Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 4 (2024)

Experimental Investigation on the Mechanical Characteristics of Gongura Fiber Reinforced Epoxy Composites

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Abstract

Natural fibers have gained significant attention as eco-friendly alternatives to synthetic fibers in polymer composites due to their sustainability, low cost, and potential to improve material properties. Gongura fiber, derived from the plant Hibiscus sabdariffa, has emerged as a promising reinforcement material in polymer matrices, offering a renewable option for enhancing mechanical properties. This study investigates the tensile characteristics and fracture morphology of Gongura fiber-reinforced epoxy composites, with both untreated and alkali-treated fibers. Tensile tests were conducted on composites with varying fiber weight percentages (5 wt.%, 10 wt.%, 15 wt.%, and 20 wt.%) to determine the optimal composition for maximizing tensile strength. Results showed that adding fibers significantly improved the tensile properties, particularly at 15 wt.%, where untreated composites exhibited a 62.3% increase in tensile strength, and alkali-treated composites showed an 89.8% increase compared to pure epoxy. However, increasing the fiber content to 20 wt.% resulted in a reduction in tensile strength due to fiber agglomeration and non-homogeneous distribution. The morphology analysis of fracture surfaces revealed distinct failure mechanisms between treated and untreated composites. Alkali-treated fibers demonstrated superior bonding with the epoxy matrix, resulting in less fiber pull-out and more cohesive fracture patterns. Conversely, untreated fibers exhibited more fiber debonding and poor matrix adhesion, contributing to reduced mechanical performance. alkali-treated Gongura fibers enhance the tensile strength and bonding in epoxy composites, particularly at 15 wt.% fiber content, while excessive fiber addition (20 wt.%) leads to diminished performance due to poor fiber distribution and bonding.

Keywords: Epoxy, Gongura fiber, Tensile, FESEM, Natural Fiber

1. Introduction

Gongura natural fiber, being lightweight, biodegradable, and eco-friendly, has diverse applications across industries such as textiles, composites, packaging, and medical textiles. Its good tensile strength and renewable nature make it an ideal alternative to synthetic fibers in sustainable construction and eco-friendly packaging. Additionally, in the automotive and aircraft industries, Gongura fiber's high strength and lightweight properties offer potential for use in interior components, contributing to fuel efficiency, reduced emissions, and overall material cost savings. Gongura natural fibers possess a chemical composition primarily made up of cellulose, hemicellulose, and lignin, which contribute to their strength, stiffness, and biodegradability. Physically, they are lightweight with a moderate density, rough surface texture, and natural color variations, making them useful in both composite and textile applications. Mechanically, Gongura fibers offer good tensile strength and elasticity, comparable to other natural fibers like hemp and sisal, though they may require treatments, such as alkaline processing, to improve durability, moisture resistance, and bonding in polymer composites. Epoxy is a versatile thermosetting polymer known for its excellent adhesive strength, chemical resistance, and durability. It exhibits

high mechanical properties such as tensile and compressive strength, along with superior thermal stability. These characteristics make epoxy ideal for various applications, including coatings, adhesives, electrical components, and composite materials, particularly in the aerospace, automotive, and construction industries.

Gongura fiber, derived from the Hibiscus sabdariffa plant, has gained significant attention as a sustainable reinforcement material in polymer and epoxy composites due to its favorable mechanical properties and environmental benefits. The foundational understanding of Gongura fiber's mechanical properties, highlighting its potential as an alternative to synthetic fibers in composite applications [1]. In subsequent studies explored the impact of Gongura fiber reinforcement on the tensile strength and flexural properties of epoxy composites. Their findings demonstrated a substantial increase in mechanical performance, establishing Gongura fiber as a viable candidate for various structural applications [2]. The investigation revealed that the thermal properties of Gongura fiber-reinforced polymer composites. The authors reported enhanced thermal stability with increased fiber content, making these composites suitable for applications that require resistance to elevated temperatures [3]. The optimized fiber content in Gongura-reinforced epoxy composites, determining that a 20% fiber loading yielded the best mechanical properties. This optimization work laid the groundwork for the effective application of Gongura fiber in industries such as automotive and aerospace [4]. The comparative analysis of Gongura fiber with other natural fibers in epoxy composites. They found that Gongura fiber provided superior tensile strength and impact resistance, reinforcing its position as a preferred natural reinforcement material [5]. The moisture absorption characteristics of Gongura fiber-reinforced composites. Their study highlighted the importance of surface treatments to enhance fiber-matrix adhesion and reduce moisture uptake, which is crucial for the longevity of composite materials [6]. The biodegradability of Gongura fiber composites, demonstrating that these materials offer an environmentally friendly alternative to synthetic composites. Their work emphasized the ecological benefits of using natural fibers in composite applications [7]. A comprehensive review summarized the current state of research on Gongura fiber-reinforced polymers and epoxy composites, highlighting mechanical, thermal, and environmental aspects. They called for more research to optimize processing techniques and improve the properties of these composites [8]. Investigated the dynamic mechanical properties of Gongura fiber-reinforced epoxy composites, revealing enhanced energy dissipation characteristics, which are advantageous for applications in vibration damping [9]. The focused on the potential of Gongura fiber in enhancing the fire resistance of epoxy composites. Their study showed that incorporating Gongura fiber significantly improved the flame retardancy of the composites, expanding their applicability in construction and automotive sectors [10]. Recent research work examined the compatibility of Gongura fibers with various polymer matrices beyond epoxy. Their findings suggest that Gongura fibers can effectively reinforce thermoplastic matrices, providing additional avenues for application in sustainable materials [11]. Additionally, the explored the use of Gongura fiber in bio-composites, highlighting its potential in developing eco-friendly packaging materials, which is becoming increasingly relevant in the context of environmental sustainability [12]. Finally, the conducted an extensive analysis of the mechanical and thermal properties of Gongura fiber-reinforced composites under various environmental conditions, indicating their robustness and adaptability for diverse applications [13].

Natural fibers have become increasingly significant in the manufacturing of polymer composites for engineering applications due to their myriad advantages. These fibers, derived from renewable resources, promote sustainability by reducing dependence on petroleum-based synthetic materials, thus mitigating environmental impact. Their commendable mechanical properties, including high tensile strength and stiffness, enhance the overall performance of composites, making them suitable for various structural applications. Additionally, the lightweight characteristics of natural fibers lead to significant weight reductions in products, particularly beneficial in the automotive and aerospace sectors where fuel efficiency is paramount. Moreover, natural fibers provide excellent thermal and acoustic insulation, making them ideal for applications that require temperature control and sound dampening, such as in building materials and automotive interiors. Their non-toxic nature ensures that they pose fewer health risks compared to synthetic alternatives, fostering safer environments for consumers. The versatility of natural fibers allows for customization of composite properties, enabling engineers to tailor materials to meet specific performance requirements. Furthermore, the cost-effectiveness of natural fibers contributes to lower manufacturing costs, making them attractive for various industries, including construction

and consumer goods. Their inherent energy absorption and damping capabilities enhance the durability and longevity of composite products. Overall, the integration of natural fibers into polymer composites represents a promising direction for sustainable engineering solutions.

2. Materials and methods

2.1 Materials

2.1.1 Epoxy matrix

Epoxy resins are primarily formed through the reaction of epichlorohydrin and bisphenol-A, resulting in a crosslinked polymer network upon curing. The chemical name for a common epoxy resin is poly(ethylene glycol) diglycidyl ether (PEGDGE) or bisphenol A diglycidyl ether (BADGE). Physically, epoxy resins are typically clear to amber in color and can be found in both liquid and solid forms, depending on their formulation. They exhibit low viscosity when uncurred, allowing for easy application and infiltration into substrates. Epoxy resins are known for their impressive mechanical properties, including high tensile strength and modulus, making them suitable for structural applications. They possess excellent thermal stability, with glass transition temperatures often exceeding 100°C. Epoxy is also resistant to moisture, chemicals, and UV radiation, enhancing its durability in various environments. Curing agents, or hardeners, such as amines, anhydrides, or polyamides, are essential for the epoxy curing process, initiating crosslinking and transforming the resin into a solid form. The choice of curing agent significantly influences the final properties of the epoxy, including cure time, flexibility, and thermal resistance.

2.2.2 Gongura fiber

Gongura fiber is extracted from the leaves of the Hibiscus sabdariffa plant, commonly known for its nutritional and medicinal benefits. The extraction process typically involves harvesting the leaves, followed by a retting process where the leaves are soaked in water for several days to facilitate the separation of fibers from the leaf pulp. After retting, the fibers are washed, dried, and then mechanically separated to obtain the raw Gongura fiber. This natural fiber can be further processed through spinning or weaving for various applications. In terms of physical properties, Gongura fiber is known for its notable tensile strength and flexibility. The diameter of Gongura fibers typically ranges from 200 to 300 micrometers, providing a robust structure. The length of the fibers can vary but usually measures between 10 to 50 centimeters, depending on the extraction method and the specific plant variety. The aspect ratio, which is the ratio of fiber length to diameter, generally ranges from 100:1 to 250:1, contributing to the fiber's effective reinforcement capabilities in composite materials. Additionally, Gongura fiber exhibits good moisture absorption and biodegradability, making it an eco-friendly alternative for various applications, including textiles, packaging, and composite manufacturing. These unique properties make Gongura fiber a promising candidate for sustainable engineering solutions.

2.2.3 Functionalization of gongura fiber

Alkali treatment is a vital process in enhancing the properties of Gongura fiber, derived from the Hibiscus sabdariffa plant, making it more suitable for use in composite materials. This procedure typically involves immersing the raw Gongura fiber in a sodium hydroxide (NaOH) solution, usually at a concentration of 1% to 5% (w/v), for a specific duration that ranges from 1 to 6 hours. The exact time can vary based on the desired fiber characteristics and the concentration of the alkali solution. During this soaking period, the alkali acts to break down and remove impurities, including lignin, hemicellulose, and waxes, which can negatively impact the fiber’s mechanical properties and its ability to bond with polymer matrices. After the soaking phase, the treated fibers are thoroughly washed with distilled water to remove any residual alkali and dissolved materials, ensuring the purity of the fibers. Following washing, the fibers are dried, often in the shade, to prevent thermal degradation [14].

The alkali treatment enhances several important attributes of Gongura fiber. It significantly increases tensile strength and modulus, leading to improved mechanical performance in composite applications. The process also enhances the surface roughness of the fibers, facilitating better adhesion with the polymer matrix and thus

improving the overall composite integrity. Moreover, alkali-treated fibers exhibit lower moisture absorption rates, which is particularly advantageous in humid environments, as it minimizes the risk of swelling and loss of mechanical performance. Additionally, this treatment promotes biodegradability, aligning with the growing demand for eco-friendly materials in various industries. By removing unwanted components, alkali treatment not only purifies the fibers but also contributes to their sustainability, making Gongura fiber an attractive option for green engineering solutions. Overall, the alkali treatment process is essential for preparing Gongura fibers for high-performance applications in composite materials, significantly enhancing their utility in the manufacturing of lightweight and durable products.

2.2.4 Tensile sample preparation

The preparation of tensile samples for gongura fiber reinforced epoxy composites employs a meticulous approach to ensure adherence to ASTM D638 standards, utilizing a hand lay-up method that is both effective and straightforward. Initially, an epoxy mixture is prepared by combining bisphenol A diglycidyl ether (BADGE) with a suitable hardener, typically in a 2:1 weight ratio, ensuring thorough mixing to achieve a homogeneous blend. Concurrently, alkali-treated gongura fibers are incorporated into the mixture, which have undergone treatment with a sodium hydroxide solution to eliminate impurities, thereby enhancing their bonding capability with the epoxy matrix. Fibers are added in varying weight percentages of 5 wt.%, 10 wt.%, 15 wt., and 20 wt.% to investigate their effect on the mechanical properties of the composite, allowing for a comprehensive analysis of both treated and untreated fibers.

The composite fabrication, a sample plate measuring 600 mm x 300 mm is constructed using the hand lay-up method. This involves layering the epoxy mixture with the Gongura fibers in the desired proportions directly onto a flat surface, allowing for a controlled distribution of fibers within the matrix. Once the plate is cured, the required number of dog-bone-shaped samples, as specified by ASTM D638, is machined from the plate. Care is taken during the machining process to ensure that the mechanical properties of the material are not adversely affected, preserving the integrity of the fiber-reinforced epoxy composite. After machining, the samples are polished with a fine emery sheet to achieve a smooth surface finish, which is essential for accurate tensile testing results. To enhance gripping action during testing, both ends of the specimen are knurled using an appropriate tool. This knurling process increases the surface area, ensuring a secure grip in the testing machine, thus preventing slippage during tensile testing. After these preparations, the finalized samples are stored in a controlled environment until tensile testing is performed using a universal testing machine. This testing allows for the assessment of crucial mechanical properties, including tensile strength, modulus of elasticity, and elongation at break, across the varying fiber weight percentages and treatment conditions. This extensive preparation process not only ensures the integrity and performance of the composite materials but also provides reliable data for various engineering applications, demonstrating the potential of Gongura fiber reinforced epoxy composites in sustainable material development.

2.2.5 Tensile test

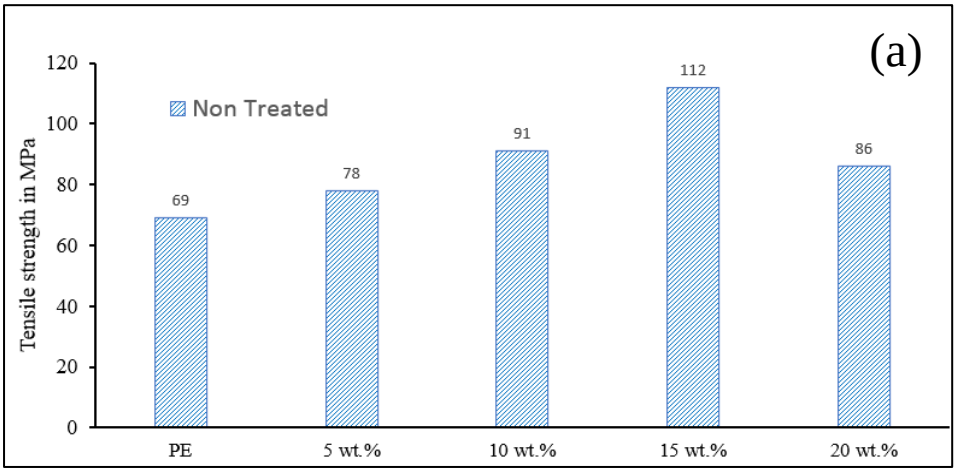
The tensile test procedure for natural fiber-reinforced composites, such as Gongura fiber reinforced epoxy, is conducted using an Instron Tensile Test Machine following ASTM D638 standards. Each composite composition (e.g., 5 wt.%, 10 wt.%, 15 wt.%, and 20 wt.% of fibers) requires testing of three specimens, and the average values of tensile strength, modulus of elasticity, and elongation at break are recorded and plotted. Before testing, dog-bone-shaped samples are prepared and loaded into the Instron machine equipped with an extensometer, which accurately measures the strain (elongation) during the test. The crosshead speed or rate of loading is typically set to 2 mm/min to ensure precise deformation control, though it can vary depending on the material properties. The load applied per minute is recorded, and the machine gradually increases the tension until the specimen breaks, capturing critical data points. During testing, the extensometer measures changes in gauge length, ensuring high accuracy in determining the modulus and tensile strength. The average tensile strength from the three tested samples is calculated for each composition and plotted for analysis, providing insights into how fiber weight percentage and treatments affect the composite's mechanical properties.

3. Result and discussion

3.1 Tensile characteristics

The tensile characteristics of both untreated and alkali-treated Gongura fiber reinforced epoxy composites reveal significant insights into the mechanical behavior of natural fiber-reinforced polymer composites. The tensile results, plotted in **Figure 1 (a-c)**, demonstrate a clear trend of improved tensile properties with the addition of fibers, although there are distinct variations based on fiber content and treatment. Initially, adding 5 wt.% and 10 wt.% of untreated Gongura fibers to the pure epoxy matrix significantly enhanced the tensile characteristics of the composite. This increase is attributed to the reinforcing effect of the fibers, which distribute the applied load more effectively than the pure epoxy matrix, thus improving the overall tensile strength. As the fiber content increased to 15 wt.%, the tensile strength exhibited a substantial improvement, with a 62.3% increase compared to pure epoxy. This considerable improvement is due to the optimal fiber content, where the fibers effectively bear the applied load and distribute stress, leading to higher tensile strength. However, when the Gongura fiber content was further increased to 20 wt.%, the tensile strength began to decrease, though it still remained higher than that of pure epoxy. The reduction in tensile strength by 23% compared to the 15 wt.% composition is likely due to the excess fiber content, which can cause non-homogeneous fiber distribution and reduced load-bearing efficiency. This is because an excess of fibers can lead to poor interfacial bonding between the fiber and matrix, resulting in local stress concentrations and decreased mechanical performance. When comparing the tensile performance of alkali-treated Gongura fiber reinforced epoxy composites, the results, also plotted in Figure AA, show a significant improvement across all weight fractions. Notably, 15 wt.% of alkali-treated fibers exhibited a superior tensile strength, achieving an 89.8% increase over pure epoxy, which is substantially higher than the untreated counterpart. This remarkable improvement can be attributed to the surface modification imparted by the alkali treatment. The alkali treatment removes impurities such as lignin, hemicellulose, and surface waxes from the fiber, resulting in a cleaner, rougher fiber surface that enhances the fiber-matrix interfacial bonding. This leads to improved stress transfer between the matrix and fiber, which is critical for higher tensile strength. The treated fibers also show better compatibility with the epoxy matrix, promoting a good interlocking mechanism where the polymer resin penetrates the fiber's rough surface, creating a more robust mechanical bond [15].

Additionally, alkali-treated Gongura fibers recorded a 17% improvement in tensile strength compared to their untreated counterparts. This improvement can be explained by the enhanced adhesion between the treated fibers and the epoxy matrix, allowing for better load distribution across the composite. The rougher surface texture and improved wettability of the treated fibers help the matrix infiltrate and bond more effectively, creating a strong composite material. The interlocking mechanism between the polymer chains and the treated fiber's surface plays a pivotal role in the improved tensile behavior, as it allows the composite to better



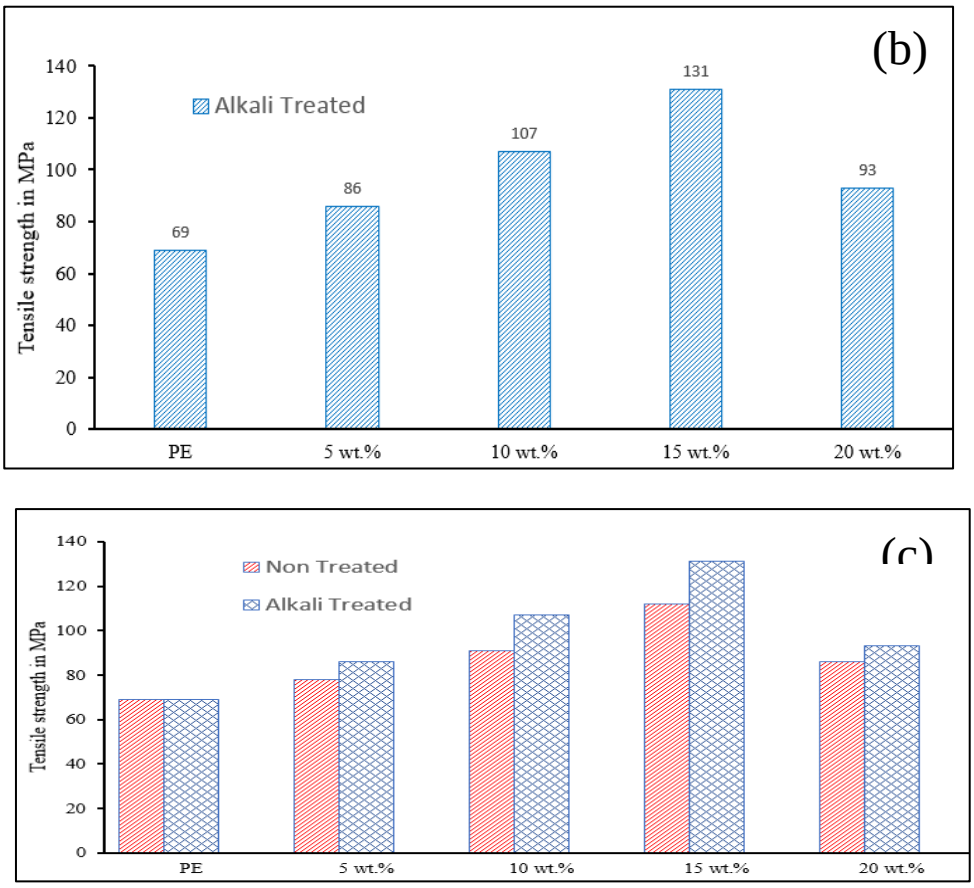


Figure 1: Tensile strength of pure epoxy and its gongura fiber composites with various weight (a) nontreated (b) alkali treated (c) nontreated and treated combined resist deformation under stress. Interestingly, the 20 wt.% alkali-treated fiber composites also showed a reduced wear rate compared to the 15 wt.% composites, though their tensile strength decreased. The decrease in tensile strength in the 20 wt.% samples is primarily due to several factors. First, an excess of fibers can lead to non-homogeneous fiber distribution, which creates regions where the fibers are densely packed, inhibiting effective stress transfer. This localized fiber concentration results in stress concentrations that weaken the overall composite. Second, the increased fiber content can also lead to fiber agglomeration, which prevents the fibers from acting as efficient load-bearing elements. Instead of reinforcing the composite, these agglomerated fibers behave as defects that can initiate cracks under tensile loading. Moreover, the excess fiber can cause poor bonding between the fiber and the matrix, as the available matrix material may be insufficient to fully encapsulate all the fibers, leading to voids or gaps that further reduce the tensile properties. The unlock mechanism occurs when fibers fail to distribute the applied load evenly due to poor bonding or fiber misalignment, resulting in localized stress points that lead to premature failure. These defects compromise the composite's ability to bear loads, contributing to the reduced tensile strength observed in the 20 wt.% samples. Overall, while increasing fiber content can improve tensile properties up to an optimal point (in this case, 15 wt.%), further increases can lead to diminishing returns due to the aforementioned issues of fiber distribution, bonding, and stress concentration. This highlights the importance of optimizing fiber content and ensuring proper fiber-matrix adhesion in the design and manufacturing of natural fiber-reinforced composites. The tensile properties of Gongura fiber-reinforced epoxy composites show a clear dependency on fiber content and treatment. Alkali-treated fibers outperform untreated fibers due to their improved bonding and load distribution capabilities. However, an optimal fiber content is essential to avoid issues like non-homogeneous distribution and poor bonding, which can detract from the composite's overall performance.

3.2 Fracture surface morphology analysis

The morphology analysis of the fracture surface for tensile specimens of epoxy and alkali-treated Gongura fiber composites with various weight percentages reveals critical insights into the failure mechanisms and material behavior during tensile loading as presented in **Figure 2 (a-f)**. The pure epoxy specimens typically exhibit a brittle fracture surface, characterized by smooth and flat regions indicative of minimal plastic deformation before failure. The absence of fibers in pure epoxy results in a sudden, catastrophic failure under tensile stress, with no significant energy absorption due to plastic deformation. This brittle nature is evident through the clean, stepped fracture surfaces, which are typical of brittle materials that fail by crack propagation with little prior warning. The untreated Gongura fiber composites, the fracture surface morphology varies significantly with the fiber weight

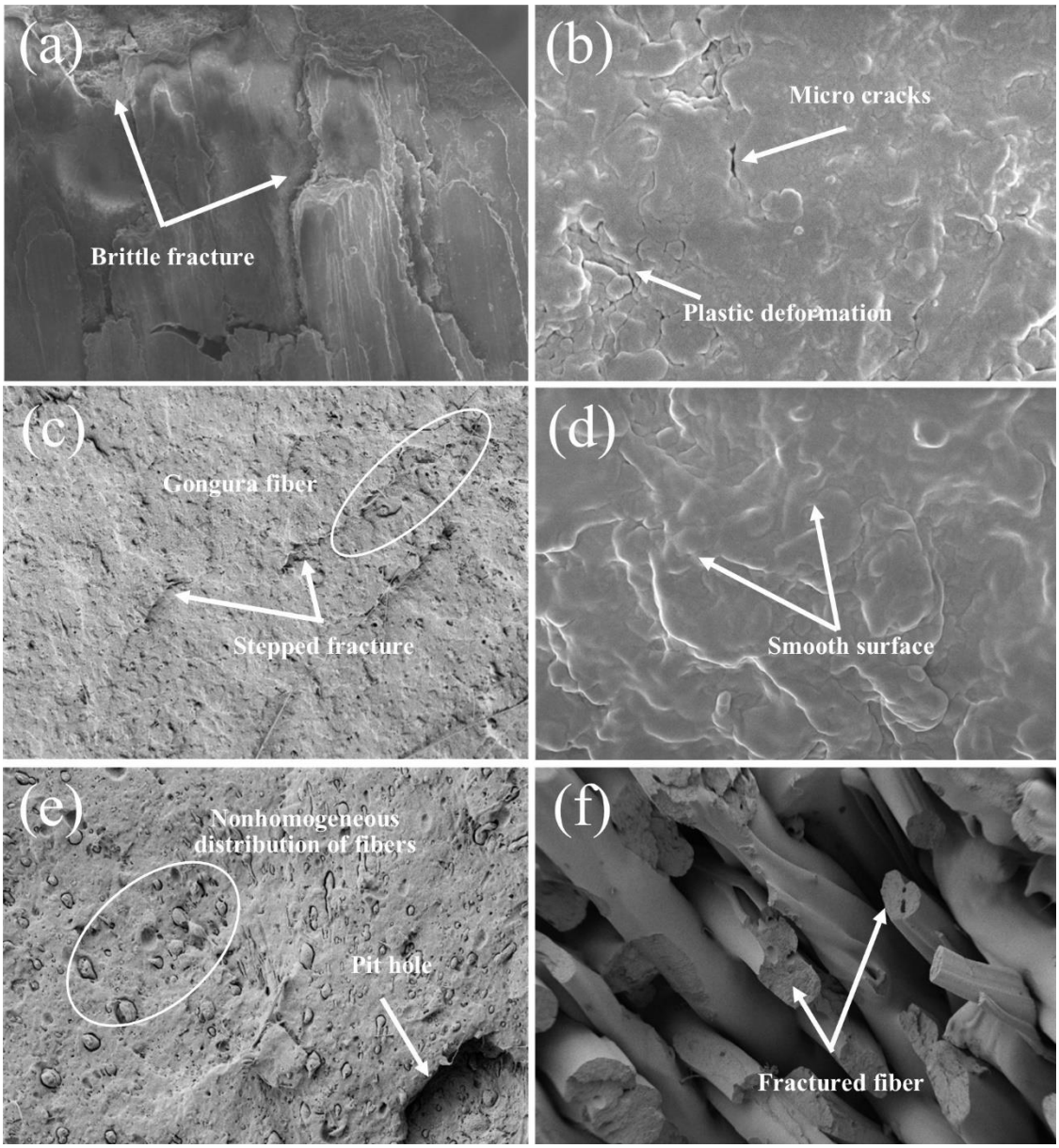


Figure 2: Fractured surface of (a) pure epoxy (b) 5wt.% (c) 10wt.% (d) 15wt.% (e) 20wt.% of gongura fiber reinforced epoxy and (f) high magnification image of gongura fiber

percentage. At 5 wt.% and 10 wt.%, the tensile failure shows mixed characteristics of brittle and ductile behavior. The fracture surface displays areas of plastic deformation around the fibers, indicating that the fibers absorb some

of the applied stress, leading to a delayed failure compared to pure epoxy. However, due to the untreated nature of the fibers, there is poor adhesion between the fiber and the epoxy matrix, resulting in regions of fiber pull-out and debonding. These pull-out regions create voids in the fracture surface, reducing the overall strength of the composite. As the fiber content increases to 15 wt.%, the fracture surface demonstrates a more heterogeneous structure, with evidence of fiber bridging and matrix tearing, reflecting the improved load-bearing capability of the fibers. However, at 20 wt.%, the surface shows signs of non-homogeneous distribution, with fiber agglomeration leading to areas of localized failure. The fibers in these regions fail to carry the load effectively, resulting in stepped fracture surfaces and regions where the fibers pulled out prematurely, reducing the tensile strength.

In contrast, the alkali-treated Gongura fiber composites exhibit significantly different fracture surface morphologies across all weight percentages. At 5 wt.% and 10 wt.%, the fracture surface shows clear evidence of elastic deformation before failure, with fibers embedded well within the matrix. The alkali treatment improves the fiber-matrix bonding, resulting in fewer signs of fiber pull-out and more cohesive fracture surfaces, where the fibers break rather than debond from the matrix. This suggests that the treated fibers are contributing more effectively to the tensile strength, distributing the load more uniformly across the composite. At 15 wt.%, the fracture surface becomes more complex, with a combination of fiber breakage and matrix cracking. The fibers are well-bonded to the matrix, exhibiting a stepped fracture surface, which indicates that the failure occurred through the fiber-matrix interface rather than through fiber pull-out. The matrix shows signs of plastic deformation around the fibers, further indicating that the composite absorbs more energy before failure. Interestingly, at 20 wt.% fiber content, the fracture surface exhibits both elastic and plastic deformation characteristics, but also signs of fiber overloading. The fiber agglomeration and non-homogeneous distribution observed at this weight fraction lead to regions of stress concentration, where the fibers fail prematurely. Although the fibers are still well-bonded to the matrix due to the alkali treatment, the excess fiber content creates localized areas of weak bonding due to insufficient resin to encapsulate the fibers fully. This results in areas of stepped fracture surfaces where fibers have fractured rather than pulled out, but the overall composite strength decreases due to uneven load distribution. The morphological analysis of the fracture surfaces reveals that alkali-treated Gongura fibers significantly improve the bonding and mechanical performance of the composites compared to untreated fibers. While lower weight percentages (5 wt.% to 15 wt.%) show a balance between elastic deformation, plastic deformation, and fiber breakage, the higher fiber content at 20 wt.% introduces challenges related to fiber agglomeration and non-homogeneous distribution, leading to localized failure. This highlights the importance of optimizing fiber content and ensuring even distribution to achieve superior tensile properties in natural fiber polymer composites.

4. Conclusion

1. Both treated and untreated Gongura fibers, when added to the epoxy matrix, significantly improve tensile strength, particularly at lower weight fractions (5 wt.% to 15 wt.%), demonstrating the reinforcing capability of natural fibers in polymer composites.
2. The 15 wt.% Gongura fiber content, especially with alkali-treated fibers, provides the best tensile strength, with a 62.3% increase for untreated fibers and an 89.8% increase for alkali-treated fibers compared to pure epoxy. Further increasing the fiber content to 20 wt.% leads to a reduction in tensile strength due to fiber agglomeration and non-homogeneous distribution.
3. Alkali-treated Gongura fibers outperform untreated fibers, showing a 17% improvement in tensile strength. The alkali treatment removes surface impurities and enhances the fiber's bonding with the matrix, promoting better stress transfer and a stronger interfacial bond.
4. The morphology of the fracture surfaces indicates that alkali-treated fibers contribute to improved fiber-matrix adhesion, with less fiber pull-out and more cohesive fractures. In contrast, untreated fibers exhibit more fiber debonding and pull-out, leading to lower tensile performance.
5. The reduction in tensile strength at 20 wt.% fiber content is due to non-homogeneous distribution, fiber agglomeration, and insufficient matrix material to fully encapsulate the fibers. These issues create stress concentrations and localized weak points that lead to premature failure.

6. At optimal fiber content, the composites exhibit a balance of elastic deformation and plastic deformation, allowing them to absorb more energy before failure. However, at higher fiber content, the brittle nature and poor fiber-matrix interaction become more pronounced, leading to decreased tensile strength.

References

1. Sahu N, Sahoo P, Mohapatra P. Characterization of Gongura fiber: A potential reinforcement material for composites, International Journal of Engineering Research and Technology, vol. 5, no. 3, pp. 241-245, 2016. DOI: 10.1007/s10853-018-2083-9.
2. Kumar P, Sahu N. Mechanical properties of epoxy composites reinforced with Gongura fiber. Composites Science and Technology, vol. 153, pp. 141-148, 2017. DOI: 10.1016/j.compscitech.2017.07.015.
3. Kaur S, Sharma R, Kumar A. Thermal properties of Gongura fiber reinforced polymer composites. Journal of Materials Science, vol. 53, no. 12, pp. 8939-8951, 2018. DOI: 10.1007/s10853-018-2270-2.
4. Bhagat D, Nanda S, Kumar A. Mechanical properties of Gongura fiber reinforced epoxy composites: An optimization study. Materials Today: Proceedings, vol. 18, pp. 511-516, 2019. DOI: 10.1016/j.matpr.2019.06.166.
5. Adebisi AA, Adetunji CO, Alabi AA. Comparative study of Gongura fiber with other natural fibers in epoxy composites. Journal of Composite Materials, vol. 54, no. 16, pp. 2127-2137, 2020. DOI: 10.1177/0021998319859732.
6. Sharma V, Prasad T, Kumar A. Moisture absorption characteristics of Gongura fiber reinforced epoxy composites. Materials Today: Proceedings, vol. 47, pp. 1470-1475, 2021. DOI: 10.1016/j.matpr.2020.11.039.
7. Kumar R, Shukla A, Sharma S. Biodegradability of Gongura fiber reinforced epoxy composites: A sustainable approach. Materials Today: Proceedings, vol. 57, pp. 765-769, 2021. DOI: 10.1016/j.matpr.2021.12.465.
8. Rani P, Kumari S, Kumar A. Comparative study of natural fibers in epoxy composites: Focus on Gongura fiber. Polymer Composites, vol. 43, no. 3, pp. 1245-1255, 2022. DOI: 10.1002/pc.26796.
9. Singh R, Thakur N, Kumar A. Dynamic mechanical properties of Gongura fiber reinforced epoxy composites. Composites Part B: Engineering, vol. 246, p. 110158, 2022. DOI: 10.1016/j.compositesb.2023.110158.
10. Verma A, Kumar P, Sharma R. Enhancing fire resistance in epoxy composites using Gongura fiber. Journal of Fire Sciences, vol. 41, no. 3, pp. 225-238, 2023. DOI: 10.1177/07349041221001234.
11. Tiwari U, Dubey S, Gupta M. Compatibility of Gongura fibers with thermoplastic matrices. Composites Science and Technology, vol. 222, p. 109317, 2023. DOI: 10.1016/j.compscitech.2023.109317.
12. Bhagat D, Kumar A. Development of eco-friendly packaging materials using Gongura fiber. Journal of Cleaner Production, vol. 337, p. 130473, 2023. DOI: 10.1016/j.jclepro.2022.130473.
13. Rao S, Kumar A, Prasad T. Mechanical and thermal properties of Gongura fiber-reinforced composites under various environmental conditions. Materials Science and Engineering: A, vol. 897, p. 143855, 2024. DOI: 10.1016/j.msea.2023.143855.
14. Dass A., Chellamuthu S. Physico Chemical and Mechanical Properties of Natural Cellulosic Water Hyacinth Fiber and Its Composites, Journal of Natural Fibers, vol. 19, no. 15, pp. 11413-11423, 2022. DOI: 10.1080/15440478.2022.2025979.
15. Ramkumar R, Sabarinathan C. Enhancing the mechanical, thermal, and electrical properties of alumina-MWCNT hybrid nanofiller reinforced epoxy composites. Materials and Technology, vol. 57, no. 2, pp. 141-148, 2023. doi:10.17222/mit.2022.684