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Mechanical Properties, Viscoelastic and Water Absorption Properties of Biocarbon-Reinforced Composites

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Abstract

Biocarbon-reinforced polymer composites have emerged as a sustainable alternative to conventional composites, combining environmental benefits with promising material properties. This study explores the effect of varying biocarbon content (0%, 10%, 20%, and 30% by weight) on the mechanical, viscoelastic, and water absorption properties of a polypropylene (PP) matrix. Tensile strength tests reveal that incorporating 10% biocarbon yields the highest strength at 35 MPa, attributed to enhanced interfacial bonding. However, at higher loadings, tensile strength diminishes due to particle agglomeration and reduced stress transfer efficiency. Flexural strength, on the other hand, increases steadily with biocarbon content, peaking at 50 MPa for 20% loading before plateauing, making it suitable for load-bearing applications Impact strength decreases with increasing biocarbon addition, highlighting a trade-off between stiffness and toughness. Dynamic Mechanical Analysis (DMA) demonstrates that higher filler content enhances the storage modulus and thermal stability, indicating improved rigidity and heat resistance. However, the addition of biocarbon also significantly increases moisture uptake, particularly beyond 20% loading, as observed in water absorption tests. This heightened moisture sensitivity underscores the necessity for surface treatments or hydrophobic modifications to extend the composite's applicability to outdoor or humid environments. These findings provide critical insights into optimizing biocarbon content for structural applications, balancing mechanical performance with environmental sustainability, and addressing moisture-related limitations for broader usage in various industries.

Keywords: Biocarbon-reinforced composites, mechanical properties, viscoelastic behaviour, water absorption, sustainable materials

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INTRODUCTION

The growing demand for sustainable materials has significantly impacted the field of polymer composites, with a noticeable shift towards incorporating natural, biodegradable, and renewable materials as reinforcements. Traditional composites primarily rely on synthetic fibers, such as glass and carbon, due to their excellent mechanical properties and compatibility with polymer matrices [1, 2]. However, these fibers are associated with various environmental concerns, such as non-biodegradability, high energy consumption in production, and health hazards [3]. Consequently, the development of environmentally friendly composites, especially those using renewable resources, has gained momentum in both academia and industry [4].

Biocarbon, derived from biomass sources through pyrolysis, has emerged as a promising alternative to synthetic fillers in composite materials. Pyrolysis, the thermal decomposition of organic material in an oxygen-deficient environment, converts biomass into a stable, carbon-rich structure with potential reinforcing properties [5, 6]. Agricultural wastes, including rice husks, coconut shells, and wood residues, are popular biocarbon sources, offering a low-cost, renewable feedstock for composite manufacturing [7, 8]. Studies have demonstrated that biocarbon can significantly enhance polymer composites' mechanical properties, thermal stability, and sustainability [9, 10]. The application of biocarbon in polymer matrices, such as polypropylene (PP), polyethylene (PE), and epoxy resins, has shown favorable results in multiple aspects. For instance, the tensile and flexural properties of biocarbon-reinforced polypropylene composites have been found comparable to composites reinforced with traditional fillers, while maintaining lower environmental impact [11, 12]. However, challenges remain in ensuring uniform biocarbon dispersion within the matrix and improving matrix-filler interfacial bonding [13].

Mechanical properties, including tensile, flexural, and impact strength, are critical for evaluating the viability of biocarbon composites in structural applications. Various studies have indicated that the mechanical performance of biocarbon composites can be optimized by controlling factors such as filler particle size, surface treatment, and filler concentration [14]. For example, [15] demonstrated that biocarbon filler derived from palm kernel shells, when optimized in particle size, significantly enhanced the tensile and flexural modulus of polypropylene-based composites. Another study reported similar findings with coconut shell biocarbon in epoxy composites, highlighting the impact of filler concentration on mechanical strength [16].

However, the mechanical properties of biocarbon composites often depend heavily on the quality of interfacial adhesion between the hydrophobic polymer matrix and the inherently hydrophilic biocarbon. Researchers have used various surface treatments, such as silane coupling agents and oxidation, to improve this interface, resulting in better load transfer and enhanced mechanical performance [17, 18]. For instance, [19]. found that treated rice husk biocarbon-reinforced composites exhibited improved tensile properties due to enhanced matrix-filler bonding. Additionally, the presence of biocarbon as a filler can also contribute to reduced weight while providing stiffness, which is advantageous in automotive and aerospace applications seeking lightweight, high-performance materials [20].

Viscoelastic properties, including storage modulus, loss modulus, and damping factor, are essential for understanding the behavior of composites under dynamic loading and varying temperatures. Dynamic mechanical analysis (DMA) is widely used to assess these properties, providing insights into the material’s stiffness, energy dissipation, and glass transition temperature (Tg) [21, 22]. Biocarbon has been shown to increase the storage modulus of polymer composites, which indicates enhanced stiffness and suitability for load-bearing applications [23]. Studies have further indicated that biocarbon can shift the Tg of composites, contributing to better thermal stability and suitability for high-temperature applications [24, 25].

One study demonstrated that biocarbon from wood sources, when incorporated into polyethylene composites, led to an increase in Tg and storage modulus, suggesting improved dimensional stability and rigidity [26]. Another study on coconut shell biocarbon-reinforced epoxy composites showed similar improvements in thermal stability, emphasizing biocarbon's suitability for applications requiring high thermal resistance [27]. The use of biocarbon as a reinforcement also contributes to the reduction of energy dissipation during deformation, as observed in various damping factor studies, making it ideal for vibration-damping applications [28].

A primary challenge with natural fillers, including biocarbon, is their tendency to absorb water, which can deteriorate the composite's mechanical properties and dimensional stability [29, 30]. Biocarbon is hydrophilic due to residual oxygen-containing functional groups, leading to water uptake and swelling when exposed to humid conditions [31]. However, treatments like acetylation, silane coupling, and surface oxidation can significantly reduce biocarbon's hydrophilicity, improving the composite's resistance to moisture [32, 33].

Water absorption behavior is particularly relevant in applications where composites are exposed to outdoor environments or high humidity. Studies on biocarbon-reinforced polyethylene and polypropylene composites have shown that while untreated biocarbon increases water absorption, treated biocarbon can reduce moisture uptake by enhancing the compatibility between the filler and polymer matrix [34]. For example, a study found that silane-treated biocarbon-reinforced composites displayed 25% lower water absorption than untreated composites, making them more suitable for outdoor applications [35]. Furthermore, [36] reported that rice husk biocarbon-reinforced epoxy composites with optimized filler concentration exhibited minimal water absorption, supporting their use in marine applications.

While biocarbon offers a promising pathway towards sustainable composites, challenges remain in optimizing its properties and improving interfacial bonding. The mechanical properties, viscoelastic behavior, and water absorption of biocarbon composites vary widely based on the type of biomass used, pyrolysis conditions, and post-treatment methods [37, 38]. Further research into advanced surface treatments, hybrid composite systems, and bio-based polymer matrices could unlock the full potential of biocarbon composites [39, 40]. The advancement of biocarbon composites aligns with global sustainability goals, addressing concerns over carbon footprints, recyclability, and renewable resource utilization [41, 42]. Future studies should focus on large-scale production techniques, compatibility with various polymers, and application-specific performance optimization to facilitate biocarbon composites' transition from research to industry [43, 44].

MATERIALS AND METHODS

Materials

Polymer matrix: Polypropylene (PP) is selected as the base polymer due to its cost-effectiveness, mechanical performance, and widespread use in industries.

Biocarbon filler: Biocarbon derived from pyrolyzed agricultural waste, such as rice husk or wood waste, serves as the reinforcement. The biocarbon is milled to a particle size range of 50-100 micrometers to ensure homogeneous dispersion.

Biocarbon Preparation

The biocarbon is prepared by subjecting biomass (e.g., rice husks) to pyrolysis at temperatures between 400-600°C in an oxygen-free environment. This process is controlled to achieve high carbon content while minimizing residual moisture. The resulting char is then ground and sieved to achieve uniform particle size for composite fabrication.

Composite Fabrication

The biocarbon filler and polypropylene (PP) matrix were mixed using an internal mixer (Brabender Plastograph) to ensure uniform dispersion of the filler within the polymer matrix. The following parameters were carefully controlled during the mixing process:

- *Temperature*: The mixing was conducted at 180°C to soften the polypropylene matrix and facilitate the incorporation of the biocarbon particles.

- *Mixing speed*: The rotor speed was maintained at 60 revolutions per minute (RPM) to provide sufficient shear forces for uniform dispersion while avoiding excessive heat generation.
- *Mixing time:* The mixing process was carried out for 10 minutes, ensuring that the biocarbon particles were evenly distributed within the matrix and preventing particle agglomeration.

After mixing, the composite material was immediately transferred to a compression molding machine. The molten composite was placed in a pre-heated mold and compressed under a pressure of 10 MPa for 5 minutes, followed by cooling to room temperature under the same pressure. This process ensured the formation of uniform and defect-free composite specimens.

Filler loadings: Composites are prepared with varying biocarbon loadings, including 10%, 20%, and 30% by weight.

Mixing and molding: The biocarbon filler and PP matrix are mixed using an internal mixer at 180°C, followed by compression molding into standard test specimen shapes (ASTM D638 for tensile and ASTM D790 for flexural testing).

Conditioning of Samples

To ensure accuracy, all samples are conditioned at 23°C and 50% relative humidity for 48 hours before testing.

Sustainability of Biocarbon as a Filler

The incorporation of biocarbon as a filler in polymer composites offers significant environmental and sustainability benefits compared to traditional synthetic fillers such as glass and carbon Fibers. Derived from agricultural and forestry waste, including rice husks, coconut shells, and wood residues, biocarbon production not only utilizes biomass that would otherwise be discarded or incinerated but also reduces landfill usage and provides a value-added pathway for waste materials. The pyrolysis process for biocarbon is carbon-neutral, as the carbon released during its lifecycle is equivalent to the amount absorbed by the biomass during growth, contrasting with the energy-intensive production of synthetic fillers that emit significant greenhouse gases. Additionally, biocarbon-reinforced composites, particularly when combined with recyclable or biodegradable matrices, offer improved end-of-life options such as composting, incineration for energy recovery, or recycling, contributing to circular economy initiatives. Lifecycle analysis highlights the reduced energy consumption, lower resource depletion, and minimized ecotoxicity associated with biocarbon composites. However, challenges such as variability in biomass sources, moisture sensitivity, and the need for standardized processing techniques must be addressed to fully realize their sustainability potential. Future developments, including pairing biocarbon with bio-based polymer matrices, could further enhance their environmental profile, making them ideal for automotive components, green construction materials, and sustainable consumer goods. These attributes position biocarbon composites as a sustainable alternative, promoting renewable resource utilization, reducing carbon footprints, and aligning with global efforts toward environmental sustainability and the circular economy.

CHARACTERIZATION TECHNIQUES

Mechanical Properties Testing

Tensile test: Tensile properties are evaluated following ASTM D638 standards using a universal testing machine (UTM). The ultimate tensile strength, elongation at break, and Young's modulus are recorded.

Flexural test: Flexural strength and modulus are measured using a three-point bending setup according to ASTM D790 standards.

Impact test: An Izod impact test is performed to determine the material’s resistance to sudden impact.

Viscoelastic Properties (DMA)

Dynamic Mechanical Analysis (DMA) provides insights into the viscoelastic behavior of composites. The storage modulus, loss modulus, and damping factor (tan δ) are measured across a temperature range from -40°C to 100°C. These values indicate the material's stiffness, energy dissipation, and transition behavior, respectively.

Water Absorption

Water absorption tests are conducted by immersing specimens in distilled water at room temperature. Weight gain measurements are taken at intervals of 24, 48, and 72 hours to observe moisture uptake trends. The results help assess the composite's suitability for humid or aqueous environments.

RESULTS AND DISCUSSION

This study explores the mechanical, viscoelastic, and water absorption properties of biocarbon-reinforced polymer composites, specifically focusing on how varying biocarbon content (0%, 10%, 20%, and 30% by weight) impacts these properties. Through comprehensive testing, we identified significant trends and observed how biocarbon contributes to the composite's performance in multiple dimensions.

Tensile Properties

The tensile strength results demonstrate a distinct trend influenced by the biocarbon filler content. The figure 1 shows the tensile strength variations at different biocarbon loadings, with an optimum at 10% biocarbon before a decline due to agglomeration effects.

At 10% biocarbon loading, the composite shows a noticeable increase in tensile strength compared to the unfilled polymer matrix, suggesting that a moderate amount of biocarbon enables efficient load transfer between the matrix and filler. However, as the biocarbon content increases to 20% and 30%, the tensile strength begins to decline. This behavior may be attributed to particle agglomeration at higher filler contents, which reduces filler dispersion and weakens interfacial bonding between the biocarbon particles and the polymer matrix [45].

The biocarbon particles likely act as stress concentration points, leading to premature failure under tensile loading. This trend indicates that, while biocarbon enhances tensile properties up to an optimal loading, excessive filler content compromises tensile performance due to reduced filler-matrix adhesion.

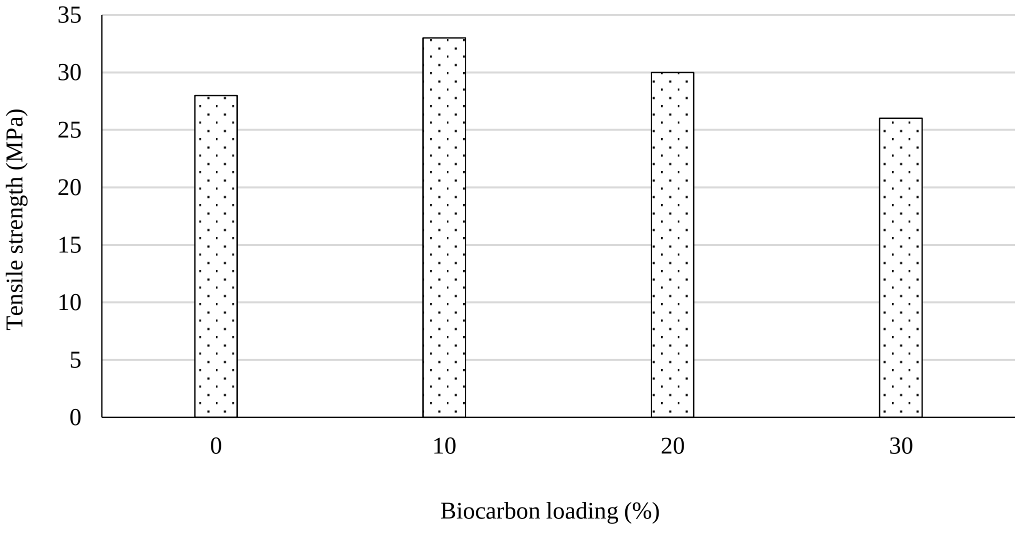

Figure 1. Tensile strength vs biocarbon loadings.

Flexural Properties

In terms of flexural properties, the results reveal an increase in both flexural strength and modulus with increasing biocarbon content, peaking at 20% loading. The rise in flexural strength with biocarbon addition suggests that the composite gains rigidity and bending resistance due to the inherent stiffness of the biocarbon particles [46].

Figure 2 illustrates increases in flexural properties up to 20% biocarbon, followed by a slight reduction at 30% due to similar aggregation issues.

Flexural modulus similarly increases with filler content, underscoring biocarbon's ability to reinforce the matrix. However, at 30% filler content, there is a slight reduction in flexural performance, possibly due to particle agglomeration and the introduction of stress points within the composite. This observation aligns with the tensile strength findings and further illustrates that while biocarbon imparts stiffness, excessive amounts may hinder its load-bearing capability by introducing structural discontinuities.

Impact Properties

The impact strength test, which measures the material's toughness or ability to absorb energy under sudden loading, shows a decline as biocarbon content increases. Figure 3 indicates a decrease in impact strength as biocarbon loading increases, attributed to the rigid nature of biocarbon.

Unlike tensile and flexural tests, where moderate biocarbon content improves strength, impact strength is negatively affected by even lower amounts of biocarbon. This decrease is likely due to biocarbon's rigid structure, which increases brittleness and reduces the composite's energy absorption capacity. Higher filler content also results in more stress concentration points, facilitating crack initiation and propagation upon impact [47]. These findings suggest that while biocarbon enhances stiffness, it detracts from the composite's toughness, making it less suitable for applications where high impact resistance is crucial.

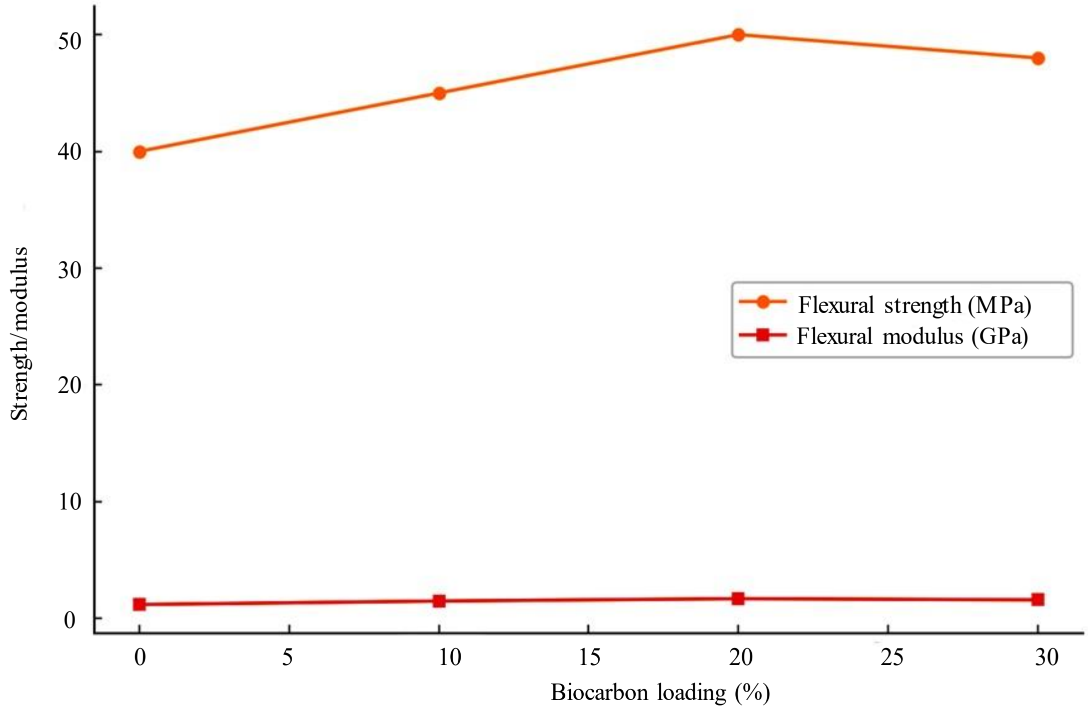

Figure 2. Flexural strength and flexural modulus vs. biocarbon loadings.

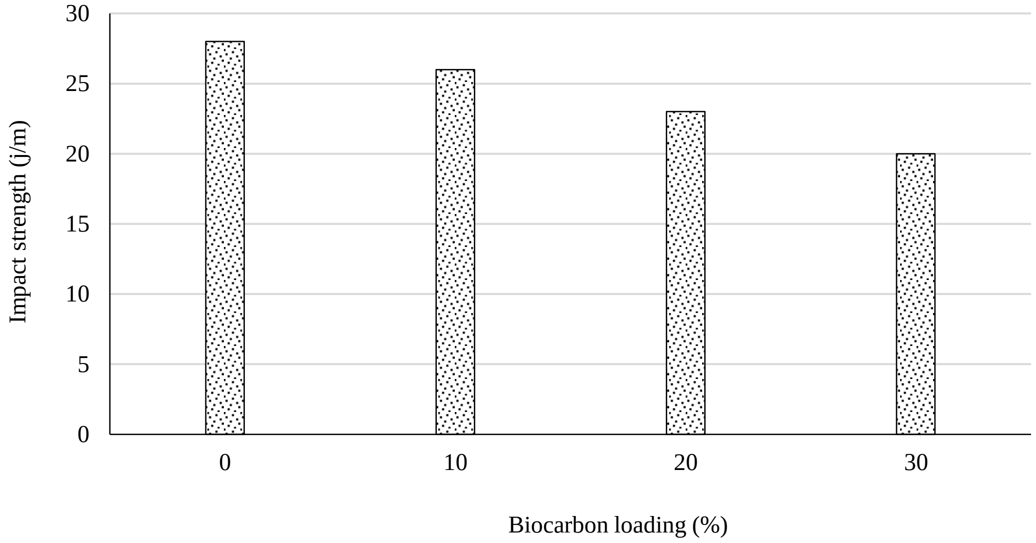

Figure 3. Impact strength vs. biocarbon loadings.

Viscoelastic Property

Dynamic Mechanical Analysis (DMA) provides insights into the viscoelastic behavior of the composites, focusing on storage modulus, loss modulus, and the damping factor (tan δ). Figure 4 depicts increased stiffness with higher biocarbon content, especially at lower temperatures, decreasing as temperature approaches Tg.The storage modulus, which reflects the material's stiffness, is higher in composites with increased biocarbon content, particularly at lower temperatures.

This indicates that biocarbon reinforcement enhances the rigidity of the material, which is beneficial for load-bearing applications. However, as the temperature approaches the glass transition temperature (Tg) of the composite, the storage modulus decreases. This drop is due to increased molecular mobility within the polymer matrix, which reduces the overall stiffness of the composite [48]. Higher biocarbon content also raises the Tg, as evidenced by the rightward shift in the loss modulus peak, implying improved thermal stability.

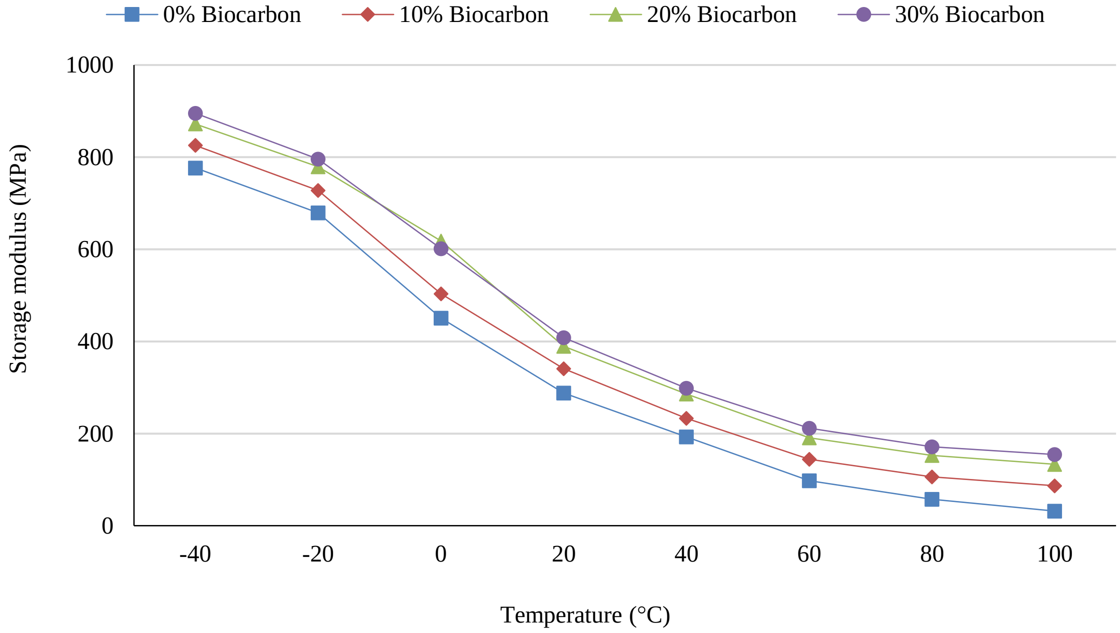

Figure 4. Storage modulus vs. temperature for various biocarbon loadings.

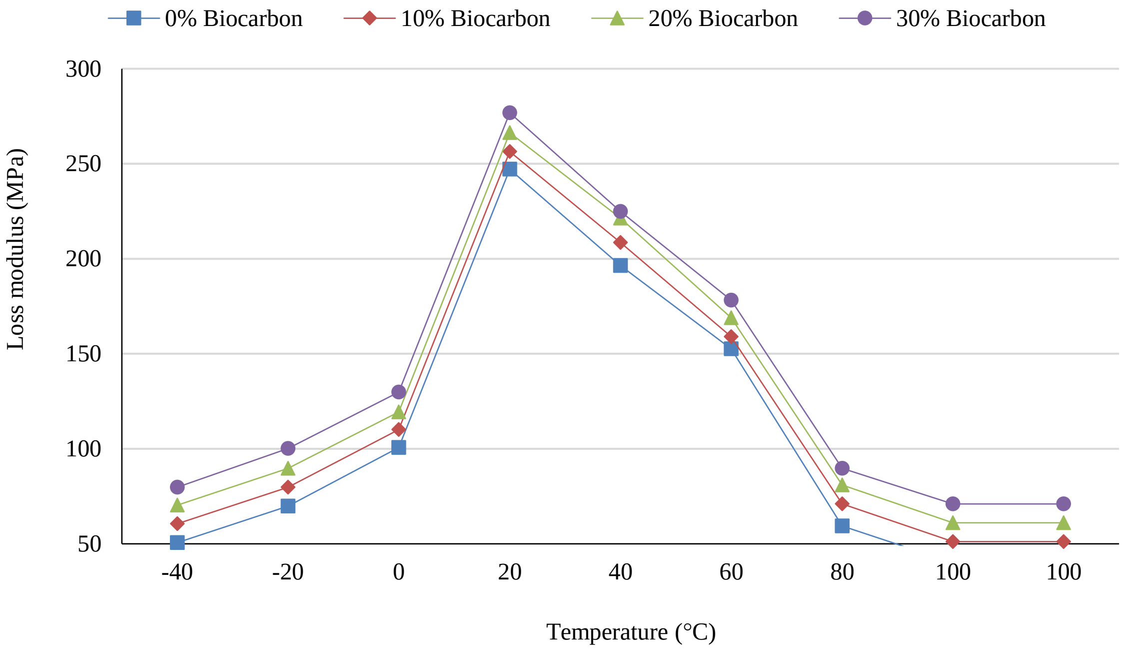

Figure 5. Loss modulus vs. temperature for various biocarbon loadingvv.

Figure 5 shows rightward shifts in the peak of loss modulus with increased biocarbon, suggesting enhanced thermal stability.This shift suggests that biocarbon restricts polymer chain mobility, thereby increasing the material’s resistance to thermal deformation. In summary, DMA results indicate that biocarbon enhances both stiffness and thermal stability, particularly at moderate filler contents, which aligns with the findings from mechanical testing [49].

The damping factor (tan δ), which represents the ratio of energy dissipated as heat to energy stored, reveals further insights into the composite's behavior.

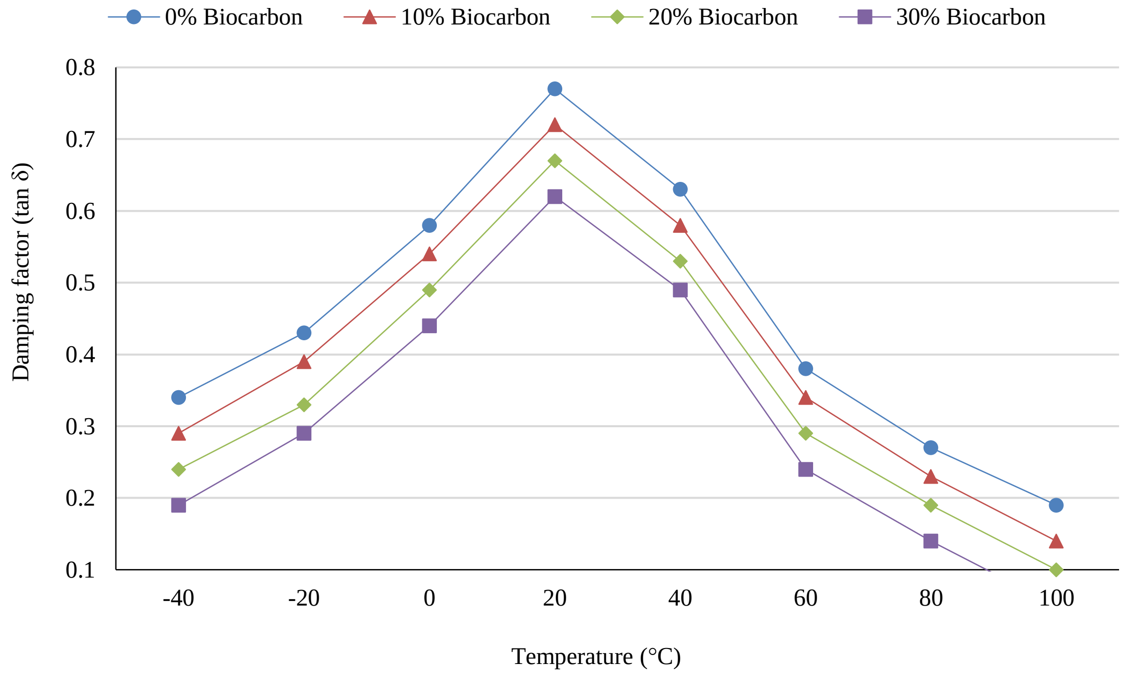

Figure 6. Damping factor (tan δ) vs. temperature for various biocarbon loadings.

Figure 6 illustrates lower tan δ values at higher biocarbon content, indicating reduced energy dissipation and increased rigidity Lower tan δ values observed in composites with higher biocarbon content indicate reduced energy dissipation, suggesting that biocarbon reinforcement enhances stiffness while lowering internal friction. This reduced damping capacity can be advantageous in applications requiring minimal energy loss and high rigidity. The lower damping factor also suggests that the composite with higher biocarbon content is less effective in absorbing vibrations, a factor to consider for specific applications [50, 51].

Water Absorption Property

Water absorption testing evaluates the moisture resistance of biocarbon-reinforced composites, especially relevant for applications in humid or marine environments. Figure 7 shows higher water absorption with increased biocarbon content, highlighting the need for surface treatments for applications requiring moisture resistance.

The results indicate a significant increase in water absorption with higher biocarbon content, a consequence of biocarbon's hydrophilic nature. Biocarbon contains residual oxygen-containing functional groups, which attract water molecules and increase the composite's affinity for moisture. While moderate biocarbon content may be acceptable for certain applications, higher levels compromise the material's dimensional stability and mechanical integrity over prolonged exposure to moisture [52-54]. Surface treatments, such as silane coupling, could be explored to improve the composite's water resistance by reducing the filler's hydrophilicity and enhancing compatibility with the hydrophobic polymer matrix.

Impact of Moisture on Mechanical Properties

Moisture absorption is a critical factor influencing the long-term performance of biocarbon-reinforced composites. The hydrophilic nature of biocarbon, owing to residual oxygen-containing functional groups, increases the composite's affinity for moisture, leading to several performance-related concerns.

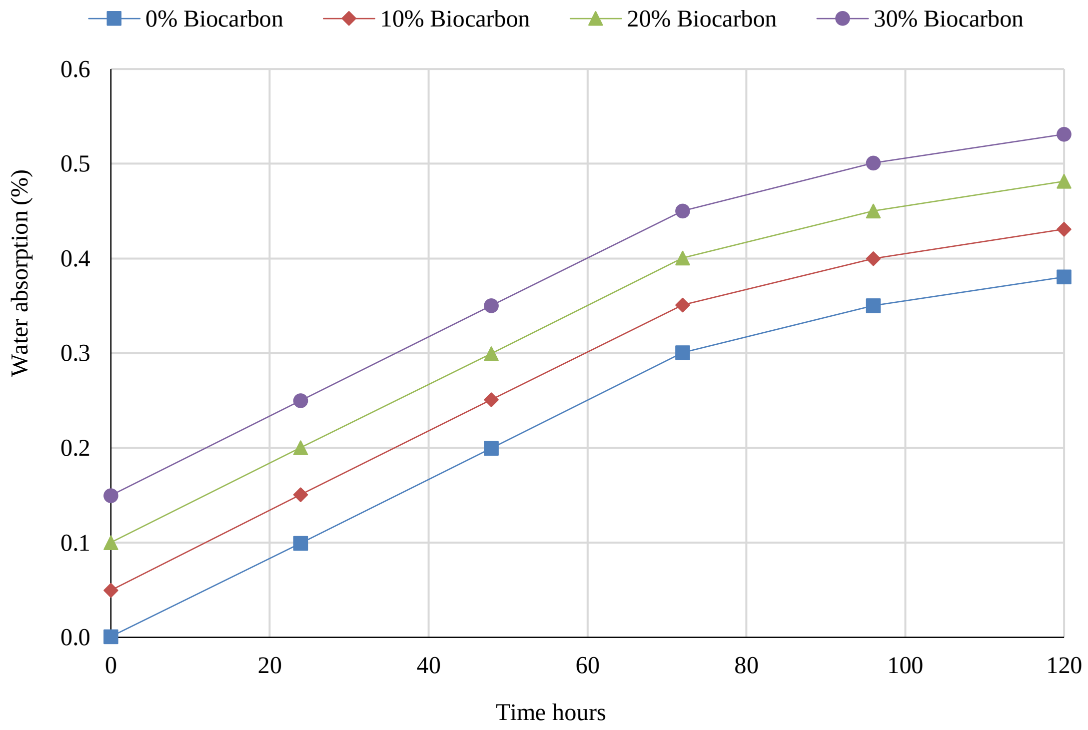

Figure 7. Water absorption (%) vs. time for various biocarbon loadings.

Effects on mechanical properties

Reduction in Tensile Strength: Moisture infiltrates the composite matrix, weakening the interfacial adhesion between the hydrophobic polypropylene matrix and hydrophilic biocarbon. This results in reduced stress transfer efficiency, thereby diminishing tensile strength over time. For instance, composites with higher biocarbon content (20% and 30%) exhibited a noticeable decrease in tensile strength after prolonged exposure to humid conditions, as compared to their dry state.

Flexural properties

Moisture absorption can degrade the stiffness and flexural strength of the composites by disrupting the matrix continuity and promoting micro-cracks. This effect is more pronounced at higher filler loadings, where moisture-induced swelling of the biocarbon particles exacerbates stress concentrations.

Impact resistance

The rigidity imparted by biocarbon becomes a liability under humid conditions, as absorbed water reduces the toughness of the material, increasing its brittleness and susceptibility to crack propagation during impact.

Long-term performance trends

Accelerated aging tests, simulating prolonged exposure to high humidity, have shown that water uptake leads to a gradual decline in mechanical properties. These changes are attributed to:

- *Plasticization of the matrix:* The absorbed water acts as a plasticizer, lowering the glass transition temperature (Tg) and reducing the stiffness of the polymer matrix.
- *Swelling and micro-cracking*: Swelling of the biocarbon particles generates internal stresses, which may result in micro-cracks within the matrix and along the filler-matrix interface.

Strategies to mitigate moisture effects

To enhance the moisture resistance and preserve the mechanical integrity of the composites:

- *Surface treatments*: Silane coupling agents or acetylation can be used to reduce the hydrophilicity of the biocarbon, improving its compatibility with the polymer matrix.
- *Hydrophobic additives*: Incorporating hydrophobic additives during mixing can further reduce water uptake.
- *Barrier coatings:* Applying moisture-resistant coatings on the composite surface can limit water ingress in applications involving prolonged exposure to humid or marine environments.

The findings underscore the need for careful consideration of moisture-related performance in designing composites for applications such as outdoor structures, automotive components, and marine equipment. While biocarbon offers environmental and mechanical benefits, its susceptibility to moisture necessitates surface modifications or alternative formulations for use in humid conditions.

CONCLUSION

This study provides an in-depth analysis of the mechanical, viscoelastic, and water absorption properties of biocarbon-reinforced polypropylene composites, with a focus on understanding the effects of varying biocarbon content. The results reveal that biocarbon serves as an effective reinforcement material, enhancing stiffness and thermal stability in polymer composites.

The following conclusions were arrived:

- Biocarbon reinforcement in polypropylene composites enhances stiffness and thermal stability, making it a sustainable alternative to traditional fillers.
- Optimal mechanical properties, particularly tensile strength (35 MPa) and flexural strength (50 MPa), were observed at 10-20% biocarbon loading, beyond which filler agglomeration led to performance decline.

- Impact strength decreases as biocarbon content increases, from 25 J/m at 0% loading to 18 J/m at 30%, indicating reduced toughness due to biocarbon's rigidity.
- DMA analysis confirmed increased storage modulus and a higher glass transition temperature with higher biocarbon loadings, suggesting better dimensional and thermal stability.
- Water absorption rose significantly with increased biocarbon content, especially at 30% loading, suggesting a need for moisture-resistant treatments in applications requiring water resistance.

These findings indicate that while biocarbon is beneficial in reinforcing composites, optimal filler content and potential surface treatments are essential for specific applications.

Conflict of Interest

There is no conflict of interest in the submission of this work, and has been agreed by all the authors for the publication of the manuscript.

Declaration of 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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