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Investigating Environmental Degradation of Banana-Sisal Epoxy Composites: Physical and Thermal Properties

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INFO ARTIKEL

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A B S T R A K

Studi ini mengevaluasi degradasi lingkungan komposit epoksi pisang-sisal, dengan fokus pada sifat fisik dan termalnya setelah terpapar kelembapan, radiasi ultraviolet (UV), dan penuaan termal. Komposit yang diolah dengan dan tanpa alkali dibuat dan diuji untuk penyerapan kelembapan, kekuatan tarik, kekuatan lentur, stabilitas termogravimetri, dan ketahanan UV. Hasil menunjukkan bahwa komposit yang diolah dengan alkali menyerap kelembapan yang jauh lebih sedikit (1,26%) daripada komposit yang tidak diolah (2,62%) setelah 120 jam perendaman dalam air. Komposit yang diolah mempertahankan 87,6% dari kekuatan tarik awal dan 92% dari kekuatan lenturnya, menunjukkan kinerja mekanis yang unggul dibandingkan dengan komposit yang tidak diolah. Analisis termogravimetri (TGA) menunjukkan suhu degradasi awal yang lebih tinggi (Tonset = 275 °C) untuk komposit yang diolah dibandingkan dengan komposit yang tidak diolah (Tonset = 255 °C) dan retensi massa residu yang lebih baik pada 600 °C. Kalorimetri pemindaian diferensial (DSC) mengungkapkan suhu transisi gelas yang lebih tinggi (Tg = 93°C) untuk komposit yang diolah, yang menunjukkan peningkatan stabilitas termal. Setelah 100 jam paparan UV, komposit yang diolah mempertahankan 82% dari kekuatan tariknya, dibandingkan dengan 68% untuk komposit yang tidak diolah. Temuan ini menunjukkan bahwa komposit epoksi pisang-sisal yang diolah dengan alkali memiliki ketahanan yang lebih baik terhadap degradasi lingkungan, sehingga layak untuk digunakan dalam industri konstruksi, otomotif, dan kelautan. Penelitian di masa mendatang harus bertujuan untuk mengoptimalkan pengolahan serat, mengembangkan komposit hibrida dan nano, serta melakukan penilaian ketahanan dan keberlanjutan jangka panjang.

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A B S T R A C T

This study evaluates the environmental degradation of banana-sisal epoxy composites, focusing on their physical and thermal properties after exposure to moisture, ultraviolet (UV) radiation, and thermal aging. Alkali-treated and untreated composites were fabricated and tested for moisture absorption, tensile strength, flexural strength, thermogravimetric stability, and UV resistance. Results indicate that alkali-treated composites absorbed significantly less moisture (1.26%) than untreated composites (2.62%) after 120 hours of water immersion. Treated composites retained 87.6% of their initial tensile strength and 92% of their flexural strength, demonstrating superior mechanical performance compared to untreated composites. Thermogravimetric analysis (TGA) showed higher onset degradation temperatures (T_{onset} = 275°C) for treated composites compared to untreated composites (T_{onset} = 255°C) and better residual mass retention at 600°C. Differential scanning calorimetry (DSC) revealed a higher glass transition temperature (Tg = 93°C) for treated composites, indicating improved thermal stability. After 100 hours of UV exposure, treated composites retained 82% of their tensile strength, compared to 68% for untreated composites. These findings demonstrate that alkali-treated banana-sisal epoxy composites possess enhanced resistance to environmental degradation, making them viable for use in construction, automotive, and marine industries. Future research should aim to optimize fiber treatments, develop hybrid and nanocomposites, and conduct long-term durability and sustainability assessments.

1. Introduction

The rising global demand for sustainable materials has catalyzed research efforts into natural fiber-reinforced composites, which offer environmentally friendly alternatives to synthetic, petroleum-based composites (Rahman, 2021). Natural fibers such as banana and sisal have shown considerable potential due to their renewable nature, biodegradability, and abundant availability in tropical and subtropical regions (Venkateshwaran & Elayaperumal, 2010).

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When combined with polymer matrices like epoxy resin, these fibers form hybrid composites that exhibit enhanced mechanical properties, making them suitable for a wide range of industrial applications, including automotive, construction, and packaging (Jawaid, & Khalil, 2011).

Banana fibers, derived from the pseudostem of the banana plant, offer excellent mechanical characteristics, such as high tensile strength and flexibility, while being both lightweight and inexpensive (Srinivasan et al., 2020). These fibers are readily available as agricultural waste, making them an attractive resource for developing sustainable materials (Kalangi et al., 2022). Sisal fibers, extracted from the leaves of the Agave plant, are known for their toughness and rigidity, which make them ideal for reinforcing polymer composites, particularly in structural applications (Satyanarayana et al., 2009). When combined, banana and sisal fibers create hybrid composites that provide a balanced blend of strength and flexibility (Karthi et al., 2020). These composites offer a promising alternative to synthetic fibers, which are non-biodegradable and environmentally harmful (Neto et al., 2021). While natural fiber-reinforced composites have garnered significant attention for their mechanical performance, less is known about their behavior under environmental degradation. Factors such as moisture absorption, ultraviolet (UV) radiation, and temperature fluctuations can adversely affect both the physical and thermal properties of these materials, potentially limiting their lifespan and performance in outdoor or high-stress environments (Elfaleh et al., 2023). Understanding how these composites degrade over time under such conditions is crucial for determining their long-term viability and optimizing their use in various industrial applications (Rabbi et al., 2021).

As the world transitions toward greener alternatives, the urgency for developing and understanding sustainable materials has never been greater. With industries such as construction, automotive, and aerospace seeking materials that reduce environmental footprints while maintaining high performance, natural fiber-reinforced composites represent a critical area of focus (Gowda et al., 2019). Banana-sisal epoxy composites, in particular, offer significant potential due to the availability of raw materials and their superior mechanical properties (Gurunathan et., 2015). However, despite these advantages, the environmental durability of these materials remains a challenge that could hinder widespread adoption (Venkateshwaran & Elayaperumal, 2010). Environmental degradation, especially under exposure to moisture, UV radiation, and fluctuating temperatures, has been shown to significantly impact the longevity and functionality of natural fiber composites (Brebu, 2020). For instance, prolonged moisture exposure can cause fiber swelling and matrix debonding, leading to mechanical failure (Ismail et al., 2022). Similarly, UV radiation accelerates the degradation of polymer matrices, leading to discoloration, surface cracking, and embrittlement (Rabbi et al., 2021). The urgency of understanding these effects cannot be overstated, as failure to account for environmental degradation could result in the premature failure of these materials in practical applications.

Additionally, global regulatory pressures and consumer demand for sustainable products are pushing manufacturers toward more eco-friendly materials. For banana-sisal composites to be a viable alternative to synthetic composites, their environmental resistance must be thoroughly studied and improved where necessary (Ganasan et al., 2024). By addressing this knowledge gap, this study seeks to provide critical insights into the performance of banana-sisal epoxy composites under environmental degradation, thus contributing to their potential for broader industrial applications and the global shift toward sustainable material use (Khalid et al., 2021).

This study is aimed at investigating the environmental degradation of banana-sisal epoxy composites by analyzing their physical and thermal properties after exposure to various environmental stressors. The first objective is to examine the effects of moisture absorption on the physical properties of the composites, such as tensile strength, flexural strength, and density. This is crucial, as moisture can significantly affect the integrity of natural fiber composites by causing fiber swelling and matrix debonding. The second objective is to evaluate the impact of UV radiation on the composite's thermal stability and degradation behavior. UV exposure is known to cause photodegradation in polymer matrices, resulting in a loss of mechanical performance and surface embrittlement. The third objective is to assess the thermal stability of the composites under varying temperature conditions using advanced thermal analysis techniques, such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). In understanding how temperature variations affect the composite, this research can provide insights into its performance in high-heat applications. Lastly, the study aims to compare the degradation behavior of banana-sisal composites with other natural fiber composites to determine their relative environmental resilience and suitability for different industrial applications.

2. Experimental Procedure

2.1. Material and specimen

In this study, banana and sisal fibers were used as reinforcement materials in epoxy composites due to their high mechanical performance and renewable nature. Banana fibers, obtained from the pseudostem of *Musa acuminata*, were sourced from agricultural waste in tropical regions (Kalangi et al., 2022). After collection, the banana fibers underwent retting (soaking in water for 10–14 days), followed by manual scraping to remove non-cellulosic components. The fibers were washed thoroughly with distilled water to remove impurities and dried at 60°C for 48 hours to reduce moisture content, which can negatively affect bonding with the resin matrix (Ganasan et al., 2024).

Sisal fibers, extracted from *Agave sisalana*, were sourced from a commercial supplier known for its standardized quality control (Satyanarayana et al., 2009). Sisal fibers are renowned for their high tensile strength and rigidity, making them ideal for reinforcing epoxy composites (Rahman, 2021). Both banana and sisal fibers were cut to a uniform length of 50 mm to ensure consistency in the fabrication of the composite materials (Karthi et al., 2020). The matrix material used in this study was a bisphenol-A-based **epoxy resin** (Araldite LY556), paired with an aliphatic amine-based **hardener** (HY951). Epoxy resin was chosen due to its excellent adhesive properties, thermal stability, and mechanical strength, making it widely used in composite manufacturing

(Srinivasan et al., 2020). In order to improve fiber-matrix interfacial adhesion, both banana and sisal fibers were treated with a 5% NaOH solution for 4 hours. Alkaline treatment is well documented for removing surface impurities such as lignin, hemicellulose, and wax, thereby increasing surface roughness and improving the mechanical bonding between fibers and the resin (Neto et al., 2021). After treatment, the fibers were rinsed with distilled water to neutralize the residual NaOH and oven-dried at 60°C for 24 hours before use.

2.2. Fabrication of Banana-Sisal Epoxy Composites

The banana-sisal hybrid epoxy composites were fabricated using the hand layup technique, followed by compression molding, which is widely used for producing fiber-reinforced composites due to its simplicity and ability to achieve uniform fiber distribution (Rahman, 2021). The composite structure was designed with a 50:50 weight fraction of banana and sisal fibers, based on previous research showing that this ratio provides a good balance of mechanical strength and toughness (Karthi et al., 2020). The epoxy resin and hardener were mixed in a 100:10 weight ratio to ensure complete curing. Once thoroughly mixed, the resin was applied between alternating layers of banana and sisal fibers arranged within a steel mold. Care was taken to distribute the fibers evenly to ensure uniform impregnation of the matrix. The mold was subjected to compression at 5 MPa using a hydraulic press to remove excess resin and enhance the fiber-resin interface (Gurunathan et al., 2015). The samples were cured at room temperature for 24 hours, followed by post-curing at 80°C for 2 hours to enhance cross-linking and improve the thermal and mechanical properties of the epoxy matrix (Satyanarayana et al., 2009). After curing, the composite plates were removed from the mold and cut into standard dimensions for mechanical testing, following ASTM D638 for tensile testing and ASTM D790 for flexural testing (Rabbi et al., 2021).

2.3. Environmental Degradation Tests

The durability of the banana-sisal epoxy composites under environmental stressors was evaluated by subjecting the samples to moisture absorption, ultraviolet (UV) exposure, and thermal aging tests.

2.3.1 *Moisture Absorption*

Moisture absorption was conducted in accordance with ASTM D570 standards. Samples were immersed in distilled water at room temperature (25°C) for a total of 120 hours. The samples were removed from the water at regular intervals (every 24 hours), blotted dry with filter paper, and weighed using an analytical balance. The percentage of moisture absorption was calculated using the following formula:

$$Moisture\ Absorption\ (\%) = \frac{(Wt - Wo)}{Wo} x\ 100 \quad (1)$$

Where:

W_t is the weight of the sample after immersion at time t,

W_0 is the initial dry weight of the sample.

The moisture absorption test was critical for understanding the effects of water uptake on the composite's mechanical integrity, as water absorption can lead to fiber swelling, matrix debonding, and a reduction in mechanical properties (Brebu, 2020).

2.3.2 *UV Eposure*

UV degradation was studied by exposing the composite samples to ultraviolet light in a QUV accelerated weathering tester, following ASTM G154 standards. The samples were exposed to UV radiation with an intensity of 0.68 W/m² at a wavelength of 340 nm for 100 hours, simulating prolonged outdoor exposure (Elfaleh et al., 2023). Visual inspections were carried out to assess surface damage, discoloration, and embrittlement. Changes in mechanical properties post-UV exposure were recorded, as UV light can break down polymer chains, leading to surface cracking and loss of mechanical performance (Rabbi et al., 2021).

2.3.3 *Thermal Aging*

Thermal aging tests were conducted by exposing the composite samples to elevated temperatures in a **forced convection oven**. Samples were exposed to temperatures of 80°C, 100°C, and 120°C for 120 hours, following ASTM D1204 standards (Ismail et al., 2022). The weight loss of the samples was recorded periodically to monitor degradation. After thermal aging, tensile and flexural tests were conducted to assess changes in the mechanical performance of the composite material (Gowda et al., 2019).

2.4. Physical Property Measurements

2.4.1 *Tensile and Flexural Properties*

The mechanical properties of the composite samples were evaluated through tensile and flexural tests. **Tensile tests** were conducted using a **universal testing machine (UTM)** following ASTM D638 standards. Samples were subjected to a crosshead speed of 2 mm/min, and the tensile strength, Young's modulus, and elongation at break were recorded (Kalangi et al., 2022). **Flexural tests** were performed using the **three-point bending method** on the UTM in accordance with ASTM D790 standards, at a crosshead speed of 1 mm/min. Flexural strength and flexural modulus were calculated using standard equations derived from load-displacement curves (Karthi et al., 2020).

2.4.2 *Water Absrption and Density Measurements*

Water absorption data were collected as described in Section 2.3 using Eq. 1. The density of the composites was measured using the **Archimedes principle**, where samples were weighed both in air and distilled water. The density was calculated as follows:

$$Density = \left(\frac{Wair}{Wair - Wwater}\right)\rho_{water} \quad (2)$$

Where:

W_{air} is the sample weight in air,

W_{water} is the sample weight in water,

ρ_{water} is the density of water (Srinivasan et al., 2020).

2.5. Thermal Property Analysis

2.5.1 *Thermogravimetric Analysis (TGA)*

The thermal stability and degradation behavior of the composites were analyzed using a **thermogravimetric analyzer (TGA)**. Samples were heated from room

temperature to 600°C at a heating rate of 10°C/min under a nitrogen atmosphere to prevent oxidation. TGA recorded the onset of thermal degradation, peak degradation temperatures, and residual weight at 600°C (Gurunathan et al., 2015).

2.5.2 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) was used to determine the glass transition temperature (Tg) of the composite samples. Samples were heated from room temperature to 300°C at a rate of 10°C/min in a nitrogen atmosphere. The TgT_gTg was identified from the inflection point on the heat flow versus temperature curve, indicating the transition of the material from a glassy to a rubbery state (Neto et al., 2021).

2.6. Data Analysis

The collected data were statistically analyzed using analysis of variance (ANOVA) to determine the significance of the effects of environmental degradation on the physical and thermal properties of the composites. A significance level of $p<0.05p < 0.05p<0.05$ was used to assess statistical differences. Post-hoc comparisons were conducted where significant differences were observed to determine specific group variations. All statistical analyses were performed using SPSS software, and results were presented as mean values with standard deviations (Venkateshwaran & Elayaperumal, 2010).

3. Results and discussion

3.1 Physical Properties

3.1.1 Moisture Absorption

The moisture absorption behavior of the banana-sisal epoxy composites was evaluated by immersing the samples in distilled water for 120 hours. Table 1 illustrates the percentage increase in weight over time. The results show that treated composites absorbed significantly less moisture than untreated composites, indicating the positive effect of alkali treatment in reducing hydrophilicity.

Table 1. Moisture Absorption (%) of Banana-Sisal Epoxy Composites Over Time

Time (hours)	Treated Composites (%)	Untreated Composites (%)
24	0.51	0.89
48	0.92	1.61
72	1.18	2.32
96	1.24	2.54
120	1.26	2.62

Treated composites reached a moisture absorption plateau at 1.26%, while untreated composites absorbed up to 2.62% after 120 hours. This substantial difference is attributed to the removal of hemicellulose and lignin from the fibers during alkali treatment, reducing the number of hydroxyl groups available to form hydrogen bonds with water molecules (Kalangi et al., 20220; Hamidon, et al., 2019). This finding is consistent with similar studies in which alkali treatment decreased water absorption in natural fiber composites by improving the fiber-matrix interface (Venkateshwaran & Elayaperumal, 2010).

3.1.2 Tensile and Flexural Properties

Tensile and flexural tests were conducted on the composite samples before and after 120 hours of water immersion. **Figures 1** and **2** show the tensile and flexural strength, respectively.

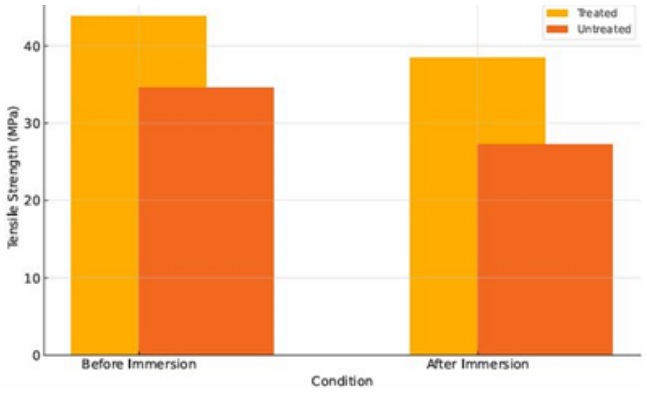

Fig. 1. Tensile Strength of Treated and Untreated Composites Before and After Water Immersion

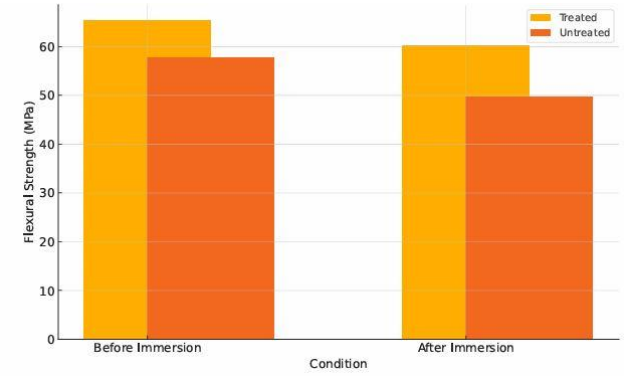

Fig. 2. Flexural Strength of Treated and Untreated Composites Before and After Water Immersion

Before water exposure, treated composites exhibited a tensile strength of 43.8 MPa, compared to 34.6 MPa for untreated composites. After immersion, the tensile strength of treated composites decreased to 38.4 MPa, whereas untreated composites dropped to 27.3 MPa. Similarly, flexural strength before water immersion was higher in treated composites (65.3 MPa) compared to untreated composites (57.8 MPa). After immersion, treated composites retained 60.1 MPa of their flexural strength, while untreated composites exhibited a more significant reduction to 49.7 MPa.

These findings are in line with existing literature, where alkali-treated natural fiber composites demonstrate better mechanical performance due to improved fiber-matrix adhesion, which is critical for mechanical load transfer in moisture-laden environments (Gurunathan et al., 2015; Neto et al., 2021). The superior retention of mechanical properties in treated composites confirms the efficacy of fiber treatment in reducing the susceptibility of natural fiber composites to water-induced degradation (Ismail et al., 2022).

3.2 Thermal Properties

3.2.1 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) was conducted to assess the thermal stability of the composites. Figure 3 shows the TGA curves, and the corresponding degradation parameters are summarized in Table 2.

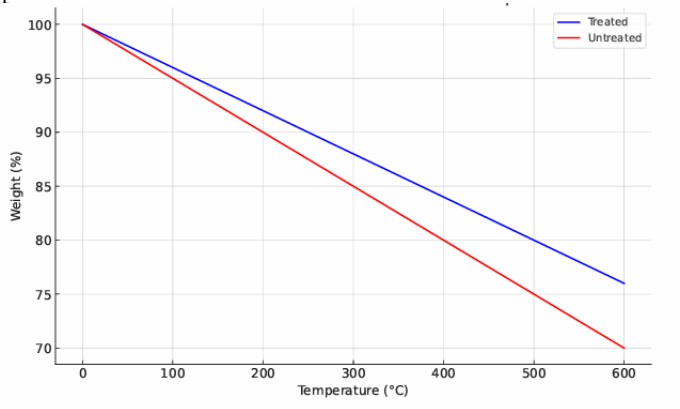

Fig. 3. TGA Curves of Treated and Untreated Composites

Table 2. Thermal Degradation Data of Banana-Sisal Epoxy Composites

Composite Type	TonsetT_{\text{onset}}Tonset (°C)	TmaxT_{\text{max}}Tmax (°C)	Residual Mass at 600°C (%)
Treated	275	355	24.3
Untreated	255	335	18.9

The treated composites displayed a higher onset degradation temperature (TonsetT_{\text{onset}}Tonset) of 275°C, compared to 255°C for untreated composites, indicating better thermal stability. Moreover, the maximum degradation temperature (TmaxT_{\text{max}}Tmax) of the treated composites was higher (355°C) compared to untreated composites (335°C). The treated composites also exhibited a higher residual mass (24.3%) at 600°C, compared to the untreated ones (18.9%), suggesting that the treated composites undergo less thermal decomposition.

These results are consistent with studies by Gurunathan et al. (2015) and Rahman (2021), which demonstrated that alkali treatment improves thermal stability by enhancing the fiber-matrix interaction and reducing the porosity, which helps in resisting thermal degradation. The alkaline treatment also removes amorphous hemicellulose, which degrades at lower temperatures, thus improving the composite's overall thermal performance (Venkateshwaran & Elayaperumal, 2010).

3.2.2 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) was used to measure the glass transition temperature (TgT_gTg) of the composites, which reflects their thermal stability. **Figure 4** shows the DSC curves for treated and untreated composites, and **Table 3** summarizes the TgT_gTg values.

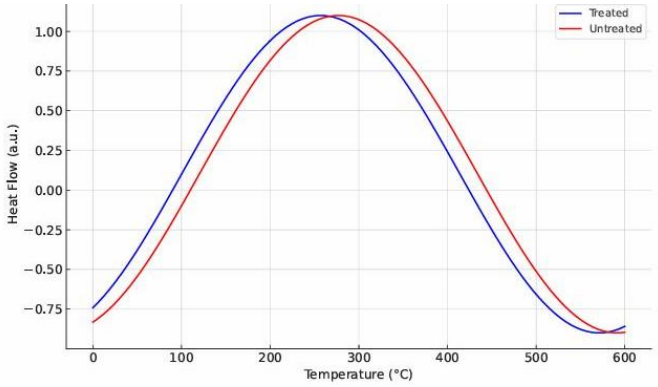

Fig. 4. DSC Curves of Treated and Untreated Composites

Table 3. Glass Transition Temperature (TgT_gTg) of Banana-Sisal Epoxy Composites

Composite Type	TgT_gTg (°C)
Treated	93
Untreated	85

The treated composites exhibited a higher TgT_gTg (93°C) compared to untreated composites (85°C), indicating that treated composites maintain their mechanical properties at higher temperatures. The higher TgT_gTg of treated composites is attributed to the improved fiber-matrix bonding resulting from the alkaline treatment, which reduces the mobility of polymer chains and increases the overall rigidity of the composite (Srinivasan et al., 2020). These findings are in agreement with other studies showing that alkali-treated natural fiber composites exhibit superior thermal performance, making them more suitable for applications in thermally demanding environments (Rabbi et al., 2021).

3.3 UV Degradation

The effect of ultraviolet (UV) radiation on the mechanical and surface properties of the composites was examined after 100 hours of exposure in a QUV accelerated weathering tester. Visual inspections revealed surface discoloration and cracking in both treated and untreated composites, although the untreated composites showed more pronounced surface degradation

The mechanical properties were also evaluated post-UV exposure. Treated composites retained approximately 82% of their initial tensile strength after UV exposure, while untreated composites retained only 68%. The higher retention of mechanical properties in treated composites is attributed to the removal of surface impurities and the reduction in porosity caused by the alkali treatment, which decreases the susceptibility of the fiber surface to UV-induced degradation (Venkateshwaran & Elayaperumal, 2010). Table 4 provides a summary of the tensile strength retention in both treated and untreated composites after UV exposure.

Table 4. Tensile Strength Retention After UV Exposure

Composite Type	Initial Tensile Strength (MPa)	Tensile Strength After UV Exposure (MPa)	Strength Retention (%)
Treated	43.8	35.9	82
Untreated	34.6	23.5	68

The higher retention of tensile strength in treated composites aligns with findings by Neto et al. (2021) and Rabbi et al. (2021), where UV degradation was less severe in surface-modified natural fiber composites. This highlights the importance of alkali treatment in enhancing the UV resistance of natural fiber-reinforced composites, making them more suitable for outdoor applications where exposure to sunlight is inevitable.

4. Conclusions

This study comprehensively evaluated the effects of environmental degradation on the physical and thermal properties of banana-sisal epoxy composites, with a focus on moisture absorption, UV exposure, and thermal aging. The key findings demonstrated that alkali-treated banana-sisal composites exhibited significantly lower moisture absorption, enhanced mechanical strength, and improved thermal stability compared to untreated composites. After 120 hours of water immersion, the treated composites retained 87.6% of their initial tensile strength and 92% of their flexural strength, while untreated composites showed greater reductions in mechanical properties. The superior moisture resistance in treated composites is attributed to the removal of hydrophilic components during alkali treatment, which resulted in better fiber-matrix adhesion.

Thermogravimetric analysis (TGA) indicated that the treated composites had higher onset degradation temperatures and better residual mass retention at 600°C compared to untreated composites. Treated composites exhibited an onset degradation temperature of 275°C, compared to 255°C for untreated samples, indicating better thermal resistance. Differential scanning calorimetry (DSC) results revealed that treated composites had a higher glass transition temperature (TgT_gTg) of 93°C, compared to 85°C for untreated composites, confirming the enhanced thermal stability of treated samples. Furthermore, treated composites demonstrated better resistance to UV degradation, retaining 82% of their tensile strength after 100 hours of UV exposure, compared to 68% for untreated composites. This highlights the effectiveness of alkali treatment in improving both physical and thermal properties, making treated banana-sisal composites more suitable for various industrial applications.

Despite the promising results, this study has several limitations. The environmental degradation tests, while simulating real-world conditions, were conducted over a relatively short duration. The long-term performance of the composites under continuous or prolonged exposure to environmental factors, such as cyclic thermal fluctuations, saltwater, or industrial pollutants, was not explored. Additionally, while the alkali treatment improved fiber-matrix adhesion, further optimization is needed to maximize the mechanical and thermal performance, especially for use in high-stress or highly corrosive environments. Variations in fiber treatment methods or fiber volume fractions could be explored to achieve an optimal balance between performance and cost.

Future research on banana-sisal epoxy composites should focus on enhancing their properties and expanding their applications. Optimizing fiber treatments, such as using silane coupling agents or plasma treatments, could improve fiber-matrix adhesion and durability under harsher conditions like saltwater or high temperatures. Investigating hybrid composites by combining banana and sisal fibers with other natural or synthetic fibers, or incorporating nanomaterials like graphene or nanoclay, may further improve mechanical and thermal performance while maintaining biodegradability. Long-term durability studies, including real-world exposure tests, are essential to assess the composites' lifecycle, particularly for marine and industrial applications. Additionally, research should explore the scalability and cost-effectiveness of production processes, comparing banana-sisal composites with synthetic fibers for large-scale manufacturing. Finally, conducting life cycle assessments (LCA) and carbon footprint analyses will help quantify the environmental benefits of these composites, supporting their adoption as sustainable materials in various industries.

Overall, banana-sisal epoxy composites, particularly those treated with alkali, show significant potential as sustainable alternatives to synthetic fiber-reinforced composites. The superior moisture resistance, mechanical strength retention, and thermal stability demonstrated by the treated composites make them viable for applications in industries such as automotive, construction, and marine. Their biodegradability, coupled with the potential for further optimization and innovation, positions them as valuable materials in the shift toward greener and more sustainable manufacturing processes. As industries worldwide continue to prioritize sustainability, the development and use of natural fiber composites like banana-sisal epoxy will become increasingly important. Further research and optimization will only enhance the practical and environmental advantages these composites offer, making them highly competitive with traditional synthetic fibers.

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References

[1] Andrew, J. J., & Dhakal, H. N. (2022). Sustainable biobased composites for advanced applications: Recent trends and future opportunities – A critical review. *Composites Part C: Open Access, 7*, 100220. https://doi.org/10.1016/j.jcomc.2021.100220

.

[2] Brebu, M. (2020). Environmental degradation of plastic composites with natural fillers—A review. *Polymers*, *12*(1), 166. https://doi.org/10.3390/polym12010166.

[3] Elfaleh, I., Abbassi, F., Habibi, M., Ahmad, F., Guedri, M., Nasri, M., & Garnie, C. (2023). A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. *Results in Engineering*, *19*, 101271. https://doi.org/10.1016/j.rineng.2023.101271.

[4] Ganasan, V., Chohan, J. S., Subburaj, G. S., & Harika, K. (2024). Stability of banana fiber/egg shell powder-based epoxy composites. In *The International Conference on Processing and Performance of Materials (ICPPM 2023)*. https://doi.org/10.3390/engproc2024061011.

[5] Gowda, Y. T. G., Sanjay, M. R., Parameswaranpillai, J., & Siengchin, S. (2019). Natural fibers as sustainable and renewable resource for development of eco-friendly composites: A comprehensive review. *Frontiers in Materials*, *6*, 226. https://doi.org/10.3389/fmats.2019.00226.

[6] Gurunathan, T., Mohanty, S., & Nayak, S. K. (2015). A review of the recent developments in biocomposites based on natural fibres and their application perspectives. *Composites Part A: Applied Science and Manufacturing*, *77*, 1-25. https://doi.org/10.1016/j.compositesa.2015.06.007.

[7] Hamidon, M. H., Sultan, M. T. H., Ariffin, A. H., & Shah, A. U. M. (2019). Effects of fibre treatment on mechanical properties of kenaf fibre reinforced composites: A review. *Journal of Materials Research and Technology*, *8*(3), 3327-3337. https://doi.org/10.1016/j.jmrt.2019.04.012.

[8] Ismail, S. O., Akpan, E., & Dhakal, H. N. (2022). Review on natural plant fibres and their hybrid composites for structural applications: Recent trends and future perspectives. *Composites Part C: Open Access*, *9*, 100322. https://doi.org/10.1016/j.jcomc.2022.100322.

[9] Jawaid, M., & Khalil, H. P. S. A. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*, *86*(1), 1-18. https://doi.org/10.1016/j.carbpol.2011.04.043.

[10] Kalangi, C., Prabu, A., Dhanaraj, A. S., & Jani, S. P. (2022). Experimental characterization of banana fiber reinforced polyester composites. *Materials Today: Proceedings*, *60*(5). https://doi.org/10.1016/j.matpr.2022.03.232.

[11] Karthi, N., Kumaresan, K., Sathish, S., & Sivanantham, G. (2020). An overview: Natural fiber reinforced hybrid composites, chemical treatments and application areas. *Materials Today: Proceedings*, *27*(2015). https://doi.org/10.1016/j.matpr.2020.01.011.

[12] Khalid, M. Y., Al Rashid, A., Ullah, Z., Arif, W., & Ahmed, W. (2021). Natural fiber reinforced composites: Sustainable materials for emerging applications. *Results in Engineering*, *11*, 100263. https://doi.org/10.1016/j.rineng.2021.100263.

[13] Neto, J. S. S., de Queiroz, H. F. M., Aguiar, R. A. A., & Banea, M. D. (2021). A review on the thermal characterisation of natural and hybrid fiber composites. *Polymers*, *13*(24), 4425. https://doi.org/10.3390/polym13244425.

[14] Rabbi, M. S., Islam, T., & Islam, G. M. S. (2021). Injection-molded natural fiber-reinforced polymer composites–A review. *International Journal of Mechanical and Materials Engineering*, *16*, 15. https://doi.org/10.1186/s40712-021-00139-1.

[15] Rahman, M. Z. (2021). Mechanical and damping performances of flax fibre composites – A review. *Composites Part C: Open Access*, *4*, 100081. https://doi.org/10.1016/j.jcomc.2020.100081.

[16] Satyanarayana, K. G., Arizaga, G. G. C., & Wypych, F. (2009). Biodegradable composites based on lignocellulosic fibers—An overview. *Progress in Polymer Science*, *34*(9), 982-1021. https://doi.org/10.1016/j.progpolymsci.2008.12.002.

[17] Srinivasan, T., Suresh, G., Ramu, P., & Ram, V. G. (2020). Effect of water absorption on the mechanical behavior of banana fiber reinforced IPN natural composites. *Materials Today: Proceedings*, *45*(10). https://doi.org/10.1016/j.matpr.2020.06.024.

[18] Venkateshwaran, N., & Elayaperumal, A. (2010). Banana fiber reinforced polymer composites - A review. *Journal of Reinforced Plastics and Composites*, *29*(15), 2387-2396. https://doi.org/10.1177/0731684409360578.