Indonesian Journal of Maritime Technology (ISMATECH)
Vol. 03, Issue 02, December 2025
eISSN: 3025-518X
DOI: https://doi.org/10.35718/ ismatech.v3i2. 8481890

Assessment of Coconut Petiole Fiber–Reinforced Hybrid Composites as Sustainable Materials for Ship Components

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KEYWORDS
Natural fiber composite
Fiberglass
Coconut petiole fiber
Water absorption
Tensile strength

ABSTRACT – The use of synthetic fibers in composite materials in the shipping industry provides mechanical advantages but produces non-biodegradable waste. This encourages the development of more environmentally friendly natural fiber-reinforced composite materials. This study examines the physical properties and tensile strength of composites made from a mixture of coconut petiole fibers and fiberglass, including the effect of immersion in seawater and freshwater for 30 days. The results show that the composites experience an average water absorption of 0.074% (freshwater) and 0.065% (seawater). Tensile tests show average tensile strength values of 35.837 MPa (freshwater), 31.890 MPa (seawater), and 41.290 MPa (without immersion). Immersion in an aqueous medium reduces the tensile strength due to interfacial degradation between the fiber and the matrix. Coconut petiole fiber–fiberglass composites have the potential to be an alternative material for ship components with competitive and environmentally friendly mechanical characteristics.

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INTRODUCTION

The national shipping industry is required to develop innovative materials that are not only strong, lightweight, and corrosion-resistant, but also environmentally friendly. Fiberglass–polyester composites have long been used for ship hull construction due to their ease of fabrication and good mechanical properties [1-3]. However, fiberglass waste is not easily biodegradable, thus raising sustainability concerns.

Research into natural fiber-based composites has grown rapidly in the last two decades. Fibers such as kenaf, jute, sisal, ramie, bamboo, and coconut fiber are of interest due to their low density, high biodegradability, and abundant availability [4]. Moreover, natural fiber composites (NFCs) are potential candidates to replace synthetic materials in lightweight structural applications, including ship components [5-9].

Indonesia has great potential of lignocellulosic fibers, and one of them is coconut petiole. The coconut petiole has high lignocellulose content, it provides good mechanical strength, making it a candidate for reinforcing local biomass-based composites. However, its hygroscopic nature causes natural fibers to easily absorb water, which can trigger swelling and reduce the mechanical strength of the composite [10]. Furthermore, The advantages and drawbacks of lignocellulosic fibers have been extensively discussed [11-15].

Various studies have demonstrated the challenges of natural fibers in maritime applications. Alamsyah et al., noted that rattan and jute fiber composites exhibited a decrease in strength after contact with water [8]. Research on banana stem fiber concluded that pure natural fiber composites do not meet BKI standards for underwater hull applications [6]. Even pure fiberglass–polyester composites experience a decrease in strength after immersion in seawater and freshwater [16]. Research on empty oil palm fruit bunch fibers for ship hulls also demonstrated the limitations of pure natural fiber strength [17].

To improve mechanical characteristics and environmental resistance, a hybrid composite approach was developed, namely combining natural fibers and synthetic fibers such as fiberglass. Hybridization has been proven to increase the tensile strength, stiffness, and dimensional stability of the composite [18]. However, studies related to coconut petiole fiber–fiberglass hybrid composites for maritime applications are still limited.

This study aims to analyze the water absorption of coconut petiole fiber–fiberglass hybrid composites, evaluate the effect of immersion on tensile strength, and assess the potential of hybrid composites as alternative materials for more environmentally friendly ship components.

MATERIALS AND METHODS

This research was conducted to develop a hybrid composite reinforced with chopped strand mat (CSM) fiberglass and woven coconut petiole fibers using the hand lay-up technique, followed by an assessment of its hygro-mechanical behavior under seawater and freshwater immersion. The methodological framework encompasses material preparation, composite formulation, laminate fabrication, specimen machining, immersion conditioning, and mechanical testing.

Materials and Equipment

Fiberglass reinforcement was provided in the form of chopped strand mat (CSM), while coconut petiole fibers were prepared as natural reinforcement through a sequence of peeling, mechanical pounding, solar drying, and manual weaving. The matrix system employed polyester resin (orthophthalic type) cured with methyl ethyl ketone peroxide (MEKP). A commercial release agent was used to facilitate demolding. Two aqueous environments—natural seawater and freshwater—served as conditioning media.

The primary equipment included a glass mold (25 × 10 × 0.5 cm), volumetric measuring tools, a digital balance (accuracy ±0.01 g), a caliper (±0.02 mm), clamping fixtures, and a Universal Testing Machine (UTM) for tensile characterization. Composite plates and specimens were cut using a handheld grinder equipped with cutting wheels.

Composite Formulation

Fiberglass The composite laminate was designed with a fiber-to-matrix volume fraction of 30:70. The mold volume was determined as:

$$V_{mold} = 25 \; x \; 10 \; x \; 0.5 = 125 \; cm^3$$

Thus, the volumes of fiber and matrix required were:

$$V_f = 0.30 V_{mold} = 37.5 \; mL$$

$$V_f = 0.70 V_{mold} = 87.5 \; mL$$

The resin–catalyst ratio was set to 100:1.5 (v/v), resulting in the required catalyst volume:

$$V_k = V_f \; x \; 0.015 = 1.31 \; mL$$

These proportions were kept constant for all fabricated specimens to ensure consistency in laminate structure and curing behavior.

Laminate Fabrication

The laminate panels were fabricated using the hand lay-up process. The mold surfaces were coated with release agent prior to lay-up. Fiberglass sheets and woven coconut fiber mats were cut to the required dimensions. The polyester resin and MEKP catalyst were mixed for 2–3 min to achieve uniform dispersion.

The laminate architecture consisted of the following sequence: resin layer, CSM layer, resin layer, woven coconut fiber layer, resin layer, CSM layer, and a final resin layer. After lay-up, the mold was closed and mechanically clamped to ensure uniform thickness and to minimize void formation. Panels were allowed to cure at ambient conditions for 24 h and were then demolded and inspected for surface quality and dimensional accuracy.

Specimen Machining

The composite panels were machined into tensile specimens in accordance with ASTM D3039. Cutting was performed using a handheld grinder, followed by light surface finishing to eliminate edge defects and stress concentrators. Three specimens were prepared for each test condition (unconditioned, seawater immersion, freshwater immersion), resulting in a total of nine specimens.

Immersion Conditioning

Specimens were immersed in seawater and freshwater for 30 days to simulate marine and terrestrial aqueous environments. Prior to immersion, each specimen was weighed (W_1) using a precision digital balance. After 30 days, the specimens were removed, surface-dried, and reweighed (W_2). Water absorption was calculated using:

$$W_{abs}(\%) = \frac{W_2 - W_1}{W_1} x\,100 \quad (1)$$

This procedure allows quantification of moisture uptake and preliminary assessment of hygrothermal degradation.

Tensile Testing

Tensile tests were carried out on a Universal Testing Machine following the guidelines of ASTM D3039. The tensile properties obtained include ultimate tensile strength (UTS), tensile modulus, and failure strain. These properties were computed using:

$$\sigma_{max} = \frac{F_{max}}{A}, \qquad E = \frac{\Delta\sigma}{\Delta\epsilon}, \qquad \epsilon_{break} = \frac{\Delta L}{L_0} \quad (2)$$

where F_{max} is the maximum load, A is the cross-sectional area, and L0L_0L0 is the initial gauge length.

The degradation of tensile strength after immersion was expressed as:

$$\Delta\sigma\ (\%) = \frac{\sigma_0 - \sigma_i}{\sigma_0} x\,100 \quad (3)$$

with σ_0 being the strength of unconditioned specimens and σ_i the strength after immersion.

RESULTS AND DISCUSSION

The resistance of hybrid composites to aqueous environments, specifically freshwater and seawater, which represent typical operating conditions for marine applications, was assessed through water absorption tests. To determine the percentage of water absorption, the specimens were periodically weighed after being submerged for 30 days, and periodic weighing was performed to calculate the percentage of water absorption.

Freshwater Absorption

All specimens (FW1, FW2, and FW3) showed an increase in weight with increasing immersion time, according to Table 1 and the freshwater absorption graph in Figure 1. After the tenth day of immersion, the absorption trend showed a nearly linear increase. On the 30th day, the water absorption percentages were 0.047% (FW1), 0.100% (FW2), and 0.075% (FW3), with an average of 0.074%.

Table 1. Freshwater absorption data.

Specimen	Initial Weight (g)	Weight After 30 Days (g)	Water Absorption (%)
FW1	43	45	0.047
FW2	50	55	0.100
FW3	53	57	0.075
Average water absorption		0.074	

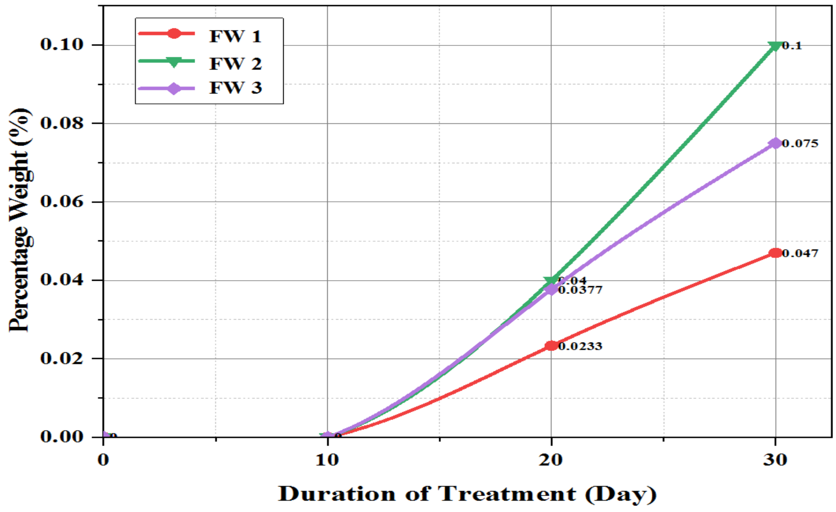

Figure 1. Freshwater absorption

The presence of microstructural variations, especially in relation to fiber distribution and the potential creation of voids during the fabrication process, is indicated by the variation in absorption values among specimens. Because there are no dissolved ions to prevent water from penetrating the matrix and fiber–matrix interface, freshwater has a higher diffusion capability into the composite.

Seawater Absorption

The seawater absorption results presented in Table 2 and Figure 2 show relatively lower values compared to freshwater immersion. On the 30th day, the seawater absorption percentages were 0.035% (SW1), 0.075% (SW2), and 0.085% (SW3), with an average value of 0.065%.

Table 2. Seawater absorption data.

Specimen	Initial Weight (g)	Weight After 30 Days (g)	Water Absorption (%)
SW1	57	59	0.035
SW2	40	43	0.075
SW3	47	51	0.085
Average water absorption		0.065	

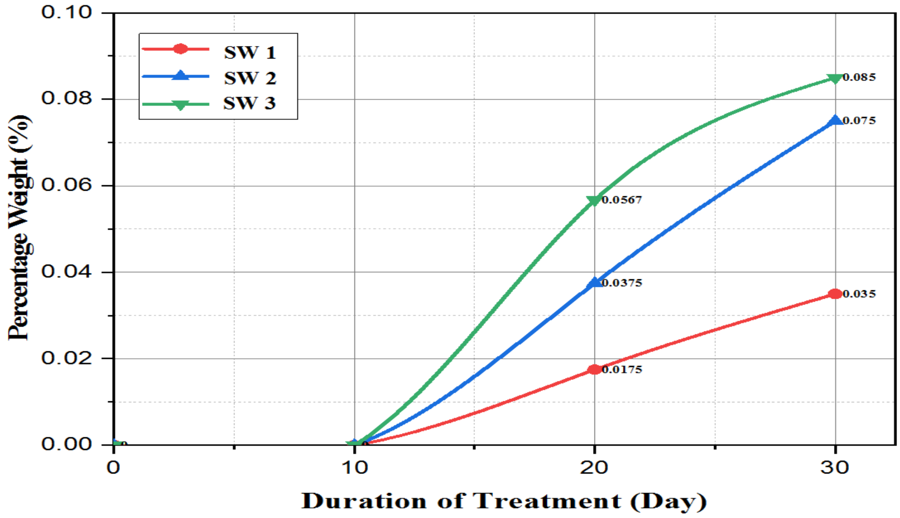

Figure 2. Seawater absorption

The lower seawater absorption compared to freshwater is attributed to the presence of salts, which increase water density and reduce the diffusion coefficient of water into the composite material. In addition, dissolved ions in seawater can inhibit water penetration into microgaps and pores within the composite structure.

Comparison between Freshwater and Seawater Absorption

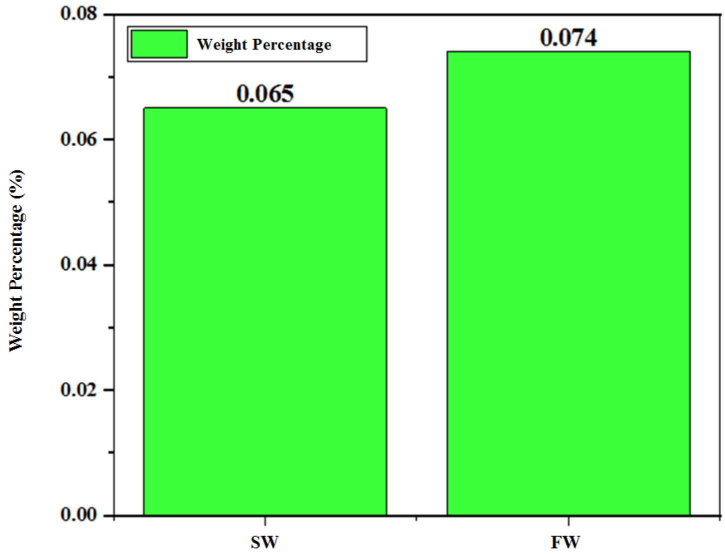

Figure 3. Comparison between seawater and freshwater absorption

Figure 3 compares the average water absorption of coconut petiole fiber–fiberglass hybrid composites after 30 days of immersion in seawater (SW) and freshwater (FW). A slight difference in weight gain is observed between the two immersion media.

The specimens immersed in seawater show an average absorption of 0.065%, while those in freshwater exhibit a higher value of 0.074%. This difference is attributed to micro-voids and non-uniform specimen density, which affect water penetration. The higher absorption in freshwater confirms the influence of the hygroscopic nature of coconut petiole fibers; however, the overall absorption remains low (<0.1%), indicating adequate water resistance for lightweight structural applications.

Stress–Strain Behavior of Freshwater-Immersed Composites

Tensile testing was conducted to evaluate the effect of immersion on the mechanical properties of the composites, particularly tensile strength, elongation at break, and elastic modulus. The tests were performed in accordance with the ASTM D3039 standard.

The stress–strain curves for freshwater-immersed specimens in Figure 4 show that the composites experienced elastic deformation followed by brittle fracture after reaching the maximum stress. Based on Table 3, the average tensile strength was 35.837 MPa, with an average elongation at break of 0.012%.

The reduction in tensile strength compared to the neutral specimens indicates that freshwater diffusing into the composite weakened the fiber–matrix interfacial bonding. The absorbed water caused swelling of the natural fibers and reduced the efficiency of load transfer from the matrix to the fibers.

Table 3. Tensile test results after freshwater immersion.

Specimen	Tensile Strength (MPa)	Elongation (%)	Modulus of Elasticity (kgf/mm²)
FW1	34.601	0.012	288.339
FW2	37.548	0.008	469.353
FW3	35.364	0.016	221.026
Average	35.837	0.012	326.239

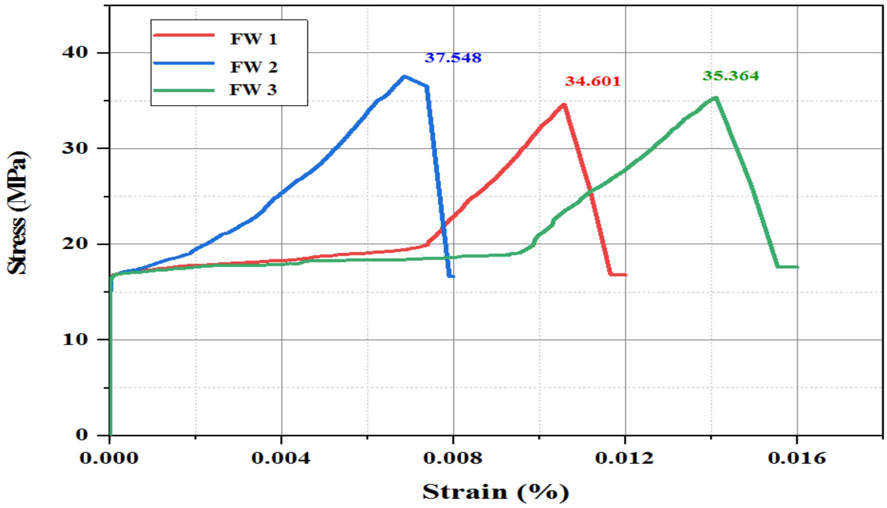

Figure 4. Stress–strain curves for freshwater-immersed specimens

Stress–Strain Behavior of Seawater-Immersed Composites

The tensile test results for seawater-immersed specimens (Table 4 and Figure 5) show an average tensile strength of 31.890 MPa, which is lower than that of the freshwater-immersed specimens. However, the average elongation value was higher, at 0.016%. This phenomenon indicates that seawater immersion tends to reduce the stiffness of the material, making the composite slightly more ductile. Salt ions in seawater may accelerate the degradation of the fiber–matrix interface, particularly for natural fibers, resulting in lower tensile strength but increased deformability prior to fracture.

Table 4. Tensile test results after seawater immersion.

Specimen	Tensile Strength (MPa)	Elongation (%)	Modulus of Elasticity (kgf/mm²)
SW1	31.910	0.016	199.437
SW2	32.324	0.016	202.025
SW3	31.437	0.016	196.481
Average	31.890	0.016	199.314

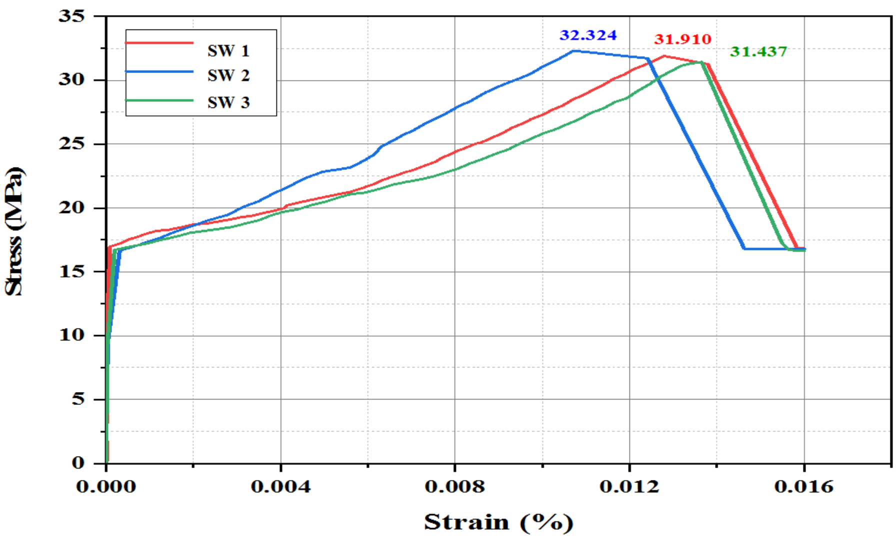

Figure 5. Stress–strain curves for seawater-immersed specimens

Table 5. Tensile test results of neutral (non-immersed) specimens.

Specimen	Tensile Strength (MPa)	Elongation (%)	Modulus of Elasticity (kgf/mm²)
Neutral 1	41.036	0.016	256.437
Neutral 2	42.655	0.012	355.416
Neutral 3	40.180	0.012	334.833
Average	41.290	0.013	315.562

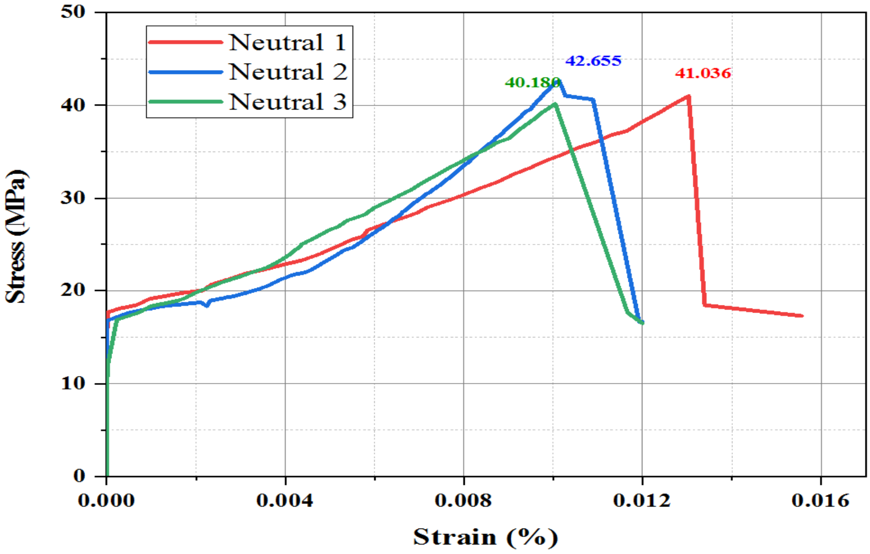

Figure 6. Stress–strain curves of neutral (non-immersed) specimens

Stress–Strain Behavior of Neutral (Non-Immersed) Composites

Neutral specimens exhibited the best mechanical performance among all tested specimens. Based Table 5 and Figure 6, the average tensile strength reached 41.290 MPa, with an elongation at break of 0.013%. The stress–strain curve shows a more stable profile and a higher maximum stress.

This condition confirms that the absence of aqueous environmental exposure preserves the quality of the fiber–matrix interfacial bonding, allowing a more efficient load transfer mechanism.

CONCLUSION

This study demonstrates that coconut petiole–fiberglass hybrid composites with a polyester matrix exhibit relatively low water absorption, with average values of 0.074% in freshwater and 0.065% in seawater after 30 days of immersion, while freshwater induces a higher absorption rate. Immersion leads to a reduction in mechanical performance, as evidenced by a decrease in tensile strength from 41.29 MPa in the neutral condition to 35.84 MPa and 31.89 MPa for freshwater- and seawater-immersed specimens, respectively, primarily due to water penetration and degradation of the fiber–matrix interfacial bonding. Nevertheless, the incorporation of fiberglass significantly enhances the resistance of the hybrid composite to aqueous environments, limiting water uptake and preserving acceptable mechanical performance, thereby indicating that this material remains suitable for non-structural to semi-structural marine applications such as interior panels, lightweight bulkheads, and cladding components, while offering a more environmentally friendly alternative to fully synthetic composites.

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