Optimizing Biomedical Facilities Performance with Dombeya Fiber-Paper Particle Hybrid Reinforced Epoxy Composites

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Abstract

Over the last two decades, the use of natural fiber-reinforced polymer composites has garnered significant attention over synthetic fiber-reinforced composites owing to their numerous advantages and unique properties. Likewise, epoxy resins have attracted the interest of many researchers for composite synthesis because of their chemical stability and thermal and mechanical characteristics. Hence, the primary aim of this study was to investigate the influence of Dombeya fiber and paper particulates on the physical and mechanical properties of Dombeya fiber and paper particulate-reinforced polymer composites for structural applications. Dombeya fiber and paper particles are renewable and biodegradable materials, thereby making them environmentally friendly alternatives to synthetic materials. The hand lay-up technique was utilized to fabricate hybrid-reinforced biocomposites, after which they were subjected to mechanical, wear, density, and moisture absorption properties. The morphology of the fractured surface was analyzed to investigate its microstructural features. It was discovered from the results that hybrid biocomposites demonstrated improved properties over the unreinforced composite, with composites from 9-wt% dombeya fiber-paper particle-reinforced biocomposites exhibiting the most suitable properties with commensurate density with the unreinforced epoxy matrix. These characteristics make the material suitable for biomedical apparatus applications such as orthopedic implants, surgical instruments, and bone fixation devices.

Keywords: *Natural fiber, Dombeya-fiber, Paper Particle, Hybrid, Epoxy, Biocomposite, Biomedical, Mechanical, Wear.*

1. Introduction

The Polymer composites, alternatively referred to as polymer matrix composites (PMCs), are distinguished multimaterial polymer systems consisting of a plethora of materials with diverse characteristics that are integrated into a polymer system, functioning as a parent or base matrix to exhibit exceptional physical, mechanical, and chemical capabilities. Polymer matrix composites are endowed with extraordinary mechanical and physiochemical attributes while possessing an incredibly low weight compared to mere polymer materials [1]. PMCs fabrication process relies heavily on the matrix material, which serves as a crucial load distributor among the reinforcement materials during the application of external pressure. Polymer-based

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materials are broadly classified as either thermosets or thermoplastic polymers and are distinguished by their matrix materials. Unlike thermoplastics, thermosets cannot be recycled because the resin cannot revert to its original state after curing. However, thermoplastics can change their shape simply by applying heat. Because thermoset polymer resins have many uses, material scientists are more interested in their use than thermoplastic resins. Epoxy resins are the most well-known thermoset resins because of their excellent mechanical qualities, minimal shrinkage and curing time, resistance to moisture permeability, and adhesive qualities. Additionally, epoxy resins are perfect for bonding with a variety of materials, including fibers, steel, plastics, and wood, because of their strong adhesive qualities. To create a robust, network-like structure between the reinforcement and matrix material, a curing agent, also known as a hardener, is typically added to epoxy resin [2], [3]. Nevertheless, the inability of epoxy resins to undergo recycling, reprocessing, or dispersion owing to their perpetual cross-linked arrangements renders them ecologically inimical when linked to other thermoplastic materials. Mitigating the environmental predicament instigated by thermoset materials is of significant concern, particularly during disposal. The manufacturing of biodegradable polymers and composites could potentially offer a solution to this issue at the fabrication level [4]. Therefore, the augmentation of this particular polymer utilizing natural fibers as opposed to synthetic fibers in polymer composites is a feasible substitute for environmental restoration and holds potential in the realm of structural, automobile, packaging, and several other applications [4].

Recently, the utilization of natural fibers for composite reinforcement, particularly in polymers, has been exploited and researched by scientists [5]. These fibers, derived from natural sources, possess noteworthy attributes such as strength, lightweight, cost-effectiveness, and biodegradability. The constituents of plant-based natural fibers are primarily hemicellulose, cellulose, and lignin, with varying percentages depending on plant type and geographical location [6]. Natural fibers represent a highly promising resource that is utilized as a material for a wide range of applications that are not limited to automotive, light construction, thermal insulation, cosmetics, medicine, and fine chemicals. These fibers offer abundant benefits when linked to synthetic fibers, which are not limited by their relatively minimal cost, structural weight, favorable mechanical properties, abundance, and renewability. For instance, Betelie et al. [7] investigated the properties of seal-epoxy composites in relation to the fiber-to-epoxy ratio. This study focused on evaluating the mechanical properties of the sisal-reinforced composites. The results indicated that composites with 30 wt% sisal fiber demonstrated a maximum tensile strength of 85.5 MPa and flexural strength of 85.79 MPa. Additionally, the impact strength was found to be highest for composites with 40 wt% sisal fiber, measuring at 24.5 kJ/m2. Consequently, these composites exhibit favorable mechanical properties and are suitable alternatives for structural, automotive, and biomedical applications. In another study by Nihal et al. [8], a pineapple fiber-reinforced epoxy composite was explored for thermal insulation applications. The results indicated that the composite with 15 PALF could effectively serve as an insulator in residential homes, commercial buildings, automobile inner body panels, and electronic and refrigeration appliances. This is due to the enhanced compressive and flexural strengths of the composite, as well as its minimal thermal conductivity. Other fibers, such as banana, jute, bagasse, and coconut fibers, have also been considered for various applications.

In the medical field, natural fibers have also been employed, mainly because of their relatively high strength-to-weight ratio, fracture toughness, non-corrosive properties, and capacity for renewal. The areas that have been utilized in the biomedical field include drug delivery, tissue engineering, and orthopedics. Natural fibers can be categorized into two types depending on the nature of the source: renewable and nonrenewable. These fibers can be derived from animals or plants [6], [9]. Some research has been conducted utilizing natural fibers as reinforcement materials embedded in an epoxy matrix for biomedical applications. For instance, in order to develop a matrix for biomedical applications, Rao et al. [10] conducted a comparative analysis of the mechanical and water absorption behaviour of basalt fibre reinforced polymer matrix composites with various epoxies. In this study, an examination was conducted wherein plain-woven basalt fiber was utilized as a reinforcement material at a constant percentage of 55% in conjunction with three distinct epoxy resin-hardener combinations as a matrix. Comparative analyses were performed on the basis of

these conditions. The findings of this study indicate that the quality of the hardener affects the adhesiveness of the matrix and binds the reinforcements with a strong bond to the hardener. Additionally, the strongly bonded laminate exhibited a lower rate of water absorption for both 24 and 48 hours, thereby rendering it a viable option for biomedical applications. Although natural fiber-based composites are an appealing alternative to synthetic fiber composites, their mechanical performance remains inadequate. The mechanical capability of polymer composite materials depends on various factors such as fiber loading, fiber and matrix nature, and interfacial bonding. Hybridization has emerged as a viable solution to overcome this challenge [11]. This novel approach aims to achieve a specific property while simultaneously improving the overall performance of hybrid composites. The underlying rationale is to overcome the limitations of single fillers by incorporating additional additives that can bring about the desired properties and enhance service performance. Notably, some scholars have directed their efforts toward exploring the impact of natural fibers in conjunction with either synthetic or additional natural fillers for biomedical applications [12]. For instance, Sathish et al. [13] manufactured and studied natural biopolymer composites for biomedical applications. These composites have been used to produce joints and bone fixings to ease patient discomfort. Ramie, hemp, and coir fibers have been combined with biodegradable and bioresorbable polypropylene resins. The physical and chemical characteristics of the developed composites were similar to those of bones. Another study by Nigrawal et al. [14] examined the effects of surface modification techniques on the characteristics of epoxy composites filled with sisal fibers and jute. In this study, a hybrid composite was created using sisal and jute fibers reinforced with epoxy resin. Their mechanical characteristics and DC conductivities were also assessed. These composites can be employed in orthopedic medicine, prosthetic devices, imaging, and other medical fields. Notably, the tensile strength and conductivity of the composites were enhanced. In the area of soft tissue engineering using scaffold implant biomaterials, silk fiber has been researched as a potential material for this application [9], [15]. Other natural fibers that are becoming more and more popular include hemp, kenaf, bamboo, bananas, coconut, flour, sugar cane, palm oil, cotton, and bananas [14]. Orthotics and prosthetics fabricated from composite materials have recently garnered significant attention. Consequently, a blend of fiber-reinforced polymers has proven to be a potential material for the fabrication of modern upper- and lower-limb prostheses, thereby proving to be highly effective in orthopedic surgery [16]. In a recent study by Faheed et al. [17], the physical and chemical properties of composites were examined in relation to prosthesis sockets. These sockets were fabricated using vacuum-bagging technology and reinforced with a hybrid network of natural and synthetic fibers. The hybrid network fibers were encapsulated within a PMMA resin. In addition, in drug delivery systems, natural fibers have also been employed in this application in the form of nanofibers. Orasugh et al. [18] also created a new material by combining jute cellulose nanofibrils with hydroxypropyl methyl, which has the potential for use in delivery systems. However, for this particular research, Dombeya fiber will be considered as part of the hybrid reinforcement used in epoxy resin.

Dombeya Buettneri Fiber (DBF) is a natural cellulose-based fiber that is conveniently available in Madagascar as well as in other African countries, including Nigeria. In this crop, the stem bark is exceedingly fibrous, making it feasible to manually extract fibers for creating ropes, nets, and fishing equipment. These fibers are frequently used in the medical sciences. Given its inherent strength, DBF is a compelling option for lignocellulosic reinforcement in polymer composites [19]. This particular fiber has been the subject of investigation by various researchers, such as Bichang et al. [20], who explored its application in biodegradable polymeric composites. Their study focused on determining the physical and mechanical characteristics of the Dombeya fiber. In addition, they employed quantitative chemical analysis, Fourier Transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), thermogravimetric analysis, and scanning electron microscopy to characterize the fibers. Interestingly, their findings revealed that the fiber exhibited similar results to those of other studies on cellulosic fibers. Another study by Oladele et al. [19] also examined the impact of selected attributes on the properties of DBF/graphite hybrid reinforced polymer materials. It was revealed that the collaboration and interface of the hybrid reinforcements promoted the enhancement of polypropylene (PP) qualities in a distinctive manner, as this can be utilized in various

applications, such as household items, packaging for consumer goods, appliances, containers, specialized devices such as flexible connectors, automotive industry, and textiles, based on the specific attributes of the composite. Furthermore, paper particles obtained from paper were used as the hybrid reinforcement in the epoxy resin, which served as the filler in the composite. Paper is widely acknowledged as the material most frequently used for containers and packaging, mostly because of its relative availability and low cost. Additionally, because it comes from renewable sources (plants) and can be recycled up to 100% of the time, it is regarded as a very sustainable material. It has been noted that the wastepaper is easily accessible in settings with high paper usage, such as homes, offices, and schools. Unfortunately, waste paper is routinely burned or disposed of carelessly in Nigeria and many other developing countries, which means that the potential of this waste material is now being underutilized [21]. In fact, this study can be broken down into particles that can be applied to a variety of tasks.

On the other hand, there is a lack of comprehensive information concerning the physical and mechanical properties of Dombeya fiber, as well as the incorporation of paper particles with natural fibers in a polymer matrix for biomedical applications. These applications include bone implants, joint replacement, prosthetic limbs, biomedical equipment casings, drug delivery systems, and surgical instruments. Consequently, it is necessary to close the current knowledge gap by carrying out measurements of physical, mechanical, and wear properties, in addition to using scanning electron microscopy for characterization. During the course of this endeavor, it is envisaged that the groundwork will be established for future research endeavors that will concentrate on the synthesis of DBF fibers and paper particles as a viable substitute for synthetic fibers in the construction of bio-composites for a variety of biomedical applications. Hence, this investigation was conducted to analyze the influence of Dombeya fiber and paper particles on the physical, mechanical, and wear properties, as well as the density of epoxy matrix composites. The primary aim was to explore the significance and potential applications of these materials in the biomedical industry based on the results of property tests.

2. Experimental

2.1. Materials

The present study employed various materials, including locally sourced Bisphenol A diglycidyl ether epoxy resin and diethylene triamine curative, applied as a form of hardener. Additionally, waste paper, Dombeya buettneri stems, NaOH, and distilled water were utilized. The epoxy resin and triamine curative were acquired from a local vendor in Lagos State, Nigeria. Dombeya buettneri stems were obtained from pinkball trees in a shrub farm located in the city of Akure, Nigeria while waste paper was sourced from FUTA campus.

2.2. Extraction and Treatment of Dombeya Fiber

DBF is one of the pivotal components in the execution of this research. The fiber extraction involved the removal of the stem bark, followed by manual separation of the strands. The fibers were further reduced to a short length of approximately 10 mm after a 5-day period of sun drying.

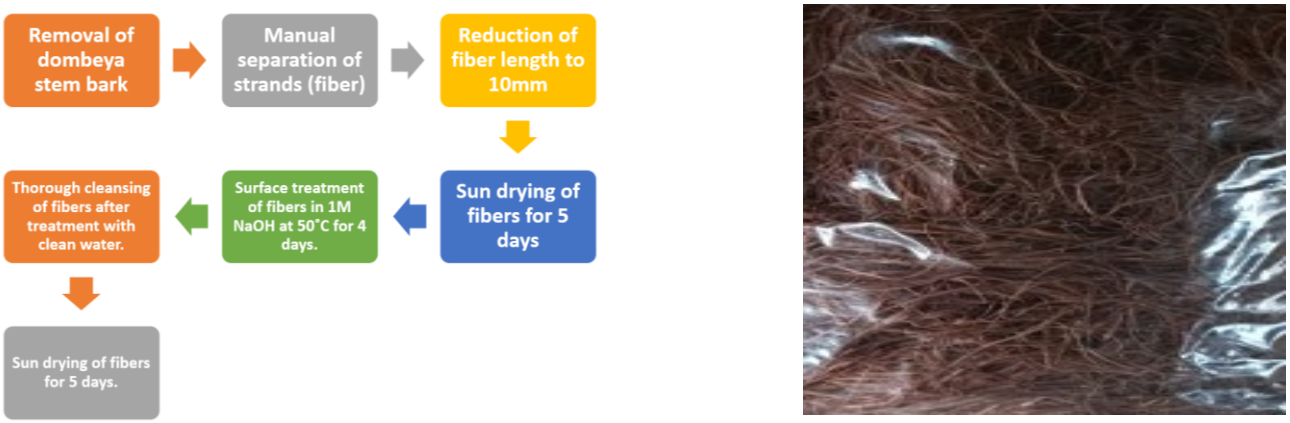

Figure 1. a) Flow chart showing extraction and treatment of dombeya fiber; b) Extracted dombeya fibers.

In order to enhance the quality of the fiber, it was subjected to a treatment process that entailed immersion in a 1 M NaOH solution, which was conducted within a shaker water bath at a temperature of 50 °C for duration of 4 hours. The treated fiber was then thoroughly cleansed with tap water and subsequently rinsed with distilled water until a neutral pH level was confirmed using litmus paper.

The treated fiber was left to sun-dry for another period of approximately five days to allow the removal of any residual moisture content. This process was performed in accordance with the method described by Oladele et al. [21]. Figure 1a shows a flow chart of the extraction and treatment of the Dombeya fiber, and Figure 1b shows the sun-dried Dombeya fiber.

2.3. Production of Paper Particles

The locally sourced paper was soaked at room temperature for 3 days. They were further pulverized by the action of the Denver pulverizing machine. The pulverized paper marsh was dried in open air for 7 days so as to completely eliminate moisture content and improve its grindability properties before grinding and sieving through a sieve size of 100 µm. Figure 2 shows the dried paper particles.

Figure 2. Dried paper particles.

2.4. Fabrication of Composite Materials

As shown in Figure 3, an open-mold hand lay-up process was used to create the composite materials. As it requires less equipment and tools, this method is affordable and can be used for prototypes and small-scale manufacturing. It can accommodate a wide range of part sizes and forms, including simple and complicated geometries, making it extremely flexible and adaptable. Unlike other methods of composite manufacturing that require specialized technology, hand lay-up can be carried out using simple, easily accessible tools and equipment.

Furthermore, a range of reinforcement materials, including textiles, mats, unidirectional roving, and chopped or woven fibers, can be used in this process, providing the composite with the flexibility to be customized to meet individual needs.

Figure 3. Open mold hand lay-up technique.

As shown in Table 1, which displays the formulation of the composites in grams, both particles and fibers were introduced into the epoxy matrix in this study, with weight percentages for Dombeya fiber and paper particles ranging from 3% to 15%. The paper particles and Dombeya fibers were strengthened in a 1:1 ratio.

To guarantee consistency in the weight percentage of the reinforcement materials and to examine how the combination of short fiber and particle cellulosic reinforcements affected the composites. In compliance with Daramola et al. [22], a 2:1 ratio of epoxy resin to hardener was added. The reinforcements, epoxy resin, and hardener were manually mixed for five minutes in a polymeric container by using a glass rod stirrer to obtain a homogenous mixture.

Table1. Formulation of Composites

Sample (% wt.)	Epoxy (g)	Hardener (g)	Fiber (g)	Paper Particles (g)
3	116.4	58.2	2.7	2.7
6	112.8	56.4	5.4	5.4
9	109.2	54.6	8.1	8.1
12	105.6	52.8	10.8	10.8
15	102.0	51.0	13.5	13.5
Unreinforced composite	120.0	60.0	-	-

The final homogenous mixes were then placed into molds that were made, especially for each attribute that needed to be studied. The molds were prepared using a release agent to prevent the composite from sticking to the surface. Before the composites were removed from the molds, they were left to cure for a full day at room temperature or approximately 28±4°C. Following extraction, the composites were left to cure for approximately 21 days under the same environmental conditions. Following curing, the samples were tested in compliance with the ASTM guidelines. Atmakuri et al. [2] and Bekele et al. [11] both used this method in their previous research works. A portion of exemplary artificial samples is shown in Figure 4.

Figure 4. Weight percent fraction of the hybrid composite samples before precision machining.

2.5. Assessment of Properties

2.5.1 Flexural Property

According to ASTM C1609 [23], which was used to assess the flexural performance of fiber-reinforced concrete and was also conducted by Luo et al. [24], the flexural properties of the samples were assessed using a three-point bending test. An apparatus for closed-loop servo-controlled compression testing was used to perform the experiments. The specimens that were utilized measured 350 mm in thickness, 100 mm in width, and 100 mm in length. For each composition, representative values were determined by averaging the outcomes of the three samples that were tested.

2.5.2 Tensile Property

The ASTM C1557 standard [25] was used to evaluate the tensile characteristics of the developed samples. A Universal Testing Machine (Model: Instron Series 3369) was used to perform this process. For the experiments, specimens with dimensions of 90 mm × 10 mm × 3 mm were formed as dumbbells. The test was conducted in the axial direction using a 50 KN load cell at a crosshead speed of 5 mm/min.

2.5.3 Impact Property

In compliance with ASTM D256-10 standard, this test was performed using an impact testing apparatus equipped with a House field balance [26]. The notched Izod samples were used for the impact test. The notched surface of the samples was positioned immediately across from the swinging axis of the pendulum in a cantilever setup. To break the samples, the testing apparatus's pendulum was freely swung 180 degrees. For every composition, three repeatability tests were conducted to guarantee the precision and reliability of the test outcomes.

2.5.4 Abrasion Resistance Test

Using the Taber Abraser, Model ISE-AO16, the abrasion resistance of the developed materials was measured. The samples were placed on a turntable board that spins at 900 revolutions per minute. The sample was first weighed using an analytical weighing scale before being placed on a turntable. The samples were placed on a turntable platform and rotated at 900 rpm for 15 min to ascertain their ultimate weight. The wear properties of the samples were determined by comparing their initial and final wear values. The wear resistance and wear index (W.I) of each sample were calculated using Equation (1).

$$fW.I = \frac{W1 - W2}{RPM} * 1000 \quad (1)$$

2.5.5 Hardness Property

In line with ASTM D2240-00, a Shore D hardness tester was used to test the specimen in this investigation [27]. This consistently quantifies the depth of an indentation made on a presser foot by a given force. Five distinct spots on the material were used to apply force to the specimens using the presser foot; the values obtained were recorded, and an average was calculated.

2.5.6 Fluid Absorption Property

Water was the fluid medium employed in this investigation to examine fluid absorption. The ASTM D5229M-12 criteria were followed when conducting the water absorption tests [28]. 250 cm^3 of water medium were poured into clean plastic containers in order to conduct the test. Analytical weighing was used to determine each sample's initial weight, and readings were recorded each day for four consecutive days. Before every weighing session, the specimens were removed and cleaned with a clean cloth. Equation 2 was used to calculate the weight gained based on the data gathered throughout the experiment.

$$\% \text{ Water Absorbed} = \frac{Wt - Wd}{Wd} * 100 \quad (2)$$

Where, W_d is the dry weight and W_t is the weight of samples after time t.

2.5.7 Density Measurement

The samples were weighed, and their volume was estimated after taking the volume and mass of each sample into consideration. Densities were then computed using equation (3).

$$\text{Density} = \frac{mass}{volume} \quad (3)$$

2.5.8 Microstructural Examination

Using a scanning electron microscope (JEOL JSM-6480LV model), the surfaces of the fragmented samples from the manufactured composites were inspected. Silver paste was used to firmly attach the samples on stubs. In order to increase the conductivity of the composite specimens, photomicrographs were taken at a voltage of 15 kV after a thin layer of platinum was vacuum evaporated onto the surface [29].

3. Presentation of Results

3.1. Tensile Properties

Figures 5 and 6 show the ultimate tensile strength and tensile modulus, respectively.

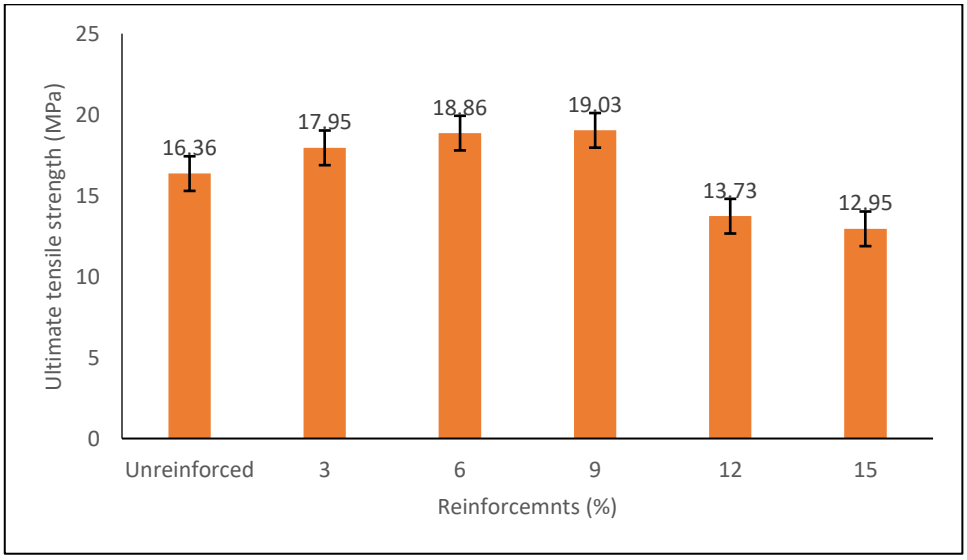

Figure 5. Ultimate tensile strength properties.

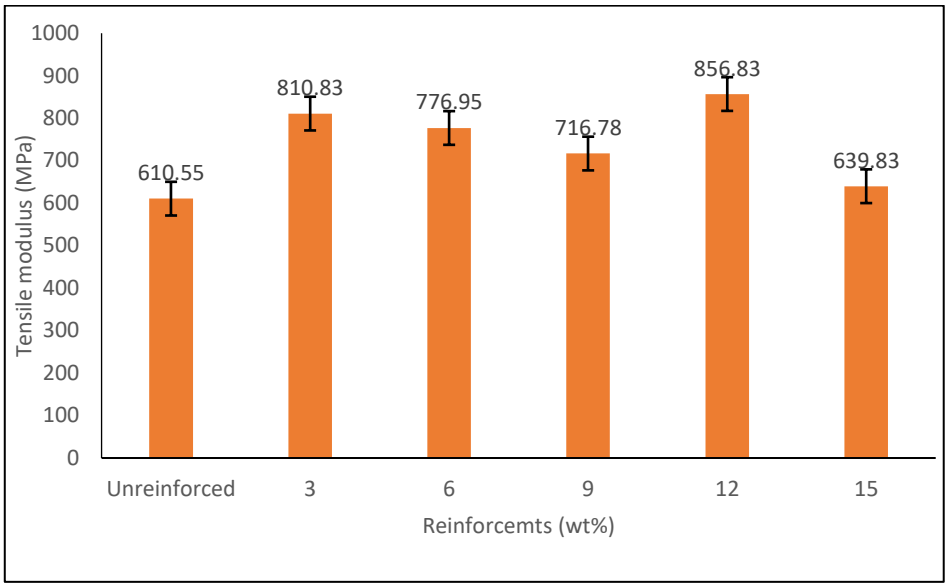

Figure 6. Tensile Modulus properties.

Figure 5 illustrates how the hybrid reinforcing materials affect the final tensile strength of the hybrid biocomposites. The outcome shown in Figure 5 shows an increase in the ultimate tensile strength of the composite materials from 3 to 9 wt percent for reinforced composites, with 9 wt percent having the highest ultimate tensile strength (19.03 MPa compared to 16.36 MPa for the unreinforced composite. After that, a decrease was observed in the weight percentages of 12 and 15. In a composite made of plantain fiber, Oladele et al. [29], with a similar methodology, also reported an increase in strength accompanied by a decrease in reinforcement content. The observed improvement in this study, ranging from 0-9wt%, can be attributed to the reinforcing effects of both Dombeya fibers and paper particles. This suggests an enhancement in the load-bearing capacity and effective stress-transfer mechanisms within the composite. Additionally, at lower fiber contents, the added Dombeya fibers likely acted as bridges within the epoxy matrix. When pulled, these fibers transferred stress more effectively than the matrix alone, leading to an improved tensile strength. It is crucial to note that good adhesion between the fibers and matrix is essential for effective stress transfer. In this case, the adhesion between the fibers and matrix might have been optimal, allowing the fibers to fully contribute to the strength. Another contributing factor is the alkaline treatment of the fibers; as previous findings have shown that such treatment enhances the tensile properties of natural fibers [30]. Furthermore, the inclusion of paper particles into the matrix, which has a high cellulose content, can also be a factor in the increase in the ultimate tensile strength of the reinforced composite compared with the unreinforced matrix. This is because the paper particles filled the voids that could have existed within the composites, thereby enhancing proper load transfer. However, beyond the optimal range, specifically at 12wt% and 15wt%, a decline in performance was observed. This decline may be indicative of compromised interfacial bonding or excess reinforcement, leading to clustering and potential agglomeration, resulting in diminished mechanical properties.

In general, the behavior of the composite suggests a synergistic effect between the Dombeya fibers and paper particles, contributing to the overall enhancement of the tensile strength. However, it is important to note that a transition from ductile to brittle behavior was observed beyond the optimum reinforcement level, indicating a shift in the failure mechanisms.

Figure 6 illustrates the tensile modulus of both the reinforced and unreinforced epoxy composites, revealing intriguing trends indicative of stiffness variations with changing reinforcement concentrations. At 3wt%, there is a notable increase in tensile modulus from 610.55 MPa (0wt%) to 810.83 MPa. This suggests an initial enhancement in stiffness owing to the introduction of

both Dombeya fibers and paper particles. Dombeya fibers are likely to possess an inherent stiffness higher than that of the epoxy matrix. However, as the concentration of the reinforcements increased, the tensile modulus exhibited a fluctuating pattern. At 6wt%, the modulus decreases to 776.95 MPa, followed by a further decrease at 9wt% (716.78 MPa). This fluctuation may be attributed to intricate interactions between the constituents of the composite, which affect the response of the material to the applied stress. The highest tensile modulus was observed at 12wt%, reaching 856.83 MPa, indicating a potential reinforcing synergy between the Dombeya fibers and paper particles within this composition. In addition, a favorable fiber alignment may contribute to the optimum tensile modulus. When the fibers align well within the matrix, they can effectively resist deformation under tension, leading to a more rigid composite and a higher modulus. Beyond this concentration, at 15wt%, there was a significant reduction in the tensile modulus (639.83 MPa), suggesting that an excess of reinforcement causing agglomeration may compromise the structural arrangement, impacting the overall stiffness. Inefficient stress transfer can contribute to the modulus decrease because poor dispersion and agglomeration may impede the effective transfer of stress from the fibers to the matrix. In general, the tensile modulus results revealed a nuanced relationship between the reinforcement concentration and stiffness in the epoxy hybrid composite. The observed fluctuations underscore the importance of optimizing the composite composition to achieve the desired mechanical properties based on specific applications, such as surgical instruments or tissue engineering scaffolds**.**

3.2. Flexural Properties

The impact of the Dombeya fiber and paper particle hybrid reinforcements on the flexural strength of the biocomposite is shown in Figure 7, and its flexural modulus is presented in Figure 8.

The flexural strength exhibited a discernible pattern with changing reinforcement concentration, as shown in Figure 7. Up to 9wt%, there was a gradual increase in flexural strength, reaching a peak value of 17.85 MPa at this concentration, which represents a 10% increase compared to the unreinforced composite (16.26MPa). This positive trend can be attributed to the reinforcing effects of both the Dombeya fibers and paper particles, suggesting an improved resistance to bending forces. Beyond the optimal concentration, at 12wt% and 15wt%, a noticeable decline in flexural strength was observed (14.67 MPa and 14.39 MPa, respectively). This decline may indicate potential issues, such as interfacial bonding or an excess of reinforcement, leading to a compromised ability to withstand bending stresses. The observed flexural behavior aligns with the findings from the tensile strength and tensile modulus tests, indicating a similar trend in the mechanical response across different loading conditions, which is in agreement with Madgule et al. [31] when banana fiber and sugarcane bagasse powder were used in epoxy-based composites. The intricate interplay between the constituents of the composite plays a crucial role in determining the flexural strength.

The stiffness of the flexural modulus demonstrated distinct variations with changes in the concentration of reinforcement, as shown in Figure 8. At a concentration of 3wt%, there was a significant increase in flexural modulus from 426 MPa (0wt%) to 503.49 MPa, indicating an initial enhancement of 18% in stiffness due to the incorporation of Dombeya fibers and paper particles. However, as the concentration of reinforcements increased, the flexural modulus exhibited a fluctuating pattern. At 6wt%, the modulus decreased to 475.88 MPa, followed by a further decrease at 9wt% (402.33 MPa). This decline can be attributed to the complex interactions between the constituents of the composite, which affect the response of the material to the applied bending stresses. The flexural modulus reached its minimum at 9wt%, suggesting that an optimal balance between the Dombeya fibers and paper particles contributes to an effective compromise between stiffness and flexibility. Beyond this concentration, at 12wt% and 15wt%, there was a slight increase in the flexural modulus (419.11 MPa and 410.25 MPa, respectively), indicating that an excess of reinforcement may result in increased stiffness. The flexural modulus results demonstrate a nuanced relationship between the concentration of reinforcement and stiffness in the epoxy hybrid composite. The observed fluctuations emphasize the importance of optimizing the composition of the composite to achieve the desired mechanical properties, particularly in biomedical applications, such as orthopedic implants and supports, where flexural stiffness is a critical factor.

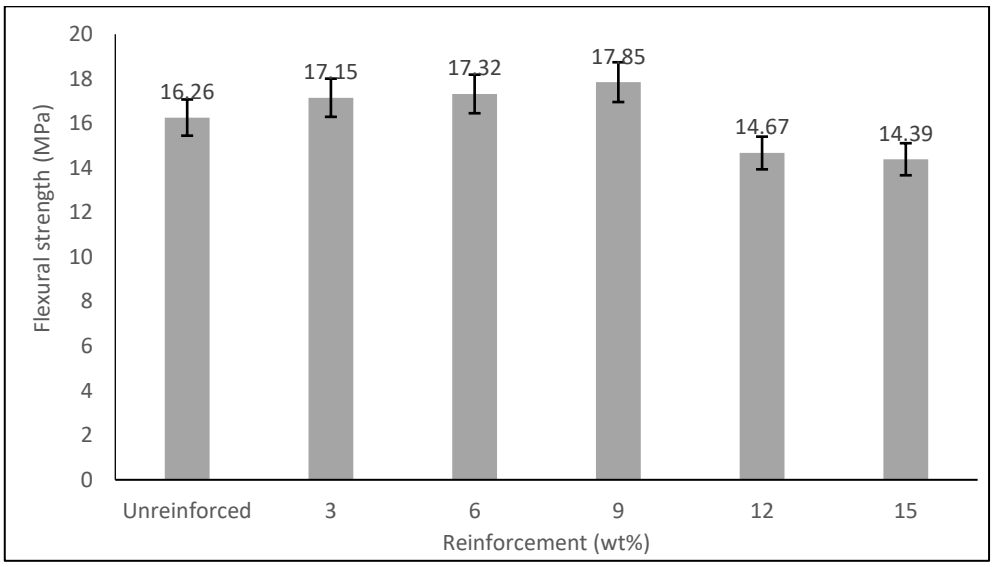

Figure 7. Flexural Strength properties.

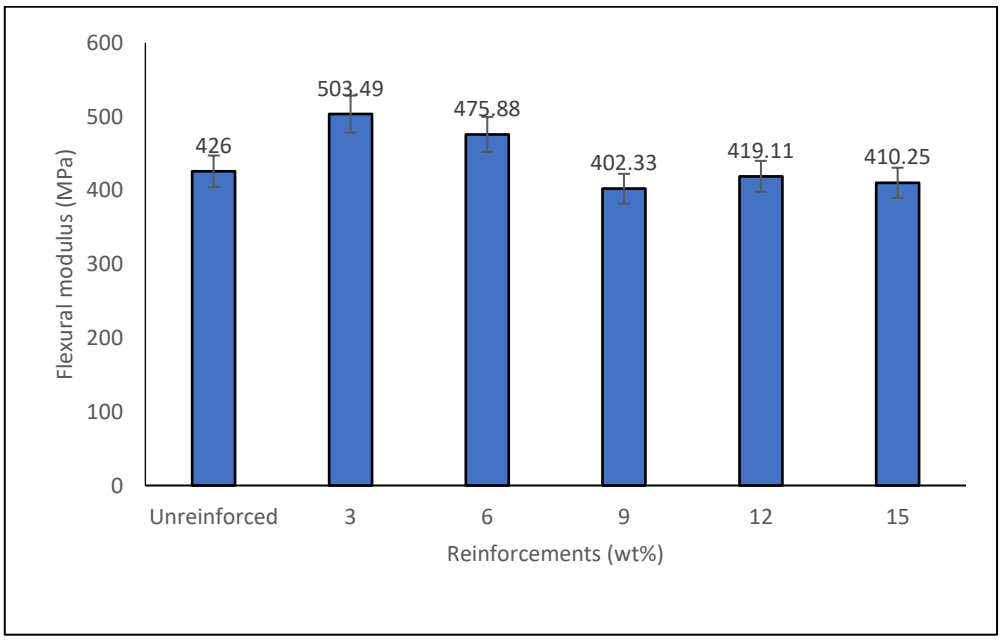

Figure 8. Flexural modulus properties.

3.3. Impact Strength

The impact strength of the developed materials is presented in Figure 9, where a congruent tendency was observed, similar to the mechanical properties in Figures (6-8). The impact strength exhibited a discernible trend, showing casing variations in the energy absorption with changing reinforcement concentrations. At 3wt%, there was a significant increase in impact strength from 6.91 kJ/m² (0wt%) to 8.96 kJ/m², indicating an initial enhancement in the material's ability to absorb impact energy due to the introduction of dombeya fibers and paper particles. Continuing the reinforcement, the impact strength continued to increase up to 9wt%, reaching a peak value of 11.87 kJ/m². This positive trend suggests that the reinforcing effects of dombeya fibers and paper particles contribute to improved resistance against impact forces slowing down crack propagation owing to the uneven dissemination of dombeya fiber and paper particles, potentially enhancing the composite's suitability for applications where impact resistance is crucial, for instance, orthopedic implants, particularly joint components.

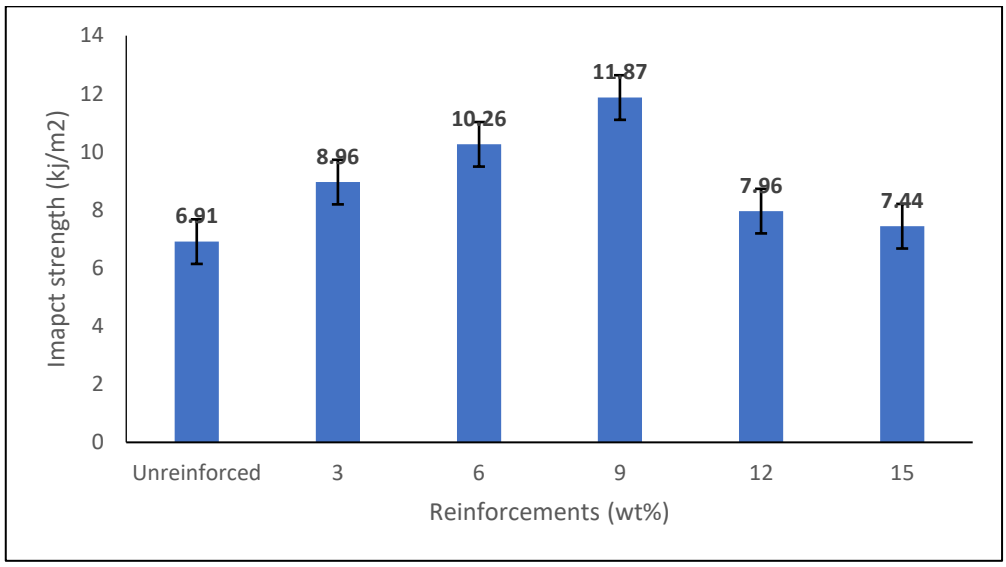

Figure 9. Impact strength properties.

However, at 12wt% and 15wt%, there was a notable decrease in impact strength (7.96 kJ/m² and 7.44 kJ/m², respectively). This decline may be indicative of potential issues, such as agglomeration, interfacial bonding, or an excess of reinforcement, leading to a compromised ability to absorb impact energy [32]. As observed in Figure 9, all the reinforced hybrid composites exhibited enhanced impact strength compared to the unreinforced composite, irrespective of the variation observed among the reinforced samples. Similar findings have been reported by Adekomaya et al. [33], Teboho et al. [34] and Gudayu et al. [35] showed that the addition of reinforcement led to a significant increase in the impact strength of the composite.

3.4. Hardness Property

The variation in the hardness properties of the hybrid-reinforced biocomposites is shown in Figure 10. A noticeable increase in hardness from 58HS (0wt%) to 60HS was observed at 3wt%, indicating an initial improvement in the ability of the material to withstand penetration as a result of the introduction of Dombeya fibers and paper particles. With further reinforcement, the hardness continued to increase up to 9wt%, reaching a peak value of 67HS, representing a 16% increase. This positive trend suggests that the reinforcing effects of Dombeya fibers and paper particles contribute to improved hardness, potentially enhancing the suitability of the composite for applications where resistance to surface penetration is crucial. This finding implies a favorable combination of hardness properties in the biocomposite, which is advantageous for composite development [1]. The effective interfacial adhesion between the fibers/particles and the epoxy matrix, the uniform dispersion of Dombeya fibers within the matrix, and the method of reinforcing the paper particles within the polymer matrix are all responsible for the observed improvement. This may be because the addition of particulate reinforcement materials reduced the elasticity of the biocomposites and enhanced the surface resistance of the matrix to indentation.

Additionally, the strong interfacial adhesion between the matrix and reinforcing agents, which improves the hardness, is responsible for the increase in stiffness. Furthermore, an increase in stiffness and fiber interlocking may be linked to this phenomenon [29]. However, at 12wt% and 15wt%, there was a decrease in the hardness (61HS and 57HS, respectively). This decline may indicate potential issues, such as agglomeration, interfacial bonding, or an excessive amount of reinforcement, which compromises the ability to resist indentation.

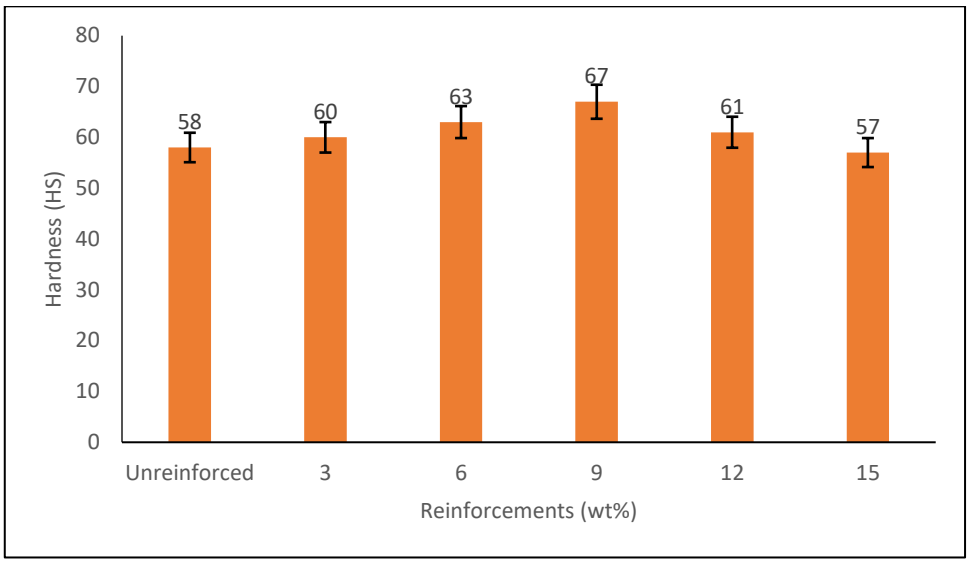

Figure 10. Hardness properties.

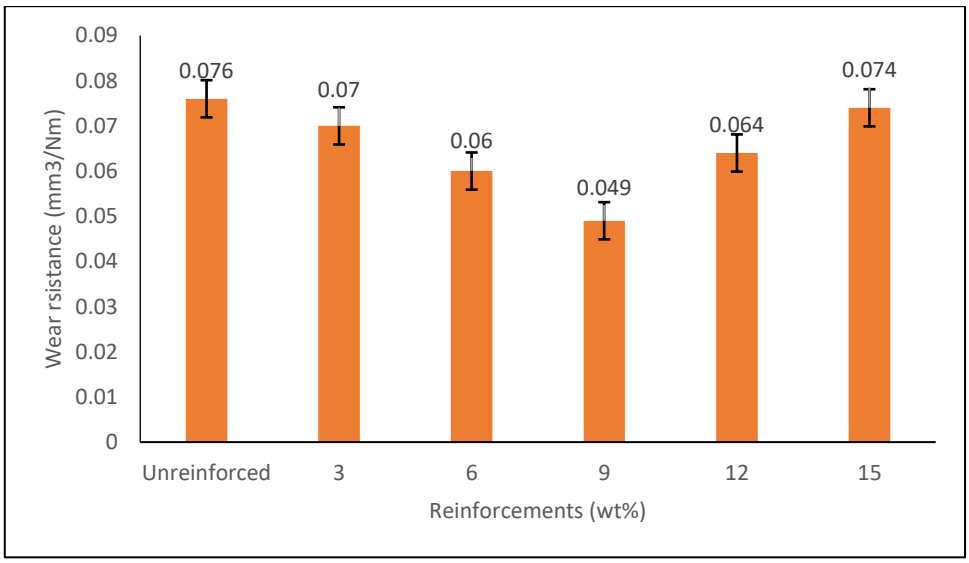

Figure 11. Abrasion properties.

3.5. Abrasion Property

The wear- and abrasion-resistance properties of the biocomposites are shown in Figure 11. A decreased wear index denotes higher durability against wear because wear resistance measures how quickly materials resist surface degradation when touching a sliding or rotating surface. The results showed that, in comparison to the unreinforced composite sample, all the produced composites had a decreased wear index, indicating a higher degree of wear resistance. Thus, in biomedical applications where surface abrasion is common, adding these reinforcements can improve the wear resistance of epoxy materials. Across the reinforced composites, the wear index values revealed a distinct trend, showing variations in the material wear resistance with changing reinforcement concentrations. At 9wt%, there was a significant decrease in the wear index from 0.076 mg (0wt%) to 0.049 mg, indicating a notable enhancement in the material's ability to resist wear due to the introduction of Dombeya fibers and paper particles. With continued reinforcement, the wear index continued to fluctuate, with 6wt% displaying the lowest wear index of 0.06 mg. This suggests that the reinforcing effects of Dombeya fibers and paper particles contribute to improved wear resistance, potentially enhancing the

suitability of the composite for applications where resistance to surface wear is crucial. However, at 12wt% and 15wt%, there was a slight increase in the wear index (0.069 and 0.074 mg, respectively). This increase may be indicative of potential issues, such as wear particle accumulation, interfacial bonding, or an excess of reinforcement, leading to a compromised ability to withstand wear. Similar findings in the research of Ramesh et al. [36] and Shalwan and Yousif [37] support this conclusion.

3.6. Fluid Absorption Properties (Water media)

In Figure 12, the fluid absorption properties of the composites in water media were studied over a 96-hour immersion period. The results revealed a direct correlation between the increase in reinforcement content and the increase in water absorption, especially in the 9wt%-15wt% hybrid composite. This trend is related to the inherent hydrophilicity of natural fibers [38]. Interestingly, the composites reinforced with 3wt% and 6wt% DF-PP showed lower water absorption than the unreinforced matrix, particularly during the initial 24 h. Unlike the other reinforced composites, these biocomposites exhibited a gradual reduction in water absorption after an initial increase. Various factors, including the particle amount, dispersion effectiveness, immersion temperature, area exposed to water, permeability of the particulates, void content in the epoxy, and hydrophilicity of individual components, influence water absorption in epoxy-based biocomposites.

For composites reinforced with 9 to 12wt% dombeya fiber/paper particles, an initial high absorption rate was observed, followed by a decrease at 48 h, and further reduction up to 96 h. This behavior demonstrates the effect of the reinforcing content on the water absorption potential and is correlated with the fraction of dombeya fiber-paper particles in this range. This shows that the absorption capacity is smaller below this level than above this range. In the case of 15wt% dombeya fiber-paper particles, an increase in the immersion period beyond 96 h leads to a continuous increase in the absorption rate, with no observed saturation. This suggests that despite the hydrophobic nature of the epoxy matrix, water continued to diffuse into the composite. As water interacts with the epoxy matrix, the rate of absorption increases until it reaches the saturation threshold. These findings prompted further investigation into water absorption rates beyond 96 h, as discussed in a study by Akash et al. [39], where sisal/coir fibers were used as reinforcements. Notably, the 3wt% and 6wt% reinforced biocomposites demonstrated superior water resistance properties. Hydrophilic behavior might be caused by insufficient wettability and interfacial adhesion between the fibers/fillers and the polymer matrix, as previous studies have shown [1], [29]. Consequently, Dombeya fiber/paper-particle-hybrid-reinforced biocomposites could find applications in areas where water resistance is crucial.

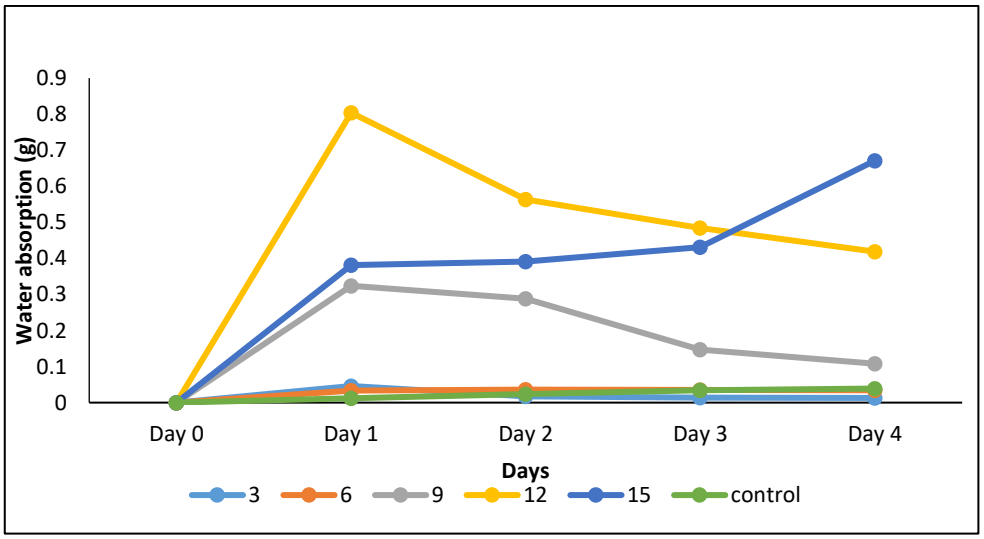

Figure 12. Fluid absorption properties in a water media.

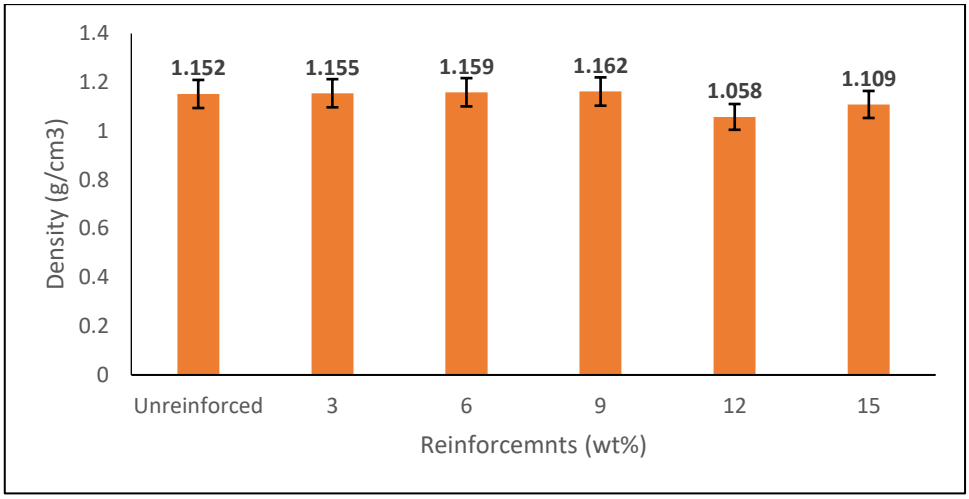

Figure 13. Density properties.

3.7. Density Properties

Figure 13 shows the response of an epoxy composite strengthened by Dombeya fiber-paper particles in relation to its density. The results have indicated that the density increases within the range of 3-9 wt% before subsequently declining as the reinforcement content increases, with the highest density of 1.162gcm^{-3} observed at 9 wt%. However, there is a decrease in the density between 12-15wt% reinforcement, which falls below the density of the unreinforced composite. Notably, the densities of the developed composites were within a similar range to that of the unreinforced matrix, indicating that the composites possessed improved properties at these densities and were of superior quality. A range of 1.2 to 1.6 g/cm^3 was observed in the natural fiber density, according to Asokan et al. [40].

The results shown in Figure 13 indicate that the reinforced composite was not within this range. This discovery is significant because it raises the possibility of using these low-density composites in lightweight biomedical applications such as orthotics and prosthetics, where there is a critical need for environmentally friendly and biocompatible materials. Furthermore, this discovery encourages the development of completely biodegradable composite materials for sustainable and ecologically friendly applications.

3.8. Microstructural Examination

Figures 14 and 15 depict the scanning electron microscopy (SEM) images of the biocomposites reinforced with hybrid materials containing 3 wt% and 9 wt%. Analysis of the micrographs revealed that the biocomposite reinforced with 3 wt. % exhibited a more pronounced dispersion of the reinforcement materials. This dispersion was attributed to the relatively low weight fraction of reinforcements present in the epoxy matrix. The dispersion facilitated the effective adhesion of the reinforcement materials within the matrix, thereby enhancing certain properties of the biocomposite. Additionally, the absence of agglomeration in this particular biocomposite contributed to improved density and flexural properties.

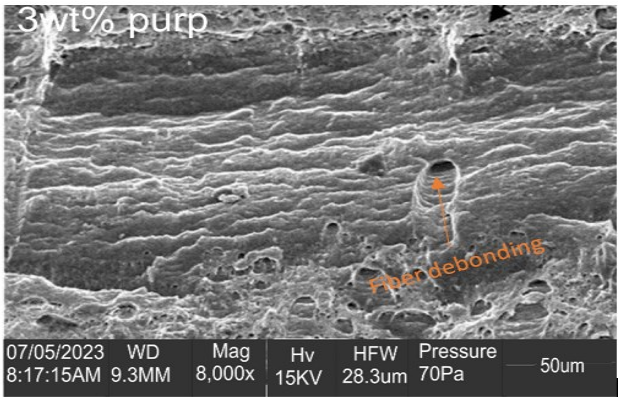

Figure 14. SEM Micrographs of the 3 wt% Hybrid Reinforced Biocomposite.

Nevertheless, it is worth noting that the limited number of reinforcements in this weight fraction had an impact on the enhancements observed in certain properties of the biocomposites, as well as the presence of fiber pull-out.

In Figure 15, the scanning electron microscopy (SEM) image of the biocomposite reinforced with 9wt% exhibited superior improvements in comparison to the other biocomposites. The presence of hybrid reinforcement materials in the epoxy matrix facilitated the effective adhesion of the hybrid reinforcements within the matrix. The favorable values achieved for the mechanical properties can be attributed to the moderate quantity of hybrid reinforcements incorporated in the matrix.

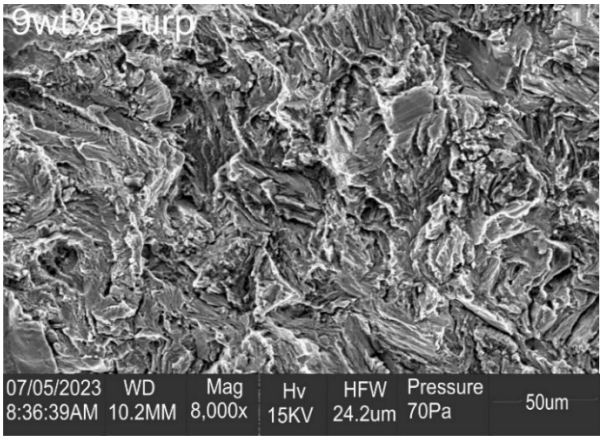

Figure 15. SEM/EDS Micrographs of the 9 wt% Hybrid Reinforced Biocomposite.

Furthermore, this particular sample displayed commendable water absorption and density characteristics, rendering it suitable for biomedical applications. Consequently, the addition of a moderate weight fraction of hybrid reinforcements consisting of dombeya fiber-paper particles in the epoxy matrix would augment the mechanical and absorption properties of the epoxy composite, thus making it appropriate for use in biomedical applications in areas such as prosthetics, orthotics, and surgical instruments.

4. Conclusion

Based on the findings derived from this investigation, it was determined that composites incorporating the chosen plant fibers are suitable for the development of polymer composites with epoxy resin. The examination revealed that composites consisting of Dombeya fiber-paper particles exhibited enhanced tensile strength within the range of 3-9wt%, with the optimal tensile strength observed at 9wt% (19.03MPa). Furthermore, a heightened tensile modulus was observed in composites ranging from 3-15wt%, reaching its pinnacle at 12wt% (856.83MPa). The composites reinforced with 3-9wt% have showcased superior flexural properties, with 9wt% exhibiting the optimal strength (17.85MPa) and 3wt% demonstrating the optimal flexural modulus (503.49MPa). Moreover, all reinforced composites have demonstrated improvement in terms of impact, hardness, and wear properties, with 9wt% showing the optimal impact strength (11.87kJ/m2), hardness (67HS), and wear index (0.049 mg). Notably, the biocomposites reinforced with 3wt% and 6wt% exhibited superior water resistance properties. Additionally, all reinforced composites presented lower densities compared to the reported range of natural fiber density of 1.2–1.6 g/cm^3. The amalgamation of favorable mechanical properties and low density makes these composites potential materials for biomedical applications, particularly within biomedical facilities such as orthopedic implants, surgical implants, and bone fixation devices. This study introduces the utilization of recycled waste paper particles as fillers in thermosets for the development of lightweight materials that complement fiber reinforcement, where both reinforcement shapes (particles and fibers) play synergistic roles. Furthermore, this research advances the utilization of natural resources as sustainable materials for biomedical applications. Although recycled waste paper has not been extensively employed for composite development in most biomedical applications, this material is currently recommended for use in sustainable, low-technology, and lightweight material development as an alternative to other fillers. Future research endeavors should encompass additional moisture absorption tests to evaluate the suitability of these composites in various moist environments. Furthermore, testing and validation of the thermal conductivity and biocompatibility properties are vital to guarantee the safety and effectiveness of the composite material for use in biomedical applications.

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Declaration of Conflicting Interests

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Data and Materials Accessibility

Supplementary materials and data used in this research are accessible upon request.

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