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Enhancing carbon fiber composites with fish scale biochar for superior strength and environmental sustainability

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ABSTRACT

There is a pressing need to develop carbon fiber composites with sustainable fillers that enhance their strength without increasing costs or environmental impact. Such advancements would not only improve performance in high-stress applications but also align with global sustainability goals by utilizing eco-friendly materials and reducing waste. This study explores the use of biochar derived from fish scales as a sustainable filler material in carbon fiber epoxy composites. The biochar was produced through pyrolysis and incorporated into the composites at various weight percentages (0 %, 1 %, 3 %, 6 %, 9 %, 12 %, and 15 %). Mechanical properties, including tensile strength, flexural strength, impact strength, and interlaminar shear strength, were evaluated according to ASTM standards. The results demonstrated that the incorporation of biochar significantly improved the mechanical properties of the composites, with optimal performance observed at 9 % biochar content. At this concentration, the tensile strength increased by 60.02 %–674.21 MPa, the tensile modulus by 74.96 % to 46.05 GPa, the flexural modulus by 58.32 GPa, and the impact strength reached 102.32 kJ/m^2. It was found that achieving the optimal performance requires an optimal weight percentage of biochar. This study highlights the potential of fish scale-derived biochar as an effective and sustainable filler material for enhancing the performance of carbon fiber composites.

1. Introduction

In light of the world's current environmental challenges, sustainable development has emerged as an urgent priority. Materials chosen for specific applications have a significant impact on environmental pollution and degradation (Salvia et al., 2019). The global demand for lightweight materials in industries such as aerospace, automotive, and construction has resulted in the widespread use of synthetic fiber composites such as carbon fiber and glass fiber composites (Arunachalam et al., 2025). While these materials have higher strength-to-weight ratios and perform better, their production and disposal cause significant environmental problems (Singh et al., 2017). The carbon footprint associated with producing carbon fiber composites is significantly high, notably manufacturing carbon fiber requires around 198–595 MJ/kg of energy, which is about ca.10 times higher than the energy required to produce other types of synthetic fiber composites such as glass fiber (J. Zhang et al., 2020). This is also significantly high when compared to steel production, where the energy consumption is typically in the range of 20–30 MJ/kg (Khayyam et al., 2021). Furthermore, because these materials are not biodegradable, disposal is also difficult. Currently, less than 15 % of CFRP scrap is recycled, leaving about 85–95 % to be landfilled or incinerated. This trend highlights a significant waste management challenge, especially as CFRP usage continues to rise steadily ("LIFE 3.0 - LIFE20 ENV/DE/000312," n.d.). In the long term, it is projected that the aerospace sector alone will generate between 4500 and 6800 tonnes of CFRP scrap annually, with over 8500 end-of-life

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aircraft expected to be dismantled, adding to the volume of CFRP waste in need of sustainable disposal solutions (Chen et al., 2023). The Carbon Fiber Market, valued at USD 6.4 billion in 2024, is projected to exceed USD 24.56 billion by 2037, reflecting a compound annual growth rate (CAGR) of over 10.9 % from 2025 to 2037 ("Carbon Fiber Market Size, Share Growth Forecasts, 2037," n.d.). This growth is driven by advancements in the civil construction and building, automotive, aerospace, defence, and wind energy sectors (Sathish et al., 2025b). This trend exacerbates environmental concerns, such as resource depletion, greenhouse gas emissions, and waste management issues (Q. Zhang et al., 2020). This created a critical need for more sustainable alternatives, such as bio-based fillers, that can reduce the environmental impact of synthetic composites while maintaining and improving mechanical performance (Sathish et al., 2025a). Integrating bio-fillers into these composites can significantly reduce their environmental footprint, improve recyclability, and provide a path towards more sustainable production methods. To address these challenges, integrating bio-based fillers has emerged as a promising approach. Bio-fillers can reduce the environmental impact of synthetic composites while maintaining or improving their mechanical properties (Vinod et al., 2020). Carbon fiber composites, known for their exceptional strength-to-weight ratio, stiffness, and corrosion resistance, are widely used in applications requiring durability under extreme mechanical stress, such as in aerospace and automotive industries (Zhang et al., 2023). Reinforcing these composites with suitable fillers can further enhance their tensile strength, impact resistance, and fatigue performance, resulting in safer, more durable components (Higuchi et al., 2020). However, choosing the right filler material is essential; it should not only improve performance but also align with sustainability goals (Koyanagi et al., 2019). While bio-fillers offer a sustainable alternative, natural biomass fillers can compromise composite strength under humid conditions due to water absorption (Kang et al., 2010). Biochar presents a viable solution as it is sustainable, cost-efficient, and can even improve mechanical properties while lowering overall costs (Cuthbertson et al., 2019). This work explores the use of biochar derived from fish scales as a filler in carbon fiber composites. Incorporating fish-scale biochar not only recycles waste but also reduces the environmental footprint of composite production, aligning with global sustainability goals and meeting the rising consumer demand for eco-friendly products.

Biochar stands out as a promising solution due to its carbon-rich composition and the diverse benefits it offers (Zhang et al., 2022). Produced through the pyrolysis of organic matter, biochar has a highly porous structure and a large surface area, making it useful in several applications. Its role in carbon sequestration is particularly noteworthy, as biochar can lock away carbon that would otherwise contribute to atmospheric CO_2 levels (Li et al., 2020). This characteristic aligns well with global efforts to mitigate climate change (Yang et al., 2021). Moreover, biochar's application in soil amendment has been extensively studied. It enhances soil fertility, improves water retention, and promotes microbial activity (Matuštík et al., 2020). However, its potential as a filler material in composites is a relatively new and exciting development. When incorporated into composite materials, biochar can enhance mechanical strength, thermal stability, and even provide flame retardant properties (Sundarakannan et al., 2022). These attributes make biochar an attractive component for high-performance composites. For instance, in the investigation by (Das et al., 2021) it was reported that the incorporation of biochar into polymer matrices significantly improved the tensile strength of the composites by 12.6 %. Another study by (Kane et al., 2022) demonstrated that biochar-filled composites exhibited enhanced impact resistance, with an increase of 40 % compared to unfilled composites, highlighting biochar's multifunctional role in composite materials. These findings suggest that biochar can effectively enhance the mechanical performance of carbon fiber composites, making it a valuable addition to various high-performance applications.

The seafood industry generates a significant amount of waste, including fish scales. Typically considered a nuisance, fish scales are often discarded, leading to environmental pollution. Fish scales are an abundant biowaste by-product of the seafood processing industry, typically disposed of without further utilization. Pyrolysis transforms this waste into biochar, thereby mitigating environmental pollution and promoting circular economy principles by converting a low-value waste into a value-added product. Moreover, fish scale biochar possesses elevated carbon content, intrinsic mineral constituents (including hydroxyapatite), and a porous microstructure, which can enhance the mechanical reinforcement of polymer composites. Fish scale biochar is more competitive than other bio-fillers such as nutshells, wood powder, or agricultural waste-based biochars due to its availability in coastal regions, reduced feedstock costs, and inherent microstructure that facilitates mechanical interlocking with polymer matrices. However, these scales are composed of valuable materials such as collagen and hydroxyapatite (Qin et al., 2022). Collagen provides a natural source of carbon, while hydroxyapatite, a mineral, offers additional structural benefits. Utilizing fish scales to produce biochar not only addresses the waste problem but also taps into a resource with unique properties (Bhattacharya et al., 2024). Integrating fish scale-derived biochar into carbon fiber composites presents a novel approach to material development. By incorporating biochar, particularly from fish scales, into these composites, it is possible to enhance their properties while also introducing sustainability into the equation. The synthesis of biochar from fish scales involves pyrolysis, a thermal decomposition process conducted in an inert atmosphere (Lv et al., 2021). This process transforms the organic components of the scales into biochar while preserving the beneficial properties of collagen and hydroxyapatite (Othmani et al., 2021).

This study aims to thoroughly investigate the feasibility and benefits of incorporating fish scale-derived biochar into carbon fiber composites. The research is structured around several key objectives: developing an optimized pyrolysis process for converting fish scales into high-quality biochar, conducting detailed analyses to understand the physical, chemical, and structural properties of the biochar, exploring methods for uniformly dispersing biochar within carbon fiber matrices to ensure optimal performance, and assessing the mechanical and morphological properties of the biochar-enhanced composites through rigorous testing. The significance of this research extends beyond the immediate benefits of improved composite materials. By repurposing fish scales into valuable biochar, this study addresses several sustainability challenges simultaneously. First and foremost, it contributes to waste reduction by transforming an abundant and problematic byproduct into a valuable resource. Secondly, the integration of biochar into carbon fiber composites enhances the sustainability of these materials. Moreover, the insights gained from this research could pave the way for broader applications of biochar in various composite systems. By examining the mechanical, and morphological characteristics of these biochar-enhanced composites, this work seeks to establish a foundation for the development of environmentally friendly and high-performance materials. While this study focuses on carbon fiber composites, the principles and techniques developed here could be adapted for other types of composites, such as glass fiber or natural fiber composites.

2. Materials and methods

2.1. Fish scale

Fish scales (Fig. 1a) of various species and sizes were collected from the Vanagaram fish market in Chennai, India.

2.2. Epoxy resin

The epoxy resin (Fig. 1b) used in this study was purchased from Vasavi Bala Resin, Chennai, India. The epoxy's product code is VBR 8912. The resin is a mildly yellow clear liquid with a density of

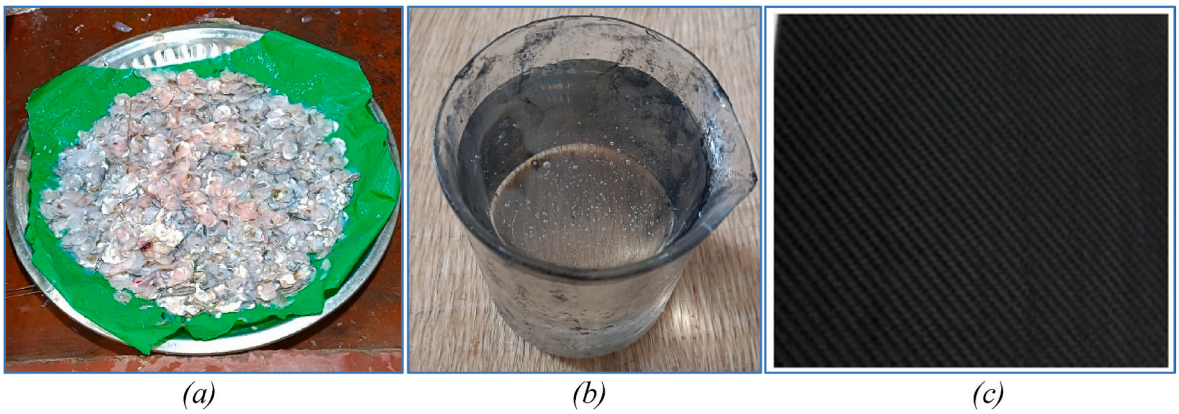

Fig. 1. (a) Fish scales, (b) Epoxy resin, and (c) Bi-directional carbon-fiber fabric/mat.

1.15–1.18 g/ml and a viscosity at 25 °C ranging from 11,000 to 15,000 MPa.

2.3. Bi-directional carbon-fiber fabric/mat

Bi-directional carbon fiber (Fig. 1c) in the form of a woven mat was procured from Marktech Composites, Bangalore, India. The carbon-fiber fabric is a woven type with a plain pattern, a GSM range of 200, and a twill weave structure.

2.4. Fish scale biochar production process

Fig. 2 illustrates the process of producing biochar from fish scales. Fish scales were collected and thoroughly rinsed with distilled water to remove any residual tissue and contaminants. After cleaning, the scales were dried on a tray in an oven at 60 °C until they were completely moisture-free. The dried scales were then placed in a pyrolysis reactor (Fig. 3), a metal container with a tight-fitting lid, ensuring an airtight environment to prevent oxygen entry. The reactor was gradually heated using a furnace to a temperature of 600 °C, which was maintained for 3 h, allowing the organic material in the fish scales to decompose into biochar. Following the pyrolysis process, the reactor was allowed to cool naturally to room temperature, and once cooled, it was opened to collect the resulting biochar, which was characterized by its black and porous particles. The biochar was then processed further by ball milling into a fine powder and sieved to achieve a consistent particle size of less than 3 mm, making it suitable for composite fabrication (Fig. 4). Notably, the fish-scale biochar was utilized as a filler in carbon epoxy composite preparation, where its porous and carbon-rich properties contributed to enhancing the mechanical and thermal properties of the resulting material.

After the ball milling process, the fish scale biochar is analyzed using Scanning Electron Microscopy (SEM), as shown in Fig. 5.

2.5. Carbon-fiber fabric – biochar composite fabrication

Carbon-fiber fabric–biochar composites were fabricated using the compression molding process (Fig. 6) using a compression molding

Fig. 3. Muffle furnace used as a pyrolysis reactor.

Fig. 4. Biochar: powder form.

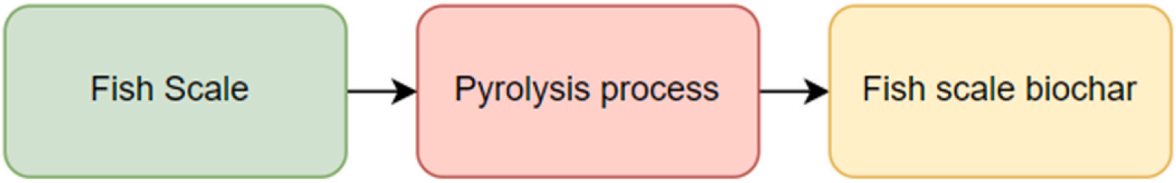

Fig. 2. Fish scale biochar production process.

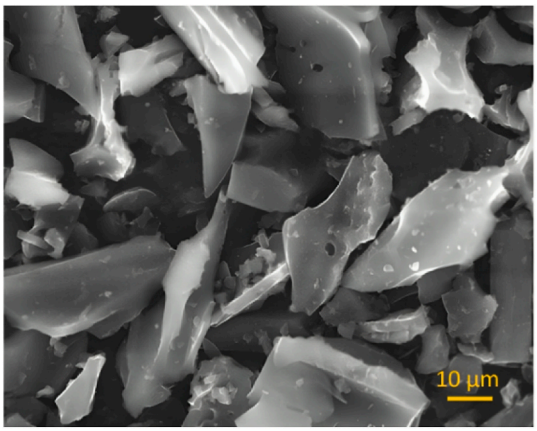

Fig. 5. SEM image of fish scale biochar after the ball milling process.

machine (Fig. 7). Initially, epoxy resin and hardener were mixed in a weight ratio of 10:1 to ensure robust chemical bonding and structural integrity. Various weight percentages of biochar (0 %, 1 %, 3 %, 6 %, 9 %, 12 %, and 15 % by weight) were added to the epoxy resin mixture while maintaining a constant weight percentage of 50 ± 2 % carbon fibers across all formulations. Table 1 presents the weight fraction of carbon fiber, biochar and epoxy resin.

In the compression molding process, the resin-biochar-carbon fiber mixture was carefully applied layer by layer into a steel mold cavity. Each layer of fiber was impregnated with the epoxy biochar solution, and excess resin was removed by rolling with a roller to prevent bubble formation. Once all layers were coated and rolled, the mold was sealed with a die. The mold was then subjected to a controlled pressure of 50 MPa and temperature of 80 °C for curing over a period of 30 min. After curing, the temperature was gradually reduced and maintained at room temperature to stabilize the composite structure. After 24 h of curing, the composite was demoulded and underwent post-processing steps to achieve final dimensions and surface finishes suitable for their intended testing. Fig. 2 shows the methodology for preparing fish waste-filled carbon fiber epoxy composites.

2.6. X-ray diffraction (XRD) analyses

The X-ray diffraction (XRD) analyses were performed using a Bruker D8 AD-VANCE diffractometer (see Fig. 8), employing the refraction method with nickel-filtered CuKα radiation (λ = 1.54 Å).

This experimental configuration was selected to ensure precise and accurate measurements of diffraction patterns, thereby facilitating the reliable characterization of the crystalline structures present in the composite materials. The analysis of the resulting diffraction patterns provided detailed insights into the arrangement and orientation of the crystalline phases within the composites, which is essential for understanding their mechanical and thermal properties. The Bruker RFS 27 multi-RAM FT Raman spectrometer was utilized to perform Raman spectroscopy on the biochar sample. The system employed a Nd laser operating at a wavelength of 1064 nm as the excitation source. The scattered light was detected using a liquid nitrogen-cooled ultra-high

Fig. 7. Compression molding machine.

Table 1
Comparison of carbon-based fillers in carbon fiber composites.

Carbon fiber (wt.)	Biochar (wt.)	Epoxy Resin (wt.)
50 %	0 %	50 %
50 %	1 %	49 %
50 %	3 %	47 %
50 %	6 %	44 %
50 %	9 %	41 %
50 %	12 %	38 %
50 %	15 %	35 %

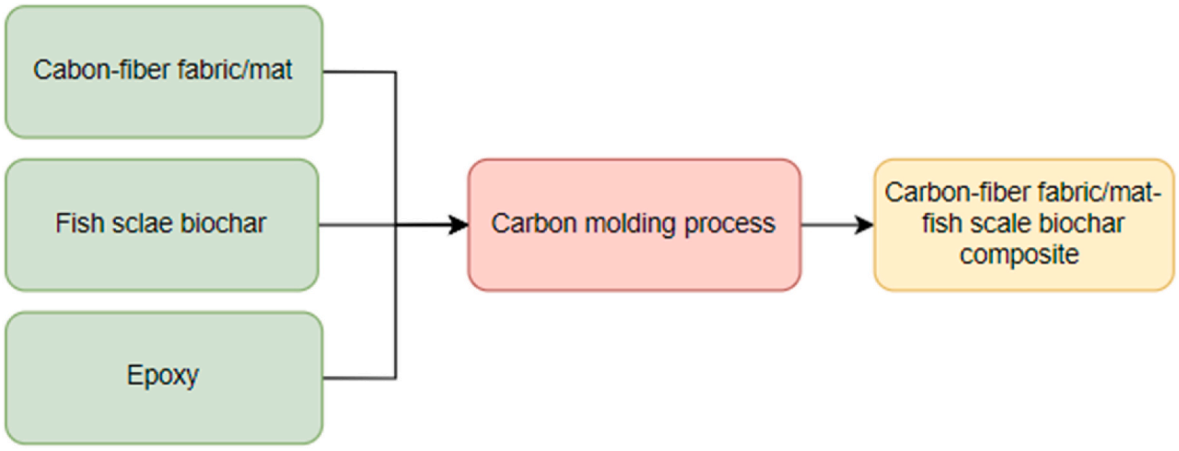

Fig. 6. Carbon-fiber fabric/mat-fish scale biochar composite fabrication process.

Fig. 8. Bruker D8 AD-VANCE diffractometer.

sensitivity germanium (Ge) detector. The spectral measurements were conducted across a range of 1000–1800 cm^{-1}, providing detailed insights into the vibrational modes of the biochar material.

2.7. Mechanical properties and standards used

The mechanical properties of epoxy carbon fiber composites containing varying percentages of biochar (0 %, 1 %, 3 %, 6 %, 9 %, 12 %, and 15 % by weight) were evaluated following ASTM standards. While the tensile strength was assessed using ASTM D3039/D3039M (Armynah et al., 2018), with specimens tested using a universal tensile tester machine (Fig. 9) at a speed of 2 mm/min at room temperature (25 °C). Flexural strength was measured according to ASTM D7264/D7264M (Armynah et al., 2018), employing a testing speed of 5 mm/min and supporting the specimen span per standard guidelines. Impact strength, tested via ASTM D256/D256M (Kim et al., 2012) with Charpy V-notch specimens, utilized a hammer velocity of 3.5 m/s at 23 °C. Interlaminar shear strength (ILSS) was determined using ASTM D2344/D2344M, employing a double cantilever beam setup at 0.5 mm/min and at room temperature (25 °C).

Notably, the mechanical test was conducted on a set of 3 samples, and the average values obtained from these tests were reported in the result section. The standard deviation method was used to calculate the error to represent the variability in the data. Error bars in the figures reflect a 5 % deviation from the mean values. These error bars provide a clear visual representation of the statistical variation in the measured mechanical properties.

3. Results and discussion

3.1. X-ray diffraction (XRD) and Raman shift

Fig. 10 shows the X-ray diffraction (XRD) analysis of the fish scale biochar. That pattern shows that the biochar predominantly exhibits an amorphous structure.

This is evidenced by a broad hump in the 2θ range between 20° and 30°, which is typical of amorphous carbon structures. This can be confirmed by the investigation of (Kim et al., 2012). The absence of sharp, well-defined peaks throughout the pattern indicates that there are no significant crystalline phases, such as graphite, present in the biochar. There are no distinct peaks indicating the presence of mineral impurities. These findings confirm that the fish scale biochar is primarily composed of non-crystalline carbon.

The Raman spectrum of the fish scale biochar exhibits two prominent bands: the D band at approximately 1350 cm^{-1} and the G band around 1580 cm^{-1}. The D band, associated with disordered carbon and structural defects, is notably more intense than the G band, which corresponds to the graphitic structure and in-plane stretching of sp^2 carbon-carbon bonds. This higher intensity of the D band indicates a significant degree of disorder within the biochar's carbon structure. The broad nature of both the D and G bands suggests limited crystalline order, reinforcing the conclusion that the biochar is predominantly amorphous. These findings are consistent with the XRD analysis, which also indicated an amorphous carbon structure with minimal crystalline phases. Thus, the Raman analysis confirms that the fish scale biochar is characterized by a high concentration of structural defects and amorphous carbon, with small, disordered graphitic domains. This structural

Fig. 9. (a) Universal tensile tester machine, and (b) Zoomed view of the testing carbon fiber-fish scale biochar composite sample.

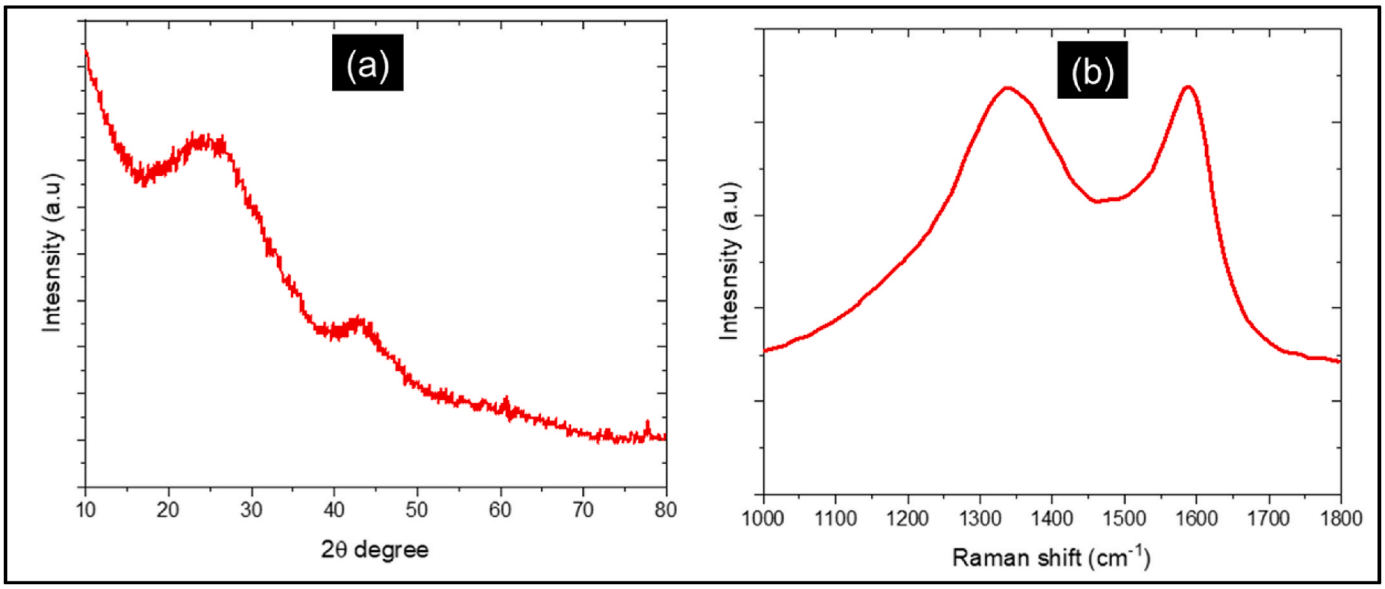

Fig. 10. (a) XRD analysis and (b) Raman shift analysis of fish scale biochar.

disorder is typical for biochars derived from organic materials through pyrolysis. The results agree with the Raman shift findings of (He et al., 2023), both of whom reported similar structural characteristics in their studies on biochar. Specifically, He et al. observed a high intensity ratio indicative of significant structural disorder in biochar derived from agricultural residues and fish scales. Similarly (Dou et al., 2022), reported prominent D and G bands in biochar, highlighting the amorphous nature and presence of defects.

3.2. *Tensile strength of fish scale biochar filled carbon epoxy composites*

The tensile strength and tensile modulus of carbon fiber composites were systematically investigated with varying percentages of biochar to evaluate the impact of biochar incorporation on the tensile strength (Fig. 11a) and modulus (Fig. 11b) of the composites.

It has been observed that the incorporation of biochar into carbon fiber composites can significantly enhance their mechanical properties, with the optimal biochar content for achieving maximum tensile modulus and tensile strength identified as 9 %. At this concentration, the composite exhibited a tensile modulus of 46.05 GPa and a tensile strength of 674.21 MPa, demonstrating the potential of biochar as an effective filler material for improving the performance of carbon fiber composites.

The incorporation of biochar into carbon fiber epoxy composites has a noticeable impact on tensile properties. Biochar acts as a reinforcing filler that enhances load-bearing capabilities due to its porous structure and high surface area. At lower concentrations, the biochar particles are well dispersed within the matrix, which promotes effective interfacial bonding between the biochar and the epoxy. This improved bonding aids in stress distribution across the composite material, reducing

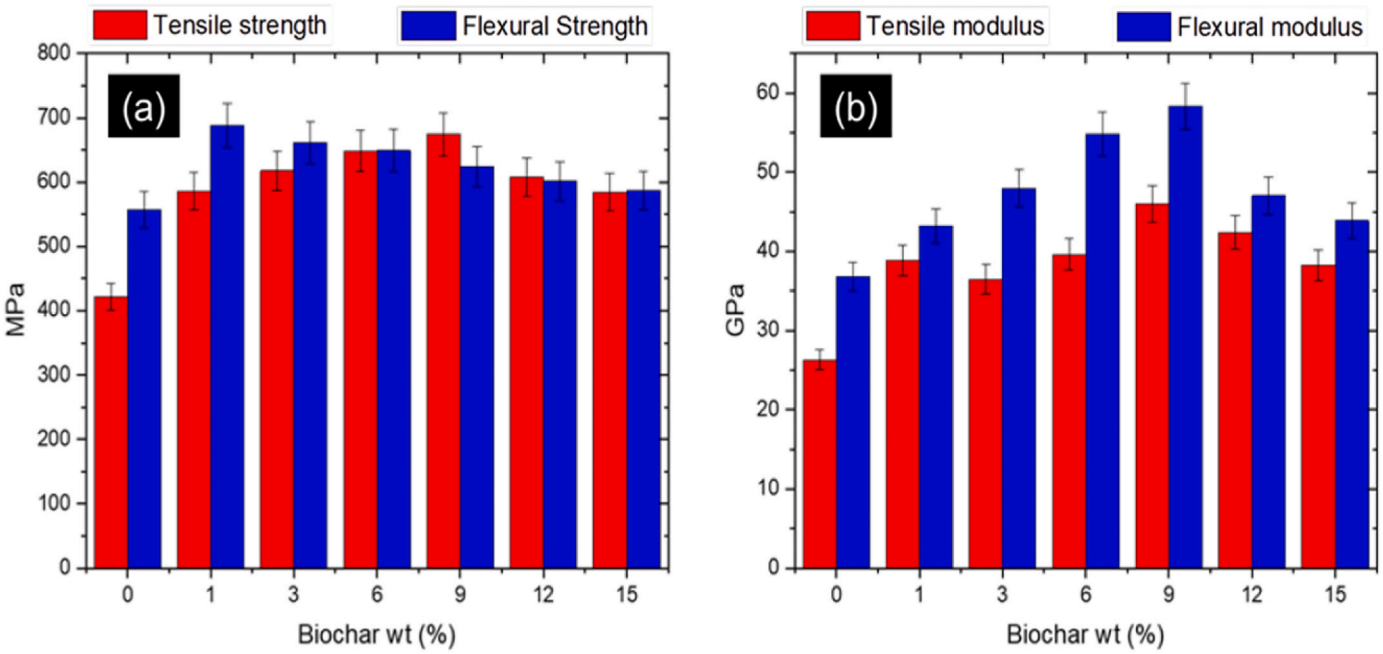

Fig. 11. (a) Tensile, flexural strength and (b) Tensile, flexural modulus analysis of fish scale biochar composites.

localized stress concentrations and improving the composite's overall tensile strength and modulus.

The optimal tensile properties are observed at 9 % biochar content, where the tensile strength reaches a peak. This enhancement can be attributed to the efficient load transfer from the epoxy matrix to the biochar particles, facilitated by their strong interfacial adhesion. The porous nature of biochar likely promotes a mechanical interlocking mechanism within the matrix, which further contributes to the composite's ability to resist tensile forces.

However, beyond this optimal content (above 9 %), a reduction in tensile properties is observed. This decrease can be explained by the tendency of biochar particles to agglomerate at higher loadings. Agglomeration, or clustering of biochar particles, disrupts the uniform dispersion within the matrix, creating stress concentration points where cracks can initiate under tensile load. These stress concentration points impair the load transfer efficiency between the biochar particles and the epoxy, as the agglomerated regions serve as weak zones that are more susceptible to crack propagation. Additionally, the larger clusters of biochar reduce the effective bonding surface area between the particles and the matrix, further weakening the composite's overall structural integrity.

This trend aligns with other studies on particulate fillers in composite materials, which indicate that while low to moderate filler contents enhance mechanical performance, excessive filler concentrations often lead to particle-particle interactions that detract from composite strength. Thus, for biochar-carbon fiber composites, an optimal balance in biochar content is crucial to maximize tensile properties without triggering detrimental effects from particle agglomeration. Future studies may consider approaches like particle surface modification or advanced dispersion techniques (e.g., ultrasonication) to prevent agglomeration and retain mechanical improvements at higher biochar loadings.

The flexural properties of carbon fiber composites were evaluated with varying percentages of biochar, revealing significant improvements in both flexural strength and flexural modulus. At 0 % biochar content, the flexural strength and modulus were recorded at 557.27 MPa and 36.78 GPa, respectively. Introducing 1 % biochar into the composite significantly enhanced its flexural strength by approximately 23.4 %–687.65 MPa and increased its flexural modulus by about 17.4 %–43.18 GPa. This notable improvement can be attributed to the effective dispersion of biochar particles within the epoxy matrix, which enhances load transfer and increases the overall stiffness of the composite. With a biochar content of 3 %, the flexural strength decreased slightly by 3.8 %–661.63 MPa compared to the 1 % biochar composite, while the flexural modulus continued to increase, reaching 47.98 GPa, representing an increase of approximately 11.1 %. The slight reduction in flexural strength at 3 % biochar content might be due to the onset of particle agglomeration, which can create localized stress concentrations. At 6 % biochar content, the composite exhibited a flexural strength of 649.15 MPa and a flexural modulus of 54.84 GPa, indicating a further increase of 14.3 % in modulus compared to the 3 % biochar composite.

This continued improvement in modulus highlights the reinforcing effect of biochar particles, which contribute to the overall rigidity of the composite. The highest flexural modulus was observed at 9 % biochar, measuring 58.32 GPa, representing an increase of approximately 8.6 % from the 6 % biochar composite. However, the flexural strength at this concentration slightly decreased to 623.73 MPa, a reduction of 3.9 % compared to the 6 % biochar composite. This decrease in strength may be due to the increased likelihood of biochar particle agglomeration at higher concentrations, which can weaken the composite structure by creating stress concentration points. Beyond 9 % biochar content, the flexural properties showed a noticeable decline. At 12 % biochar content, the flexural strength was 601.13 MPa, a decrease of 3.6 % from the 9 % biochar composite, and the flexural modulus dropped to 47.04 GPa, representing a reduction of 19.4 %. Finally, at 15 % biochar, the flexural strength and modulus further decreased to 587.08 MPa and 43.87 GPa, respectively, showing reductions of 2.3 % and 6.7 %. Fig. 4 presents the results for tensile strength, flexural strength, and their respective modulus values.

The observed enhancements in flexural properties with increasing biochar content can be attributed to several factors. Biochar's high surface area and porous structure facilitate strong interfacial bonding with the epoxy matrix, leading to better stress distribution and increased resistance to bending forces. Additionally, biochar's inherent stiffness contributes to the overall rigidity of the composite. However, beyond 9 % biochar content, the tendency of biochar particles to agglomerate becomes more pronounced, leading to the formation of stress concentration points that can adversely affect the mechanical performance of the composite. Despite the slight reduction in flexural properties at higher biochar contents, the composites with biochar still demonstrated superior performance compared to the baseline composite without biochar.

3.3. Impact of fish scale biochar filled carbon epoxy composites

The impact strength of biochar carbon fiber composites is shown in Fig. 12. It is noted that the 0 % biochar composite's impact strength was 71.87 kJ/m^2, which was increased after the biochar addition similar as that of the tensile and flexural strength.

Addition of 1 % biochar resulted in a substantial increase in impact strength, indicating a notable improvement of approximately 19.8 %. This enhancement is likely due to the initial reinforcement provided by the biochar particles, which facilitate better energy absorption during impact. When the biochar content was increased to 3 %, the impact strength further improved to 91.72 kJ/m^2, demonstrating an additional enhancement of 6.6 %, and at 6 % biochar, the impact strength reached 96.51 kJ/m^2, reflecting a continued upward trend with a 5.2 % increase from the previous increment. The highest impact strength was observed at 9 % biochar content, achieving 102.32 kJ/m^2. However, further increases in biochar content led to a decline in impact strength. At 12 % biochar, the impact strength decreased to 95.52 kJ/m^2, a reduction of 6.7 % from the peak value. The trend continued with 15 % biochar, where the impact strength dropped to 90.82 kJ/m^2, showing a further decrease of 4.9 %. Despite the reduction in impact strength at higher biochar contents, composites with biochar still outperformed the baseline composite. The results indicated that the impact strength, similar to the tensile and flexural strength, decreased after the biochar content exceeded 9 wt%. Despite the different failure mechanisms observed under each testing condition, the results consistently showed a reduction in mechanical performance beyond this threshold. This led to the

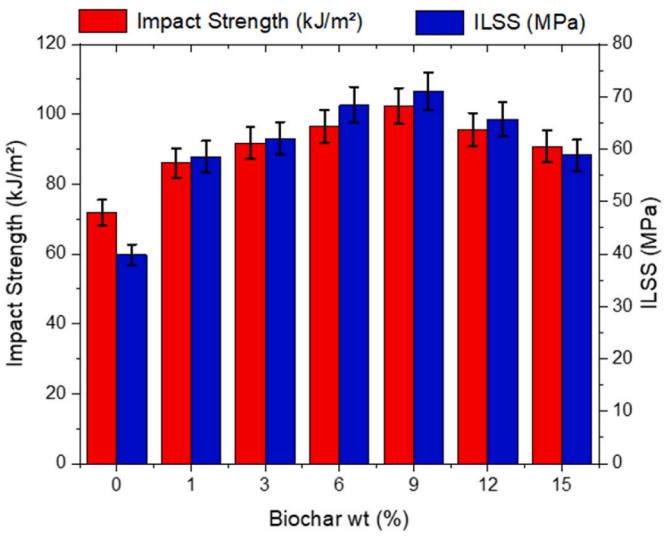

Fig. 12. Impact strength and ILSS analysis of fish scale biochar composites.

conclusion that biochar concentrations above 9 wt% adversely affect the composite's integrity. The increased biochar content likely caused particle agglomeration, which introduced stress concentration points and disrupted the uniform stress distribution within the composite matrix. Consequently, this reduced the composite's stress-carrying ability, leading to diminished strength. Additionally, the excessive biochar may have compromised the interfacial bonding between the biochar particles and the epoxy matrix, further contributing to the observed reduction in mechanical properties.

The Interlaminar Shear Strength of biochar carbon fiber composites is presented in Fig. 12 revealing a trend similar to that observed in the tensile, flexural, and impact strength tests. At 0 % biochar content, the ILSS was measured at 39.82 MPa. Incorporating 1 % biochar significantly increased the ILSS to 58.61 MPa, representing an improvement of approximately 47.2 %. With 3 % biochar, the ILSS further increased to 62.07 MPa, demonstrating an additional enhancement of 5.9 %. The highest ILSS was observed at 9 % biochar content, achieving 70.98 MPa, which corresponds to a 3.7 % increase from the 6 % biochar composite. However, beyond 9 % biochar content, the ILSS began to decline. At 12 % biochar, the ILSS decreased to 65.73 MPa, a reduction of 7.4 % from the peak value, and at 15 % biochar content, the ILSS further dropped to 58.85 MPa, indicating a reduction of 10.5 %. These results are consistent with the observations from tensile, flexural, and impact strength tests, where the mechanical properties improved with increasing biochar content up to 9 % but declined beyond this point. The reduced bonding effectiveness is evident in the similar trends observed across all mechanical tests, underscoring the critical role of optimal biochar dispersion and content in maintaining composite performance.

3.4. Fracture analysis fish scale biochar filled carbon epoxy composites

The SEM images presented in Fig. 13 provides critical insights into the failure mechanisms observed in the 12 and 15-wt.% carbon fiber and biochar-filled epoxy composites.

Fig. 13 (a) revealed fibers protruding from the fractured surface accompanied by matrix cracking, indicative of fiber pull-out and matrix cracking as primary failure mechanisms. Fiber pull-out occurred when the interfacial bonding between the fibers and the epoxy matrix was insufficient, resulting in fibers being extracted rather than fracturing. Meanwhile, the matrix cracking indicated brittle failure within the epoxy matrix itself, likely due to stress concentrations or inadequate toughness. Fig. 13 (b) corroborated these observations, showing a noticeable crack traversing the composite, which further emphasized the poor load transfer between the matrix and fibers, leading to cohesive matrix failure and fiber-matrix debonding.

Fig. 13 (c) displayed aligned fibers with clean surfaces, suggesting minimal matrix adhesion and pointing to fiber-matrix debonding as the dominant failure mechanism. This debonding occurred when the interfacial bond strength was inadequate to facilitate effective load transfer, causing fibers to separate from the matrix without substantial damage to the fibers themselves. Fig. 13 (d) revealed significant particle agglomeration within carbon fiber and biochar-filled epoxy composites, characterized by clusters of particles and fibers. This clustering suggested insufficient dispersion techniques and strong inter-particle attractions, such as van der Waals forces, leading to stress concentration sites within the composite material. The irregular interface between the particles/fibers and the epoxy matrix indicated poor interfacial bonding, which resulted in weak spots where stress was not effectively transferred. Additionally, voids around agglomerated particles further weakened the composite by providing pathways for crack initiation and propagation under mechanical stress.

The cause of agglomeration was due to the inadequate dispersion methods at higher wt.% of biochar i.e 12 and 15 wt%. This agglomeration negatively impacted the composite's mechanical properties by creating local stress concentrations that decreased tensile strength, impact resistance, and toughness. To mitigate agglomeration, strategies such as surface modification of particles to enhance compatibility with the epoxy matrix, advanced dispersion techniques like ultrasonication and high-shear mixing, optimized processing conditions, and the use of hybrid fillers should be employed. Addressing particle agglomeration is crucial for improving the performance and reliability of carbon fiber and biochar-filled epoxy composites.

3.5. Discussion

The discussion highlights the Synergistic Role of the hybrid composites carbon fiber and biochar. Carbon fiber, with its high tensile strength and modulus, serves as the backbone, enhancing strength, stiffness, and load-bearing capacity by effectively transferring applied loads and resisting deformation. Biochar, as a secondary reinforcement, improves mechanical properties by filling voids, reducing shrinkage, and enhancing matrix-filler bonding. At an optimal 9 % weight fraction,

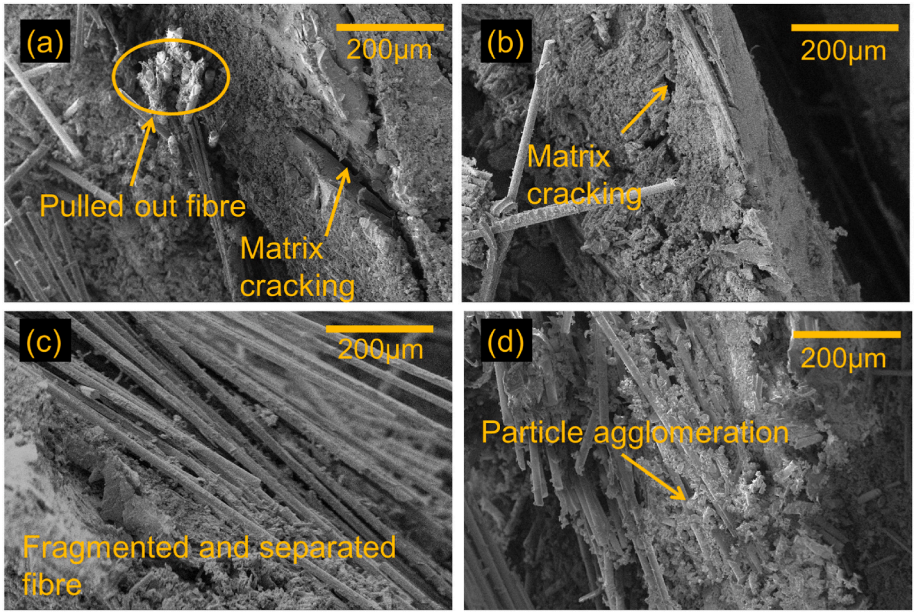

Fig. 13. Failure analysis (a) & (b): 12 wt% biochar composites, and (c) & (d): 15 wt% biochar composites.

biochar significantly increases tensile modulus (46.05 GPa) and tensile strength (674.21 MPa) by 75 % and 59 %, respectively, due to its porous structure and high surface area. However, higher biochar concentrations cause property declines due to particle agglomeration and stress concentration points. Notably, beyond this optimal content (i.e., 9 % biochar), a decrease in tensile properties has been observed. The observed reduction is attributable to the agglomeration of biochar particles at elevated loadings. This clustering disrupts the uniform distribution within the matrix, forming stress concentration points that may initiate cracking under tensile loading conditions. The study underscores a synergistic effect between carbon fiber and biochar, with biochar reinforcing the matrix and carbon fiber bearing most of the load, resulting in optimized mechanical performance at 9 % biochar content. This balance ensures improved tensile and flexural properties, making the composite more resilient and efficient.

4. Conclusion

This study demonstrated the feasibility and benefits of incorporating biochar from fish scales into carbon fibre epoxy composites. With a 60.02 % increase in tensile strength to 674.21 MPa, a 74.96 % increase in tensile modulus to 46.05 GPa, and a 58.32 % improvement in flexural modulus, the results showed significant increases in mechanical properties. At 9 % biochar, the impact strength reached 102.32 kJ/m^2. These improvements were attributed to strong interfacial adhesion between the biochar particles and the epoxy matrix, which allowed for effective load transmission. The concentrations of biochar greater than 9 % resulted in particle agglomeration, which reduced mechanical properties and produced stress concentration spots. Scanning electron microscopy (SEM) analysis revealed that fibre pull-out, matrix cracking, and biochar particle aggregation were the most common failure causes at higher biochar loadings. This finding emphasises the importance of optimal filler distribution in maximising biochar's reinforcing capability. As a filler in carbon fibre composites, fish scale-derived biochar emphasises sustainability and high-performance potential, thereby reducing waste and promoting environmentally friendly composite development. Future research should look into surface changes or sophisticated dispersion methods to improve biochar distribution and thus enable its efficient use at higher loadings.

CRediT authorship contribution statement

Sundarakannan Rajendran: Writing – original draft, Methodology, Investigation. **Geetha Palani:** Writing – review & editing. **Arumugaprabu Veerasimman:** Writing – review & editing, Validation, Resources, Formal analysis, Conceptualization. **Vigneshwaran Shanmugam:** Writing – review & editing, Validation, Conceptualization. **Uthayakumar Marimutthu:** Writing – review & editing. **Kinga Korniejenko:** Writing – review & editing, Validation. **Herri Trilaksana:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Arnas Majumder:** Writing – review & editing, Validation, Funding acquisition, Formal analysis, Conceptualization. **Flavio Stochino:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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