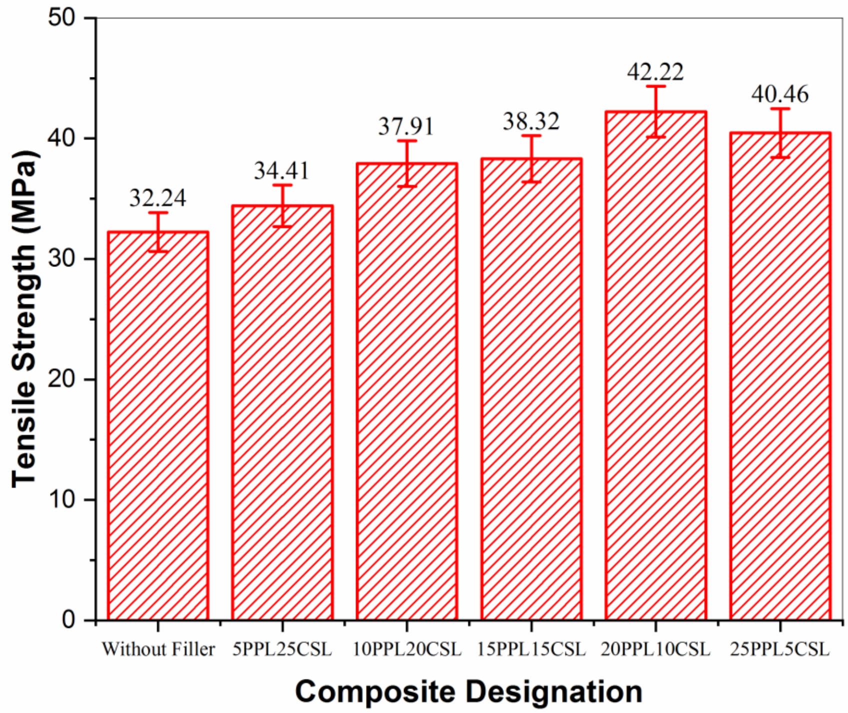

Fig. 6. Tensile Characteristics

Flexural Strength

The flexural strength data highlights the effectiveness of hybrid composites reinforced with palmyra palm leaflet (PPL) fibers, coconut sheath leaf (CSL) fibers, and tamarind shell powder (TSP) as a filler. As the PPL fiber content increased from 5% to 20%, a significant improvement in flexural strength was observed, with the 20PPL10CSL composite showing the highest value of 94.4 MPa. The improvement can be attributed to the high cellulose content of PPL fibers, which enhances the material's load-bearing capacity. The cellulose helps transfer stress more efficiently between the matrix and fibers, strengthening the composite. This interaction increases the composite's ability to resist bending deformation, resulting in superior flexural strength. The uniform distribution of the fibers within the matrix also helps optimize stress transmission, reducing the likelihood of failure or crack propagation under bending stress. However, when the PPL content was increased to 25%, the flexural strength slightly decreased to 89.6 MPa, suggesting that an optimal balance exists for fiber content. This reduction may be due to fiber agglomeration, which can interfere with matrix bonding. Agglomerated fibers reduce the effectiveness of fiber-matrix adhesion, which weakens the stress transfer and creates potential weak spots in the composite. These weak spots can lead to failure under flexural loads. The result underscores the importance of carefully optimizing fiber content to avoid negative effects on the composite's mechanical properties, as excessive fiber concentration can disrupt the uniformity of the material (Blokhin *et al*. 2020). The addition of TSP as a filler significantly enhanced the flexural strength, as seen by the much lower strength (52.3 MPa) of the composite without filler. TSP helps improve the fiber-matrix bonding by filling voids in the matrix and contributing additional reinforcement. This leads to better distribution of stress under flexural loads and reduces the risk of matrix cracking. Furthermore, the combination of PPL and CSL fibers offers a balanced approach, where PPL provides tensile strength and CSL adds rigidity and moisture resistance. The synergy between these fibers ensures that the composite exhibits both strength and flexibility, making the 20PPL10CSL composite ideal for structural applications. By optimizing fiber ratios and incorporating bio-fillers such as TSP, these hybrid composites present a sustainable and high-performance alternative to synthetic materials, offering enhanced mechanical properties with environmental benefits (Kasinathan and Rajamani 2022; Guo *et al.* 2021). Figure 7 shows the flexural characteristics.

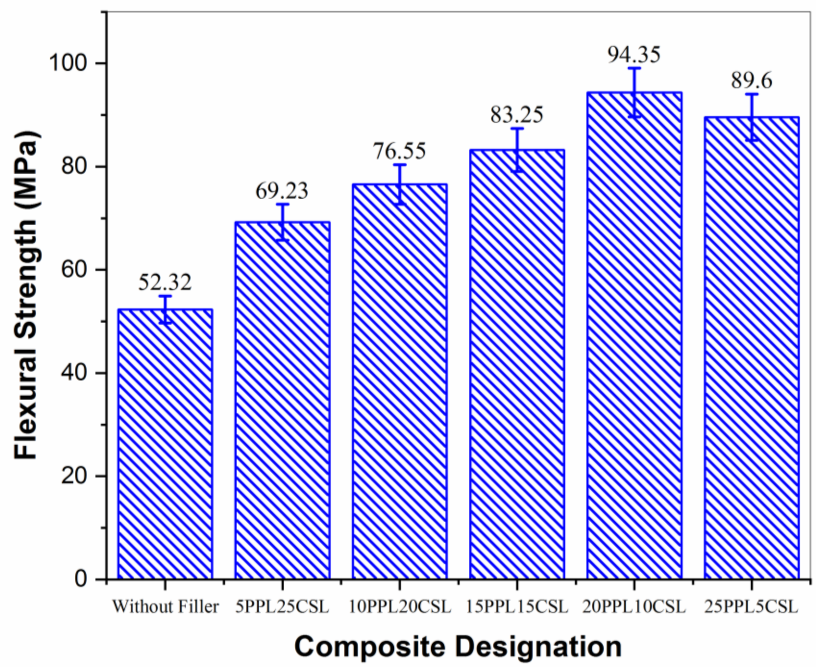

Fig. 7. Flexural characteristics

Interlaminar Shear Strength (ILSS)

The chart displays the interlaminar shear strength of hybrid composites with varying amounts of PPL and CSL fibers, along with a fixed 10% TSP filler. ILSS is crucial for assessing a composite's resistance to shear forces between its layers. As the PPL content increased from 5% to 20%, the ILSS improved, peaking at 7.52 MPa for the 20PPL10CSL composite. This enhancement can be attributed to the superior stiffness and load-bearing capacity of PPL fibers, which provide better fiber-matrix adhesion, allowing for effective stress distribution and resistance to shear forces (Aisyah *et al.* 2021). However, the ILSS decreased slightly to 6.34 MPa for the 25PPL5CSL composite. This reduction may result from fiber overcrowding, which can impair the resin's ability to wet the fibers, leading to weaker bonding and reduced shear resistance (Clifton *et al*. 2020). The composite without TSP filler showed the lowest ILSS at 4.62 MPa, highlighting the reinforcing effect of TSP.

As a micro-filler, TSP enhances the matrix’s bonding capability and increases stiffness, improving interlaminar shear strength (Gao *et al*. 2022). Overall, the findings indicate that optimizing the balance of PPL and CSL fibers with TSP filler is essential for maximizing the interlaminar shear properties of hybrid composites. Figure 8 shows the interlaminar shear strength characteristics.

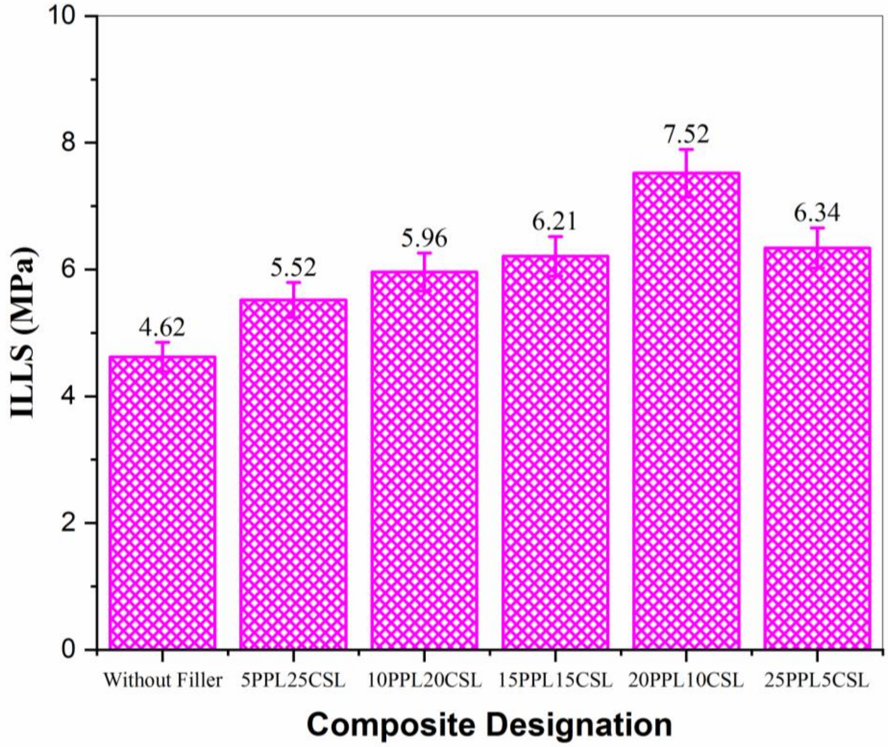

Fig. 8. Interlaminar shear strength characteristics

Impact Strength

Figure 9 presents the impact strength of hybrid composites made with varying amounts of PPL and CSL fibers, along with a fixed 10% TSP filler. Impact strength measures a material’s ability to withstand sudden forces without fracturing. As PPL content increased from 5% to 20%, impact strength improved, peaking at 5.98 J for the 20PPL10CSL composite. This increase is likely due to the toughness and flexibility of PPL fibers, which enhance energy absorption during impacts. However, the impact strength decreased slightly for the 25PPL5CSL composite (5.56 J), suggesting that exceeding a certain fiber content may not further enhance toughness, possibly due to fiber overcrowding or reduced bonding (Osterberg *et al*. 2023; Qureshi *et al*. 2024). The composite without TSP filler showed the lowest impact strength at 4.03 J, highlighting TSP's role in improving energy absorption and fiber-matrix interaction. Overall, optimizing the ratios of PPL and CSL fibers, along with TSP filler, is essential for maximizing the impact strength of hybrid composites and enhancing their performance against sudden loads. Figure 9 shows the impact characteristics.

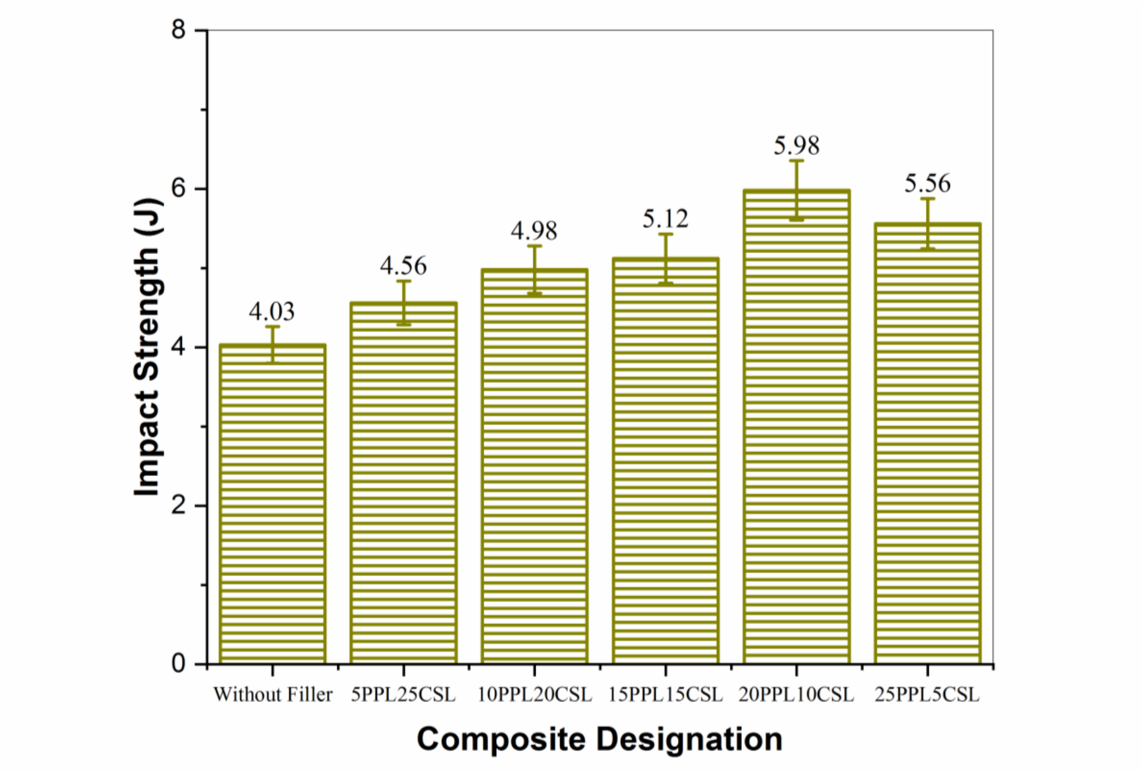

Fig. 9. Impact characteristics

Shore D Hardness

The graph presents the Shore D hardness values of hybrid composites made with varying amounts of PPL and CSL fibers, along with a fixed 10% TSP filler. Shore D hardness is a measure of a material's resistance to indentation, indicating its rigidity and durability (Pintaude 2023). As the PPL content increased from 5% to 20%, the Shore D hardness improved, reaching a maximum of 84.1 SD for the 20PPL10CSL composite. This increase can be attributed to the high cellulose content and structural integrity of PPL fibers, which reinforce the epoxy matrix, enhancing its overall rigidity and resistance to deformation (Nurazzi *et al*. 2021). However, the hardness value slightly decreased for the 25PPL5CSL composite (82.8 SD). This reduction may indicate that excessive PPL content can lead to fiber agglomeration or uneven dispersion within the matrix, potentially creating weak spots that lower hardness. The composite without TSP filler showed the lowest Shore D hardness at 60.6 SD, emphasizing the significant role of TSP in enhancing the mechanical properties of the composite (Neitzel *et al*. 2011). TSP acts as a reinforcing agent, improving the bonding between the fibers and the matrix, and contributing to a more uniform force distribution throughout the composite. The findings suggest that optimizing the balance of PPL and CSL fibers with TSP filler is essential for maximizing Shore D hardness in hybrid composites (Nurazzi *et al*. 2021). The combination of natural fibers and fillers enhances the material's resistance to indentation and wear, making these composites suitable for applications requiring superior mechanical performance. Figure 10 shows the hardness results.

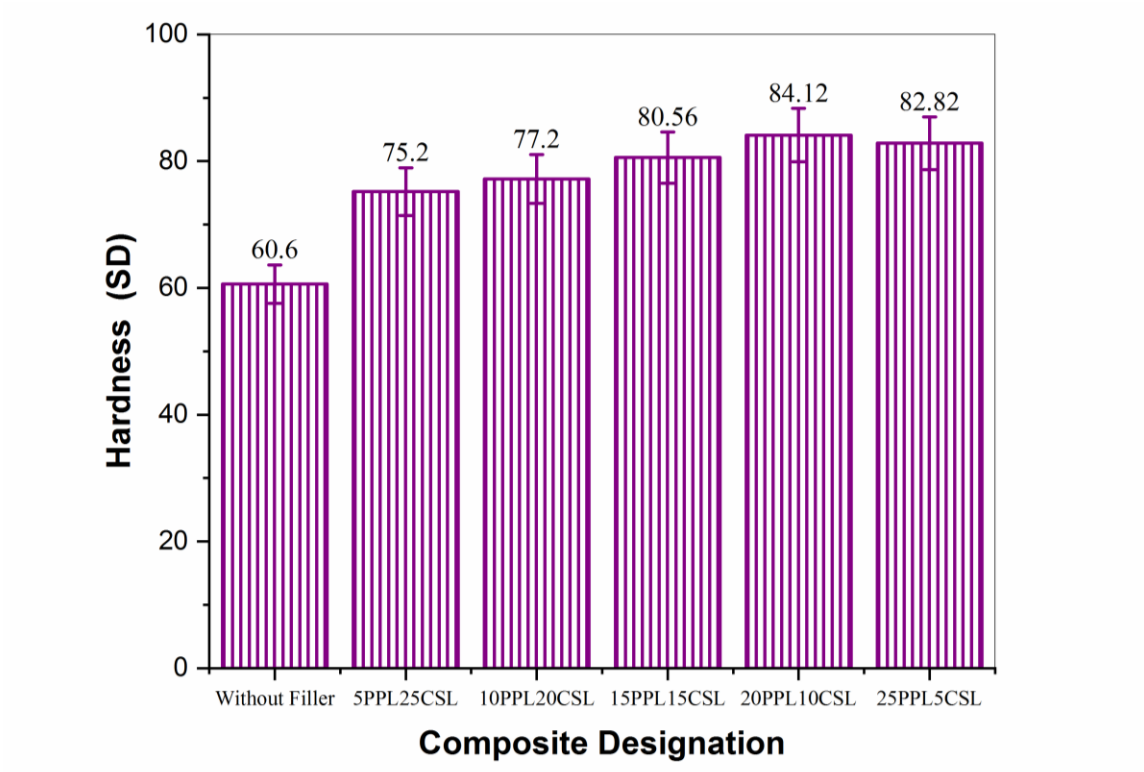

Fig. 10. Hardness characteristics

Water Absorption

Water absorption is an important indicator of a material's resistance to moisture, which can affect its mechanical properties and durability. The water absorption increased with higher concentrations of PPL and CSL fibers. The composite with 10% PPL and 20% CSL exhibited the highest water absorption percentage at 51.4%, whereas the composite with 20% PPL and 10% CSL showed a lower absorption of 42.6%. This rise in water absorption can be attributed to the porous structure of the natural fibers, which allows for greater moisture absorption, thus increasing the overall weight of the composite. Generally, a higher fiber content results in more voids and gaps within the matrix, facilitating water penetration. In contrast, the composite without any filler had a water absorption of 42.2%, which is relatively low compared to the composites containing tamarind shell powder. The presence of TSP likely enhances the interfacial bonding between the fibers and the epoxy matrix, thereby reducing the amount of water that can permeate the composite structure (Chen *et al*. 2021; Zaghloul *et al*. 2023).

Overall, these findings indicate that while natural fibers contribute to improved mechanical properties, they also lead to increased water absorption. Careful optimization of fiber and filler content is essential to achieve a balance between mechanical performance and moisture resistance in hybrid composites (Nurazzi *et al*. 2021). Figure 11 shows the water absorption test result.

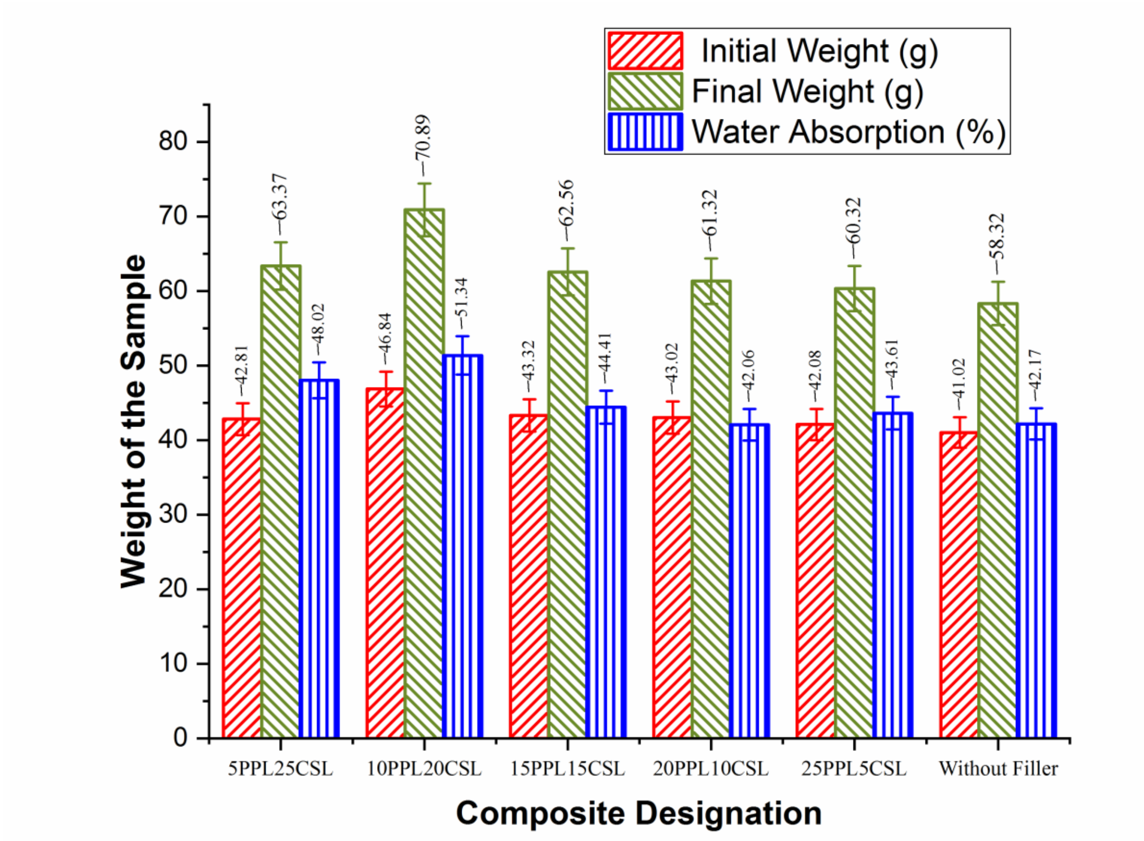

Fig. 11. Moisture characteristics

Scanning Electron Microscopy

The SEM micrographs presented in Figures 12A, 12B, and 12C depict the fractured surfaces of PPL and CSL fiber-reinforced epoxy composites with varying weight percentages of TSP filler. In Figures. 12A, a significant number of fibers are detached from the matrix in various directions, indicating poor bonding between the fibers and the epoxy. This weak adhesive interaction points to insufficient fiber-matrix interface engagement, which may compromise the overall integrity of the composite (Shakil *et al*. 2020). Such inadequate bonding could result from insufficient surface treatment of the fibers or improper mixing techniques, leading to a lack of interfacial adhesion essential for effective load transfer during mechanical stress (Teklal *et al*. 2018; Marques *et al*. 2020). Conversely, Figures 12B illustrates strong adhesion between the fibers and the matrix, marked by reduced fiber pullout and enhanced resistance to crack propagation. This improved adhesion is likely attributed to the presence of TSP, which serves as a reinforcing agent, enhancing interfacial bonding between the fibers and the epoxy matrix (Kasinathan and Rajamani 2022). The addition of TSP may increase the resin’s viscosity and fill any voids, resulting in a denser and more uniform matrix that effectively adheres to the fibers, thereby improving the overall strength properties of the composites (Shahari *et al*. 2021). Figure 12 C presents a mixed scenario, revealing some fibers pulling out along with visible cracks on the fractured surface, indicating an intermediate level of bonding effectiveness (El-Abbasy 2023).

The presence of agglomerations indicates potential issues with matrix curing, which could negatively affect the mechanical performance. Inadequate curing can lead to incomplete polymerization, resulting in a weaker matrix that is less effective in supporting the fibers (Mostafa *et al*. 2017; El-Abbasy 2023). Compared to unfilled composites, Fig. 12 C reflects a noticeable improvement in fiber-matrix adhesion, suggesting that while challenges remain, the addition of TSP has positively influenced the overall composite integrity by promoting better fiber distribution and interaction within the matrix (Binoj *et al*. 2016). These observations highlight the critical role of filler content in optimizing fiber-matrix adhesion and mechanical performance in hybrid composites.

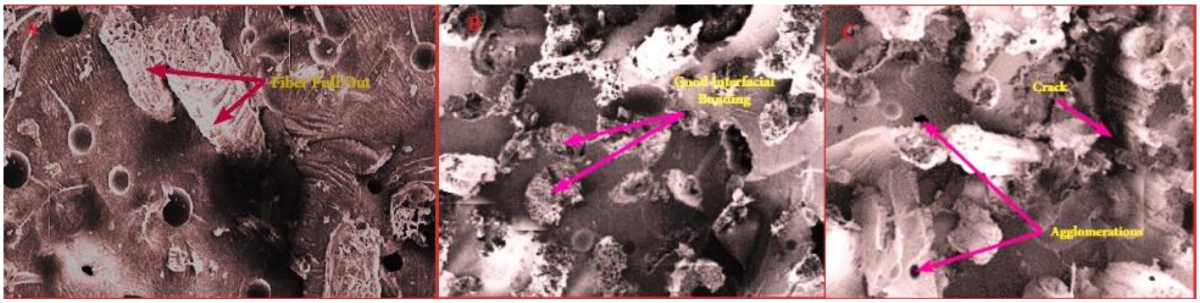

Fig. 12. (A) Fiber pullout; (B) good bonding; (C) crack and agglomerations

Overall, the study emphasizes the significant potential of PPL and CSL fibers, combined with TSP filler, for developing high-performance hybrid composites. The results indicate that careful optimization of fiber and filler content is essential for maximizing the mechanical properties while minimizing water absorption, making these composites suitable for various applications in the fields of construction, automotive, and consumer products. Future work should focus on further refining the processing techniques to enhance fiber distribution and adhesion, ultimately improving the overall performance of these composite materials.

CONCLUSIONS

1. The results demonstrated that increasing palmyra palm leaf (PPL) content enhanced tensile strength, reaching a peak at 42.2 MPa for the 20PPL10CSL composite. This suggests that an optimal balance of fiber content is crucial for achieving maximum strength, as excessive PPL may lead to decreased performance.
2. The flexural tests indicated a similar trend, with a maximum value of 94.4 MPa observed for the 20PPL10CSL composite. The improvements in flexural strength can be attributed to the effective reinforcement provided by PPL fibers and the adhesive properties of tamarind shell powder (TSP), contributing to better load distribution.
3. The impact strength improved with increased fiber content, peaking at 5.98 J for the 20PPL10CSL composite. The ability of the fibers to dissipate energy during impact is vital for applications requiring toughness and durability.
4. ILSS values showed a positive correlation with PPL content, with the highest strength of 7.52 MPa observed in the 20PPL10CSL composite. This highlights the importance of fiber-matrix adhesion in resisting shear forces, essential for the structural integrity of layered composites.

5. Hardness values improved significantly with increased PPL content, peaking at 84.1 Shore D hardness (SD). This enhancement reflects the contribution of PPL fibers to the composite's rigidity and wear resistance.
6. The water absorption tests revealed a tendency for increased moisture uptake with higher fiber content, particularly for the 10PPL20CSL composite, which had the highest absorption at 51.4%. This underscores the porous nature of natural fibers and the need for careful optimization to balance mechanical properties with moisture resistance.
7. The scanning electron microscope (SEM) images provided insights into the fiber-matrix interactions, revealing both the benefits and challenges of using natural fibers. Improved adhesion in composites with TSP filler highlighted the role of fillers in enhancing mechanical performance, although some challenges, such as fiber agglomeration and incomplete curing, were noted.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES CITED

Ahmad, J., and Zhou, Z. (2022). "Mechanical properties of natural as well as synthetic fiber reinforced concrete: A review," *Construction and Building Materials* 333, article 127353. DOI: 10.1016/j.conbuildmat.2022.127353

Ain, U., Sultan, M. T. H., Jawaid, M., Cardona, F., and Talib, A. R. A. (2016). "A review on the tensile properties of bamboo fiber reinforced polymer composites," *BioResources* 11(4), 1-23. DOI: 10.15376/biores.11.4.Shah

Aisyah, H. A., Paridah, M. T., Sapuan, S. M., Ilyas, R. A., Khalina, A., Nurazzi, N. M., Lee, S. H., and Lee, C. H. (2021). "A comprehensive review on advanced sustainable woven natural fibre polymer composites," *Polymers* 13(3), article 471. DOI: 10.3390/polym13030471

Alam, M. I., Maraz, K. M., and Khan, R. A. (2022). "A review on the application of high-performance fiber-reinforced polymer composite materials," *GSC Advanced Research and Reviews* 10(2), 20-36. DOI: 10.30574/gscarr.2022.10.2.0036

Alaneme, K. K., and Sanusi, K. O. (2015). "Microstructural characteristics, mechanical and wear behaviour of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite," *Engineering Science and Technology* 18(3), 416-422. DOI: 10.1016/j.jestch.2015.02.003

An, Z., Cheng, X., Zhao, D., Ma, Y., Guo, X., and Cheng, Y. (2024). "Tensile and compressive properties of woven fabric carbon fiber-reinforced polymer laminates containing three-dimensional microvascular channels," *Polymers* 16(5), 665. DOI: 10.3390/polym16050665

Anggraini, V., Asadi, A., Syamsir, A., and Huat, B. B. K. (2017). "Three point bending flexural strength of cement treated tropical marine soil reinforced by lime treated natural fiber," *Measurement* 111, 158-166. DOI: 10.1016/j.measurement.2017.07.045

Arockiasamy, F. S. (2022). "Experimental investigation on the effect of fiber volume fraction of sponge gourd outer skin fiber reinforced epoxy composites," *Polymer Composites* 43(10), 6932-6942. DOI: 10.1002/pc.26754

Aruchamy, K., Sampath, P. S., Bhuvaneshwaran, M., Umachitra, G., Palanisamy, S., and Mubarak, S. (2024). "Metallic fibers: Applications and composites," in: *Synthetic and Mineral Fibers, Their Composites and Applications*, pp. 433-460. DOI: 10.1016/B978-0-443-13623-8.00016-2

ASTM D2240-15 (2021). "Standard test method for rubber property—Durometer hardness," ASTM International, West Conshohocken, PA, USA.

ASTM D2344/D2344M-22 (2022). "Standard test method for short-beam strength of polymer matrix composite materials and their laminates," ASTM International, West Conshohocken, PA, USA.

ASTM D256-23e1 (2023). "Standard test methods for determining the Izod pendulum impact resistance of plastics," ASTM International, West Conshohocken, PA, USA.

ASTM D570-22 (2022). "Standard test method for water absorption of plastics," ASTM International, West Conshohocken, PA, USA.

ASTM D638-14 (2022). "Standard test method for tensile properties of plastics," ASTM International, West Conshohocken, PA, USA.

ASTM D790-17 (2017). "Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials," ASTM International, West Conshohocken, PA, USA.

Asyraf, M. R. M., Ishak, M. R., Syamsir, A., Nurazzi, N. M., Sabaruddin, F. A., Shazleen, S. S., Norrrahim, M. N. F., Rafidah, M., Ilyas, R. A., and Abd Rashid, M. Z. (2022). "Mechanical properties of oil palm fibre-reinforced polymer composites: A review," *Journal of Materials Research and Technology* 17, 33-65. DOI: 10.1016/j.jmrt.2021.12.122

Asyraf, M. R. M., Syamsir, A., Ishak, M. R., Sapuan, S. M., Nurazzi, N. M., Norrrahim, M. N. F., Ilyas, R. A., Khan, T., and Rashid, M. Z. A. (2023). "Mechanical properties of hybrid lignocellulosic fiber-reinforced biopolymer green composites: A review," *Fibers and Polymers* 24(2), 337-353. DOI: 10.1007/s12221-023-00034-w

Azwa, Z. N., Yousif, B. F., Manalo, A. C., and Karunasena, W. (2013). "A review on the degradability of polymeric composites based on natural fibres," *Materials & Design* 47, 424-442. DOI: 10.1016/j.matdes.2012.11.025

Bahrami, M., Abenojar, J., and Martínez, M. Á. (2020). "Recent progress in hybrid biocomposites: Mechanical properties, water absorption, and flame retardancy," *Materials* 13(22), article 5145. DOI: 10.3390/ma13225145

Barjasteh, E., and Nutt, S. R. (2012). "Moisture absorption of unidirectional hybrid composites," *Composites Part A: Applied Science and Manufacturing* 43(1), 158-164. DOI: 10.1016/j.compositesa.2011.10.003

Binoj, J. S., Raj, R. E., Sreenivasan, V. S., and Thusnavis, G. R. (2016). "Morphological, physical, mechanical, chemical and thermal characterization of sustainable indian areca fruit husk fibers (*Areca catechu* L.) as potential alternate for hazardous synthetic fibers," *Journal of Bionic Engineering* 13(1), 156-165. DOI: 10.1016/S1672-6529(14)60170-0

Blokhin, A. N., Dyachkova, T. P., Maksimkin, A. V, Stolyarov, R. A., Suhorukov, A. K., Burmistrov, I. N., and Kharitonov, A. P. (2020). "Polymer composites based on epoxy resin with added carbon nanotubes," *Fullerenes, Nanotubes and Carbon Nanostructures* 28(1), 45-49. DOI: 10.1080/1536383X.2019.1671364

Carmona, A. R., and Colorado L, H. A. (2021). "Luffa fibers as promising reinforcement for polymer composites: Mechanical characterization of NaOH treated and untreated dumbbell test-pieces with Weibull statistics," *Journal of Composite Materials* 55(12), 1667-1681. DOI: 10.1177/0021998320976800

Chen, Z., Jiang, J., Yu, Y., Chen, G., Chen, T., and Zhang, Q. (2021). "Layer-by-layer assembled bagasse to enhance the fire safety of epoxy resin: A renewable environmental friendly flame retardant," *Journal of Applied Polymer Science* 138(11), article 50032. DOI: 10.1002/app.50032

Chen, Z., Liao, S., Ge, L., Amaniampong, P. N., Min, Y., Wang, C., Li, K., and Lee, J. M. (2020). "Reduced graphene oxide with controllably intimate bifunctionality for the catalytic transformation of fructose into 2, 5-diformylfuran in biphasic solvent systems" *Chemical Engineering Journal* 379, article 122284. DOI: 10.1016/j.cej.2019.122284

Clifton, S., Thimmappa, B. H. S., Selvam, R., and Shivamurthy, B. (2020). "Polymer nanocomposites for high-velocity impact applications – A review," *Composites Communications* 17, 72-86. DOI: 10.1016/j.coco.2019.11.013

Dattu, V. S. N. C. H., Lokesh, M., Kumar, A., Rajkumar, M., Vallavi, M. S. A., and Britto, A. S. F. (2022). "Mechanical characterization of polymer composite reinforced with bio-fillers," *Materials Today: Proceedings* 69(3), 695-699. DOI: 10.1016/j.matpr.2022.07.126

De Cicco, D., Asaee, Z., and Taheri, F. (2017). "Use of nanoparticles for enhancing the interlaminar properties of fiber-reinforced composites and adhesively bonded joints—A review," *Nanomaterials* 7(11), article 360. DOI: 10.3390/nano7110360

Deshmukh, G. S. (2022). "Advancement in hemp fibre polymer composites: A comprehensive review," *Journal of Polymer Engineering* 42(7), 575-598. DOI: 10.1515/polyeng-2022-0033

Deshmukh, G. S., and Palanisamy, S. (2024). "Alumina fibers: Composites and applications," in: *Synthetic and Mineral Fibers, Their Composites and Applications*, pp. 363-381. DOI: 10.1016/B978-0-443-13623-8.00013-7

Ead, A. S., Appel, R., Alex, N., Ayranci, C., and Carey, J. P. (2021). "Life cycle analysis for green composites: A review of literature including considerations for local and global agricultural use," *Journal of Engineered Fibers and Fabrics* 16, 15589250211026940. DOI: 10.1177/15589250211026940

El-Abbasy, A. A. (2023). "Tensile, flexural, impact strength, and fracture properties of ultra-high-performance fiber-reinforced concrete-A comprehensive review," *Construction and Building Materials* 408, article 133621. DOI: 10.1016/j.conbuildmat.2023.133621

Fragassa, C., Vannucchi de Camargo, F., and Santulli, C. (2024). "Sustainable biocomposites: Harnessing the potential of waste seed-based fillers in eco-friendly materials," *Sustainability* 16(4), article 1526. DOI: 10.3390/su16041526

Gao, X., Zhu, D., Fan, S., Rahman, M. Z., Guo, S., and Chen, F. (2022). "Structural and mechanical properties of bamboo fiber bundle and fiber/bundle reinforced composites: A review," *Journal of Materials Research and Technology* 19, 1162-1190. DOI: 10.1016/j.jmrt.2022.05.077

Ghori, W., Saba, N., Jawaid, M., and Asim, M. (2018). "A review on date palm (phoenix dactylifera) fibers and its polymer composites," in: *IOP Conference Series: Materials Science and Engineering* 368, article 12009. DOI: 10.1088/1757-899X/368/1/012009

Goutham, E. R. S., Hussain, S. S., Muthukumar, C., Krishnasamy, S., Kumar, T. S. M., Santulli, C., Palanisamy, S., Parameswaranpillai, J., and Jesuarockiam, N. (2023). "Drilling parameters and post-drilling residual tensile properties of natural-fiber-reinforced composites: A review," *Journal of Composites Science* 7(4), article 136. DOI: 10.3390/jcs7040136

Govindarajan, P. R., Antony, J. A., Palanisamy, S., Ayrilmis, N., Khan, T., Junaedi, H., and Sebaey, T. A. (2024). "Advances in manufacturing of carbon-based molecular nanomaterials based on rice husk/hull waste," *BioResources* 19(4), 1-19. DOI: 10.15376.biores.19.4.Govindarajan

Guo, Y., Zhou, M., Yin, G.-Z., Kalali, E., Wang, N., and Wang, D.-Y. (2021). "Basalt fiber-based flame retardant epoxy composites: Preparation, thermal properties, and flame retardancy," *Materials* 14(4), article 902. DOI: 10.3390/ma14040902

Gurusamy, M., Soundararajan, S., Karuppusamy, M., and Ramasamy, K. (2024). "Exploring the mechanical impact of fine powder integration from ironwood sawdust and COCO dust particles in epoxy composites," *Matéria (Rio de Janeiro)* 29, article e20240216. DOI: 10.1590/1517-7076-RMAT-2024-0216

Gutowski, T. G., Allwood, J. M., Herrmann, C., and Sahni, S. (2013). "A global assessment of manufacturing: Economic development, energy use, carbon emissions, and the potential for energy efficiency and materials recycling," *Annual Review of Environment and Resources* 38(1), 81-106. DOI: 10.1146/annurev-environ-041112-110510

Hajiha, H., Sain, M., and Mei, L. H. (2014). "Modification and characterization of hemp and sisal fibers," *Journal of Natural Fibers* 11(2), 144-168. DOI: 10.1080/15440478.2013.861779

Hasan, K. M. F., Horváth, P. G., Bak, M., and Alpár, T. (2021). "A state-of-the-art review on coir fiber-reinforced biocomposites," *RSC Advances* 11(18), 10548-10571. DOI: 10.1039/D1RA00231G

Hassan, M. M., Le Guen, M. J., Tucker, N., and Parker, K. (2019). "Thermo-mechanical, morphological and water absorption properties of thermoplastic starch/cellulose composite foams reinforced with PLA," *Cellulose* 26, 4463-4478. DOI: 10.1007/s10570-019-02393-1

Iroegbu, A. O. C., and Ray, S. S. (2021). "Bamboos: From bioresource to sustainable materials and chemicals," *Sustainability* 13(21), article 12200. DOI: 10.3390/su132112200

Kamarudin, S. H., Mohd Basri, M. S., Rayung, M., Abu, F., Ahmad, S., Norizan, M. N., Osman, S., Sarifuddin, N., Desa, M. S. Z. M., Abdullah, U. H., Mohamed Amin Tawakkal, I. S., and Abdullah, L. C. (2022). "A review on natural fiber reinforced polymer composites (NFRPC) for sustainable industrial applications," *Polymers* 14(17), article 3698. DOI: 10.3390/polym14173698

Karimah, A., Ridho, M. R., Munawar, S. S., Adi, D. S., Damayanti, R., Subiyanto, B., Fatriasari, W., and Fudholi, A. (2021). "A review on natural fibers for development of eco-friendly bio-composite: Characteristics, and utilizations," *Journal of Materials Research and Technology* 13, 2442-2458. DOI: 10.1016/j.jmrt.2021.06.014

Karthik, A., Bhuvaneshwaran, M., Senthil Kumar, M. S., Palanisamy, S., Palaniappan, M., and Ayrilmis, N. (2024). "A review on surface modification of plant fibers for enhancing properties of biocomposites," *ChemistrySelect* 9(21), article e202400650. DOI: 10.1002/slct.202400650

Karthik, A., Jeyakumar, R., Sampath, P. S., Soundararajan, R., and Manikandan, G. K. (2023a). "Study and fabrication of fan blade using coconut leaf sheath fibre/epoxy-reinforced composite materials," *Journal of The Institution of Engineers (India): Series D* 105, 405-412. DOI: 10.1007/s40033-023-00478-7

Karthik, A., Sampath, P. S., Thirumurugan, V., and Prakash, C. (2023b). "Effect of sample cutting angle on mechanical properties of jute/cotton fabric epoxy composite laminates," *Biomass Conversion and Biorefinery* 14, 17635-17645. DOI: 10.1007/s13399-023-04166-0

Karuppiah, G., Kuttalam, K. C., and Palaniappan, M. (2020). "Multiobjective optimization of fabrication parameters of jute fiber / polyester composites with egg shell powder and nanoclay filler," *Molecules* 25(23), 1-11. DOI: 10.3390/molecules25235579

Karuppiah, G., Kuttalam, K. C., Ayrilmis, N., Nagarajan, R., Devi, M. P. I., Palanisamy, S., and Santulli, C. (2022). "Tribological analysis of jute/coir polyester composites filled with eggshell powder (ESP) or nanoclay (NC) using grey rational method," *Fibers* 10(7), article 60. DOI: 10.3390/fib10070060

Kasinathan, R. K., and Rajamani, J. (2022). "Investigation on mechanical properties of basalt/epoxy fiber reinforced polymer composite with the influence of turtle shell powder," *Polymer Composites* 43(9), 6150-6164. DOI: 10.1002/pc.26920

Khan, M. Z. R., Srivastava, S. K., and Gupta, M. K. (2018). "Tensile and flexural properties of natural fiber reinforced polymer composites: A review," *Journal of Reinforced Plastics and Composites* 37(24), 1435-1455. DOI: 10.1177/0731684418799528

Koffi, A., Koffi, D., and Toubal, L. (2021). "Mechanical properties and drop-weight impact performance of injection-molded HDPE/birch fiber composites," *Polymer Testing* 93, article 106956. DOI: 10.1016/j.polymertesting.2020.106956

Kotik, H. G., and Ipina, J. E. P. (2021). "Suggested modifications of the ASTM D2344-16 short-beam shear test method to be applied to fiber metal laminates," *Journal of Testing and Evaluation* 49(2), 1213-1221. DOI: 10.1520/JTE20170399

Kumar, P., Kumar, M., and Roopa, C. P. (2022a). "Natural nano-fillers materials for the Bio-composites: A review," *Journal of the Indian Chemical Society* 99(10), article 100715. DOI: 10.1016/j.jics.2022.100715

Kumar, R. P., Muthukrishnan, M., and Sahayaraj, A. F. (2022b). "Experimental investigation on jute/snake grass/kenaf fiber reinforced novel hybrid composites with annona reticulata seed filler addition," *Materials Research Express* 9(9), article 95304. DOI: 10.1088/2053-1591/ac92ca

Lal, S. S., and Mhaske, S. T. (2021). "Old corrugated box (OCB)-based cellulose nanofiber-reinforced and citric acid-cross-linked TSP-guar gum composite film," *Polymer Bulletin* 78(2), 885-915. DOI: 10.1007/s00289-020-03138-y

Laureto, J. J., and Pearce, J. M. (2018). "Anisotropic mechanical property variance between ASTM D638-14 type i and type iv fused filament fabricated specimens," *Polymer Testing*, 68, 294-301. DOI: 10.1016/j.polymertesting.2018.04.029

Lotfi, A., Li, H., Dao, D. V., and Prusty, G. (2021). "Natural fiber-reinforced composites: A review on material, manufacturing, and machinability," *Journal of Thermoplastic Composite Materials* 34(2), 238-284. DOI: 10.1177/0892705719844546

Mahir, F. I., Keya, K. N., Sarker, B., Nahiun, K. M., and Khan, R. A. (2019). "A brief review on natural fiber used as a replacement of synthetic fiber in polymer composites," *Materials Engineering Research* 1(2), 86-97. DOI: 10.25082/MER.2019.02.007

Manickaraj, K., Ramamoorthi, R., Karuppasamy, R., Sakthivel, K. R., and Vijayaprakash, B. (2024a). "A review of natural biofiber-reinforced polymer matrix composites," *Evolutionary Manufacturing, Design and Operational Practices for Resource and Environmental Sustainability*, Ch 11, 135-141. DOI: 10.1002/9781394198221.ch11

Manickaraj, K., Ramamoorthi, R., Ramakrishnan, T., and Karuppasamy, R. (2024b). "Enhancing solid waste sustainability with iroko wooden sawdust and african oil bean shell particle-strengthened epoxy composites," *Global Nest Journal* 26(1), 1-5. DOI: 10.30955/gnj.005467

Manickaraj, K., Ramamoorthi, R., Sathish, S., and Johnson Santhosh, A. (2023). "A comparative study on the mechanical properties of African teff and snake grass fiber-reinforced hybrid composites: Effect of bio castor seed shell/glass/SiC fillers," *International Polymer Processing* 38(5), 551-563. DOI: 10.1515/ipp-2023-4343

Manickaraj, K., Ramamoorthi, R., Sathish, S., and Makeshkumar, M. (2022). "Effect of hybridization of novel African teff and snake grass fibers reinforced epoxy composites with bio castor seed shell filler: Experimental investigation," *Polymers & Polymer Composites* 30. DOI: 10.1177/09673911221102288

Manickaraj, K., Ramamoorthy, R., Babu, M. S., and Jeevabharath, K. V. (2019). "Bio-fiber reinforced polymer matrix composites: A Review," *Turkish Journal of Computer and Mathematics Education (TURCOMAT)* 10(2), 740-748.

Marques, A. C., Mocanu, A., Tomić, N. Z., Balos, S., Stammen, E., Lundevall, A., Abrahami, S. T., Günther, R., de Kok, J. M. M., and Teixeira de Freitas, S. (2020). "Review on adhesives and surface treatments for structural applications: Recent developments on sustainability and implementation for metal and composite substrates," *Materials* 13(24), article 5590. DOI: 10.3390/ma13245590

Maslinda, A. B., Majid, M. S. A., Ridzuan, M. J. M., Afendi, M., and Gibson, A. G. (2017). "Effect of water absorption on the mechanical properties of hybrid interwoven cellulosic-cellulosic fibre reinforced epoxy composites," *Composite Structures* 167, 227-237. DOI: 10.1016/j.compstruct.2017.02.023

Mayandi, K., Rajini, N., Ayrilmis, N., Devi, M. P. I., Siengchin, S., Mohammad, F., and Al-Lohedan, H. A. (2020). "An overview of endurance and ageing performance under various environmental conditions of hybrid polymer composites," *Journal of Materials Research and Technology* 9(6), 15962-15988. DOI: 10.1016/j.jmrt.2020.11.031

Mehdikhani, M., Gorbatikh, L., Verpoest, I., and Lomov, S. V. (2019). "Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance," *Journal of Composite Materials* 53(12), 1579-1669. DOI: 10.1177/0021998318772152

Mikulčić, H., Klemeš, J. J., Vujanović, M., Urbaniec, K., and Duić, N. (2016). "Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process," *Journal of Cleaner*

Production 136, 119-132. DOI: 10.1016/j.jclepro.2016.04.145

Mohammed, M., Oleiwi, J. K., Mohammed, A. M., Jawad, A. J. M., Osman, A. F., Adam, T., Betar, B. O., Gopinath, S. C. B., Dahham, O. S., and Jaafar, M. (2023). "Comprehensive insights on mechanical attributes of natural-synthetic fibres in polymer composites," *Journal of Materials Research and Technology* 25, 4960-4988. DOI: 10.1016/j.jmrt.2023.06.148

Mohammed, M., Rahman, R., Mohammed, A. M., Adam, T., Betar, B. O., Osman, A. F., and Dahham, O. S. (2022). "Surface treatment to improve water repellence and compatibility of natural fiber with polymer matrix: Recent advancement," *Polymer Testing* 107707. DOI: 10.1016/j.polymertesting.2022.107707

Mostafa, N. H., Ismarrubie, Z. N., Sapuan, S. M., and Sultan, M. T. H. (2017). "Fibre prestressed polymer-matrix composites: A review," *Journal of Composite Materials* 51(1), 39-66. DOI: 10.1177/0021998316637906

Murugesan, T. M., Palanisamy, S., Santulli, C., and Palaniappan, M. (2022). "Mechanical characterization of alkali treated Sansevieria cylindrica fibers-Natural rubber composites," *Materials Today: Proceedings*, 62, 5402-5406. DOI: 10.1016/j.matpr.2022.03.609

Mylsamy, B., Shanmugam, S. K. M., Aruchamy, K., Palanisamy, S., Nagarajan, R., and Ayrilmis, N. (2024). "A review on natural fiber composites: Polymer matrices, fiber surface treatments, fabrication methods, properties, and applications," *Polymer Engineering & Science* 64(6), 2345-2373, DOI: 10.1002/pen.26713

Neitzel, I., Mochalin, V., Knoke, I., Palmese, G. R., and Gogotsi, Y. (2011). "Mechanical properties of epoxy composites with high contents of nanodiamond," *Composites Science and Technology* 71(5), 710-716. DOI: 10.1016/j.compscitech.2011.01.016

Niang, B., Schiavone, N., Askanian, H., Ndiaye, D., and Verney, V. (2021). "Morphological, rheological and mechanical properties of PLA-Typha based biocomposites," *Open Journal of Composite Materials* 11(4), 111-122. DOI: 10.4236/ojcm.2021.114009

Nurazzi, N. M., Asyraf, M. R. M., Fatimah Athiyah, S., Shazleen, S. S., Rafiqah, S. A., Harussani, M. M., Kamarudin, S. H., Razman, M. R., Rahmah, M., and Zainudin, E. S. (2021). "A review on mechanical performance of hybrid natural fiber polymer composites for structural applications," *Polymers* 13(13), 2170. DOI: 10.3390/polym13132170

Osterberg, M., Henn, K. A., Farooq, M., and Valle-Delgado, J. J. (2023). "Biobased nanomaterials─ The role of interfacial interactions for advanced materials," *Chemical Reviews* 123(5), 2200-2241. DOI: 10.1021/acs.chemrev.2c00492

Palaniappan, M., Palanisamy, S., mani Murugesan, T., Tadepalli, S., Khan, R., Ataya, S., and Santulli, C. (2024a). "Influence of washing with sodium lauryl sulphate (SLS) surfactant on different properties of ramie fibres," *BioResources* 19(2), 2609-2625. DOI: 10.15376/biores.19.2.2609-2625

Palaniappan, S. K., Aruchamy, K., Bhuvaneshwaran, M., Velayutham, T., and Manickaraj, K. (2024b). "Polyacrylonitrile fiber: Composites and applications," in: *Synthetic and Mineral Fibers, Their Composites and Applications*, 269-290. DOI: 10.1016/B978-0-443-13623-8.00009-5

Palanisamy, S., Kalimuthu, M., Santulli, C., Palaniappan, M., Nagarajan, R., and Fragassa, C. (2023a). "Tailoring epoxy composites with Acacia caesia bark fibers: Evaluating the effects of fiber amount and length on material characteristics," *Fibers* 11(7), 63. DOI: 10.3390/fib11070063

Palanisamy, S., Murugesan, T. M., Palaniappan, M., Santulli, C., and Ayrilmis, N. (2023b). "Use of hemp waste for the development of myceliumgrown matrix biocomposites: A concise bibliographic review," *BioResources* 18(4), 8771-8780. DOI: 10.15376/biores.18.4.Palanisamy

Palanisamy, S., Ramakrishnan, S. K., Santulli, C., Khan, T., and Ahmed, O. S. (2024). "Mechanical and wear performance evaluation of natural fiber/epoxy matrix composites," *BioResources* 19(4), 8459-8478. DOI: 10.15376/biores.19.4.8459-8478

Pintaude, G. (2023). "Hardness as an indicator of material strength: A critical review," *Critical Reviews in Solid State and Materials Sciences*, 48(5), 623-641. DOI: 10.1080/10408436.2022.2085659

Prabhu, P., Wan, Y. and Lee, J.M. (2020). "Electrochemical conversion of biomass derived products into high-value chemicals" *Matter, 3*(4), 1162-1177. DOI: 10.1016/j.matt.2020.09.002

Qureshi, M., Li, J., Wu, C., and Sheng, D. (2024). "Mechanical strength of rubberized concrete: Effects of rubber particle size, content, and waste fibre reinforcement," *Construction and Building Materials* 444, 137868. DOI: 10.1016/j.conbuildmat.2024.137868

Rajeshkumar, G., Hariharan, V., and Scalici, T. (2016). "Effect of NaOH treatment on properties of Phoenix sp. fiber," *Journal of Natural Fibers* 13(6), 702-713. DOI: 10.1080/15440478.2015.1130005

Rajeshkumar, G., Seshadri, S. A., Devnani, G. L., Sanjay, M. R., Siengchin, S., Maran, J. P., Al-Dhabi, N. A., Karuppiah, P., Mariadhas, V. A., and Sivarajasekar, N. (2021). "Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites-A comprehensive review," *Journal of Cleaner Production* 310, 127483. DOI: 10.1016/j.jclepro.2021.127483

Rashid, M. E., Khan, M. R., Haque, R. U., and Hasanuzzaman, M. (2023). "Challenges of textile waste composite products and its prospects of recycling," *Journal of Material Cycles and Waste Management* 25(3), 1267-1287. DOI: 10.1007/s10163-023-01614-x

Reddy, G. R., Kumar, M. A., and Jayaramudu, J. (2014). "Biodegradable *Sansevieria cylindrica* leaves fiber/tamarind fruit fiber based polymer hybrid composites on characterization," *International Letters of Chemistry, Physics and Astronomy* 20(2), 116--118.

Safri, S. N. A., Sultan, M. T. H., Jawaid, M., and Jayakrishna, K. (2018). "Impact behaviour of hybrid composites for structural applications: A review," *Composites Part B: Engineering* 133, 112-121. DOI: 10.1016/j.compositesb.2017.09.008

Sathish, S., Prabhu, L., Gokulkumar, S., Karthi, N., Balaji, D., and Vigneshkumar, N. (2021). "Extraction, treatment and applications of natural fibers for bio-composites-A critical review," *International Polymer Processing* 36(2), 114-130. DOI: 10.1515/ipp-2020-4004

Shahari, S., Fathullah, M., Abdullah, M. M. A. B., Shayfull, Z., Mia, M., and Darmawan, V. E. B. (2021). "Recent developments in fire retardant glass fibre reinforced epoxy composite and geopolymer as a potential fire-retardant material: A review," *Construction and Building Materials* 277, 122246. DOI: 10.1016/j.conbuildmat.2021.122246

Shakil, U. A., Hassan, S. B. A., Yahya, M. Y., and Nauman, S. (2020). "Mechanical properties of electrospun nanofiber reinforced/interleaved epoxy matrix composites—A review," *Polymer Composites* 41(6), 2288-2315. DOI: 10.1002/pc.25539

Singh, S., Deepak, D., Aggarwal, L., and Gupta, V. K. (2014). "Tensile and flexural behavior of hemp fiber reinforced virgin-recycled HDPE matrix composites," *Procedia Materials Science* 6, 1696-1702. DOI: 10.1016/j.mspro.2014.07.155

Sonar, T., Ivanov, M., Trofimov, E., Tingaev, A., and Suleymanova, I. (2024). "A comprehensive review on fusion welding of high entropy alloys-processing, microstructural evolution and mechanical properties of joints," *International Journal of Lightweight Materials and Manufacture* 7(1), 122-183. DOI: 10.1016/j.ijlmm.2023.06.003

Stalin, B., Nagaprasad, N., Vignesh, V., and Ravichandran, M. (2019). "Evaluation of mechanical and thermal properties of tamarind seed filler reinforced vinyl ester composites," *Journal of Vinyl and Additive Technology* 25(s2), E114-E128. DOI: 10.1002/vnl.21701

Sumesh, K. R., Ajithram, A., Palanisamy, S., and Kavimani, V. (2023). "Mechanical properties of ramie/flax hybrid natural fiber composites under different conditions," *Biomass Conversion and Biorefinery* 1-12. DOI: 10.1007/s13399-023-04628-5

Sumesh, K. R., Kavimani, V., Rajeshkumar, G., Indran, S., and Saikrishnan, G. (2021). "Effect of banana, pineapple and coir fly ash filled with hybrid fiber epoxy based composites for mechanical and morphological study," *Journal of Material Cycles and Waste Management* 23(4), 1277-1288. DOI: 10.1007/s10163-021-01196-6

Sumesh, K. R., Palanisamy, S., Khan, T., Ajithram, A., and Ahmed, O. S. (2024). "Mechanical, morphological and wear resistance of natural fiber/glass fiber-based polymer composites," *BioResources* 19(2), 3271-3289. DOI: 10.15376/biores.19.2.3271-3289

Teklal, F., Djebbar, A., Allaoui, S., Hivet, G., Joliff, Y., and Kacimi, B. (2018). "A review of analytical models to describe pull-out behavior-Fiber/matrix adhesion," *Composite Structures* 201, 791-815. DOI: 10.1016/j.compstruct.2018.06.091

Thapliyal, D., Verma, S., Sen, P., Kumar, R., Thakur, A., Tiwari, A. K., Singh, D., Verros, G. D., and Arya, R. K. (2023). "Natural fibers composites: Origin, importance, consumption pattern, and challenges," *Journal of Composites Science* 7(12), 506. DOI: 10.3390/jcs7120506

Thirupathi, S., Mallichetty, E., Gopalan, V., and Velu Pitchumani, S. (2024). "Areca fiber reinforced bio-materials: A review on processing, properties and advanced optimization technique," *Journal of Natural Fibers* 21(1), 2357236. DOI: 10.1080/15440478.2024.2357236

Vinod, A., Sanjay, M. R., and Siengchin, S. (2021). "Fatigue and thermo-mechanical properties of chemically treated *Morinda citrifolia* fiber-reinforced bio-epoxy composite: A sustainable green material for cleaner production," *Journal of Cleaner Production* 326, 129411. DOI: 10.1016/j.jclepro.2021.129411

Wan, Y. and Lee, J.M. (2021). "Toward value-added dicarboxylic acids from biomass derivatives *via* thermocatalytic conversion" *ACS Catalysis, 11*(5), 2524-2560. DOI: 10.1021/acscatal.0c05419

Zaghloul, M. M. Y., Zaghloul, M. M. Y., and Fuseini, M. (2023). "Recent progress in epoxy nanocomposites: Corrosion, structural, flame retardancy and applications—A comprehensive review," *Polymers for Advanced Technologies* 34(11), 3438-3472. DOI: 10.1002/pat.6144

Zhao, J., Yan, Y., Hu, Z.T., Jose, V., Chen, X. and Lee, J.M. (2020). "Bifunctional carbon nanoplatelets as metal-free catalysts for direct conversion of fructose to 2, 5-diformylfuran," *Catalysis Science & Technology*, *10*(13), 4179-4183. DOI: 10.1039/D0CY00489H
Zhao, J., Chen, X., Du, Y., Yang, Y. and Lee, J.M. (2018). "Vanadium-embedded mesoporous carbon microspheres as effective catalysts for selective aerobic oxidation of 5-hydroxymethyl-2-furfural into 2, 5-diformylfuran" *Applied Catalysis A: General*, *568*, 16-22. DOI: 10.1016/j.apcata.2018.09.015

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