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Performance of Carbon Fiber-Reinforced Date Palm Midrib Composites

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Highlights

What are the main findings?

- Epoxy-based date palm–carbon fiber composites outperformed in tensile and flexural strength in both directions.
- Polyester-based composites excelled in impact resistance and had lower thickness swelling, suggesting better dimensional stability.

What is the implication of the main finding?

- These results highlight the ability to customize sustainable hybrid composites by selecting the right resin system.
- Epoxy-based composites are better suited for high-strength structural applications, while polyester-based ones are ideal for impact-resistant or dynamic-load com-ponents.

Abstract: This paper evaluates the performance of composites made from date palm (*Phoenix dactylifera* L.) midribs reinforced with carbon fiber. Two types of adhesives—unsaturated polyester and epoxy resin—were used as binder for the experimental panels. The physical properties and mechanical strength of the composites, as a function of fiber types, lamination configuration, as well as adhesive types, were determined. The density levels of the panels made using epoxy and unsaturated polyester resin were found to be 1103 kg/m^3 and 1133 kg/m^3, respectively. Panels made using polyester adhesive had 6.05% and 3.98% for water absorption and thickness swelling values, respectively. Corresponding values of 3.09% and 6.35% were found for the panels made using epoxy resin. Mechanical properties of the samples revealed that carbon fiber-reinforced epoxy hybrids offer superior mechanical performance, whereas polyester-based hybrids may be more suitable for impact-resistant applications. Stereo-microscopy and vertical density profile (VDP) analysis of the panels resulted in variations in layer adhesion and density distribution. Based on the findings in this work, carbon fiber-reinforced epoxy-bonded hybrid panels exhibited superior mechanical properties, while those panels made using polyester-based binder would be more suitable where impact resistance is desired. The combination of date palm fibers and carbon fiber presents significant potential for sustainable applications, offering a balance of strength and durability.

Keywords: *Phoenix dactylifera*; long fibers; midribs; carbon fiber; laminate; mechanical testing; dimensional stability

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1. Introduction

The date palm (*Phoenix dactylifera* L.) is extensively grown across North Africa and the Middle East, having a rich source of cellulosic fibers from the seasonal pruning and trimming of leaves, spadix stems, midribs, and trunks [1]. This biomass resource averages 35 kg per tree [2], generating annually millions of tons of waste material. Improper disposal, including landfill or combustion, contributes to environmental hazards and greenhouse gas emissions [3,4].

The midribs of the date palm tree are key fiber sources, structurally linking the leaves and bark [5]. The fiber extraction method plays a crucial role in obtaining high-performance fibers. Successful extraction results in long, fine fibers with minimal damage, and recommended techniques include alkaline treatment with NaOH and mechanical extraction [6,7]. Previous studies indicated that alkaline treatment enhanced fiber–matrix adhesion by removing wax and hemicellulose, improving porosity, moisture resistance, and mechanical performance of the final product [8–10].

The midrib's structure consists of thick, hollow vascular tissues encased in a lignin structure, exhibiting circular cross-sections with diameters reaching up to 1 mm. These structures contain micro-fibrils approximately 12 µm in diameter, bound together by hemicellulose [11]. Extracted fibers can reach lengths of up to 3 m, significantly longer than commonly used natural fibers (i.e., flax and sisal), which need to be at least 90 cm long for spinning into yarns and limits the use of these short fibers [11]. Chemical analyses of date palm fibers show variations in cellulose (45–46 wt%), lignin (22–26 wt%), and hemicellulose (28–30 wt%) content [12,13]. Midrib fibers have cellulose (41–46 wt%), hemicellulose (25–34 wt%), and slightly higher lignin content (25–30 wt%), which may affect their mechanical and physical properties [14–16]. For instance, fibers extracted from the midrib demonstrated the lowest flexural strength, which was related to their higher lignin content [17]. Similarly, it was also observed that flexural strength decreased as the proportion of date palm in grout specimens increased in a past study [18]. Conversely, a reduction in hemicellulose content was associated with lower water absorption percentage [7]. The cellular structure of the date palm fibers is similar to that of bamboo or coir [19]. Compared to commonly used natural plant fibers like hemp, flax, jute, or sisal, date palm fibers have a lower density and significantly greater length [5], contributing to enhanced specific properties in composite matrices.

Tensile and bending strength, as the main mechanical properties of a composite, are critical for engineering applications. Using date palm waste in composite materials provides an eco-friendly alternative to conventional reinforcements such as wood or other cellulosic materials [13,20,21], having the advantage of being less expensive compared to wood or other cellulosic materials [22]. Treated date palm fibers demonstrated superior mechanical properties as reinforcement in a polyethylene matrix [23] and exhibited significantly improved mechanical performance compared to untreated raw materials when they reinforce the polyester resin [24] or epoxy resin [8].

On the other hand, synthetic reinforcements (i.e., glass fibers, Kevlar, carbon fibers) have superior mechanical strength [25–28]. These materials are widely used in industries such as marine applications, automotive, and aerospace for their exceptional tensile strength, thermal stability, and impact resistance [29,30]. Synthetic glass fibers are widely used and valued for their outstanding strength, durability, thermal stability, and resistance to impact, friction, wear, and chemicals. In contrast, carbon fibers are more rigid [31] and are characterized by excellent tensile strength (2.4 GPa–3.1 GPa), a high elastic modulus (200 GPa–280 GPa), and significant high-temperature resistance [32].

Carbon fiber-reinforced polymer composites are typically characterized by high stiffness and strength, integrating the fiber's robustness and flexibility with the adaptability of a polymer matrix [33,34]. They also offer the highest strength-to-weight efficiency [35]. Various types of carbon fiber laminates in an epoxy matrix have been developed in previous studies [36–38]. The adhesion of the fibers to the polymer matrix is a crucial factor in defining the composite's mechanical performance [34,39], and has been investigated using scanning electron microscopy (SEM) and other microscopy techniques.

There is still very limited information on the properties of polymer-reinforced composites using long fibers of date palm extracted from midribs. Therefore, the objective of this study was to evaluate the hybrid laminate polymer-reinforced composites made from long fibers extracted from date palm midribs and carbon twill fiber as reinforcements in epoxy and unsaturated polyester resin matrices. Hybridization is anticipated to positively influence the strength of the composites, surpassing the limitations of natural fibers alone. This research is expected to offer valuable insights into the mechanical behavior of hybrid composites, taking into account factors like matrix type, density, and adhesion between fibers and matrix. Additionally, stereo-microscopic analysis and a vertical density profile (VDP) of the samples would offer further information interpretation of the results with an accurate approach so that properties of such composites can be better understood. The rationale for using specific standards in testing the composites ensures the scientific validity of the research and helps in assessing their mechanical performance under loads present in real engineering applications, such in as automotive, marine, and construction industries, aiming to achieve a balance between mechanical strength, lightweight performance, and dimensional stability.

The research presented in this manuscript investigates hybrid laminate polymer-reinforced composites incorporating long date palm midrib fibers as an alternative to conventionally used natural plant fibers, in combination with carbon twill fibers. The novelty of this study lies in the utilization of date palm fibers, which, compared to traditional natural fibers such as hemp, flax, jute, or sisal, exhibit lower density and significantly greater fiber length, attributes that contribute to improved specific properties within the composite matrix.

2. Materials and Methods

2.1. Materials

2.1.1. Fibers Preparation and Extraction

The midribs were obtained from Hormozgan province in the south of Iran (27.4150° N, 56.7412° E). All midribs were gathered from a single tree during the same period to ensure uniformity and minimize the effects of cultivation factors. Fiber bundle diameters of the samples varied between 200 µm and 400 µm. The measurements were taken using a NIKON SMZ 18-LOT2 (Nikon Corporation, Tokyo, Japan) stereo-microscope with 240× magnification, as shown in Figure 1.

The fiber extraction process involved four main steps: preparing the midrib, applying an alkaline treatment, conducting mechanical extraction, and performing neutralization. This process, as outlined in previous studies, is depicted in Figure 2 [11,40]. The fibers were obtained from the central sections of the midribs, which were cut to a length of 400 mm. The midribs were first submerged in water for a week before they were reduced to strands. They were then immersed in a 1.5% NaOH solution for three hours at a temperature of 95 °C to remove lignin. After squishing, the fibers were extracted and combed, followed by neutralization with 5% acetic acid for 2–3 min before final washing and drying.

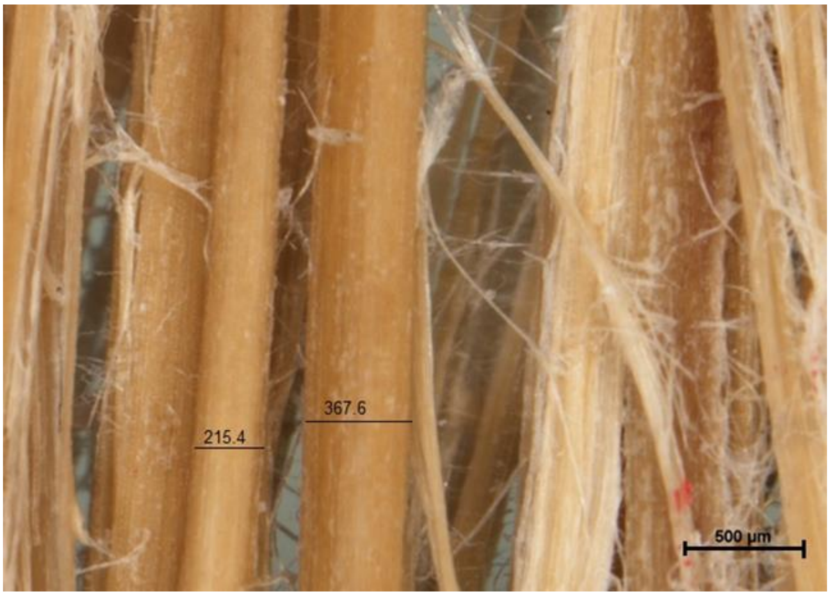


Figure 1. Fiber bundles extracted from the date palm midribs.

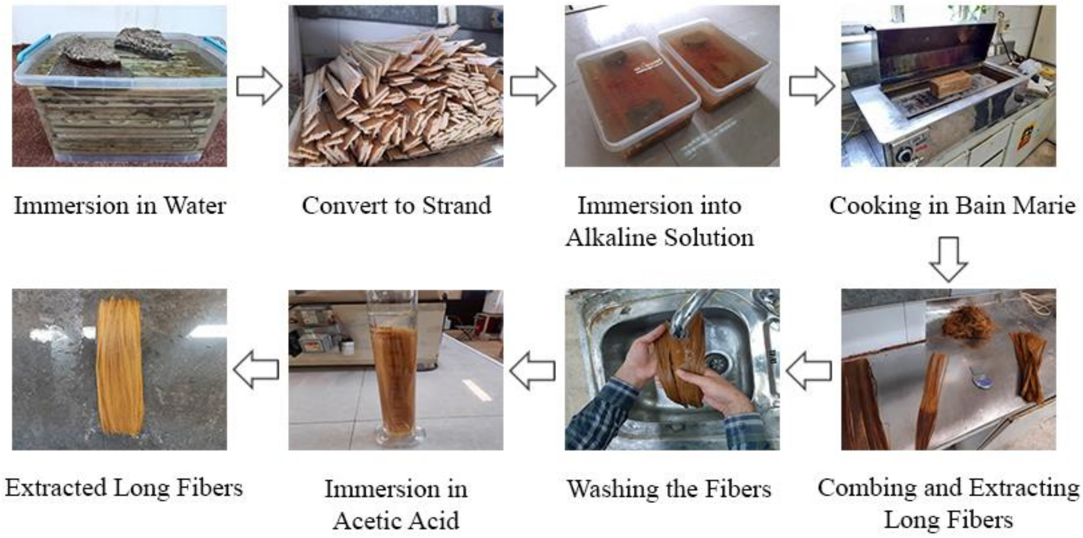


Figure 2. Process of date palm long fiber extraction.

2.1.2. Composite Panels Manufacturing

The long fibers were converted into flat mats, designed for use as layers in laminate composites. They were oriented longitudinally and placed adjacent to one another, forming mats approximately 350 mm × 350 mm in size. The mats were manually wetted and pressed before they were dried at room temperature for 24 h. No chemicals were used in the manufacturing process of the composites.

The hand lay-up method was applied to fabricate the laminates with the structures displayed in Table 1.

Table 1. Structures of the experimental laminated composites.

Code	Layers	Resin
D.Cr.-E	1, 3, and 5: Date palm midrib long fiber mats	Epoxy
D.Cr-P	2 and 5: Carbon fiber twill	Unsaturated polyester

The two-component Epoxy BK resin (Voss Chemie GmbH, Uetersen, Germany) was used to bond the five layers of the D.Cr-E composite panels. This resin has a Shore D hardness index of 80, with two components (A and B) with specific gravities of 1.15 g/cm^3 and 1.0 g/cm^3, respectively, and viscosities of 1000 mPa s and 700 mPa s, respectively, being recommended as a coating or casting resin and also as a laminating resin. When applied to a surface at an ambient temperature of approximately 20 °C, it takes up to 30 min to fully construct one hybrid composite panel. According to the data sheet, the epoxy resin has a curing time of 3–5 days to develop its full strength.

Polyester Viscovoss AZUR SUPER+ (Voss Chemie GmbH, Uetersen, Germany) is an unsaturated polyester resin that is pre-accelerated and temperature-cured, with low styrene emissions, having a Shore D hardness index of 80 and a specific gravity of 1.1 g/cm^3. It is recommended as a laminating resin, almost twice cheaper than epoxy resin, but has a styrene content of 40%, having potential harmful effects on human health. Methyl ethyl ketone peroxide (MEKP) hardener is essential for curing, and it is used in proportions ranging from 1% to 3%. The amount of hardener and the ambient temperature directly influence the working time. At an ambient temperature of approximately 20 °C, the full construction time for one hybrid composite panel is 40 min with 1% hardener, 30 min with 2% hardener, and 20 min with 3% hardener. The data sheet indicates that the polyester resin fully cures and attains maximum strength within 2 to 3 days. Since both resins are recommended for lamination, research aimed to compare their performance and potential applications.

The hybrid composite panels with combinations shown in Table 1 were manufactured under laboratory conditions. Three layers of date palm midrib long fiber (DPMLF) mats were arranged perpendicularly to each other in both types of panels. Two layers were oriented longitudinally as the outer faces, while one layer was oriented transversely as the core. The other two layers, made of carbon twill (CrT) mats, were placed between the natural fiber layers and were oriented with the length of the twill in the same direction as the length of the fibers belonging to the outer faces.

The initial step in the manufacturing process consisted of weighing the DPMLF mats with a precision of 0.01 g. The required amount of resin for each hybrid composite was calculated based on the weight of each DPMLF and CrT mat, multiplied by five and three times, respectively, as specified in the data sheet. The calculated amount of resin for each mat was applied using the hand lay-up technique to ensure proper fiber impregnation, as shown in Figure 3a–c. The CrT mats were interposed between the three layers of DPMLF, forming a five-layer lamination, as illustrated in Figure 3c,e. The core DPMLF mat was placed perpendicularly to the outer face layers (Figure 3c,d,f).

To prevent adhesion to the top and bottom plates used for pressing, both surfaces of the hybrid composites were covered with white silicon paper (Figure 3g,h). Weights were then placed on the top plate to apply a pressure of 0.02 N/cm^2 on the laminate for three days. Three samples of each composite type were produced for testing.

Before testing, the panels were acclimatized for six days at 20 °C and 55% relative humidity and then cut into test samples.

The physical and mechanical properties of the hybrid composite panels, including the vertical density profile (VDP), dimensional stability, impact resistance, flexural and tensile strength, and flexural and tensile modulus of elasticity, were evaluated in accordance to European standards.

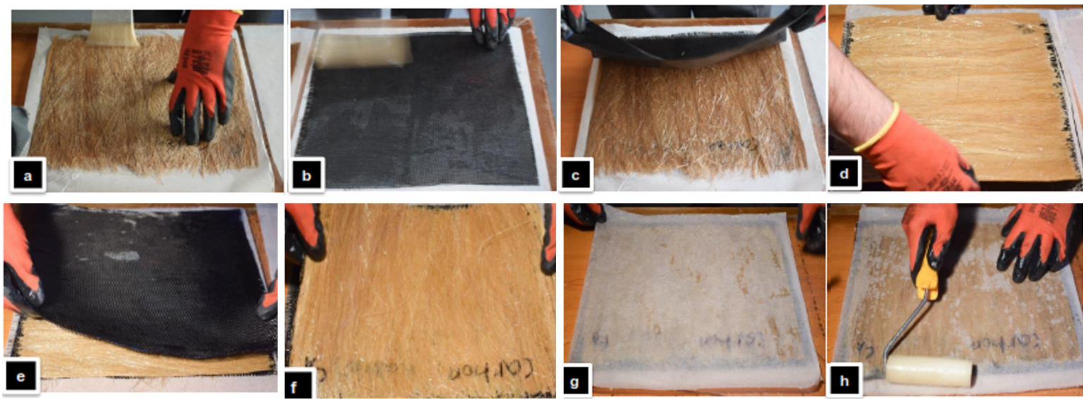


Figure 3. Experimental composite panel manufacturing; (**a**). resin applied by hand lay-up technique on the face layer; (**b**). carbon twill layer; (**c**). placement of carbon twill layer as the 2nd layer; (**d**). the 3rd layer of date palm fibers arranged transversally to the direction of faces; (**e**). the carbon twill 4-th layer; (**f**). the face layer oriented longitudinally; (**g**). silicon paper sheet for protection; (**h**). pre-pressing the laminate.

2.1.3. Vertical Density Profile (VDP) of the Samples

The vertical density profile (VDP) of the experimental composites was determined by analyzing five square-shaped specimens (50 mm × 50 mm) for each type of sample. Each specimen was first weighed using the precision scale EU-C-LCD (Gibertini Elettronica, Novate Milanese, Italy), measured, and then tested with the DPX300 X-ray analyzer (IMAL, San Damaso, Italy).

2.1.4. Water Absorption (WA) and Thickness Swelling (TS) of the Samples

The dimensional stability of the hybrid composite specimens, assessed through WA and TS, was evaluated by immersing the samples in a bath (pH 7, 20 °C) for 24 h, following the EN 317:1996 standard [41].

Initially, the specimens (50 mm × 50 mm) were measured with a precision of 0.01 mm at the diagonal cross-point using a digital caliper. Additionally, an electronic scale was used to weigh the samples with an accuracy of 0.01 g before the water immersion process. After 24 h of immersing the samples into water, they were taken out from the water bath, were wiped, and reevaluated for weight and dimensions.

Water absorption (WA) and thickness swelling (TS) were calculated using Equations (1) and (2) below.

$$\text{WA (\%)} = (\text{Ww} - \text{Wi})/\text{Wi} \times 100, \quad (1)$$

$$\text{TS (\%)} = (\text{Tw} - \text{Ti})/\text{Ti} \times 100, \quad (2)$$

where Ww is the weight in g recorded after immersion; Wi is the weight recorded in g before immersion; Tw is the thickness in mm measured after immersion; and Ti is the initial measured thickness in mm.

2.1.5. Microscopic Evaluation of the Samples

The microscopic structure of the composites and the measurement of the diameter of the natural fibers used in the structure of experimental composites were investigated using a NIKON SMZ 18-LOT2 stereo-microscope (Nikon Corporation, Tokyo, Japan). A magnification of 22.5× was used to analyze the laminate edges and highlight the adhesion between components, providing a clearer visualization of the structures.

2.1.6. Mechanical Performance of the Samples

The specifics of each mechanical test—including the method, number, shape, and dimensions of specimens—were defined according to the relevant European standards.

The EN 310:1993 standard [42] was followed to size the specimens and to evaluate their MOR and MOE under flexural loads. The flexural tests were conducted using a Zwick/Roell Z010 universal testing machine (Ulm, Germany), having the load cell capacity of 10,000 N (Figure 4a).

(**a**) (**b**) (**c**)

Figure 4. Equipment used to test the mechanical behavior of the samples: (**a**) flexural test; (**b**) tensile test; (**c**) Charpy testing equipment.

The EN ISO 527-4 standard [43] was followed to determine the tensile strength (S) and tensile modulus of elasticity (Y-modulus). The tensile modulus of elasticity was calculated for each sample based on the recorded linear dependence between stress and strain. The tensile tests were conducted on digitally controlled LFV50-HM 980 universal testing equipment (Walter and Bai, Switzerland). The crosshead speed was set to 1.5 mm/min, and the maximum capacity was 200 kN. Force (F), elongation (Δl), and time (t) were recorded at every 0.1 s (Figure 4b).

The ISO 179-1 standard [44] was applied for the Charpy test to assess impact strength (Figure 4c). The test was conducted using a Zwick/Roell HIT50P pendulum impact tester (Ulm, Germany), which is digitally controlled and has a maximum impact capacity of 50 J. The impact strength or resilience (K) was calculated using Equation (3) below.

$$K = W/A, \quad (3)$$

where W is the elastic failure energy, and A is the calculated area of the cross-section.

2.1.7. Statistical Analysis

Microsoft® Excel 2021 (Version 16) was used to perform the statistical analysis, determining the standard deviation within a 95% confidence interval and a significance level of 0.05 ($p < 0.05$). The average values of S, Y-modulus, MOR, MOE, impact resistance, WA, and TS were analyzed using the Two-Sample *T*-Test function in Minitab software (Version 21) package, version 19.2020.1.

3. Results

The recorded results after testing the two types of specimens are displayed in Table 2.

Table 2. Test results of the samples.

Panel Type	Density kg/m³	WA %	TS %	Flexural Test N/mm²				Tensile Test MPa				Impact Resistance kJ/m²	
		216 h		MOE L *	MOE T *	MOR L	MOR T	Smax L	Smax T	Y * L	Y T	L	T
D,Cr-E	1103	3.98	6.35	10077	5190	148.3	115.5	72.9	62.5	6275	6012	20.7	24.5
D,Cr-P	1133	6.05	3.09	2307	1420	56.3	47.5	55	43.8	5521	4535	26.5	24.6

* L means longitudinal; T means transversal; Y is Young Modulus.

3.1. Vertical Density Profiles of the Samples

Figure 5 illustrates the obtained VDP for both panel types, with maximum density values recorded at 1102.95 kg/m^3 for epoxy-reinforced and 1133.35 kg/m^3 for unsaturated polyester-reinforced hybrid composites.

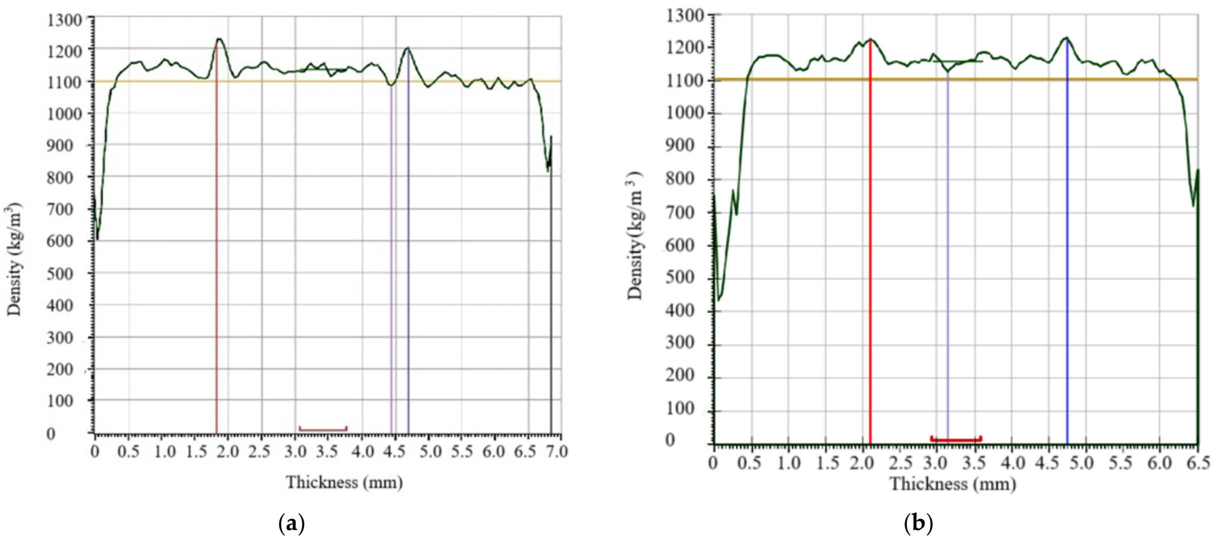


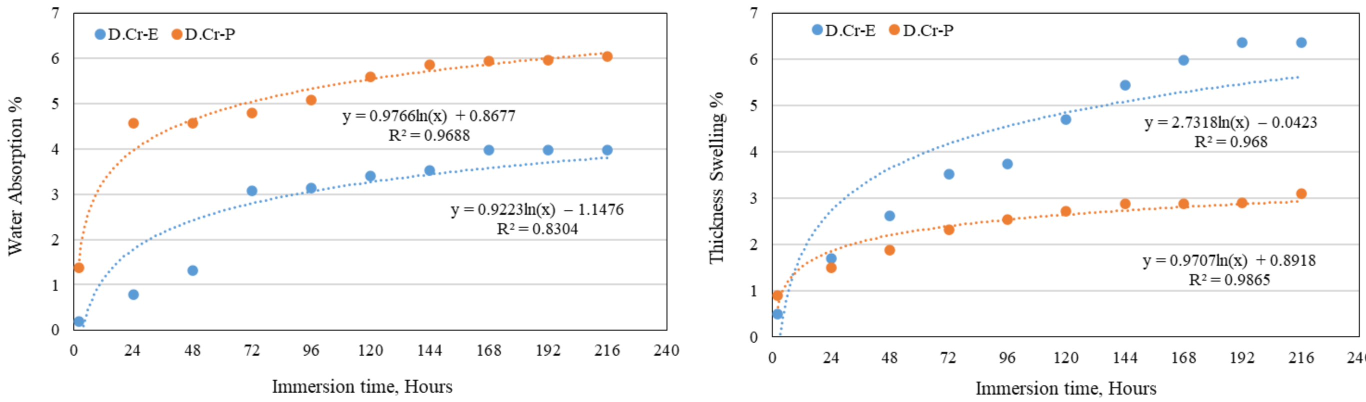
Figure 5. Density profile of D.Cr-E (**a**) and D.Cr-P (**b**).

3.2. Dimensional Stability and Water Afinity of the Samples

The dimensional stability of the samples in terms of WA and TS were examined, as summarized in Table 2.

Water absorption measurements (Figure 6a) revealed a consistent trend after 216 h of immersion at room temperature, with negligible weight changes of less than 0.1 g per 24 h period. The epoxy and unsaturated polyester hybrid composites displayed average WA values of 3.98% and 6.05%, respectively. Interestingly, D.Cr-P recorded the highest WA value, approximately 34% greater than that of D.Cr-E, indicating significant differences in their interactions with water. Statistical analyses confirmed these differences, showing significance at the 95% confidence level.

Regarding TS, the epoxy hybrid composite exhibited approximately 49% higher TS than the unsaturated polyester hybrid composite, while maintaining a 66% lower WA value (Figure 6b). This inverse relationship between TS and WA across the two composites raises questions about the interplay between resin hydrophobicity, cross-linking density, and matrix–fiber interactions.

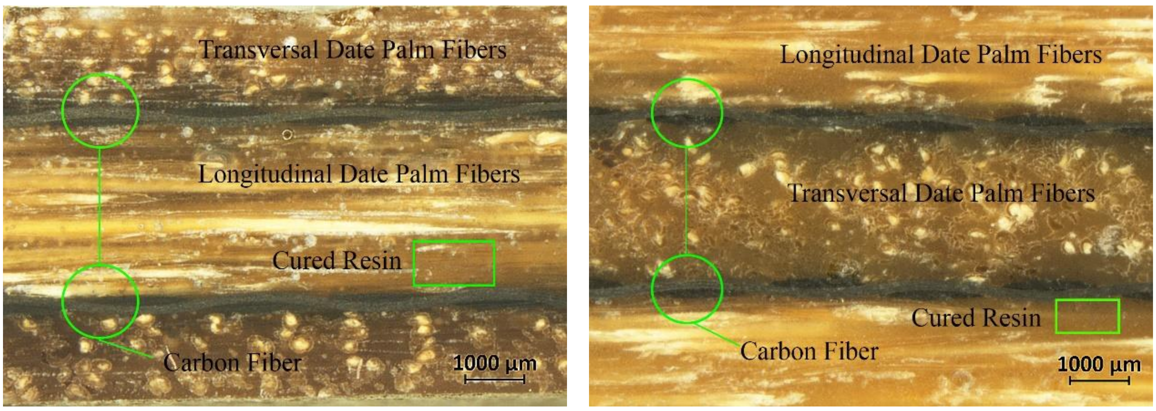


(**a**) (**b**)

Figure 6. Results of the dimensional stability testing under water immersion conditions; (**a**) water absorption; (**b**) thickness swelling.

3.3. Microscopic Investigation of the Samples

Figure 7 highlights the edge morphology of the hybrid composites, showing compact structural arrangements and well-defined adhesion interfaces between layers. Microscopic examination revealed specific features in both composites. In the epoxy-resin-reinforced hybrid composite, longitudinal sections of date palm fibers were analyzed in the core, while cross-sectional views were examined in the faces, as shown in Figure 7a. In the unsaturated polyester-reinforced composite, longitudinal sections of date palm fibers were analyzed in the faces, while cross-sectional views were examined in the core (Figure 7b). The black layers visible in both composites correspond to the carbon fibers (circled in the figure), while the uniformly dark brown regions represent cured epoxy and unsaturated polyester resins (indicated by rectangular shapes in the figure).



(**a**) (**b**)

Figure 7. Microscopic investigation for the longitudinal (**a**) and transversal (**b**) direction of the fibers.

3.4. Flexural Testing of the Samples

MOE and MOR values of the tested samples having epoxy and unsaturated polyester matrices reinforced with date palm and carbon fibers are presented in Figure 8. The tests were conducted in both the longitudinal and transverse orientations of the fibers, shown on the top surfaces of the specimens.

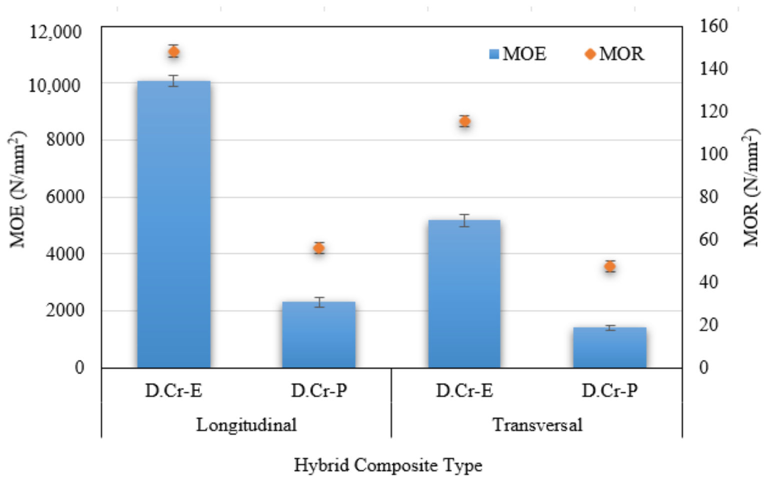


Figure 8. Flexural properties of the samples in both longitudinal and transversal fiber directions.

In the longitudinal direction, the epoxy-based hybrid composites exhibited MOE and MOR values of 10,077 N/mm^2 and 2306.6 N/mm^2, respectively. In contrast, the unsaturated polyester-based hybrid composites showed significantly lower values of 148.33 N/mm^2 and 56.33 N/mm^2. In the transverse direction, the corresponding MOE and MOR values for epoxy composites were 5190 N/mm^2 and 1420 N/mm^2, whereas for unsaturated polyester composites, they were 115.5 N/mm^2 and 47.5 N/mm^2.

The epoxy-based hybrid composite demonstrated significantly higher mechanical performance, with MOE and MOR values in the longitudinal direction increasing by approximately 77% and 62%, respectively, compared to the unsaturated polyester composite. Similarly, in the transverse direction, epoxy composites exhibited about 73% and 59% higher MOE and MOR values, respectively. These results highlight the superior flexural properties of epoxy-based hybrid composites in both fiber orientations. Statistical analysis confirmed significant differences in MOE and MOR values between the two composite types at a 95% confidence level for both fiber orientations.

3.5. Tensile Testing of the Samples

Results of the tensile testing are shown in Figure 9. The tests were conducted in both the longitudinal and transverse orientations of the date palm fibers, as they appeared on the upper surfaces of the specimens.

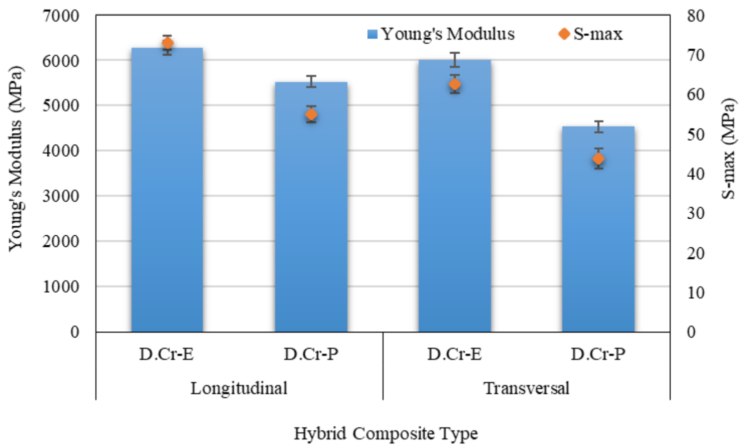


Figure 9. Tensile properties of the samples in both longitudinal and transversal fiber directions.

In the longitudinal direction, the epoxy hybrid composites exhibited Young's Modulus and tensile strength values of 6275.42 MPa and 72.9 MPa, respectively, while the unsaturated polyester hybrid composites showed values of 5520.75 MPa and 55 MPa. In the transverse direction, for the epoxy composites, values of 6012.34 MPa and 62.53 MPa were recorded, whereas the unsaturated polyester composites had values of 4535.5 MPa and 43.75 MPa.

The epoxy-based composites recorded significantly higher mechanical strengths, with an approximate increase of 12% and 25% in Young's Modulus and tensile strength, respectively, in the longitudinal direction. In the transverse direction, the epoxy hybrid composite exhibited approximately 25% and 30% higher values for Young's Modulus and tensile strength, respectively, compared to the unsaturated polyester hybrid composite. This trend shows the superior tensile performance of the epoxy hybrid composite in both fiber orientations, proved also by the failure modes of the specimens (Figure 10).

(**a**) (**b**)

Figure 10. Failure modes of the samples: (**a**) longitudinal specimens; (**b**) transverse specimens; epoxy-based specimens are on the left and polyester-based specimens are on the right; the marked areas are detailed above.

The epoxy-based specimens (Figure 10a,b, left side) show relatively sharp fractures (highlighted in yellow and blue), indicating a brittle failure mode. In contrast, the polyester-based specimens (Figure 10a,b, right side) display irregular and rougher fracture surfaces (highlighted in green and pink), suggesting an additional ductile failure component, likely due to higher elongation before breakage. The minimal fiber pull-out observed in the epoxy-based specimens indicates stronger fiber–matrix adhesion compared to the polyester-based ones.

3.6. Charpy Impact of the Samples

The recorded values of the Charpy impact investigation are presented in Figure 11. The evaluations were conducted in both the longitudinal and transverse orientations of the date palm fibers.

In the longitudinal direction, Charpy impact strength values were measured at 20.73 KJ/m^2 for epoxy hybrid composites and 26.46 KJ/m^2 for unsaturated polyester hybrid composites. In the transverse direction, the corresponding values were 24.45 KJ/m^2 and 24.6 KJ/m^2 for epoxy and unsaturated polyester hybrid composites, respectively.

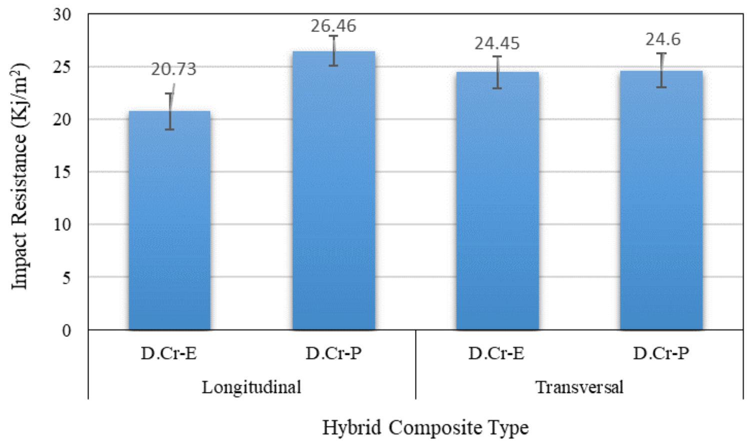


Figure 11. Charpy impact values of the samples in both longitudinal and transversal fiber directions.

4. Discussions

4.1. Vertical Density Profiles of the Samples

The similar arrangement of mat layers in both composites suggests that fiber density has minimal influence on the density profiles. The literature reports density values of 900 kg/m^3–1200 kg/m^3 for date palm materials [10,45] and 1500 kg/m^3 for carbon fibers [46]. The slightly higher density (~3%) observed in the unsaturated polyester composite is attributed to the marginally greater specific weight of polyester resin compared to epoxy resin. However, statistical analysis indicates that these differences are not significant at the 95% confidence level.

Higher-density zones in both composites are linked to the localized contribution of carbon fibers. Peaks in density, observed at approximately 2 mm and 4.7 mm from the top surface, correspond to these fiber layers. Despite these variations, the overall density trends remain linear throughout the thickness for both specimens.

The measured densities of both hybrid composites are lower than those reported for analogous matrices reinforced with particles of date palm midribs [10,47]. This suggests that material extraction methods and the specific arrangement of carbon fibers significantly affect composite density.

4.2. Dimensional Stability and Water Afinity of the Samples

The temporal behavior of water absorption revealed an initial instability during the first 72 h, followed by a consistent increase. This pattern is attributed to the hydrophilic nature of date palm fibers, which contain free hydroxyl groups capable of hydrogen bonding with water. These observations align with findings in other research, which highlight the role of natural fiber hydrophilicity in composite water absorption [47–49].

The reduced TS observed in the unsaturated polyester hybrid composite (Figure 5b) can be explained by the dimensional stability and water-resistant properties of polyester resin. Polyester resins, known for their inherent hydrophobicity, form a rigid matrix that resists swelling when exposed to water. Despite its lower cross-linking density compared to epoxy resin, the molecular structure of polyester effectively limits moisture penetration, thereby minimizing dimensional changes. These attributes result in the superior dimensional stability of the unsaturated polyester hybrid composite, as evidenced by its lower TS.

Conversely, the higher WA observed in the unsaturated polyester hybrid composite (Figure 5a) highlights the trade-offs associated with its resin properties. While epoxy resin forms a more rigid and tightly bonded matrix due to its higher cross-linking density and polar functional groups, it paradoxically exhibits greater water affinity, leading to increased moisture absorption [50]. Despite its hydrophobic nature, polyester permits higher water uptake, likely due to its reduced resistance to moisture ingress through micro-pores or weak fiber–matrix interfaces [51,52].

The results emphasize the complex interaction of resin hydrophobicity, cross-linking density, and fiber–matrix bonding in determining the composite's response to water. The excellent dimensional stability of the samples having lower TS of the unsaturated polyester hybrid composite contrasts with its higher WA, underscoring the importance of resin selection in optimizing composite performance for specific applications.

Further investigations are warranted to explore how matrix modifications or surface treatments of fibers might mitigate these trade-offs while enhancing the overall moisture resistance of hybrid composites.

4.3. Microscopic Investigation of the Samples

The morphology of the sample cross-section view revealed voids between fibers and matrix, indicating insufficient consolidation. This observation aligns with findings from previous studies, which reported similar phenomena in hybrid composites [40,53]. The fiber–matrix interfacial adhesion is influenced by the concentration of NaOH used during fiber treatment. Sodium hydroxide treatments effectively clean the fiber surface, removing impurities and inducing fibrillation [54,55]. However, variations in NaOH concentration can impact fiber properties; lower concentrations minimally affect fiber strength and adhesion, while higher concentrations lead to weakened or damaged fibers [8,56].

A 1.5% NaOH solution was employed for treating date palm midrib fibers in this work. Such a concentration appears to balance fiber surface cleaning and preservation of structural integrity. Nevertheless, the presence of voids between fibers and matrix may be explained by the partial consolidation of the hybrid composite during fabrication. Further optimization of fiber treatment and processing parameters may reduce void formation and enhance interfacial bonding.

4.4. Flexural Testing of the Samples

According to the literature, the flexural strength of polymer composites is influenced by several factors, including the characteristics of the fiber and matrix, the interfacial bonding between them, and the overall consistency of the composite material [57]. Notably, natural fiber-reinforced composites with reduced lignin proportions tend to exhibit superior flexural properties due to improved interfacial bonding between the fibers and the polymer matrix [58]. This improved bonding facilitates efficient stress transfer from the matrix to the reinforcement fibers, as corroborated by earlier research [59]. These findings align with previous studies showing that composites with diminished lignin levels possess enhanced flexural strength [17,47,60,61].

Based on the finding in this work, stronger interfacial bonding between date palm fibers and epoxy resin was determined, as compared to those of the samples bonded with unsaturated polyester resin. Furthermore, microscopic analysis suggests that alkaline treatment of date palm fibers, particularly with a more concentrated NaOH solution, enhances fiber–matrix interfacial adhesion. This improvement is likely a result of the efficient elimination of surface impurities, including lignin, which contributes to improved MOE and MOR values.

4.5. Tensile Testing of the Samples

Statistical analysis revealed no significant difference in Young's Modulus values of the samples in the longitudinal direction between the two types of panels. In contrast, significant differences were observed in Young's Modulus (transverse orientation) and tensile strength (both orientations) at the 95% confidence level.

A previous study [8] investigated the properties of date palm fibers as reinforcements in polymer composites. Tensile tests on date palm fibers treated with varying concentrations of NaOH indicated a decrease in tensile strength as NaOH concentration increased. However, higher NaOH concentrations improved fiber surface characteristics by removing the waxy coating. At lower NaOH concentrations, the bonding area's shear stress was comparatively lower, probably due to the outer waxy layer, which reduced the interaction between the epoxy matrix and the fiber surface.

Based on the findings of this study, using a 1.5% NaOH solution to treat the date palm fibers resulted in a negligible difference in Young's Modulus and tensile strength between the epoxy and unsaturated polyester hybrid composites. Nonetheless, the epoxy hybrid composite exhibited higher values for both properties, which can be attributed to superior fiber–matrix interfacial adhesion.

4.6. Charpy Impact of the Samples

The unsaturated polyester hybrid composite exhibited higher impact strength, with an approximate 22% increase in the longitudinal direction. However, in the transverse direction, the results were nearly identical for both epoxy and unsaturated polyester hybrid composites. This finding highlights the superior Charpy impact strength of the unsaturated polyester hybrid composite in the longitudinal orientation.

Additionally, statistical analysis revealed a significant difference in impact resistance values between the two composite types in the longitudinal orientation. In contrast, no significant difference was observed in the transverse orientation at the 95% confidence level.

Natural fibers exhibit limited efficiency in load transfer to the matrix at high strain rates [62]. Consequently, the impact resistance of hybrid composites is strongly influenced by the properties of the resin. The inherent brittleness of epoxy resin contributes to a reduction in impact resistance [47]. Conversely, the greater toughness of unsaturated polyester enhances the impact resistance of hybrid composite specimens [63].

5. Conclusions

Based on the results of the present research, it was found that significant differences existed between the properties of the samples made from date palm (*Phoenix dactylifera* L.) reinforced with carbon fiber using two binders, namely epoxy (D.Cr-E) and unsaturated polyester (D.Cr-P). The epoxy-reinforced hybrid composite (D.Cr-E) exhibited superior mechanical properties, including a higher MOE, MOR, tensile strength, and Young's modulus in both longitudinal and transverse directions. Specifically, D.Cr-E showed a 77% higher MOE, 62% higher MOR, and 25% greater tensile strength compared to D.Cr-P. These results indicate that the epoxy matrix is more effective at improving the stiffness, strength, and overall structural performance of the hybrid composite.

Conversely, the polyester-based composite (D.Cr-P) demonstrated greater impact resistance, with a 22% improvement over D.Cr-E, making it more suitable for applications requiring energy absorption. However, D.Cr-P also exhibited higher WA and lower TS compared to D.Cr-E, suggesting that unsaturated polyester resin composites may be more sensitive to environmental conditions like moisture exposure, despite their enhanced dimensional stability.

Overall, the findings suggest that epoxy-based composites (D.Cr-E) are more appropriate for load-bearing applications where high stiffness and tensile properties are critical (e.g., aircraft panels, automotive body parts, drone frames, structural reinforcements in boat hulls), whereas polyester-based composites (D.Cr-P) could be better suited for impact-resistant applications, although their performance could be compromised in moisture-rich environments (e.g., interior parts for automotive and marine components, such as dashboards, door panels, lightweight partitions, paneling, and molded parts). Date palm could have a great potential to be used for different applications within the perspective of development of sustainable, high-performance composite materials tailored for specific engineering members.

Future research will be conducted to investigate the behavior of these composites in aggressive environmental conditions (positive and negative temperature cycles), under UV rays, and to determine the environmental impact (carbon footprint and LCA).

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