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# Investigating the mechanical properties and water absorption behavior of hemp-based natural fiber-reinforced bio-composites for humidity-resistant applications

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**ABSTRACT:** This study presents a novel investigation into the synergistic effects of silicon carbide (SiC) filler content and fiber orientation on the mechanical properties and water absorption behavior of hemp/SiC epoxy bio-composites, aiming to enhance durability for humidity-prone applications. Unlike previous research, which often focuses on either fiber reinforcement or filler effects independently, this work uniquely combines optimized SiC loading with targeted fiber orientations i. e. unidirectional (0°/90°), quasi-isotropic (30°/60°) and cross-ply (45°/45°) to systematically analyze their interplay. Bio-composites fabricated via hand lay-up with varying SiC content (2 wt%, 5 wt% and 8 wt%) demonstrated that 5 wt% SiC delivers the maximum tensile strength driven by efficient stress transfer that surpasses typical filler loadings. Notably, the incorporation of SiC not only enhances strength but also synergistically reduces water absorption advancement over conventional natural fiber bio-composites due to the hydrophobic nature of SiC and improved fiber-matrix interface. The study reveals a significant correlation between mechanical robustness and moisture resistance, particularly in unidirectionally aligned bio-composites, highlighting potential for applications in outdoor, automotive and agricultural environments. These findings extend current understanding by identifying an optimal balance of filler content and fiber orientation that simultaneously boosts mechanical performance and moisture durability, offering a practical pathway toward thermally and moisture-resistant natural fiber bio-composites with broad industrial relevance.

**Keywords**: Fiber orientation, hemp fiber reinforcement, mechanical properties, natural fiber reinforced bio-composites, Silicon Carbide (SiC) Filler, water resistance

In recent years, the development of sustainable materials has significant interest in natural fiber-reinforced composites (NFRCs), which offer environmentally friendly, renewable and cost-effective alternatives to synthetic composites. Among various natural fibers, hemp fibers are notably promising because of their high mechanical strength, availability and biodegradability (Lotfi *et al.,* 2021). A typical hemp field is shown in Fig.1, illustrating its extensive natural resource potential.

Despite these advantages, NFRCs face significant challenges, primarily their inherent high moisture absorption resulting from the hydrophilic nature of natural fibers. This leads to swelling, fiber-matrix debonding, reduced mechanical strength and decreased durability under humid conditions. Such issues limit their application in outdoor environments such as automotive parts, construction elements and agricultural tools where exposure to moisture is unavoidable. To mitigate water absorption and improve mechanical performance, various strategies have been explored, including chemical treatments

**Fig.1: A field of hemp plants, a source of natural fibers for bio-composites**

of fibers, matrix modifications and incorporation of hydrophobic fillers (Mohammed *et al.,* 2023).

Among these, adding inorganic fillers like silicon carbide (SiC) has shown promising results in enhancing both moisture resistance and mechanical strength. SiC, a ceramic with high thermal stability, hardness, chemical inertness and low water affinity that can serve as an effective reinforcing agent. When integrated into natural fiber bio-composites, SiC can create a physical barrier against water diffusion, improve load transfer and reinforce the polymer matrix, thereby increasing overall durability (Soltys *et al.,* 2023).

Fiber orientation also significantly influences composite properties by affecting stress distribution and load transfer. Common configurations include unidirectional (0°/90°), quasi-isotropic (e. g., 30°/60°) and cross-ply (45°/45°) arrangements. Optimizing fiber orientation along with filler content is crucial for tailoring composites to specific performance requirements in humid environments (Chen *et al.,* 2025).

This study investigates the synergistic effects of SiC filler content and fiber orientation on the water absorption and mechanical properties of hemp-epoxy bio-composites. The primary goal is to elucidate how these parameters influence composite performance and their implications for moisture-prone applications. Given hemp's high strength and durability relative to other natural fibers, these bio-composites hold promise for diverse applications including automotive interiors, packaging, construction materials and agricultural tools. Specifically, this research aims to address the following questions:

- How does varying SiC filler content (2%, 5% and 8% by weight) influence the tensile, flexural and impact strengths of hemp/epoxy bio-composites?
- How do different fiber orientations (unidirectional 0°/90°, quasi-isotropic 30°/60° and cross-ply 45°/45°) affect the mechanical performance and water absorption behavior?
- Is there a synergistic interaction between maximum filler content and optimal fiber orientation that enhances both mechanical strength and moisture resistance?

**Hemp Fiber**

After sisal, hemp is another leading natural fibers (NFs) reinforcement in composite materials, which is highly regarded for its environmental advantages and historical use (Islam *et al.,* 2024). Fig.2 illustrates the Hemp fiber and the extracted fibers. Of particular interest, hemp is one of the most environmentally sustainable fibers and has a long history of human utilization. As recorded in the Columbia History of the World, bits of hemp cloth, excavated from tombs dating to around 8,000 BC are among the oldest traces of human industry. It must be mentioned that hemp's flowering tops and leaves emit resin secretions with 9-tetrahydrocannabinol (THC), the psychoactive substance linked with marijuana and hashish. But industrial hemp is grown to be less than 0.2% THC which makes it unsuitable for use as a narcotic. Hemp is a Central Asian native annual crop that has been cultivated for more than 12,000 years. Hemp culture extended to Central Europe during the Iron Age and archaeological facts relating to its existence in the UK were found from 800 to 1000 AD. Hemp is currently mainly cultivated in the Central Asia, European Union, China and the Philippines. China alone produces almost half of the industrial hemp in the world, followed by substantial production in France, Chile and the Democratic People's Republic of Spain and Korea. The fibres placed in the stem of the plant hemp provide structural support to enable the plant to grow upright. These fibers impart significant strength and stiffness, making them highly valuable as reinforcement materials in bio-composites. The recent surge in hemp's utilization across various applications underscores its growing recognition as a versatile and sustainable resource. Hemp fiber-reinforced bio-composites research has shown huge promise for applications in sustainable engineering, especially within the automotive sector. Different characteristics of these bio-composites, including mechanical properties, interfacial

**Fig.2: Hemp Fiber and its Extracted Fibers**

characteristics and effects of varied treatments and additives have been studied (Deshmukh, 2022).

***Overview of the Extraction Process***

The extraction processes differ based on the source of the fiber. Bast fibers, which occur in the external covering of plant stems are generally extracted using retting, a process involving bacteria and moisture that relaxes the fibers so that they can be easily separated (Adeniyi *et al.,* 2019). Leaf fibers are either manually obtained by hand scraping or mechanically (Trivedi *et al.,* 2023). The properties and advantages of NFs vary significantly depending on their source. Leaf fibers such as from sisal, pineapple and banana are typically well known for their tensile strength compared to bast fibers (Ramesh *et al.,* 2017). Coconut fibers, which are derived from the coconut fruit's outer husk and shell, possess unique mechanical and thermal characteristics that set them aside from other NFs (Khatri *et al.,* 2023). Seed fibers like cotton and kapok are pulled out of the seed capsules or coverings and prized for their softness and particular use in textiles and insulation. Stem or bast fibers from agricultural residues such as sugarcane, corn, wheat, rice and barley straw are characterized by their strength, relatively low weight and structural thickness (Elfaleh *et al.,* 2023). Softwood and hardwood fibers from trees are, in turn, widely used blended with virgin or recycled fibers in pulp and paper applications as well as in composite production (Agarwal *et al.,* 2020; Jawaid *et al.,* 2011). Fig.3 shows the different methods of fiber extraction. Extraction of NFs is an important stage in the manufacture of bio-composite materials. Different methodologies are utilized based on plant variety and proposed use. Decortication is a common technique of fiber extraction from fibrous-stem crops like flax, hemp and other bast fibers. Decortication is done by removing the hard exterior bark to expose the inner fibers and can be performed mechanically or chemically. The extraction method plays an important role in determining the quality, performance and application suitability of the extracted fibers (Kumar *et al.,* 2019). Table 1 lists the advantages and disadvantages of various fiber extraction methods (Asmare *et al.,* 2024).

**Retting process:** Plant fibers are obtained by extracting, dissolving and degrading pectins, gums and other binding agents (Mohanty *et al.,* 2005). Retting is an important microbiological process used to loosen plant fibers from their stems. The process depends on the controlled exposure of plant stem to microorganisms like as bacteria and fungi which efficiently destroy pectic substances holding the fibers together. It may be conducted using different methods: open-air exposure, water immersion, or the use of certain chemical agents, each suited to different types of fibers and intended purposes (Ventorino *et al.,* 2024). The effectiveness of retting significantly affects the quality of the extracted fiber, which depends on the degradation of pectin and gummy substances to facilitate fiber release (Liu *et*

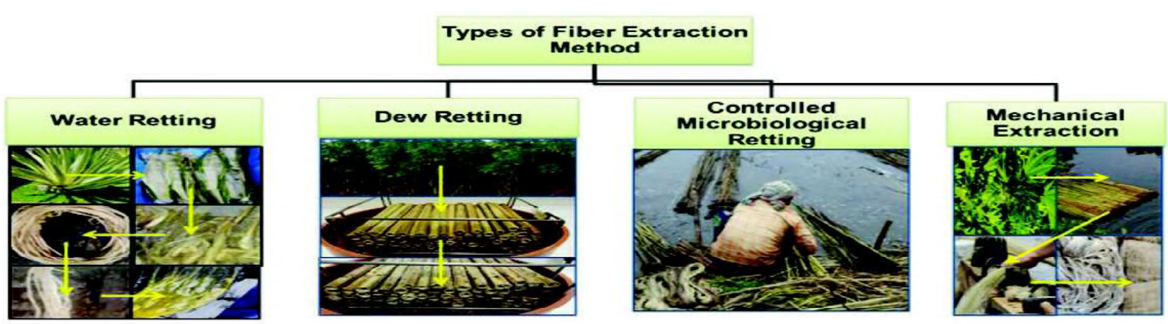


**Fig.3: Different methods of fiber extraction**

*al.,* 2016). Plant stems are generally dipped into flowing or still water for 14–21 days for retting. This process softens and dissolves pectin, facilitating the easy extraction of fibers (Hasan *et al.,* 2020). During retting, tissue rot begins in the stem and proceeds towards the peripheral regions, relaxing the fiber bundles. The fibers were manually separated following retting, washing and drying in preparation for industrial use. To remove the dark color, the fibers were soaked in tamarind water upto 15 to 20 min and then washed with clean water.

**Controlled Microbial Retting:** Controlled microbiological retting is a marked advancement over the traditional dew retting process, as it involves a more controlled and predictable mechanism of fiber liberation. The procedure relies on purposeful selection and cultivation of specific microbial strains, primarily bacteria and fungi, because of the production of pectinolytic enzymes, which provide for targeted destruction of the hemp, stem middle lamella (Lyu *et al.,* 2021). By carrying out the retting process under controlled conditions, such as in bioreactors, researchers can precisely control critical parameters such as temperature, humidity and nutrient availability, offering maximum microbial activity and minimizing variability in fiber quality (Law *et al.,* 2020). The controlled environment allows for real-time monitoring and optimization of the retting process, thus maximizing efficiency and minimizing reliance on variable environmental conditions, which are the major limitations of dew retting (Ribeiro *et al.,* 2015). This method uses certain enzymes to hydrolyze the non-fibrous portions of plants for fiber extraction. It is efficient for fibers like as kenaf and sisal yielding high-quality fibers with low impurities (Liu *et al.,* 2015). Ultimately, controlled microbiological retting provides a pathway for more sustainable and economically viable hemp fiber production through improved fiber quality, reduced environmental impact and optimal process efficiency.

**Mechanical Extraction:** Mechanical retting of hemp stem bast fibers provides a direct alternative to natural retting treatments, focusing on physical separation via mechanical action. The process usually involves crushing, breaking and scutching the dried stems to drive out the woody core and free the fibers (Fazita *et al.,* 2016). Processes such as decortication, involving rollers and beaters, are employed to extract fibers without microbial rot (Liu *et al.,* 2017). Although mechanical extraction is advantageous with respect to speed and absence of requirement for extended retting periods, it can yield coarser, more compact fibers and further processing is required to attain the desired fiber fineness (Law *et al.,* 2020). Also, the mechanical processing energy and risk of fiber damage are significant factors that necessitate careful optimization of the equipment and process conditions.

**Blow Molding:** This method is specifically efficient in the extraction of bamboo fibers. In this process, a screw extruder is utilized to thermally treat and soften the bamboo material and then it is pushed through a cooling chamber to generate continuous strands of fibers. The blow molding process has been successful in obtaining quality bamboo fibers with superior mechanical strength and consistency (Zimniewska, 2022).

**Table 1: Advantages and disadvantages of different extraction method with processing techniques (Asmare *et al.,* 2024)**

| Method of Extraction | Processing Technique | Advantages | disadvantages |
|---|---|---|---|
| Dew Retting | Bacteria, dew, fungi and sunlight break the cellular tissues and fibers are extracted | Cheap and suitable in areas of heavy dew and limited water resource. | It is weather-dependent. It results in poor-quality fiber. |
| Water Retting | Stem remains submerged in water and the pectionolytic community develops in water attacks the stalk | Achieve uniform and better quality fiber than dew retting | Anaerobic fermentation may taint the fibers. It involves high cost of operation |
| Controlled Micobiological Retting | Fiber is extracted by the aerobic and anaerobic bacteria that attack the stem | Reduction in retting time. Fiber quality is achieved | High operating cost |
| Mechanical Extraction | Hammermill or decorticator separates fibers | Produces very quickly large quantities of short fibers | Costly due to high-energy requirement |

Natural fiber bio-composites are attractive alternatives to synthetic fiber composites for environmental reasons. Nonetheless, their susceptibility to moisture remains a critical barrier. Several studies have focused on techniques to reduce water absorption and improve mechanical properties. The incorporation of fillers like silicon carbide (SiC) has been shown to improve stiffness, strength and thermal stability. SiC addition increased tensile strength and reduced water absorption in natural fiber composites (Suriya Prakash *et al.,* 2025).

## MATERIALS AND METHODS

### Materials

**Hemp Fibers:** Commercially available retted hemp fiber sheet was procured from Fiber Region supplier, Tamil Nadu and cleaned & sun-dried prior to processing.

**Epoxy Resin:** Bisphenol-A based epoxy resin (CY 230) was used as the matrix material.

**Hardener:** Isophorone diamine (HY 951) served as the hardener. Fig.4 shows the epoxy resin and hardener used.

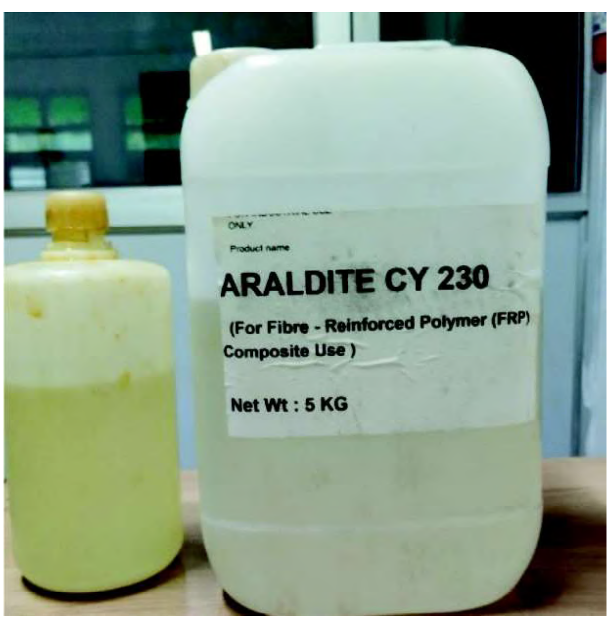


**Fig.4: Epoxy resin (ARALDITE CY 230) and hardener (HY 951) used in composite fabrication**

**Filler**: SiC powder as a filler material was weighed and used at different weight percentages (2 wt%, 5 wt% and 8 wt%)as shown in Fig.5. SiC is a semiconductor composed of silicon and carbon atoms, recognized for its outstanding physical and electronic characteristics. It exists in multiple crystalline structures, with the hexagonal (á-SiC) and cubic (â-SiC) forms being the most common. Owing to its high thermal conductivity, superior mechanical strength and excellent resistance to chemical degradation, SiC is widely employed in applications requiring reliable performance under extreme conditions, including temperatures above 1000 °C.

**Fig.5: Silicon Carbide**

**Other Materials:** Molds, release agents and curing facilities were used during composite fabrication.

### Preparation of Hemp fiber sheet

A hemp bidirectional fiber mat was used as the reinforcing material, as shown in Fig.6. To create the mold for fabricating the bio-composite sheets, clear perpex sheets measuring 300 mm in length, 300 mm in width and 10 mm in thickness were utilized. The edges of the mold were outlined using double-sided tape. To facilitate the removal of the finished bio-composite sheet from the mold, petroleum jelly was applied as a release agent. The fibers were cleaned with distilled water and dried under ambient conditions to remove dirt and moisture. To improve fiber-matrix adhesion, fibers were subjected to alkali treatment with 5% NaOH solution for 2 hours, followed by rinsing and drying. This process reduces fiber hydrophilicity and removes impurities.

**Fig.6: A prepared fiber mat (hemp fiber) for composite layering**

**Preparation of Filler-Resin Mixture**

- Silicon carbide powder was weighed precisely for the desired percentage relative to epoxy resin (i. e.2, 5 and 8 wt%).

- The SiC powder was mixed thoroughly with the epoxy resin using a glass rod to ensure homogeneous dispersion.

**Bio-composite Fabrication**

The bio-composites were fabricated using the hand lay-up technique, a versatile and widely used method for laboratory experimental work.

**Lamination Process**

The lamination process involved the following steps:

- **Mold Preparation:** The mold surface was coated with a release agent to prevent adhesion.
- **Layering:** A layer of epoxy resin with hardener was applied, followed by placement of the fiber mat.
- **Resin- filler application:** The resin-filler mixture was evenly applied onto the fiber mat (refer to Fig.8).
- **Stacking:** The process was repeated until reaching the desired thickness of 4 mm.
- **Curing:** The assembled laminate was cured at room temperature for 24 hours as shown in Fig.9.
- **Sealing:** A top coat of epoxy resin was applied to seal the surface.

**Fig.7: Initial application of epoxy resin during the hand lay-up process**

**Specimen Preparation**

After curing, specimens for tensile testing and water absorption were cut according to ASTM D3039 with dimensions of 150 mm length and 15 mm width. A tool used for cutting specimens is shown in Fig.10. After that, bio-composite sheets were cut into different orientations as per the experimental design:

- Unidirectional (0°/90°)
- Quasi-isotropic (30°/60°)
- Cross-ply (45°/45°)

**Testing Procedures**

***Tensile Testing***

The tensile testing was conducted in accordance with ASTM D3039 using a Servo Universal Testing Machine (Model No. AMT-20SC, Serial No.2533 and Capacity 200 kN), manufactured by A. S. I Sales Private Limited, New Delhi (ISO 9001:2008

**Fig.8: Spreading the resin-filler mixture onto the fiber mat during lamination**

**Fig.9: A cured hemp/SiC bio-composite specimen**


**Fig.10: A tool used for cutting composite specimens**

certified), at a crosshead speed of 2 mm/min. To ensure statistical reliability, a minimum of five specimens were tested for each configuration. The tensile strength of the specimens was determined from the maximum load at fracture. The experimental setup is illustrated in Fig.11, while Fig.12 shows the Servo Universal Testing Machine and a specimen mounted for testing in the Department of Farm Machinery and Power Engineering, G. B. Pant University of Agriculture and Technology, Pantnagar.

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### Water Absorption Test

Specimens were dried in a desiccator and weighed initially. Each specimen was then immersed in distilled water at room temperature for 7 days as shown in Fig.13 (a) and (b). Weights were recorded

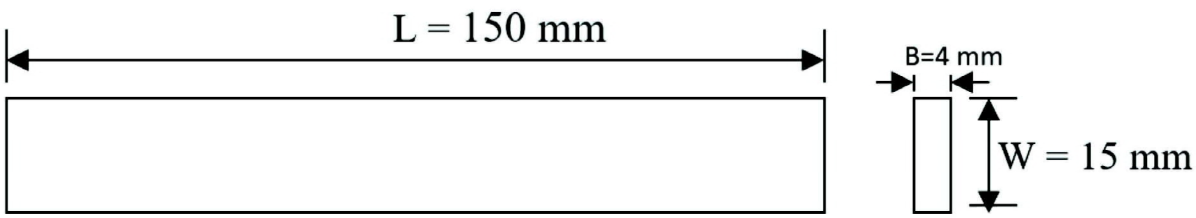


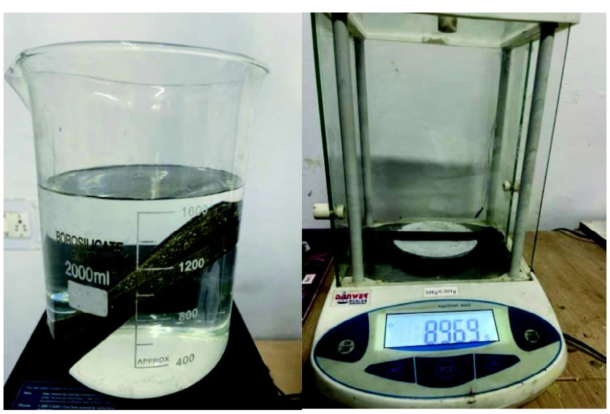

**Fig.11 : Tensile Specimen**

**Fig.12: Universal Testing Machine (UTM) used for tensile strength measurement**

after days to calculate water uptake using the formula:

Percentage of Water Absorption $= \frac{W_f - W_i}{W_i} \times 100$ - (i)

Post-immersion, specimens were surface-dried and weighed again to measure moisture retention.




**(a) (b)**

**Fig.13 (a) and (b): Samples immersed in distilled water and weight after immersion on .001g precision balance**

## RESULTS AND DISCUSSION

### Effect of Silicon Carbide Content on Mechanical Properties

The incorporation of SiC particles into the epoxy matrix was observed to influence the composite's tensile strength positively. As shown in Table 2 and Fig.14, the tensile strength increased with filler content up to 5 wt% beyond which a slight decline was observed at 8 wt%.

The enhancement in tensile strength up to 5% SiC is attributed to the effective load transfer between the filler and the matrix, as SiC particles act as stress concentrators that reinforce the matrix, distributing applied loads more evenly across the reinforcement network. The slight decline at 8% SiC indicates possible agglomeration of particles, leading to stress concentrations and potential defect sites, which hinder the load transfer process. Hemp fibers, possessing higher inherent strength, further augment these improvements, leading to higher overall tensile strength values compared to other natural fiber bio-composites.

### Effect of Fiber Orientation on Mechanical Properties

Fiber orientation was a critical factor influencing tensile performance. The orientation of fibers in composite materials plays a pivotal role in determining their mechanical properties, as numerous studies have demonstrated. Altering fiber orientation significantly influences tensile, flexural and impact strengths, affecting the composite's overall performance. For instance, (Rahman *et al.*, 2025) investigated Betel Nut (Areca palm) stem fiber-reinforced laminated polyester composites fabricated through the hand lay-up method. Their

**Table 2: Tensile Strength of Hemp/SiC Bio-composites at 0°/90°**

| SiC (%) | Tensile Strength (MPa) |
|---|---|
| 2% | 52.1 |
| 5% | 60.7 |
| 8% | 57.7 |

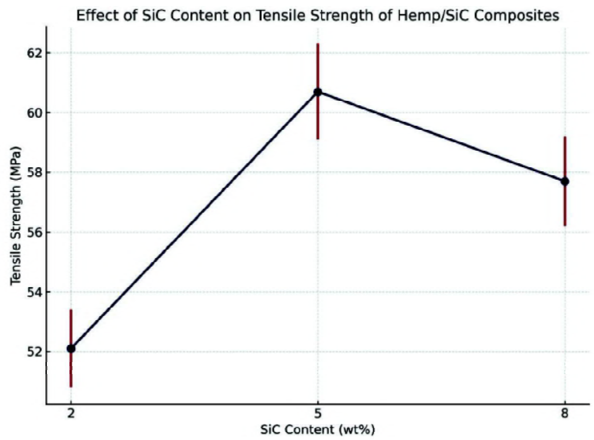



**Fig.14: Effect of SiC Content on Tensile Strength of Hemp/SiC Epoxy Bio-composites**

findings revealed that a 0°/90°/0° fiber orientation exhibited superior mechanical properties compared to a -45°/0°/45° orientation. The transverse alignment of fibers in this configuration enhanced tensile, flexural and impact strengths, indicating that aligned patterns are more effective in load distribution than inclined orientations. Similarly, Biswas *et al.* (2011) examined glass fiber-reinforced epoxy composites and discovered that a 30° fiber orientation yielded better mechanical performance, including higher microhardness, than other orientations such as 15°, 45° and 60° regardless of fiber content. This study emphasizes the critical influence of fiber orientation not only on mechanical behavior but also on factors like erosion resistance, further establishing that small changes in fiber angles can lead to notable differences in material performance.

The impact of fiber orientation was also evident in Zalacca Midrib fiber-reinforced HDPE composites, where (Lasikun *et al.,*2018) observed a gradual decline in mechanical strength as the fiber orientation shifted from 0° to 90°. This trend highlights the advantage of aligning fibers parallel to the load axis, which optimizes strength by maximizing the efficiency of stress transfer along the fiber direction. In another study, (Coura *et al.,*2020) reported that Carica papaya fiber-reinforced epoxy composites exhibited superior tensile, flexural and impact strengths when fibers were oriented at 0°, compared to orientations at 45° and 90°. The findings suggest that fiber alignment along the load direction significantly enhances load transfer efficiency, reinforcing the importance of strategic fiber placement in composite design. Furthermore, (Cordin *et al.,*2018) investigated polypropylene-lyocell composites and concluded that controlled fiber orientation, combined with proper wetting techniques, improved mechanical properties. However, the study also highlighted that imperfect fiber-matrix bonding limited the E-modulus, which was lower than theoretical predictions. This indicates that while fiber orientation is crucial, the interfacial adhesion between the fiber and matrix is equally vital for achieving the desired mechanical performance. Collectively, these studies underscore the profound effect of fiber orientation on the mechanical properties of bio-composite materials. Strategic fiber alignment enhances strength, stiffness and durability making composites more suitable for specific engineering applications. Nevertheless, achieving optimal performance also requires addressing other factors such as fiber-matrix bonding, highlighting the multifaceted nature of composite material design. These same principles of fiber orientation influencing mechanical properties apply to hemp/SiC bio-composites, resulting in high absolute mechanical property values across all orientations due to hemp's superior inherent strength.

## Effect of Silicon Carbide Content on Water Absorption

The water absorption percentage for hemp/SiC bio-composites is comparable to or even lowers than that of other natural fiber bio-composites. Hemp fibers

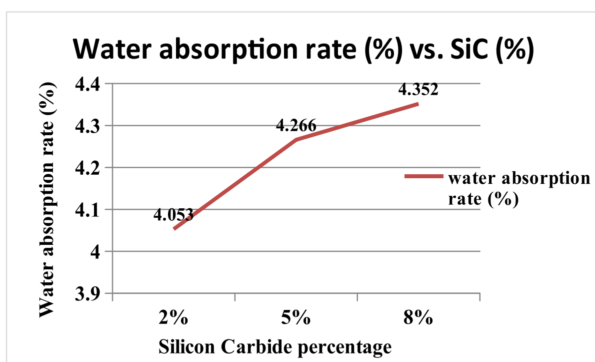



**Fig.15: Effect of SiC (%) on Water Absorption rate**

are known to exhibit improved moisture management and dimensional stability when wet. The hydrophobic nature of SiC filler which reduces moisture entering synergizes with the properties of hemp to further enhance the composite's resistance to water.

Fig.15 illustrates the water absorption rate (%) vs. SiC (%) for a composite material. It shows that as the Silicon Carbide (SiC) percentage increases from 2% to 8%, the water absorption rate consistently rises. Specifically, the rate increases from approximately 4.053% at 2% SiC to 4.352% at 8% SiC, indicating a direct correlation between higher SiC content and increased water absorption in this particular composite, same trend was followed by (Alamri and Low, 2012).

**Correlation between Mechanical Properties and Water Absorption**

The study reveals a relationship between the tensile strength and water absorption of the bio-composites. The addition of SiC further contributes to the mechanical reinforcement, improving composite durability. For hemp/SiC bio-composites, a strong correlation is observed, where the enhanced mechanical properties of hemp contribute to a more robust bio-composite that is less susceptible to degradation from moisture entering.

Improved interface quality reduces water entering and the addition of SiC contributes significantly to the mechanical reinforcement of the bio-composites, thereby enhancing their durability. When combined with hemp fibers, which inherently possess higher strength and better moisture resistance compared to other natural fibers, the overall durability and mechanical performance of the bio-composites are further improved. These synergistic effects enable the material to perform more reliably in challenging environments. The study primarily uses specific fiber orientations and SiC content levels and real-world applications may require optimization beyond these parameters.

The testing methods may not fully predict long-term durability, environmental effects, or aging behaviors.

**Limitations of this study**

The manufacturing process (hand lay-up) has limitations concerning scalability and uniformity. Despite the promising improvements observed with SiC addition and optimal fiber orientation, the current study is limited by the scope of fiber orientations and filler content examined. Additionally, the use of hand lay-up as the fabrication technique while suitable for laboratory investigation, presents challenges for large-scale and uniform production. Further research is necessary to evaluate the long-term durability and environmental stability of these composites under cyclic moisture exposure, UV radiation and temperature fluctuations.

**Correlation Between Water Absorption and Mechanical Properties**

The findings suggest a correlation where improved mechanical properties are accompanied by reduced water absorption, thus improving the bio-composite's suitability for moisture-exposed environments. For hemp/SiC bio-composites, this correlation is pronounced, with higher mechanical performance coupled with enhanced moisture resistance.

**Applications and Practical Implications**

The findings indicate that hemp/SiC bio-composites can be engineered to achieve improved moisture resistance and acceptable mechanical performance. Such materials are suitable for applications demanding moisture-resistant qualities, including automotive interiors, outdoor construction and agricultural equipment. Furthermore, the ability to tailor fiber orientation and filler content facilitates the design of bio-composites optimized for specific load-bearing and environmental conditions, promoting sustainability and durability.

Using renewable, biodegradable fibers like hemp also aligns with ecological objectives by reducing reliance on synthetic polymers. The demonstrated synergy between SiC filler content and fiber orientation paves the way for developing lightweight, high-strength, environmentally sustainable materials. These advancements support the broader goal of replacing synthetic composites in various demanding industries, including automotive, construction and agriculture.

## CONCLUSION

This research demonstrates that the mechanical and water absorption properties of hemp/SiC epoxy bio-composites are critically influenced by SiC filler content and fiber orientation. The optimal SiC loading of 5 wt% significantly enhances the tensile strength due to effective stress transfer and strong fiber-matrix interactions, outperforming higher filler contents where agglomeration reduces overall performance. Additionally, unidirectional fiber orientation (0°/90°) consistently yields superior mechanical properties, confirming the importance of strategic fiber alignment for load-bearing applications.

A notable novelty of this study is the observed synergistic effect between SiC filler and fiber orientation, which not only improves mechanical robustness but also reduces water absorption, a common limitation of natural fiber composites. The hydrophobic nature of SiC and enhanced interface quality contribute to moisture resistance, extending the potential utility of hemp-based bio-composites in outdoor and humid environments.

These findings underscore the feasibility of developing hemp/SiC bio-composites that combine high strength with moisture resistance, opening new avenues for their application in automotive interiors, outdoor construction and agricultural equipment. The correlation between mechanical integrity and water resistance established herein provides valuable insights for designing durable, sustainable and environmentally friendly composite materials.

In sum, this study advances the understanding of how microstructural factors—filler content and fiber orientation—can be optimized to produce natural fiber bio-composites with enhanced performance and durability, thus bridging the gap between laboratory research and real-world applications.

### Future Work

This research provides valuable theoretical insights into the microstructural mechanisms influencing the mechanical performance and moisture resistance of hemp/SiC bio-composites. It highlights the critical roles of fiber orientation and filler dispersion in stress transfer and durability, thereby informing the development of predictive models for bio-based composite behaviors. Building upon these findings, future investigations should focus on:

a) Exploring the long-term durability of hemp/SiC bio-composites under cyclic environmental conditions, including moisture exposure, UV radiation and temperature fluctuationsto assess their suitability for outdoor applications.
b) Investigating alternative fillers and surface treatments to further enhance interfacial bonding, mechanical properties and moisture resistance.
c) Developing advanced modeling techniques that incorporate microstructural parameters to predict composite performance more accurately under various environmental and loading conditions.

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