

Synergistic Effects of Hybridized Nano-Silica and Hemp Fiber Reinforcement on Bio-Epoxy Composites

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Abstract

Natural fiber-reinforced bio-epoxy composites have become promising sustainable alternatives to conventional synthetic-fiber petroleum-based materials, but are often limited by low fiber-matrix interfacial bonding, low thermal stability, and high moisture absorption which limit their application in structural applications. These issues are discussed in this work, by carrying out a systematic investigation of the synergistic effects of the hybridization of nano-silica particles with alkali-treated hemp fibers in a bio-epoxy matrix the composites comprising 05 wt.% nano-silica were fabricated by resorting to resin transfer molding with vacuum assistance. Mechanical tests indicated that huge improvements had been made with the 5 wt.% nano-silica variant achieving tensile strength of 119.8 MPa (74% improvement), flexural strength of 148.7 MPa (61% improvement), impact strength of 12.3 kJ/m² (98% improvement), and hardness of 97.8 Shore D (25 percentage improvement) versus the neat bio-epoxy base. Thermal treatment revealed that the temperature of the onset degradation rose by a factor of 66 o C to 358 o C and 22.4-percent weight of char, respectively, after 24 h immersion. This is attributed to enhanced interfacial adhesion and correct crack deflection as well as the formation of tortuous diffusion pathways that is precipitated by the uniformly dispersed nano-silica. The resultant hybrid composites offer one of the avenues through which lightweight, high-performance and environmentally friendly composites can be developed and applied in lightweight, high-performance and environmental-friendly automotive, marine and aerospace structural components.

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INTRODUCTION

A significant demand in various industries has been for sustainable and light-weight structural materials in recent years, so as to reduce the environmental impact while maintaining the structural performance[1] in industries. The traditional composites (glass and carbon fibre) are strong but are based on matrices made from petroleum products, and involve the production of a lot of waste and consume a lot of resources[2]. To overcome this, the natural fibre-reinforced bio-epoxy composites have emerged as the eco-friendly materials which have renewability, low density and

low carbon footprint[3], [4]. Hemp is the most readily available, the highest cellulose content of all natural fibers and has high specific strength and makes an attractive material for application as interior materials in the automotive, marine and aerospace industries[5], [6]. However, the intrinsic weaknesses often exist in the composites, like the low adhesion between fibers and the matrix, high hydrophilicity and low heat resistance, which reduce the durability in long-term using of composites and restrict their application in load-bearing parts[7], [8].

Hemp fiber has a number of important benefits as a reinforcer in polymer composites it is biodegradable and renewable, and has a limited carbon footprint in comparison with manmade fibers such as glass or carbon. Hemp contains high cellulose levels, great specific strength and stiffness (tensile strength 650 -850 Mpa, modulus 40-60 Gpa), low density (~1.45 g/cm³) and vibration damping. Its features render it appropriate in applications that are lightweight in the automotive, marine, and aerospace industries and also in alignment with sustainability.

A tensile strength and modulus (load bearing capacity), flexural strength and modulus (bending resistance), impact strength (toughness and energy absorption) and hardness (surface durability and wear resistance) are some important mechanical properties of bio-epoxy composites. These properties identify how well the composite can be used in structural applications where it should be able to perform under loading of tension, flexure as well as dynamic loading.

The term synergistic effect in hybrid composite can be regarded in context to the combined performance of several reinforcements (e.g. hemp fibers + nano-silica) than only the prediction of a rule of mixtures of the components may forecast it. This is due to enhanced interfacial bonding, crack deflection systems, enhanced dispersion and development of tortuous pathways, which provide more mechanical, thermal and moisture resistance attributes than the sum of the parts[9], [10].

Much research effort has been invested seeking solutions to these problems by changing the nanofillers. Some studies have seen improvement with the inclusion of Nano-Silica or Graphene in the jute/epoxy system and Micro/macro-silica hybrid reinforcement in the conventional epoxy matrix has been explored in other studies[11], [12], [13]. Although this progress has been made, most of the previous studies have been done with a single-filler system or petroleum-based epoxy resins, and there has been little systematic research of fully bio-based matrices[14], [15]. Moreover, the use of hemp fiber is less studied than jute fiber and multi property characterization in composites, derived from a given fiber family, of a set of mechanical, thermal, moisture resistance and interfacial properties has been rather limited[16], [17]. One of the significant research gaps is the lack of detailed studies of the hemp fiber/nano-silica mixture in bio-epoxy systems particularly the processes to produce the composites at scale such as VARTM (vacuum-assisted resin transfer molding)[18].

Thus, in the current research the synergistic effect of the hybridization of nano-silica and the alkali treatment of hemp fiber reinforcement in a bio-epoxy matrix (DGEBA + ESO) was systematically explored. The nanofiller was prepared by an optimized surface treatment of the fibers and ultrasonic dispersion technique. The composites with different amounts of nano-silica (0-5 wt.%) were produced by applying VARTM method. Mechanical properties (Figure 2 and Figure 4), fracture mechanisms, thermal stability and moisture resistance were characterized of the resulting materials. It has much synergistic improvement in tensile strength (119.8 MPa, 74% increase), flexural strength (148.7 MPa, 61% increase), impact strength (12.3 kJ/m², 98% increase), 24 h water absorption (2.4% at 69% decrease), and char yield (66°C at 22.4% increase at 600°C). The improvements are believed to be the result of the enhanced interfacial bond, effective crack deflection and creation of tortuous diffusion pathways as a result of the uniform dispersion of nano-silica particles.

This is a first-of-its-kind experimental realization of hybridization of hemp fibres and nanosilica in a fully bio-based epoxy matrix for the scalable production of high-performance sustainable composites.

The results provide a clear direction to develop new materials that can replace conventional ones in structural and insulating applications, contribute to the circular economy and comply with increasingly strict environmental legislations. In the following, materials and methods, a complete results and discussion, and implications and future directions will be presented. But, the hybridization of hemp fibre with nano-silica in the completely bio-based epoxy matrices is not yet investigated systematically. Existing studies have mainly explored the properties of jute fibers, a single-filler composite or the conventional petroleum-based epoxy, and fewer studies have evaluated multiple properties of the same family of composites. The research has considerable gaps as indicated in (Figure 1).

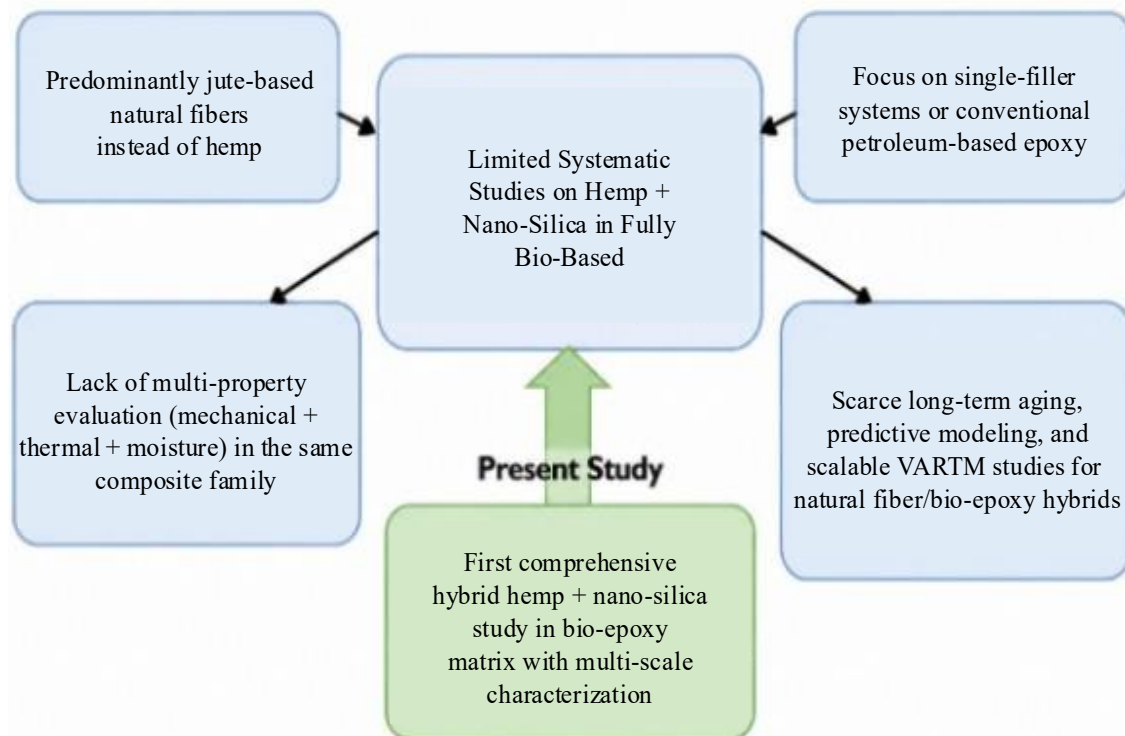


Figure 1. Identifying the issues in hemp fiber and nano-silica reinforced bio-epoxy composite and addressing these issues during the present research

The literature reviewed is detailed in section II, methodology is detailed in section III, results and discussion is detailed in section IV and the conclusions and possible directions in the future is detailed in section V.

RELATED WORK

Natural fiber-reinforced polymer composites (NFRCs) are a relatively new type of composites which are gaining popularity due to its climatic demand and regulation to reduce carbon footprint as the traditional synthetic-fiber composites[19], [20], [21]. Natural fibres have a high chance because hemp has a considerable amount of cellulose, high specific strength and is renewable many of the researches have focussed on jute and flax fibres with epoxy matrix derived from petroleum sources but the hemp fibres have not been studied as much as the other fibres[22], [23], [24]. Poor fiber-matrix interface, high moisture uptake and poor thermo-oxidative stability are a common issue with such composites that restricts their application in structural applications[25], [26].

Nanofillers Reinforcement of Epoxy Matrices

In order to overcome the interfacial and mechanical limitation, nanofillers like nano-silica and graphene have been extensively studied for their inclusion in the composite. For single filler systems, moderate increase in stiffness, hardness and wear resistance by improved stress transfer and crack

deflection has been reported[27], [28], [29]. Multi-scale toughening strategies and synergistic toughening by combining hybrid micro-nano silica strategies has been shown with the help of crack pinning by the microparticles and shear banding mechanism by the nanoparticles however[30], [31], the majority of these works used traditional epoxy resins not fully bio-based matrices, which restricts the sustainability of these materials[32], [33], [34], [35].

Hybrid Natural Fiber Nanofiller Composites

The use of hybrid reinforcement has started to be investigated involving natural fibers and nanofillers also the composite of jute and epoxy filled with nano-silica and graphene has also improved tensile strength, flexural properties and thermal stability properties significantly [36], [37]. The water absorbing capacity and wear resistance property have been reported to be lower in hybrid system with sisal or kenaf fibre than other hybrid system [38], [39]. Despite these advances, systematic research to understand the mechanical and thermal/moisture-resistance characteristics in a family of composites is still limited. In addition, hemp fiber is not explored to the extent as jute and nano-silica hybridization in completely bio-based epoxy (DGEBA + ESO) matrix has not been thoroughly investigated [40], [41], [42].

Bio-Based Epoxy Systems

Bio-epoxy resins are matrices that are based on plant oils and have caused an impression as promising. Studies of the bio-epoxy composites filled with micro-silica have revealed good thermal aging resistance and insulation properties [43], [44]. But very few of these studies involve nano-scale hybridization or natural fibres; thus, there is a huge gap to obtain a balance in the multi-functional properties[45], [46].

The literature thus exposes pointed drawbacks, being generally one or petroleum based, lack of characterization of hemp fiber and absence of multi-property characterization of bio-epoxy composite based on hemp fiber at scales with scalable processes like VARTM[47]. The present work aims at filling these gaps by comprehensively studying the synergistic effects of the hybridized nano-silica and alkali treated hemp fiber in bio-epoxy matrix[48], and presents for the first time an experimental demonstration of superior mechanical toughness, thermal stability, and moisture resistance.

MATERIALS AND METHODS

The present research used the followings materials and experimental procedures hemp fibre mats (200 g/m² plain woven) and a bio-epoxy resin, that was prepared with diglycidyl ether of bisphenol-A (DGEBA) and epoxidized soybean oil (ESO) in proportions of 7:3 and nano-silica particles (20-50 nm) were used as the main materials. VARTM was used to make composites by treating the hemp fibers with alkali and varying concentration of nano-silica (0-5 wt.%) to create the hybrid composites.

Materials

The hemp fibers used were in the form of 200 g/cm² plain woven mats the bio-epoxy matrix was formulated by mixing diglycidyl ether of bisphenol-A (DGEBA) and epoxidized soybean oil (ESO) in 7:3 weight ratio. The size of the reinforcing nanofiller adopted in this work was the nano-silica particles of different average diameters ranging from 20-50 nm. The physical and mechanical characteristics of raw materials are given in Table 1.

Table 1. Physico mechanical properties of raw materials

Material	Density (g/cm ³)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Other Properties
Hemp fiber	1.45	650–850	40–60	Good natural fiber
Bio-epoxy resin	1.12	52.3	2.6	Main matrix material
Nano-silica	2.20	—	—	Very small particles (20–50 nm)

Fiber Surface Treatment

To remove impurities and convert the hemp fiber mats to make them rougher, the mats were soaked in a 5% NaOH solution at room temperature for 2-4 hours washing the treated fibres with distilled water until the pH neutral and then drying the fibres at 60°C for 24 hrs.

The dispersion of Nano-silica and Preparation of Composite Fabric

The bio-epoxy resin was reinforced with a nano-silica particle at four varying weight percentages (0, 1, 3 and 5 wt percent-resin weight) of the resin weight. The vacuum-assisted resin transfer molding (VARTM) was used to prepare five composite variants. A closed mold was filled with alkali-treated hemp fiber mats (40 wt.%) and infusion was done under a vacuum of -0.9 bar with the nano-silica-dispersed bio-epoxy resin including hardener. The laminates were allowed to cure at room temperature and the process took 24 h after full impregnation. The last laminates were 3.0 to 3.1 mm deep on average and had a fiber volume fraction of about 34-35 percentage. Table 2 gives detailed compositions of all fabricated composites. Figure 2 shows a schematic of the entire process of fabrication of the step-by-step fabrication process such as treatment of the fiber, nano-silica dispersion, VARTM infusion and curing.

The volume fraction of fibres was determined by:

$$V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f} \quad (1)$$

If ρ_f and ρ_m are densities of fiber and matrix, respectively, then W_f and W_m are the weight fractions of fiber and matrix, respectively this equation has good accuracy in determining the reinforcement volume to predict properties

The rule of mixtures was used to estimate the modulus and strength of composite:

$$E_c = V_f E_f + V_m E_m \quad (2)$$

$$\sigma_c = V_f \sigma_f + V_m \sigma_m \quad (3)$$

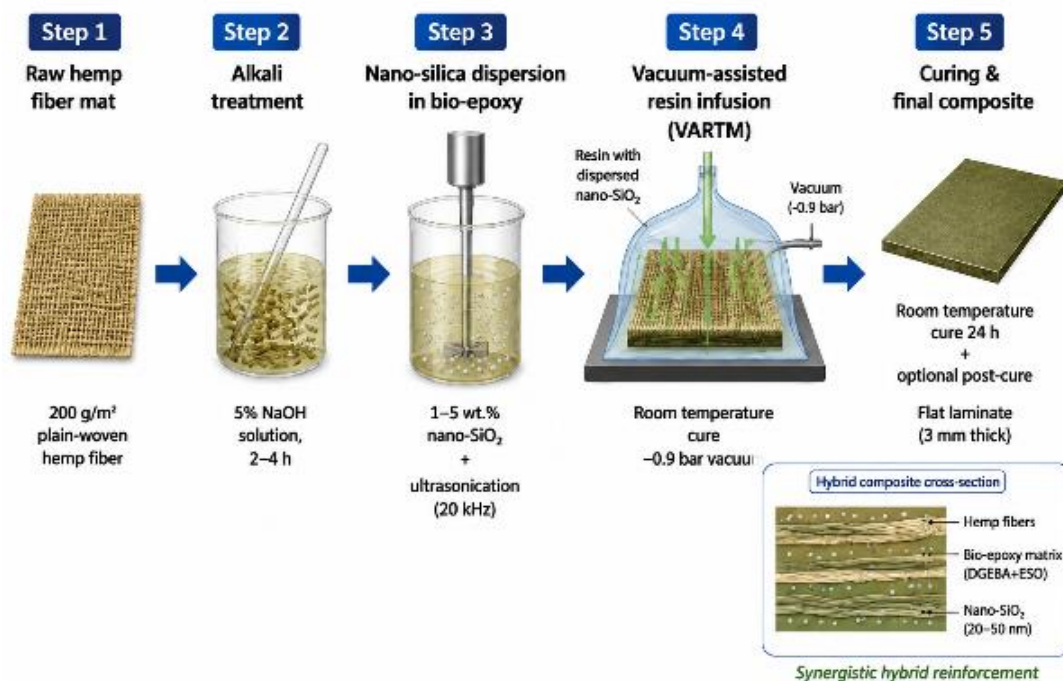


Figure 2. Flowchart of fabrication of hybridized nano-silica and hemp fiber reinforced bio-epoxy composite

The subscripts c , f , and m are used to indicate composite, fiber and matrix, respectively the expressions serve as a theoretical reference for assessing the synergistic enhancement of the hybrid composites.

The composite density was estimated as:

$$\rho_c = \rho_f V_f + \rho_m V_m \quad (4)$$

This relation can be used to check the actual densities of fabricated laminates and to make sure that it is consistent with experimental values.

Mechanical Characterization

The tensile properties were determined following ASTM D3039, flexural properties following ASTM D790, impact strength following ASTM D256 and hardness following ASTM D785

The stress and strains were calculated as follows:

$$\sigma = \frac{P}{A} \quad (5)$$

$$\varepsilon = \frac{\Delta L}{L_0} \quad (6)$$

where P is the applied load and A is the cross-sectional area, these basic definitions form the foundation for all mechanical property calculations

Flexural strength and modulus were obtained from three-point bending tests:

$$\sigma_f = \frac{3PL}{2bd^2} \quad (7)$$

$$E_f = \frac{L^3 m}{4bd^3} \quad (8)$$

where P is the load applied, L is the distance between the supports, b is the specimen width, d is the specimen thickness and m are the initial linear portion of the load-deflection curve these equations enable comparisons based on the bending performance even with different loadings of nano-silica.

Fracture Mechanics and Thermal characterization

Fracture toughness and fracture energy were defined as:

$$K_{IC} = \frac{P_C S}{BW^{3/2}} f(\xi) \quad (9)$$

$$G_{IC} = \frac{K_{IC}^2}{E} (1 - \nu^2) \quad (10)$$

In which P_C is the critical load in the specimen, S is the length of the span, B and W are the dimensions of the specimen, E is Young's modulus and ν is Poisson's ratio. These are the parameters which are used to measure crack propagation resistance of a material

Dynamic mechanical analysis (DMA) was used to determine the crosslink density and the following was used:

$$\nu_e = \frac{E'}{3RT} \quad (11)$$

The storage modulus in the rubbery region E' is related to the gas constant R and absolute temperature T by the above equation this equation is related to the degree of curing in the bio-epoxy matrix viscoelastic behavior.

The glass transition temperature found was:

$$T_g = T_{\text{peak}}(\tan \delta) \quad (12)$$

Thermal stability tests were carried out in a TGA thermometer at 10°C/ min under the condition of N₂ atmosphere, a summary of the thermal properties is given in Table 4 and Figure 5, the fracture surface analysis was done by scanning electron microscopy (SEM) and the functional characteristics of the interface and mechanism of fracture (Figure 3) were studied.

Water Absorption Test

The amount of water absorbed was determined using ASTM D570 the percentage water absorption and diffusion coefficient were calculated as:

$$M_t = \frac{W_t - W_0}{W_0} \times 100 \quad (13)$$

$$D = \frac{\pi h^2}{16t} \left(\frac{M_t}{M_\infty} \right)^2 \quad (14)$$

W_t is the wet weight, W_0 is the dry weight, h is the thickness of the specimen and t is time these equations describe the quantities of moisture uptake and moisture diffusion.

Synergistic Improvement Quantification

The quantification of degree of synergy and percentage improvement was done as follows:

$$\eta = \frac{P_{\text{hybrid}} - (P_{\text{hemp}} + P_{\text{nano}})}{P_{\text{hemp}} + P_{\text{nano}}} \times 100 \quad (15)$$

$$\% \text{ Improvement} = \frac{P_{\text{hybrid}} - P_{\text{baseline}}}{P_{\text{baseline}}} \times 100 \quad (16)$$

In order to confirm the results, each experiment was repeated minimum of 3 times in order to carry out an in-depth evaluation of the synergistic effect of the hybridized nano-silica and hemp fibers reinforcement in bio-epoxy composites.

RESULTS AND DISCUSSION

The experimental findings indicate clearly the synergistic effect of hybridized nano-silica and hemp fiber reinforcements in bio-epoxy composite. The systematically evaluated mechanical properties, thermal stability, fracture morphology and water absorption behavior were done at various nano-silica loadings (005 wt.%). Table 3 and Figure 2-4 provide the mechanical performance, Figure 3 illustrates the fracture mechanisms, Table 4 and Figure 5 give the thermal properties. Table 5 summarize the results of the water absorption.

Mechanical Properties

The mechanical strength of the composite structures made was measured to determine the synergetic reinforcement offered by nano-silica hybridization. Table 2 shows the detailed compositions of the five variants that are composites.

Table 2. Compositions of the Composites

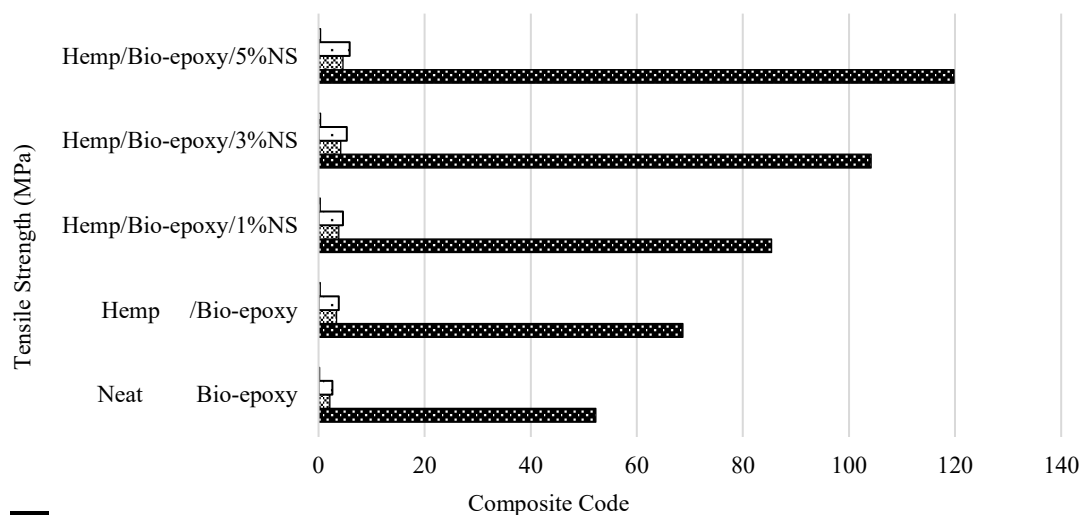
Composite Name	Hemp Fiber (%)	Bio-epoxy (%)	Nano-silica (%)	Thickness (mm)
Neat Bio-epoxy	0	100	0	3.0
Hemp/Bio-epoxy	40	60	0	3.0
Hemp/Bio-epoxy/1%NS	40	59	1	3.0
Hemp/Bio-epoxy/3%NS	40	57	3	3.1
Hemp/Bio-epoxy/5%NS	40	55	5	3.1

The baseline tensile strength and modulus of the neat bio-epoxy were 52.3 MPa and 2.6 Gpa respectively as shown in Table 3 and Figure 3 the addition of hemp fibers only enhanced these values to 68.7 MPa and 3.8 Gpa respectively.

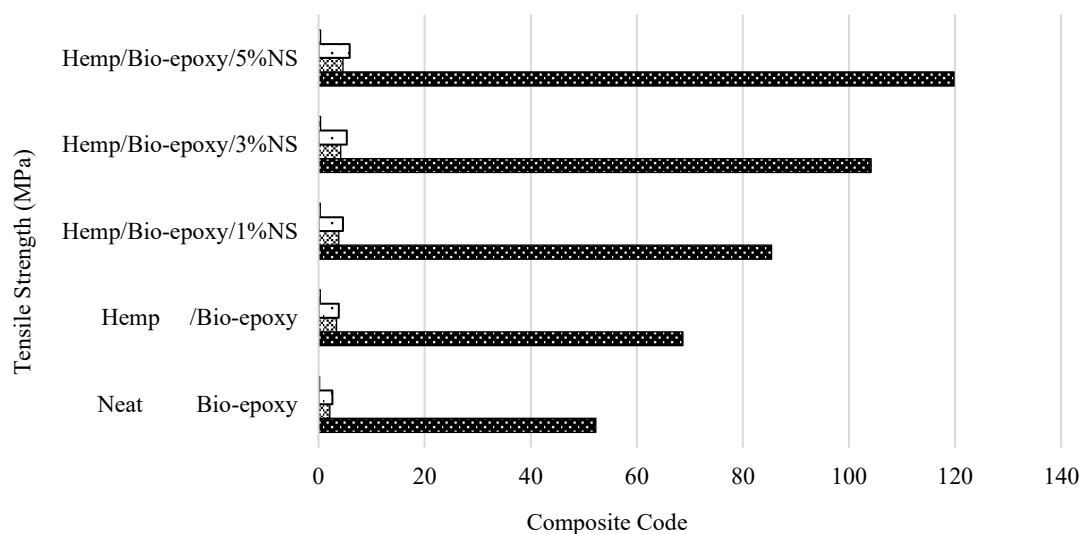
Table 3. Mechanical Properties (Strength & Stiffness)

Composite Name	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Impact Strength (kJ/m ²)	Hardness (Shore D)
Neat Bio-epoxy	52.3	2.6	68.4	3.8	78.2
Hemp/Bio-epoxy	68.7	3.8	92.5	6.2	84.5
Hemp/Bio-epoxy/1%NS	85.4	4.6	112.8	8.1	89.7
Hemp/Bio-epoxy/3%NS	104.2	5.3	131.6	10.4	94.3
Hemp/Bio-epoxy/5%NS	119.8	5.9	148.7	12.3	97.8

As we continued to add nano-silica, there was significant improvement. Nano-silica hybrid composite of 5 wt.% was found to have tensile strength of 119.8 Mpa (74 percent higher than that of neat bio-epoxy) and tensile modulus of 5.9 Gpa. Equivalent synergistic benefits were noticed in flexural properties (Figure 3b), where flexural strength (61%) and flexural modulus (6.4 Gpa) was observed to be 148.7 Mpa and 6.4 Gpa respectively with the 5 wt.% variant.



(a) Std. Deviation2 Tensile Modulus (GPa) Std. Deviation Tensile Strength (MPa)



(b) Std. Deviation2 Tensile Modulus (GPa) Std. Deviation Tensile Strength (MPa)

Figure 3. The mechanical characteristics of the hybridized nano-silica and hemp fiber reinforced bio-epoxy composites: (a) tensile strength and modulus, (b) flexural strength and modulus

Strength and Hardness of Impact

The effect of nano-silica on hardness and impact strength further attested to the toughening impact of nano-silica. Impact strength as shown in Table 3 and Figure 4(a), (b) rose to 12.3 kJ/m² in 5 wt.% hybrid (98% improvement) as compared to the neat bio-epoxy 3.8 kJ/m². Hardness rose from 78.2 to 97.8 Shore D (25% improvement). These findings suggest that nano-silica is a promising material to increase the energy absorption and surface resistance by increasing interfacial bonding and crack deflection mechanisms.

A high fiber pull-out and clear crack-deflection were evident in both the nano-silica hybrids of 3 wt.% and 5 wt.% with a notable reduction in the fiber pull-out and clear evidence of the crack-deflection bridging and matrix shear bands being observed. These are highly consistent with the improved mechanical properties in Table 3 and Figure 2.

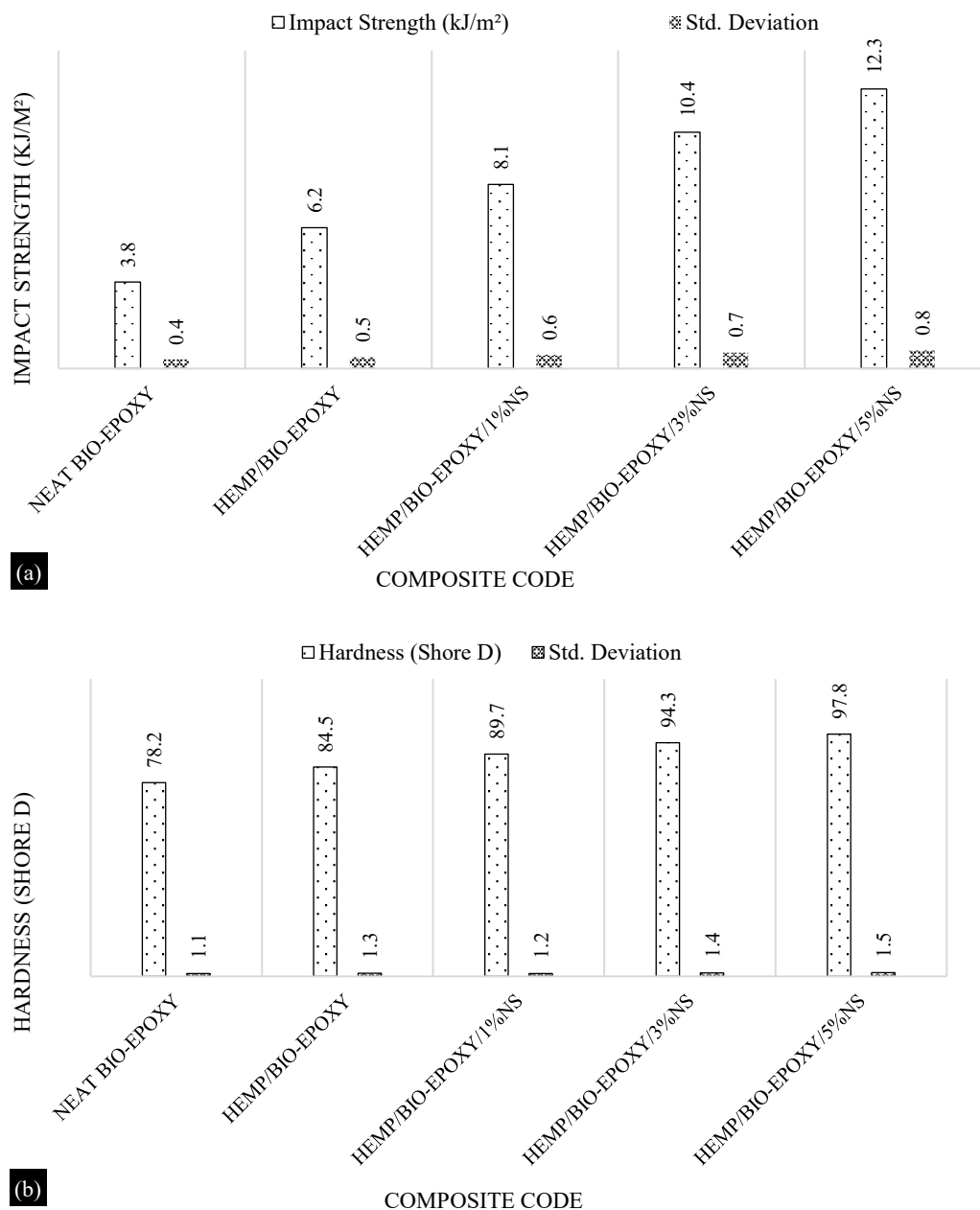


Figure 4. Tensile fracture mechanism (schematic) in the hybridized nano-silica and hemp fiber reinforced bio-epoxy composites (a) Neat Bio-epoxy, (b) Hemp/Bio-epoxy

Fracture Surface Morphology

Direct observation of tensile fracture surfaces through morphological analysis gave direct information on the reinforcement mechanisms. Figure 5 reveals that the follow-up of the neat bio-epoxy sample was smooth and brittle fracture with large voids in comparison to the hemp/ bio-epoxy sample where a large number of fibre pull-out and debonding discontinuities occurred.

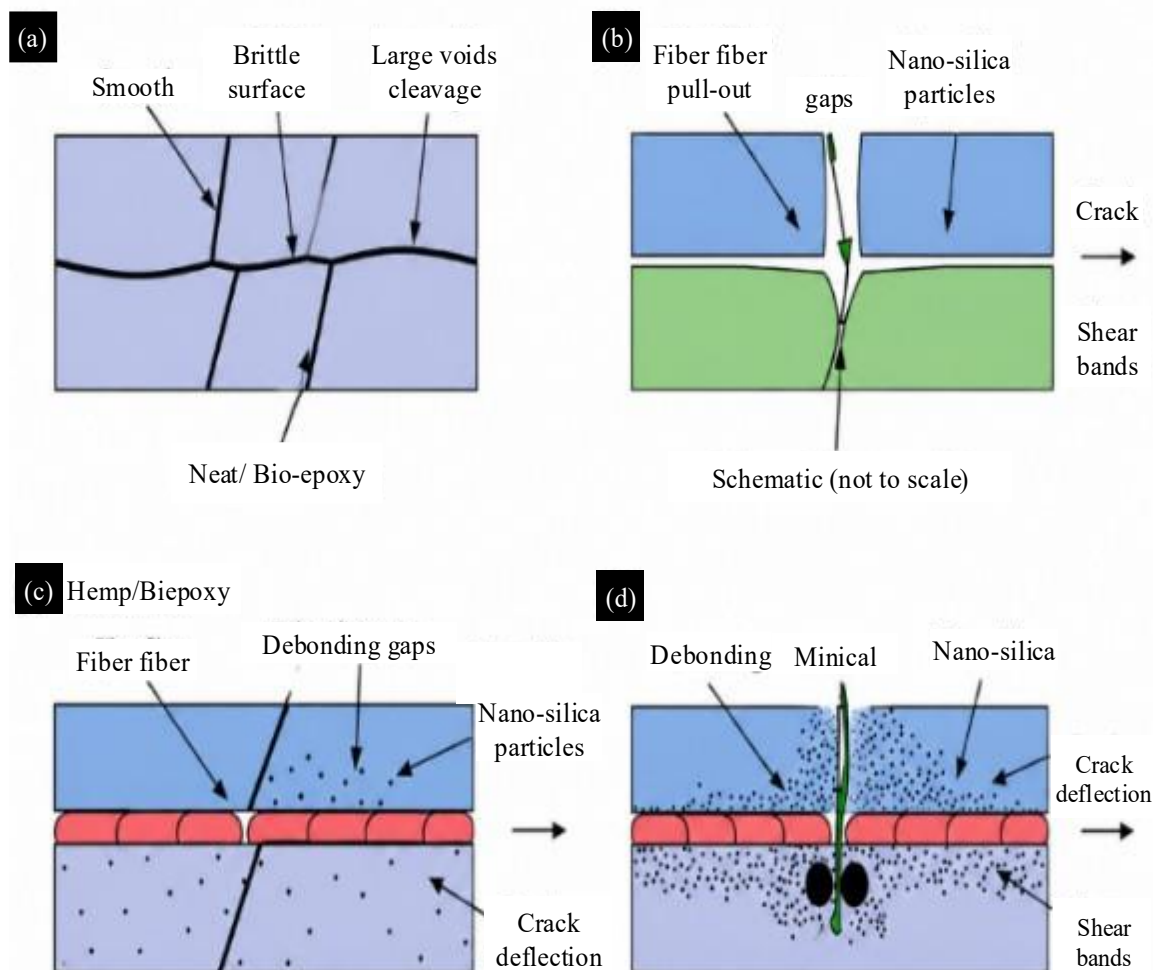


Figure 5. Illustration of tensile fracture processes of hybridized nano silica and hemp fiber reinforced bio-epoxy composites

Thermal Properties

Nano-silica incorporation had a significant impact on enhancing thermal stability. Table 4 shows that the onset temperature of degradation decreased by 66 °C (292 °C - 358 °C) between neat bio-epoxy and the hybrid (5 wt.%).

The thermal resistance (char formation and barrier effects) was shown by the increase in the char yield at 600 °C to 22.4 °C higher than the previous 4.8 °C. The temperature of glass transition was also increased to 125 °C as compared to 98 °C and this showed that there was limited movement of polymer chains.

Water Absorption Behavior

A key drawback of natural fiber composites such as moisture resistance was improved as indicated in Table 5 and Figure 6, 24 h water absorption reduced to 2.4 per cent in the nano-silica hybrid 5 wt. per cent (69 per cent reduction) compared to neat bio-epoxy.

Table 4. Thermal Property (Heat Resistance)

Composite Name	Onset Temp. (°C)	Peak Temp. (°C)	Char Yield at 600°C (%)	Glass Transition Temp. T _g (°C)
Neat Bio-epoxy	292	368	4.8	98
Hemp/Bio-epoxy	312	385	9.2	104
Hemp/Bio-epoxy/1%NS	328	402	13.6	113
Hemp/Bio-epoxy/3%NS	345	415	17.9	119
Hemp/Bio-epoxy/5%NS	358	428	22.4	125

Table 5. Water Absorption & Wear Resistance

Composite Name	Water Absorption (24 h,%)	Specific Wear Rate ($\times 10^{-6}$ mm ³ /N·m)	Coefficient of Friction
Neat Bio-epoxy	7.8	5.9	0.54
Hemp/Bio-epoxy	5.9	4.2	0.48
Hemp/Bio-epoxy/1%NS	4.1	3.1	0.41
Hemp/Bio-epoxy/3%NS	3.0	2.3	0.36
Hemp/Bio-epoxy/5%NS	2.4	1.8	0.32

The hybrid composites had lower rate of absorption and decreased equilibrium moisture content, which was due to tortuous diffusion routes formed by well-dispersed nano-silica particles, which can effectively seal off the interfacial voids and prevent the water molecules from penetrating the composite structure.

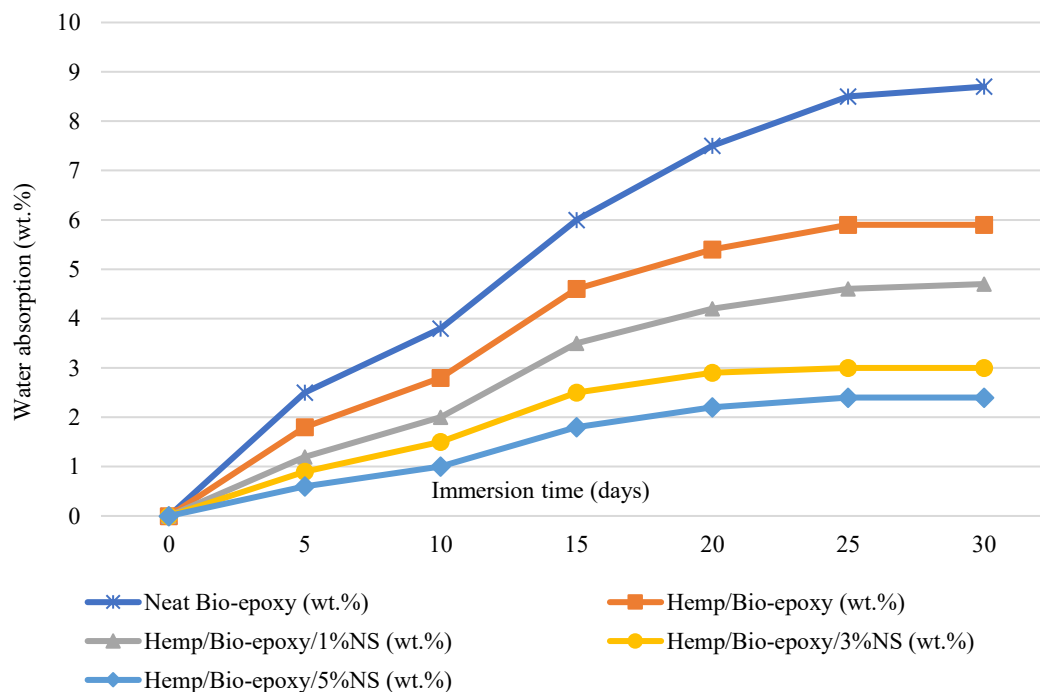


Figure 6. The behavior of the hybridized nano-silica and hemp fiber reinforced bio-epoxy composites in terms of water absorption with respect to immersion time

The improvements not only increase the long-term durability and dimensional stability of the material in humid conditions, but also increase the application of the material in outdoor applications, marine applications and structural components where moisture exposure is a major concern.

Table 6: compares the results of this research with the outcomes of the previous study

Property	Reported Literature	Previous Literature[11], [49]
Tensile Strength	119.8 MPa	93.8 MPa
Flexural Strength	148.7 MPa	125.3 MPa
Impact Strength	12.3 kJ/m ²	9.9 kJ/m ²
Hardness	97.8	98.7
Onset Temperature (°C)	358	355
Char Yield at 600°C (%)	22.4	21.4
Water Absorption (24 hours)	2.4%	—

Comparison with previous literature

A comparison with the past studies is presented in Table 6. The tensile strength (119.8 MPa vs. 93.8 MPa), flexural strength (148.7 MPa vs. 125.3 MPa), impact strength (12.3 kJ/m² vs. 9.9 kJ/m²), the onset degradation temperature (358 °C vs. 355 °C), char yield (22.4 vs. 21.4%) of the current hemp/nano-silica/ bio-epoxy system is superior to the previous work. These results confirm the originality of the use of hemp fiber with nano-silica in a completely bio-based epoxy matrix and confirm that the hybrid method is effective to overcome the main constraints found in previous literature. The findings indicate that the proposed composites have a balanced mechanical toughness, thermal stability and moisture resistance that can be used in the sustainable structures.

CONCLUSION

This research has managed to show the synergistic reinforcement obtained through the hybridisation, nano-silica particles with alkali-treated hemp fibers, in an entirely bio-based epoxy. The 5 wt.% nano-silica composites also demonstrated some impressive results, such as tensile strength (119.8 Mpa, 74 percent), flexural (148.7 Mpa, 61 percent), impact (12.3 kJ/m², 98 percent), and water absorption (2.4 percent) improvements. The thermal stability was also greatly improved where the onset degradation temperature increased by 66 °C to 358 °C and the char yield increased to 22.4% the benefits of these are due to the enhancement of interfacial bonding, crack deflection and the development of tortuous diffusion routes due to uniform distribution of nano-silica.

The hemp/nano-silica/bio-epoxy composites that were developed provide a high-performance, non-polluting substitute to traditional synthetic materials that can be used in structure in the automotive, marine, and aerospace industries. This paper represents the first complete evidence of such hybridization in a completely bio-based system and it is the threshold to more environmentally friendly and more durable composite materials. The future studies will concentrate on long-term aging behavioral studies and optimization on industrial scale.

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