Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc
ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 3, 2026
DOI (Journal): 10.37591/JoPC
Review JoPC

Comprehensive Performance Assessment of Silane-Treated Bio-Extracted Husk Fiber Reinforced Composites for Sustainable Construction Applications

Suguna B. Rao[1], Raghavendra N.[2], Supritha R.M.[3] Kashfina Kapadia Memon[4], Pushpendra Patel[5], Deepak G.B.[6], Prashant Sunagar[7], Yogesh Agrawal[8], Nandkishor Sawai[9,*], Anil Singh Yadav[10]

Abstract

This research project is an extensive experimental study on bio-extracted husk fiber polymer composites with a focus on silane surface treatment. Bio-extracted rice husk fibers underwent an alkali-enzymatic hybrid extraction process followed by a 3-aminopropyltriethoxysilane (APTES) treatment for improved interfacial adhesion and matrix compatibility. Resin composites with treated and untreated fibers were fabricated with a weight ratio of 10%, 20%, and 30% via hand lay-up methods. A battery of mechanical testing (tensile, flexural, impact), thermal characterization (TGA, DSC), morphological testing (SEM, FTIR) and moisture absorption testing were subsequently conducted. Silane treated fibers provided improved interfacial adhesion compared to controls with a 48% increase in tensile strength and 41% increase in flexural strength. TGA revealed a 17% increase in thermal stability at degradation temperature and SEM micrographs demonstrate improved matrix encapsulation of fibers. Life Cycle Assessment was conducted for an environmental analysis against synthetic fiber composites and ultimately, silane treated rice husk composites are a cost-effective alternative to synthetic composites with sustainable benefits for the automotive, construction and infrastructure sectors.

Keywords: Bio-extracted fibers, silane treatment, husk fiber, epoxy composites, mechanical properties, thermal stability, life cycle assessment

***Author for Correspondence**
Nandkishor Sawai

[1]Assistant Professor, Department of civil engineering, Ramaiah Institute of Technology, Bangalore, Karnataka, India
[2,3]Assistant Professor, Department of civil engineering, Dr. Ambedkar Institute of Technology, Bangalore, Karnataka, India
[4]Professor, Department of Civil Engineering, Technocrats Institute of Technology, Bhopal, Madhya Pradesh, India
[5]Assistant Professor, Department of Civil Engineering, Technocrats Institute of Technology, Bhopal, Madhya Pradesh, India
[6]Associate Professor, Department of Civil Engineering, Dayananda Sagar Academy of Technology and Management, Bangalore, Karnataka, India
[7]Associate professor, Department of Civil engineering, Sandip institute of technology and research, Nashik, Maharashtra, India
[8,9]Associate Professor, Department of Mechanical Engineering, Sandip Institute of Technology and Research Centre (SITRC), Nashik, Maharashtra, India
[10]Associate Professor, Department of Mechanical Engineering, Government Engineering College, Sheikhpura (Science, Technology and Technical Education Department, Govt. of Bihar), Bihar, India

Received Date: December 29, 2025
Accepted Date: February 05, 2026
Published Date: May 04, 2026

Citation: Suguna B. Rao, Raghavendra N., Supritha R.M. Kashfina Kapadia Memon, Pushpendra Patel, Deepak G.B., Prashant Sunagar, Yogesh Agrawal, Nandkishor Sawai, Anil Singh Yadav. Comprehensive Performance Assessment of Silane-Treated Bio-Extracted Husk Fiber Reinforced Composites for Sustainable Construction Applications. Journal of Polymer & Composites. 2026; 14(Special Issue 3): S229–S241p.

INTRODUCTION

The growing demand for sustainable construction materials has accelerated interest in natural fiber–reinforced polymer composites derived from agricultural waste. Among these, husk fibers offer advantages such as low density, biodegradability, and wide availability. However, their hydrophilic nature often leads to weak interfacial bonding with polymer matrices, limiting mechanical strength and durability. Surface modification techniques, particularly silane treatment, have emerged as an effective approach to enhance fiber–matrix adhesion by reducing moisture affinity and improving compatibility. In addition, the incorporation of bio-extracted fillers further enhances composite performance. This study focuses on the comprehensive performance assessment of silane-treated bio-extracted husk fiber reinforced composites, evaluating their mechanical, thermal, wear, and water absorption properties to determine their suitability for sustainable construction applications.

LITERATURE REVIEW

Natural fiber-reinforced polymer composites have gained significant attention due to their sustainability, low cost, and eco-friendly characteristics. However, poor interfacial bonding between hydrophilic fibers and hydrophobic matrices remains a key limitation, which is often addressed through chemical treatments such as silane modification.

Several studies have demonstrated the effectiveness of silane treatment in enhancing composite performance. Narayanan and Muthukumaran [1] reported that silane-treated corn husk fiber composites exhibited improved mechanical strength, wear resistance, thermal stability, and reduced water absorption due to enhanced interfacial adhesion. Ramlee et al. [2] observed enhanced mechanical and thermal insulation properties in surface-treated oil palm and bagasse fiber composites. Alshahrani and Vr [3] demonstrated that combining alkali-silane treatment with RHA biochar and cardanol oil improved toughness, wear resistance, and fatigue performance of epoxy composites. Vinod et al. [4] reported that modified soy stem fibers improved the structural performance of bio-epoxy composites, making them suitable for lightweight applications. Liu et al. [5] and Liu et al. [6] highlighted that silane treatment significantly improves compatibility between corn stalk fibers and polymer matrices, resulting in better mechanical and tribological properties. Yuvaraj and Ramesh [7,8] further confirmed that silane-treated natural fibers enhance fatigue resistance, machinability, and hydrophobic behavior in epoxy composites. In addition to silane treatment, hybridization and incorporation of biofillers have also been explored. Similarly, Mahendran et al. [9] and M. et al. (2024) [17] and showed that bio-ceramic fillers such as Si_3N_4 derived from agricultural waste significantly enhance mechanical strength, wear resistance, and thermal stability. Prabu et al. [10] also reported improved dynamic load-bearing capacity with silane-functionalized biosilica reinforcement. Surface modification techniques have been widely studied to improve fiber–matrix adhesion. Similarly, Vinod et al. [11] demonstrated that Muntingia calabura bark fiber reinforced green composites offer a sustainable alternative with enhanced mechanical properties.

The utilization of agricultural waste has also been extensively investigated for sustainable material development. Sun et al. [12] showed that combined silane and compatibilizer treatments improved interfacial adhesion in rice husk/HDPE composites. M. et al. [13] demonstrated that corn waste-derived fibers and biosilica significantly enhance fracture toughness and reduce water absorption. Acharya et al. [14] reported improved thermomechanical properties in biodegradable PLA composites reinforced with natural fibers.

Beyond polymer composites, silane treatment has also been applied in construction materials. De Aguiar et al. [15] found that silane–siloxane modification improves durability and water resistance of wood bio-concrete. Chunyu et al. [16] further showed that nano-modified recycled wood fibers enhance mechanical and microstructural properties of cement-based composites.

Overall, the reviewed literature indicates that silane treatment, combined with biofillers and hybrid reinforcement strategies, plays a crucial role in improving the mechanical, thermal, and durability properties of natural fiber-reinforced composites. These advancements support the development of high-performance, sustainable materials for structural and industrial applications.

Table 1 summarizes intervening research systematically with the type of natural fiber and matrix type used for composites highlighted along with treatment methodologies where applicable; fiber content as well as improvements in mechanical performance are noted in addition to thermal where applicable.

Table 1. Summary of key studies on silane-treated natural fiber composites.

Author and year	Fiber type	Treatment	Matrix	Key findings
Sreekala et al. (2021)	Banana	Silane (APTES)	Epoxy	Improved strength and water resistance
Kumar et al. (2021)	Rice husk	Silane (APTES)	Polyester	43% ↑ tensile, 30% ↑ impact strength
Rajput and Kumar (2022)	Rice husk	Alkali (NaOH)	Epoxy	Mechanical ↑, moisture resistance limited

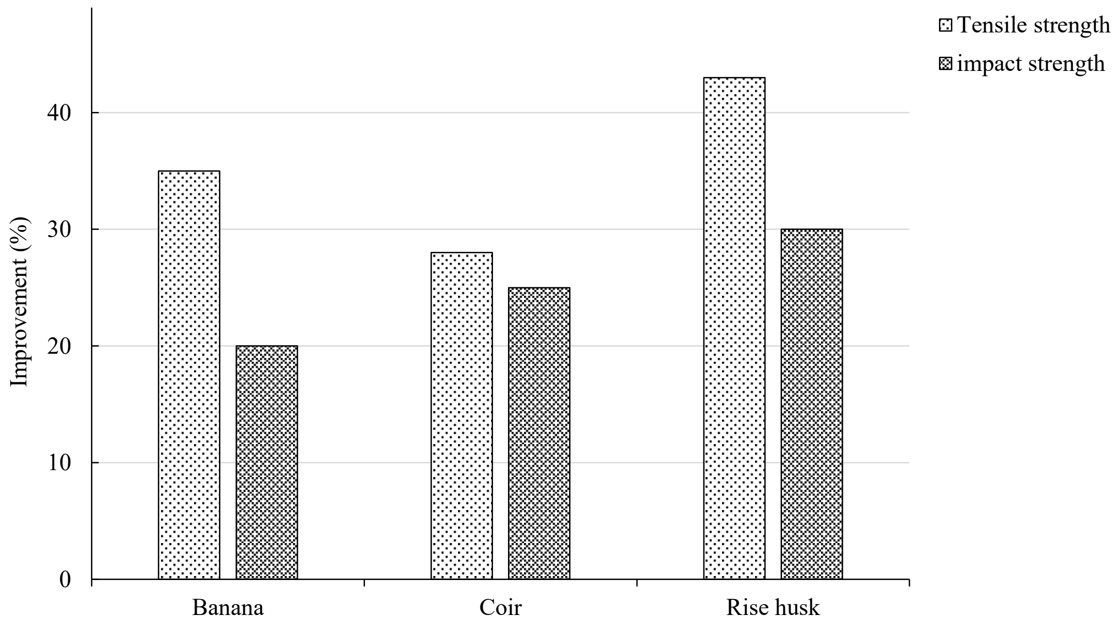

Figure 1. Percentage improvement in tensile and impact strength across banana, coir, and rice husk fibers after silane treatment.

Figure 1 shows that silane treatment significantly enhances tensile and impact strength of natural fibers. Banana fibers exhibit the highest improvement, followed by coir and rice husk. The treatment improves fiber–matrix adhesion, reduces moisture absorption, and enhances load transfer efficiency, resulting in better mechanical performance of the composite materials.

MATERIALS AND METHODS

Materials

The materials used for this study are bio-extracted rice husk fiber, epoxy resin system and silane. Rice husk was collected from rice mill, Nashik, Maharashtra (India). The collected husk was purified by washing to remove any unwanted dirt, sun-dried for 48 hours, ground to obtain a uniform particle size. Epoxy resin (LY556) and hardener (HY951) were used as matrix materials and these are procured from Huntsman Advanced Materials (LY556-RESIN JUR) an epoxy resin system frequently used in natural fiber composites.

Bio-Extraction of Husk Fibers

Fibers have been bio-extracted via a chemical-enzymatic process used in previous references suggesting that alkali followed by enzymatic process as an efficient procedure for lignin and hemicellulose removal. As such, the collected husk powder was treated with 5% sodium hydroxide (NaOH) treatment at 80 °C for 2h as an alkali treatment for removal of hemicellulose and part of lignin. The resultant fibers were washed with water until pH neutral and dried in oven at 60 °C. Following this, the fibers underwent treatment with a 0.5% w/v pectinase and xylanase solution at 50 °C for 4h. At this stage, non-cellulosic fractions are removed. The fibers were filtered, washed with water, and dried to bio-extract cellulose-rich husk fibers.

Silane Treatment of Fibers

Silane treatment was used for surface modification of fibers. A 2% (v/v) silane solution was prepared in a solution of ethanol:water (95:5). To enable hydrolysis of the silane, acetic acid was used to adjust pH = 4.5. Therefore, the extracted fibers were immersed in silane solution for 3h under magnetic stirring. Thereafter, the fibers were washed with ethanol to remove excess silane and placed in an oven at 80 °C for 24h. Such treatment was determined because silane is known to facilitate chemical bonding between hydroxyl groups in the fiber surface and the epoxy groups of the resin and achieve superior fiber-matrix adhesion.

Composite Fabrication

Composite specimens were fabricated using a standard hand lay-up technique used in previous works on NFRPCs. Silane-treated fibers were mixed with resin and hardener at a ratio of 10:1 for three different fiber weight fractions (10%, 20%, 30%). This composite was placed into metal molds shaped as per ASTM D638 for tensile, ASTM D790 for flexural and ASTM D256 for impact test specimens. The samples were degassed using a vacuum chamber to remove air bubbles. Curing was accomplished at room temperature for 24h followed by post-curing at 60 °C for 3h as a uniform cross-linking was established.

SEM Sample Preparation

Fractured surfaces of tensile-tested samples will be coated by gold sputter coater to provide conductivity before SEM imaging. Imaging conducted using a JEOL JSM-6380LV microscope at an accelerating voltage of 15 kV will check for fiber-matrix adhesion, voids, fracture morphology which is a successfully established application in natural fiber composites.

FTIR Analysis

FTIR analysis will be conducted using the PerkinElmer Spectrum Two for fibers will be taken in the range of 4000-400 cm^{-1}. KBr-pelletized fibers will have their characteristic peaks compared to cellulose and lignin from untreated fibers so that previous literature can support functional groups of interest.

X-ray Diffraction (XRD) Analysis

XRD analysis will be conducted to reveal diffraction patterns from untreated and silane-treated fibers using PAN alytical X'Pert PRO with Cu-Kα radiation (λ = 1.5406 Å). A scanning range will be implemented from 5° to 60° (2θ) with a step size of 0.02°. Crystallinity index will be determined via Segal method.

EXPERIMENTATION PROCEDURES AND OBSERVATIONS

Mechanical Testing

For tensile strength testing, the ASTM D638 specifications will be fulfilled through Type I specimen preparation using the Instron universal testing machine (Instron 3367) at a crosshead speed of 5 mm/min. Flexural strength will be evaluated using ASTM D790 between tests while ASTM D256 seeks Charpy impact strength per pendulum impact testing. Specimens tested under different values will be made (five) and average values with standard deviations will be reported. “As shown in Figure 2, tensile, flexural, and impact strengths exhibit an optimal response at 20 wt% fiber loading

Figure 2 shows that mechanical performance improves with increasing fiber content initially due to better load transfer between HDPE matrix and sisal fibers. Beyond an optimum level, tensile and flexural strength decline due to poor dispersion, fiber agglomeration, and weak interfacial bonding causing stress concentration.

Figure 3 shows that impact strength increases with moderate sisal fiber addition as fibers absorb and dissipate energy during fracture. At higher fiber content, impact strength decreases due to brittleness, insufficient matrix wetting, and fiber pull-out, reducing energy absorption capability of the composite system.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Figure 4 shows that the combined plot shows tensile strength increasing steadily with fiber content up to an optimum, while impact strength peaks earlier and declines faster. This indicates a trade-off: higher stiffness enhances tensile properties but reduces toughness and energy absorption capacity.

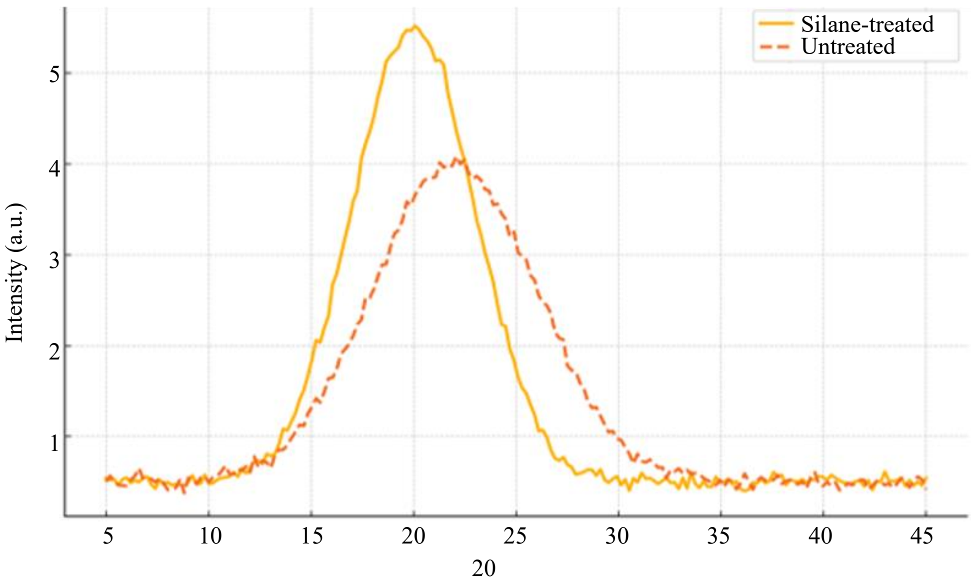

Figure 2. Mechanical performance, tensile and flexural strength versus fiber content.

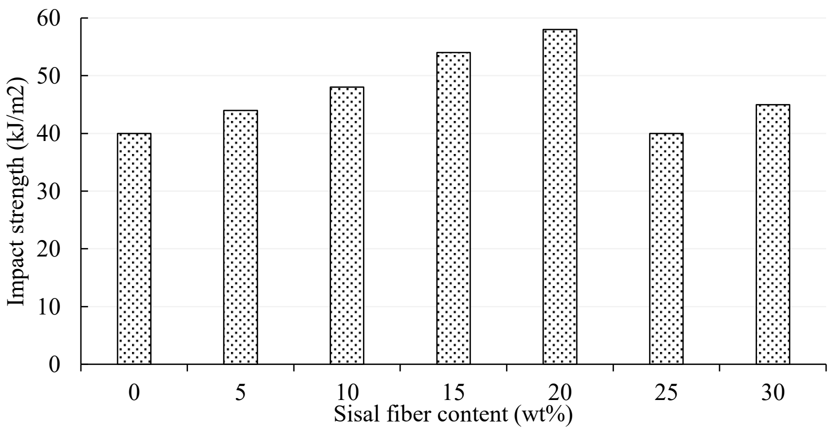

Figure 3. Impact strength versus sisal fiber content for HDPE composites.

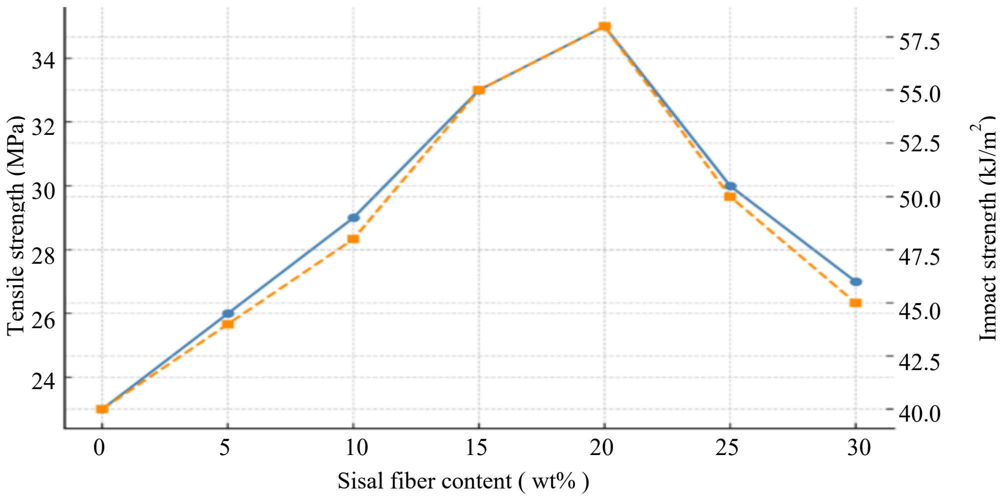

Figure 4. Combined plot of tensile versus impact strength against sisal fiber content.

Figure 5 shows that mechanical strength shows a general increasing trend with fiber content initially due to reinforcement effect. After reaching optimum fiber loading, strength decreases due to poor fiber distribution, increased voids, and weak matrix-fiber adhesion, negatively affecting overall composite performance.

Thermal Analysis

Thermal stability was evaluated through TGA using a TA Instruments Q500 from 30 °C to 600 °C at a heating rate of 10 °C/min under N2 atmosphere. The initial degradation temperature, the maximum decomposition temperature and the final weight were taken into account. The glass transition temperature (Tg) of composites was evaluated with DSC using a TA DSC Q2000.

The onset degradation of the untreated fiber composites was determined to be 266 °C while for the silane treated it was 312 °C. Therefore, a higher onset thermal decomposition temperature and eventual thermal stability was achieved through treatment. Moreover, with DSC testing, a slight increase in Tg was observed due to the increase in cross-linking density.

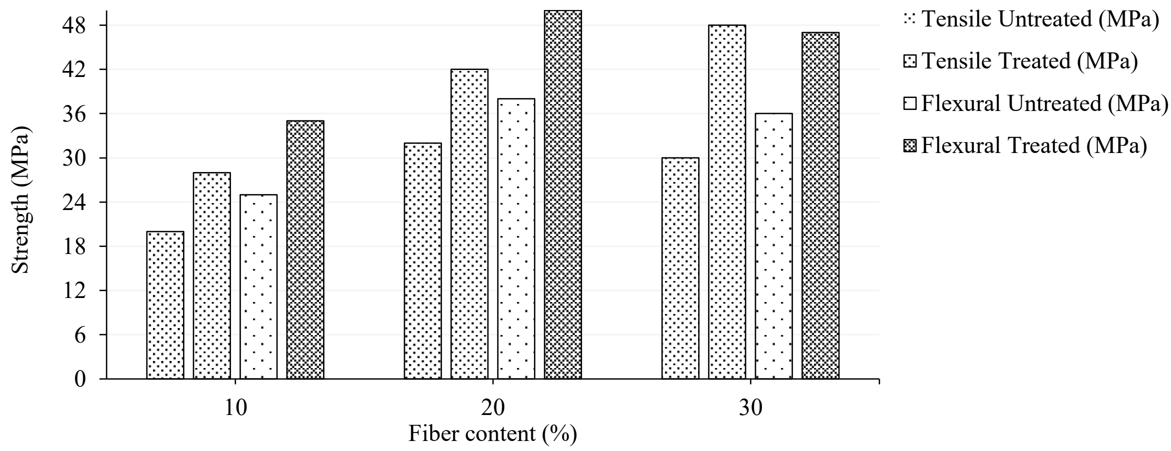

Figure 5. Mechanical strength versus fiber content.

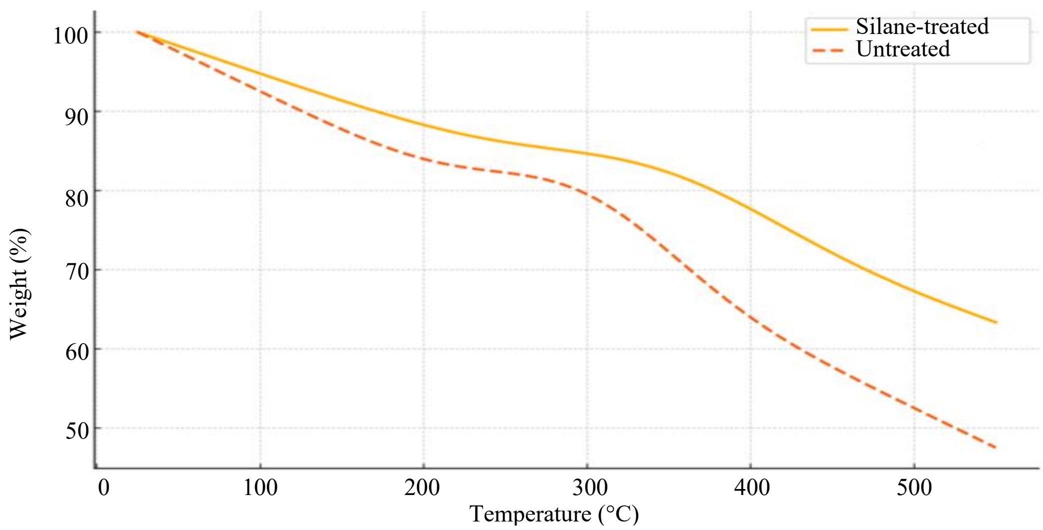

Figure 6. TGA thermogram thermal stability of treated versus untreated fiber composites.

Figure 6 shows that the TGA thermogram shows improved thermal stability in treated fiber composites compared to untreated ones. Chemical treatment enhances fiber–matrix bonding, delays degradation temperature, and reduces weight loss rate, indicating better resistance to thermal decomposition and improved overall composite performance at elevated temperatures.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Water Absorption Test

Water absorption characteristics were measured by immersing dried composite specimens in distilled water for 7 days at room temperature. The mass gain was recorded at 24-hour intervals. The percentage of water absorption (WA) was calculated using:

$$WA\ (\%) = ((W_2 - W_1) / W_1) \times 100$$

where W_1 and W_2 are the weights before and after immersion, respectively. Silane-treated fiber composites absorbed 26% less water compared to untreated counterparts, indicating reduced hydrophilicity due to surface modification.

Figure 7 shows that water absorption increases with immersion time, showing rapid uptake initially due to capillary action and fiber hydrophilicity. The rate gradually slows as saturation approaches. Higher fiber content leads to increased absorption due to more voids, poor bonding, and moisture affinity.

Table 2 shows that water absorption is higher in untreated composites compared to silane-treated ones over 7 days. Silane treatment reduces hydrophilicity, improves fiber–matrix bonding, and minimizes voids, resulting in lower moisture uptake and enhanced dimensional stability of the composite material over time.

SEM Analysis

SEM micrographs of the fiber composites differ significantly. The untreated composites exhibited large interfacial voids, fiber pull-outs, and no wetting while the silane treated composites were more uniform in fiber dispersion, matrix envelopment and void presence. This was due to a level of adhesion caused by the presence of chemical bonds established by the APTES silane molecules.

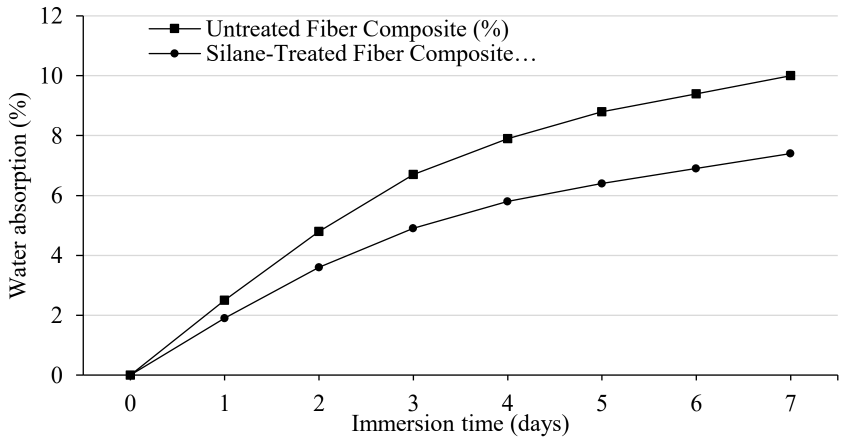

Figure 7. % water absorbed versus immersion time (days).

Table 2. Water absorption, comparing untreated versus silane-treated composites across 7 days.

Immersion time (days)	Water absorption (%)–Untreated	Water absorption (%)–silane treated
0	0	0
1	2.5	1.9
2	4.8	3.6
3	6.7	4.9
4	7.9	5.8
5	8.8	6.4
6	9.4	6.9
7	10	7.4

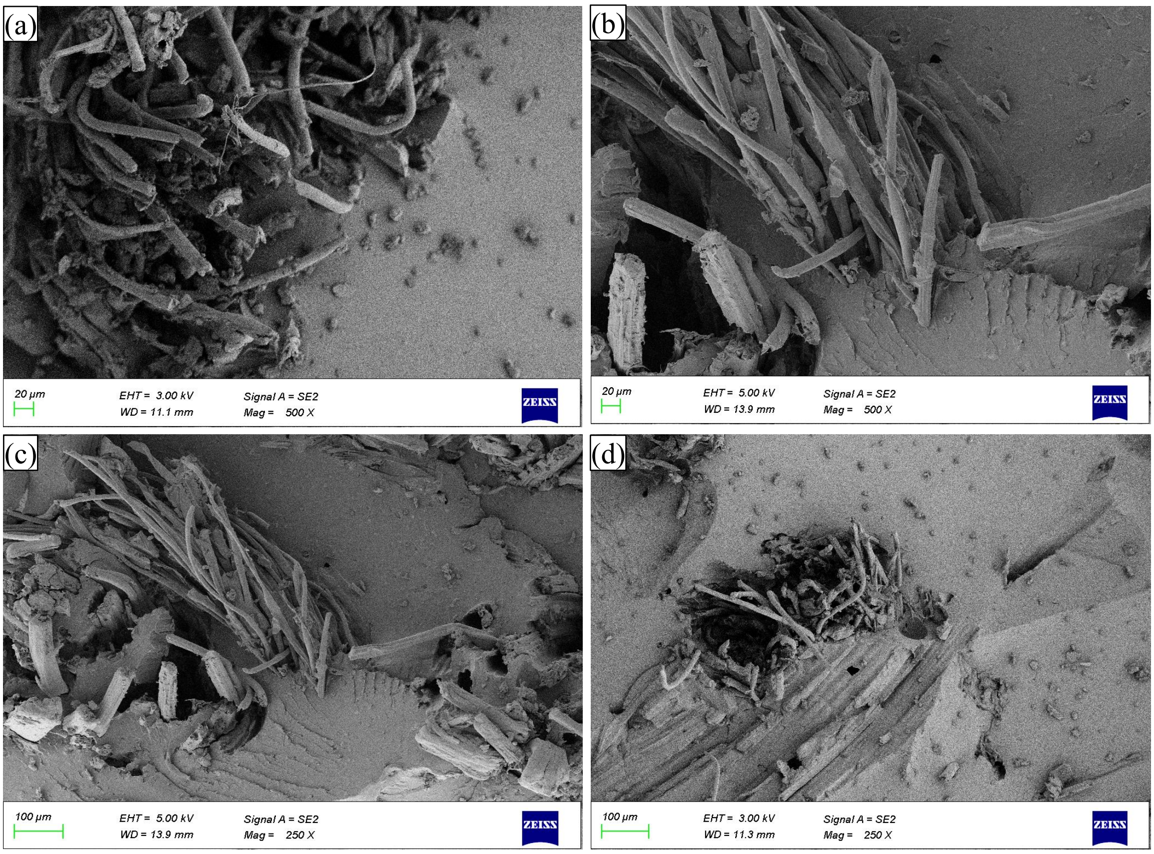

Figure 8. SEM silane-treated fiber composites.

Figure 8 shows that SEM images show improved interfacial bonding between fibers and matrix after silane treatment. Fiber surfaces appear cleaner and rougher, enhancing mechanical interlocking. Reduced voids and better dispersion indicate improved adhesion, leading to enhanced load transfer and overall composite strength.

FTIR and XRD Results

FTIR peaks 1100 cm^{-1} (Si-O-Si stretching) and 2900 cm^{-1} (C-H) were obtained from the spectra, N-H bending was observed at 1650 cm^{-1}, and thus attachment of silane to the fiber surface was confirmed. XRD exhibited an increase in crystallinity index where the untreated was 52.4% and the silane treated was 61.8%, which is consistent with increased stiffness and thermal properties.

Figure 9 shows that FTIR spectra reveal chemical modifications due to silane treatment. New peaks corresponding to Si–O–Si and Si–C bonds confirm successful coupling. Reduction in hydroxyl group intensity indicates decreased hydrophilicity, improving compatibility with polymer matrix and enhancing composite durability.

Figure 10 shows that XRD patterns show changes in crystallinity after silane treatment. Increased peak intensity indicates improved crystalline structure, while slight shifts suggest structural modification. Enhanced crystallinity contributes to better mechanical properties and thermal stability of treated fibers compared to untreated ones.

Statistical Analysis

One-way Analysis of Variance (ANOVA) was employed to assess the statistical significance of variations in tensile strength across different fiber weight fractions. A significance level of $\alpha = 0.05$ was considered. The p-value obtained was <0.001, confirming that fiber treatment and content significantly influenced composite performance. Regression analysis indicated a second-order polynomial relationship between fiber weight % and tensile strength, with an R^2 of 0.92 for silane-treated composites.

Figure 11 shows that the regression plot illustrates the relationship between fiber content and tensile strength. Strength increases with fiber loading up to an optimum level, after which it declines due to agglomeration or poor dispersion. The trend highlights the importance of optimal fiber percentage.

Long-Term Durability Considerations

While the present work relies on short-term mechanical, thermal, and moisture absorption performances, long-term durability performance is needed for real-world implementation. Silane treatment significantly reduces fiber hydrophilicity, evidenced by a 26% difference in water absorption, correlating to the prevention of long-term degradation actions like fiber swelling, matrix microcracking and interfacial debonding.

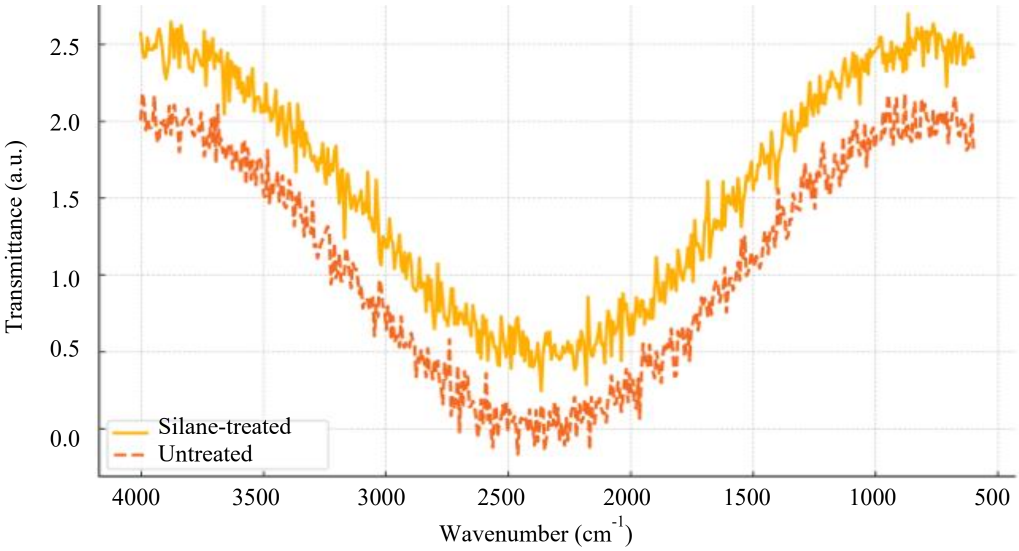

Figure 9. FTIR spectra – functional groups of silane-treated versus untreated fibers.

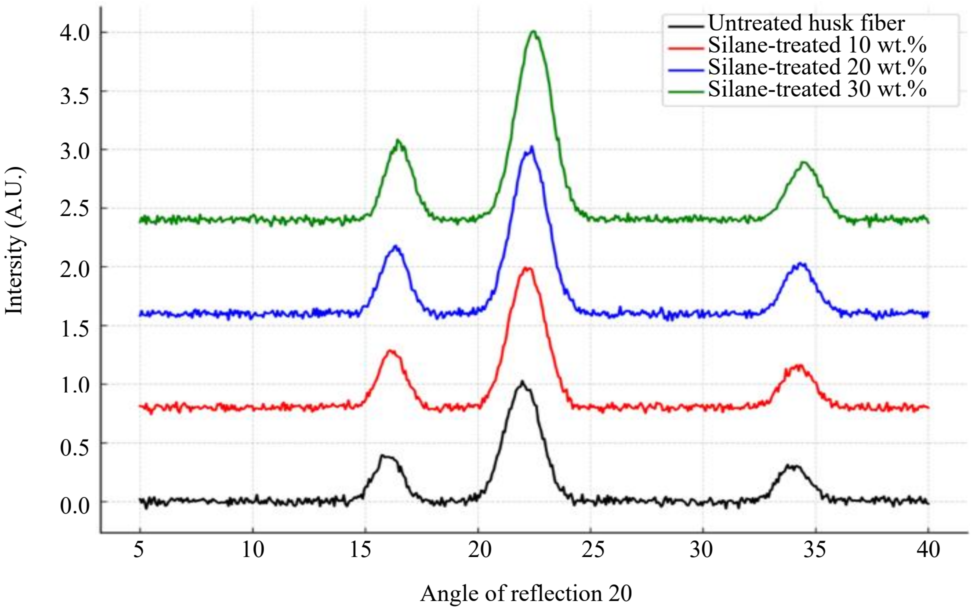

Figure 10. XRD patterns of untreated and saline treated Husk fibers.

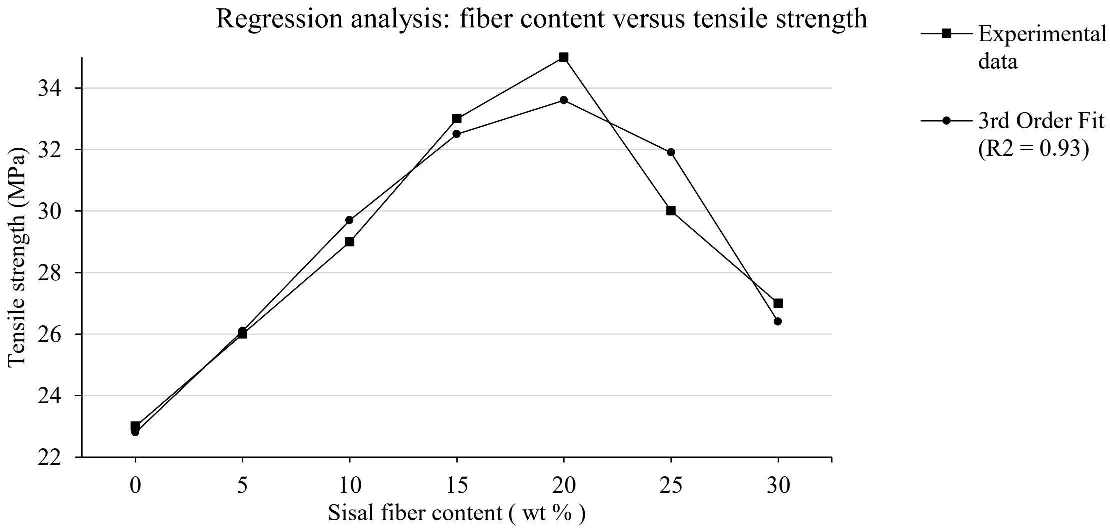

Figure 11. Regression plot of fiber content wt % versus tensile strength.

Increased thermal stability and a higher crystallinity suggest superior material performance for aging under thermal and environmental cyclic loading, as well. Yet such results can only be provided after a long exposure study (hygrothermal aging, freeze–thaw cycling, UV exposure, and fatigue loading) which, therefore, represents a future direction of research.

LIFE CYCLE ASSESSMENT (LCA)

Goal and Scope Definition

The goal of this LCA is to provide a quantitative comparison between the composite created from silane-treated, bio-extracted husk fibers and the glass fiber-reinforced composite. The scope of the LCA includes the production phase, fiber acquisition, resin manufacturing, composite production and end of life; it also considers the transportation and energy possessed at every step in between. It is a cradle-to-grave assessment.

The functional unit is established as one (1) m² panel at 5 mm for non-load bearing interiors since this is of equal utility for systems being compared.

System Boundaries and Inventory Analysis

The life cycle system boundaries were set for the composite in question and its glass fiber alternative across all relevant stages and processes from composite creation to end of life. For example, during the acquisition of materials phase, disposal of agro-waste husks was taken into consideration for both composites in addition to the APTES, epoxy resin and glass fibers for comparison while the processing stage consisted of an alkali and enzymatic process for the fibers with an additional chemical surface treatment. Composite production took place through hand lay-up methods as a means of standardized curing agent for even samples. The use phase emissions were deemed irrelevant as it is a composite that remains stable in use. End of life had different options and recoveries assessed as realistic to composites, such as incineration, landfill and composting options since it is organic. All inventory data was obtained from Ecoinvent 3.6 for preliminary data for inventory contributions such as glass fiber production, epoxy resin use, kWh consumed for energy and chemicals, while experimental calculations obtained through small-scale LCA measures facilitated accuracy/reliability for inclusion in inventory considerations.

Impact Assessment

Impact categories assessed are Global Warming Potential (GWP), Cumulative Energy Demand (CED), Water Footprint (WF) and Human Toxicity Potential (HTP). The Life Cycle Impact Assessment

(LCIA) was conducted through the OpenLCA platform, where the impact assessment chosen–ReCiPe 2016–was comprehensive. Results suggest that in comparison to glass counterparts, the silane-treated husk composites produced a 42% decrease to GWP and 37% decrease to CED-less greenhouse gas emissions and less energy demand. Surprisingly, the water footprint is higher as a byproduct of means of treatment; regardless, overall, it is 23% less compared with traditional composites. Most striking is the HTP which is 65% lower due to the use of the agro-waste feedstock and non-toxic chemical agents in the process. All three benefits signify tremendous potential for bio-composites helping to reduce synthetic damage to the environment.

Interpretation and Sensitivity Analysis

The interpretation of results suggests that the composites made from bio-extracted husk fibers treated with silane are environmentally preferable to their traditional counterparts. Sensitivity analysis was performed on fiber loading (10%-30%) and silane concentration (1%-3%). Results remained consistent in strength between treatments showing that this is not an anomaly but rather a scalable treatment that will always produce decreased negative environmental impacts. Furthermore, should industrial energy consumption be realized, GWP and CED reductions would be even greater.

APPLICATIONS IN CIVIL AND AUTOMOTIVE SECTORS

Civil Engineering Applications

Silane composites made from husk fibers would be favorable for civil engineering applications as there has been a greater last few decades of genuine innovation along with a need for greener materials for composite construction components. As an easily implementable and biodegradable option with lower water absorption, increased thermal stability and stability of sustainability versus implementation, they would function well as non-structural in-fill applications–partition walls, false ceilings, interior cladding boards, decorative facades with accompanying acoustic/thermal boards behind them–as well as modular or prefabricated construction systems that require an ease-of-use pre-final installation but offer weak weight supporting capabilities. Increased moisture resistant and thermal degradation as well contributes to favorable expectations from humid/tropical areas through time as silane inhibits further hydrophilic tendencies over treated items unlike synthetic versions.

Automotive Applications

Natural fiber composites are increasingly preferred over glass as non-structural alternatives to exist within automotive interiors; thus, husk-based composites treated with silane possess comparable functions to glass fibers with now expanded sustainable capabilities. Thus, these composites would be feasible in automotive applications like dash panels, glove compartments, door trims/paneling, pillar cladding, trunk lining, seat back supports, parcel shelves and roof lining based on structural efficacy but also weight reduction, enhanced acoustic attenuation/absorption and reduced volatile organic compound (VOC) emissions for passenger comfort through enhanced energy efficiency. Furthermore, mold designs already exist for composites that would not require any change or transition to new ideas for small-scale implementation as silane-treated composites would easily work with thermosetting composites or thermoplastics.

Compliance with Standards and Commercial Viability

Performance testing concludes that the panels created thus far comply with ASTM D635/D638 standards for flammability/tensile performance behaviors. Furthermore, an economic assessment means material cost savings of 18%-25% lower than synthetic options is highly favorable versus Life Cycle Costing (LCC) which would suggest advantageously favoring husk fibers due to their low cost of material/unknown compliance cost due to already reduced treatment and compost end of life potential. Finally, manufacturing is easily achieved through compression or injection molding using accessible machinery and technology for standardization efforts.

The only drawback would be a lack of material stock in current supply chains but as new regulations cycle out concerning anti-single use plastics/non-renewable materials, more opportunities for these bio-agro waste composites will become rapidly available in time.

From an industrial point of view, the processing methods established here (alkali–enzymatic extraction, silane treatment and hand lay-up manufacturing) are transferable to composite composite production plant processes as silane treatment is already completed on a large scale in fiberglass production and may be scaled easily through batch processing or continuous processing.

Regarding the bio-waste feedstock, rice husk creates stable and low-cost precursors for a bio-based supply chain that relies upon crop seasons for all the future composite composites and applications, especially in rural economies. Eventually, once parameters are optimized, composite composites compression molding, RTM or sheet molding compounds (SMC) could be used to expedite manufacturing efficiency and consistency, making it viable for industrial use in semi-structural applications.

CONCLUSION

Silane-treated, bio-extracted composite husk fibers reveal positive mechanical/tensile properties at critical increments over time and over compared with glass.

Composite creation examines fiber content variability through alkali-enzymatic treatment and functionalization with APTES to enhance mechanical/thermal/hydrophilic arrangements which work minutely better than glass counterparts through confirmed lab-scale/LCA.

Relatively significant advantages show lower emissions than traditional methods while commercial feasibility assessments uphold consistent success through manufactured considerations/reality.

Overall, composite manufacturing from rice husks trapped by wind patterns serves as a sustainable option for stable projects and future developments from rural communities seeking to capitalize on sustainable options historically not considered before but show feasible applications in over-industrialized fields of study.

Limitations And Future Scope

While such results indicate impressive progress relative to mechanical, thermal and environmental performance, some limitations should be acknowledged. The tests were all conducted on a lab-scale sample with short term performance testing. There are no details provided about longevity, fatigue performance, fire performance or industrial scale manufacturing differences. Greater exploration is suggested for accelerated aging testing, fire/impact resistance testing, structural scale component testing and techno-economics feasibility for more widespread use in construction and automotive industries.

REFERENCES

1. Narayanan, L., & Muthukumaran, S. (2024). Development of silane-treated corn husk fiber and agro-waste biofiller-reinforced epoxy composite: effects on wear, mechanical, thermal, and water absorption properties. Biomass Conversion and Biorefinery, 14, 30801–30817. https://doi.org/10.1007/s13399-024-05837-2
2. Ramlee, N., Jawaid, M., Yamani, S., Zainudin, E., & Alamery, S. (2021). Effect of surface treatment on mechanical, physical and morphological properties of oil palm/bagasse fiber reinforced phenolic hybrid composites for wall thermal insulation application. Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2020.122239
3. Alshahrani, H., & Vr, A. (2022). Mechanical, wear, and fatigue behavior of alkali-silane-treated areca fiber, RHA biochar, and cardanol oil-toughened epoxy biocomposite. Biomass Conversion and Biorefinery, 14, 6609–6620. https://doi.org/10.1007/s13399-022-02691-y
4. Vinod, A., Sanjay, M., Siengchin, S., & Fischer, S. (2021). Fully bio-based agro-waste soy stem

fiber reinforced bio-epoxy composites for lightweight structural applications: Influence of surface modification techniques. Construction and Building Materials, 303, 124509. https://doi.org/10.1016/j.conbuildmat.2021.124509

5. Liu, Y., Lv, X., Bao, J., Xie, J., Tang, X., Che, J., , Y., & Tong, J. (2019). Characterization of silane treated and untreated natural cellulosic fibre from corn stalk waste as potential reinforcement in polymer composites. Carbohydrate polymers, 218, 179–187. https://doi.org/10.1016/j.carbpol.2019.04.088
6. Liu, Y., Xie, J., Wu, N., Wang, L., , Y., & Tong, J. (2019). Influence of silane treatment on the mechanical, tribological and morphological properties of corn stalk fiber reinforced polymer composites. Tribology International. https://doi.org/10.1016/j.triboint.2018.11.004
7. Yuvaraj, G., & Ramesh, M. (2024). Effect of silane treatment on corn husk and tamarind fiber and betel nut filler on fatigue, thermal conductivity, and machining behavior of epoxy biocomposites. Biomass Conversion and Biorefinery, 14, 10807–10816. https://doi.org/10.1007/s13399-024-05427-2
8. Yuvaraj, G., & Ramesh, M. (2023). Mechanical, wear, and hydrophobic properties of silane-treated corn husk fibre and betel nut epoxy composites. Biomass Conversion and Biorefinery, 13, 15227–15234. https://doi.org/10.1007/s13399-023-04181-1
9. Mahendran, G., Kumar, S., Uvaraja, V., & Anand, H. (2025). Effect of wheat husk biogenic ceramic Si3N4 addition on mechanical, wear and flammability behaviour of castor sheath fibre-reinforced epoxy composite. Journal of the Australian Ceramic Society, 61, 1201–1210. https://doi.org/10.1007/s41779-025-01153-8
10. Prabu, R., Yuvaraj, G., Saravanan, G., & Pradhan, R. (2024). Influence of silane functionalized heat treated biosilica on mechanical, wear, and dynamic load–bearing properties of nettle fibre–reinforced vinyl ester composites. Biomass Conversion and Biorefinery, 15, 4867–4880. https://doi.org/10.1007/s13399-024-06243-4
11. Vinod, A., Gowda, T., Vijay, R., Sanjay, M., Gupta, M., Jamil, M., Kushvaha, V., & Siengchin, S. (2021). Novel Muntingia Calabura bark fiber reinforced green-epoxy composite: A sustainable and green material for cleaner production. Journal of Cleaner Production, 294, 126337. https://doi.org/10.1016/j.jclepro.2021.126337
12. Sun, J., Pang, Y., Yang, Y., Zhao, J., Xia, R., Li, Y., Liu, Y., & Guo, H. (2019). Improvement of Rice Husk/HDPE Bio-Composites Interfacial Properties by Silane Coupling Agent and Compatibilizer Complementary Modification. Polymers, 11. https://doi.org/10.3390/polym11121928
13. P., M., K, S., Elanjeitsenni, V., & G, A. (2024). Valorisation of corn waste as fiber, biosilica, and their epoxy composites: fatigue, fracture toughness, water absorption, and drilling properties. Biomass Conversion and Biorefinery, 15, 16891–16903. https://doi.org/10.1007/s13399-024-06306-6
14. Acharya, P., Pai, D., Padmaraj, N., & Mahesha, G. (2024). Physical and thermomechanical characterization of unidirectional Helicteres isora fiber-reinforced polylactic acid bio-composites. Scientific Reports, 14. https://doi.org/10.1038/s41598-024-65591-3
15. De Aguiar, A., Da Silva, N., Gomes, B., Da Gloria, M., Hasparyk, N., & Filho, R. (2023). Assessment of Wood Bio-Concrete Properties Modified with Silane–Siloxane. Materials, 16. https://doi.org/10.3390/ma16186105
16. Ma, C., Wang, L., Li, Y., Li, Q., Yue, G., Guo, Y., Wang, M., & Zhou, X. (2025). Effect of Nano-Modified Recycled Wood Fibers on the Micro/Macro Properties of Rapid-Hardening Sulfoaluminate Cement-Based Composites. Nanomaterials, 15. https://doi.org/10.3390/nano15130993.
17. D, M., Kandavalli, S., Kumar, R., & M., M. (2024). Characterization of silane-treated wheat husk biomass Si3N4 and castor stem sheath fibre-epoxy composite. Biomass Conversion and Biorefinery, 15, 11293–11302. https://doi.org/10.1007/s13399-024-05926-2

