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Fabrication and Mechanical Performance of Bark Cloth/Glass Fiber Reinforced Hybrid Polymer Composites for Automotive Applications

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ABSTRACT

This study developed and evaluated a sustainable hybrid composite based on bark cloth and glass fibers for lightweight automotive and semi-structural applications. Hybrid laminates were fabricated via the hand layup technique with varying fiber weight fractions (15–25 wt%), bark cloth-to-glass fiber ratios, and stacking sequences. Mechanical, physical, and microstructural characterizations were performed to assess the effects of hybridization and laminate architecture on composite performance. The results demonstrate that hybridization markedly improves the mechanical performance of bark cloth composites. Optimal properties were achieved at a bark cloth-to-glass fiber ratio of 1:3 and a fiber weight fraction of 20 wt%, yielding tensile strength of 43.24 MPa, flexural strength of 140.94 MPa, and impact strength of 78.6 kJ/m^2. Laminates with glass fibers positioned in the outer layers exhibited superior flexural and impact resistance due to enhanced surface load-bearing capacity and stress transfer efficiency. Conversely, excessive fiber loading (25 wt%) led to property degradation, attributed to insufficient resin wetting and fiber agglomeration. SEM analysis confirmed that reduced voids and improved interfacial bonding in optimized hybrids governed the observed mechanical enhancements. This work presents the first systematic investigation of bark cloth–glass fiber hybrid composites and demonstrates that an optimized hybrid architecture can achieve a favorable balance between mechanical performance and sustainability. These findings highlight the potential of bark cloth–glass fiber hybrids as promising candidates for lightweight automotive interior components and semi-structural applications, contributing to the development of greener composite materials.

1 | Introduction

Bark cloth is a unique, non-woven fibrous textile produced from the bark of various tree species, with *Ficus natalensis* being the primary species used in Uganda. Locally known as “mutuba,” this tree grows naturally in Uganda’s tropical climate and requires minimal care, as it thrives without the need for fertilizers. *Ficus natalensis*, along with other species such as *Antiaris toxicaria* and *Ficus brachypoda*, is particularly valued for its renewable nature. The bark of the tree can be harvested annually without felling the tree, making it a sustainable resource [1, 2]. A single tree can continue to produce bark cloth for over 30 years, with the bark regenerating after each harvest [3].

The production of bark cloth involves stripping the bark from the tree, which is then processed through steaming and beating with carved wooden hammers. This traditional method, passed down through generations, stretches the fibers and creates the distinctive terracotta-colored cloth. The cloth holds cultural significance in Uganda, being used for royal garments, religious ceremonies, and funerals [4]. The importance of bark cloth to Ugandan culture led UNESCO to recognize it as a “Masterpiece of the Intangible Cultural Heritage of Humanity,” emphasizing the need to protect the knowledge and traditions surrounding its production [2].

In addition to its cultural value, bark cloth has gained attention for its potential as a reinforcement material in composite applications. Studies have shown that bark cloth consists of cellulosic microfibers aligned at 45° angles, providing moderate tensile properties. Scanning electron microscopy (SEM) analysis revealed that the fibers are oval-shaped and bonded by lignin and hemicelluloses, with diameters ranging between 10 and 20 μm [5]. The strength of bark cloth was measured at 101.7 N longitudinally and 23.5 N transversely, with a fabric thickness of approximately 1.084 mm [5]. These properties, along with its thermal stability below 200°C, suggest that bark cloth can be used for composite reinforcement, particularly in applications where lightweight and biodegradable materials are desirable [6–10].

Despite its potential due to its sustainability, low density, and cost-effectiveness, the key challenges in using bark cloth and other natural fibers for structural applications, particularly in the automotive industry, are their durability. Natural fibers have a high affinity for moisture due to their hydrophilic nature, which can lead to water absorption and subsequently reduced mechanical performance over time. For example, prolonged exposure to moisture can cause swelling, fiber debonding, and degradation of fiber-matrix adhesion, leading to a significant reduction in properties such as tensile and flexural strength. In addition, they generally exhibit lower mechanical properties than synthetic fibers, such as glass and carbon fiber, which limits their use in high-performance applications [11–14]. To address these limitations, researchers have explored hybrid composites that combine natural fibers with synthetic fibers. Hybrid composites leverage the sustainability of natural fibers while benefiting from the mechanical strength of synthetic fibers. This combination offers improved mechanical performance, including tensile, flexural, and impact strengths [14, 15].

Recent studies have shown that treatments or hybridization with synthetic fibers, such as glass, can mitigate these effects by reducing moisture absorption and improving long-term stability [16–25]. For example, Santhanam et al. [26] reported significant improvements in tensile and flexural strength when glass fibers were added to banana fiber/polyester composites. Similarly, Selver et al. [27] demonstrated that hybrid composites made from jute and glass fibers showed enhanced mechanical properties compared to pure natural fiber composites. Sanjay et al. [28] reviewed the mechanical properties of natural fiber polymer composites, emphasizing that water absorption is a major factor affecting their long-term durability. The review suggests that hybridizing natural fibers with synthetic fibers or applying surface treatments can significantly mitigate these durability issues, improving the composites’ resistance to environmental degradation. Another important aspect of improving natural fiber composites is enhancing their mechanical and moisture-resistant properties by hybridization. Rangappa et al. [29] discussed how hybridizing lignocellulosic fibers with synthetic fibers, such as glass, leads to composites that demonstrate improved mechanical properties and better resistance to moisture and environmental stresses. The incorporation of synthetic fibers into natural fiber composites not only improves their structural performance but also increases their applicability in sectors such as automotive and construction, where environmental resistance is critical [30, 31]. Our study builds upon these findings by investigating the mechanical performance of hybrid composites made from bark cloth and E-glass fibers, with an emphasis on their potential for automotive applications.

The hybridization of natural fibers with E-glass fibers offers several significant advantages in composite materials, particularly for applications requiring high performance and sustainability [32, 33]. Natural fibers, such as coconut leaf sheath, jute, and sisal, are lightweight and biodegradable, contributing to both weight reduction and environmental sustainability. However, their mechanical properties are often lower compared to synthetic fibers like E-glass. Studies by Bharath et al. [34] and Arpitha et al. [35] show that the combination of these natural fibers with E-glass fibers significantly enhances tensile and flexural strength, making the resulting hybrid composites suitable for structural and automotive applications. The hybridization also provides cost benefits, as natural fibers are more affordable than synthetic materials. Moreover, the addition of E-glass fibers improves the durability and resistance to moisture of the composites, addressing the common limitation of natural fibers in harsh environmental conditions. This balance of enhanced mechanical performance, cost-effectiveness, and sustainability makes hybrid composites highly attractive for a variety of industrial uses.

The automotive industry, in particular, has shown great interest in hybrid composites due to their potential to reduce vehicle weight while maintaining strength and durability. The use of natural fibers in automotive components can reduce both material costs and environmental impact [11, 12]. For example [36], it was highlighted the role of natural fiber composites in the production of non-structural parts, while a number of studies have emphasized their potential to replace traditional materials such as aluminum and glass fibers in specific applications [37–39]. Hybrid composites, with their tailored mechanical properties, offer the versatility needed for a wide range of applications in automotive, construction, and other industries [26, 27, 40].

The mechanical properties of hybrid composites depend on several factors, including fiber weight fraction, hybrid ratio (the proportion of natural to synthetic fibers), and stacking sequence (the arrangement of fibers within the composite) [41, 42]. Studies have shown that increasing the glass fiber content improves the mechanical properties of hybrid composites [43–45]. These studies reported that the tensile and flexural strength of hybrid composites increased with higher glass fiber content, while excessive natural fiber content led to poor fiber-matrix adhesion [46, 47]. Additionally, the stacking sequence of fibers plays a critical role in determining the composite’s mechanical properties [48–51]. For example, Sanjay and Yogesha [40] found that placing glass fibers in the outer layers of hybrid composites significantly improved flexural strength compared to composites with natural fibers on the surface.

Research has demonstrated the effectiveness of hybridization in improving the mechanical properties of composites. For instance, Santhanam et al. [26] found that hybrid composites with glass and natural fibers exhibit superior flexural and tensile properties. Other studies have confirmed the benefits of hybridization, including Dalbehera and Acharya [52] who observed improved impact strength and stiffness in jute/glass hybrid composites. Moreover, Altaee and Mostafa [53] reported that hybrid composites with glass fibers in the outer layers and natural fibers in the core can offer optimal mechanical performance for specific applications, such as load-bearing and structural components.

Despite extensive research on hybrid composites using fibers such as jute, flax, and sisal, studies on bark cloth hybrid composites are still limited. However, recent research has shown that bark fibers from other plants, such as *Ficus carica* and *Prosopis juliflora*, possess desirable properties for composite reinforcement, including high cellulose content and thermal stability [9, 10]. These findings suggest that bark cloth has the potential to be an effective reinforcement material when hybridized with synthetic fibers.

Despite the growing body of research on natural–synthetic hybrid composites, studies focusing on bark cloth as a reinforcement material remain extremely limited. Existing works on hybrid composites primarily utilize conventional natural fibers such as jute, sisal, flax, and kenaf, while bark cloth, an indigenous, textile-based natural fiber with unique woven architecture and socio-economic relevance, has not been systematically investigated in hybrid composite systems. The outstanding contributions of the study include: (i) being the first to develop and experimentally evaluate bark cloth–glass fiber hybrid composites for structural applications; (ii) systematically optimizing the bark cloth-to-glass fiber ratio to balance sustainability and mechanical performance; (iii) investigating the combined effects of fiber weight fraction and stacking sequence on tensile, flexural, compressive, and impact properties; (iv) providing microstructural insights via SEM to correlate failure mechanisms with mechanical behavior; and (v) proposing bark cloth-based hybrid laminates as viable candidates for automotive interior and semi-structural components. These contributions differentiate this work from previous studies and provide new design guidelines for integrating indigenous natural textiles into high-performance hybrid composites.

Although bark cloth offers significant sustainability and socio-economic advantages as a renewable textile-based reinforcement, its application in structural composites is constrained by high moisture absorption and relatively low mechanical strength. While hybridization with synthetic fibers such as glass fiber has shown promise in enhancing natural fiber composites, there is currently limited understanding of how bark cloth can be optimally hybridized to achieve a balance between environmental sustainability and mechanical performance. In particular, the effects of bark cloth-to-glass fiber ratio, fiber weight fraction, and stacking sequence on the mechanical and microstructural behavior of hybrid composites remain largely unexplored. This lack of systematic design guidelines restricts the adoption of bark cloth-based hybrid composites in engineering applications, especially in the automotive sector. This study therefore aims to address this gap by developing and evaluating bark cloth–glass fiber hybrid composites with controlled laminate architectures to identify configurations that maximize performance while retaining sustainability benefits.

This study introduces an innovative hybrid composite system that integrates bark cloth, a renewable and underutilized natural fiber, with glass fibers to develop structurally viable and environmentally responsible materials. Unlike previous studies that treat natural fibers mainly as low-load fillers, this work elevates bark cloth into a structural reinforcement phase through hybridization and stacking sequence optimization. The novelty lies in establishing a performance–sustainability balance by systematically optimizing fiber ratio, laminate architecture, and interfacial behavior, thereby positioning bark cloth-based hybrid composites as credible candidates for automotive and semi-structural engineering applications.

2 | Materials and Method

2.1 | Materials

The materials used in this study include bark cloth, harvested from *Ficus natalensis* trees in Mukoko village, Masaka district, Uganda, and commercially available glass fabric (Figure 1). Unsaturated polyester resin, with a density of 1.12 g/cm^3, was used as the matrix, combined with methyl ethyl ketone peroxide (MEKP) catalyst in a ratio of 100:1 by weight. The glass fiber mat and resin were procured from Narkhi Enterprises Limited in Nairobi, Kenya. The characteristics of glass fiber and the unsaturated polyester resin are presented in Table 1.

2.2 | Bark Cloth and Glass Fabric Characterization

The characterization of bark cloth and glass fiber mat (also known as non-woven glass fabric) was conducted to determine their thickness, areal density, and tensile strength (Table 2). The thickness was measured using a digital thickness gauge under a pressure of 1 kPa, with the average thickness of five specimens recorded. Areal density was determined by cutting samples into 0.1 × 0.1 m squares and weighing them with an electronic balance, following ASTM D6242-98. Tensile strength was tested in both the longitudinal and transverse directions according to ASTM D5035-95 (Strip Method), using a Universal Testing Machine. The glass fiber mat's areal density and fiber length were also characterized, with fiber length measured based on ISO 6989:1981 standards.

2.3 | Composite Fabrication

The composites were fabricated using the hand layup technique in a steel mold measuring 300 mm × 300 mm × 20 mm, with a polished lid. Bark cloth and glass fiber mats were cut according to the mold dimensions as depicted in Figure 2. The polyester resin, catalyzed with methyl ethyl ketone peroxide (MEKP), was used as the matrix material. The fabrication process involved laying the first reinforcement layer into the mold, followed by resin application and consolidation with

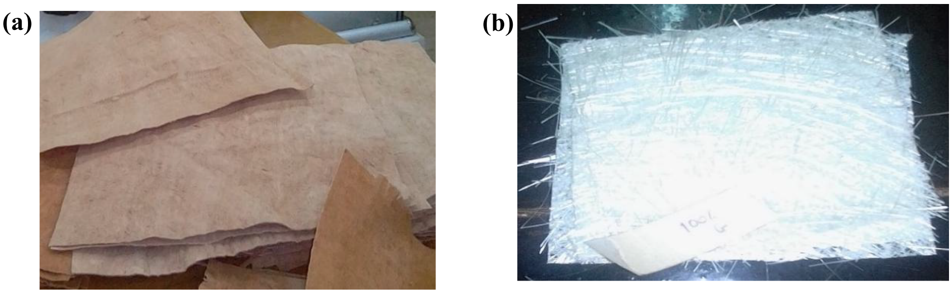

FIGURE 1 | Composite reinforcement materials (a) bark cloth; (b) glass fiber mat/fabric.

TABLE 1 | Characteristics of glass fibers and unsaturated polyester resin.

Properties	Glass fibers	Polyester resin
Appearance	—	Opaque
Viscosity	—	4–5
Water absorption (%) (7 day value)	—	0.4
Heat distortion temperature (°C)	—	63.1
Elongation at break (%)	3.1–4.8	2.9
Bending strength (kgf/mm^2)	—	8.1
Bending modulus (kgf/mm^2)	—	523.3
Tensile strength (kgf/mm^2)	203.94–356.90	2.8
Impact strength (kgf-cm/cm)	—	3.6
Density (g/cm^3)	2.5–2.7	1.12
Toughness (MJ/m^3)	40–50	—
Tensile modulus (GPa)	70–76	—
Fiber diameter (μm)	11–12	—
Moisture content (%)	0.15	—

TABLE 2 | Properties of bark cloth and non-woven glass fabric.

Properties	Bark	Glass
Fabric type	Non-woven	Non-woven
Composition	100% bark	100% E-glass
Fabric thickness (mm)	1.45	—
Areal density (gsm)	385.80	394.00
Longitudinal tensile strength (MPa)	6.30	—
Transverse tensile strength (MPa)	0.26	—
Fiber length (mm)	—	45.68

a roller to eliminate air voids. Subsequent layers were applied to achieve the desired hybrid structure, varying the stacking sequence and fiber weight fractions. Four layers of reinforcement were used.

A consolidation pressure of 3.57 kN/m^2 was applied, and the composites were cured at room temperature for 7 h before demolding.

In this study, various composite samples were prepared by varying two key factors: fiber weight fraction and the hybrid ratio of bark cloth to glass fiber. The experiments were designed to assess how these variations affect the mechanical properties of the hybrid composites. The fiber weight fraction was set at 15%, 20%, and 25%, while the hybrid ratio of bark cloth to glass fiber ranged from 3:1, 2:2, 1:3. Two control composites with bark cloth to glass fiber ratios of 4:0 and 0:4, respectively were also fabricated. Ten types of composite samples were produced, as outlined in Table 3. These samples were fabricated by adjusting both the fiber weight fraction and the reinforcement stacking sequence. The samples included controls with either 100% bark cloth or 100% glass fiber. The hybrid composites consisted of varying combinations of bark cloth and glass fiber, arranged in different stacking sequences. By varying the fiber weight fraction and hybrid ratio, a comprehensive analysis of how these factors influence the mechanical behavior of bark cloth/glass fiber hybrid composites was achieved.

2.4 | Mechanical Testing

Composite samples were prepared and cut in accordance with ASTM and ISO standards to ensure uniformity across all tests. Prior to testing, the specimens were conditioned in the laboratory for 48 h at a temperature of 23°C ± 2°C and relative humidity of 65%, which ensured that the mechanical properties were assessed under controlled conditions. This helped to minimize the effects of moisture and temperature variations on the results.

The flexural strength of the composites was determined following ASTM D790. The test was conducted using a computer-controlled Testomeric machine (Model M/C S/No: 500-10171) with a 24.5 kN capacity, operating at a crosshead speed of 10 mm/min. The span length was calculated as 16 times the specimen thickness, and the specimen width was one-quarter of the span length, with an additional 25 mm overhanging allowance on both ends. The test involved applying a load at the center of the specimen until failure occurred, with five specimens tested for each composite type. Flexural strength is a crucial property for determining a material's resistance to bending, particularly in applications such as automotive and structural components.

Tensile strength tests were conducted in accordance with ASTM D3039, using a Universal Testing Machine (Model UT-10; S/No: 2015/12) with a 100 kN capacity at a crosshead speed of 5 mm/min. The specimens had dimensions of 300 mm in length, 25 mm in width, and a gauge length of 200 mm. Tensile strength

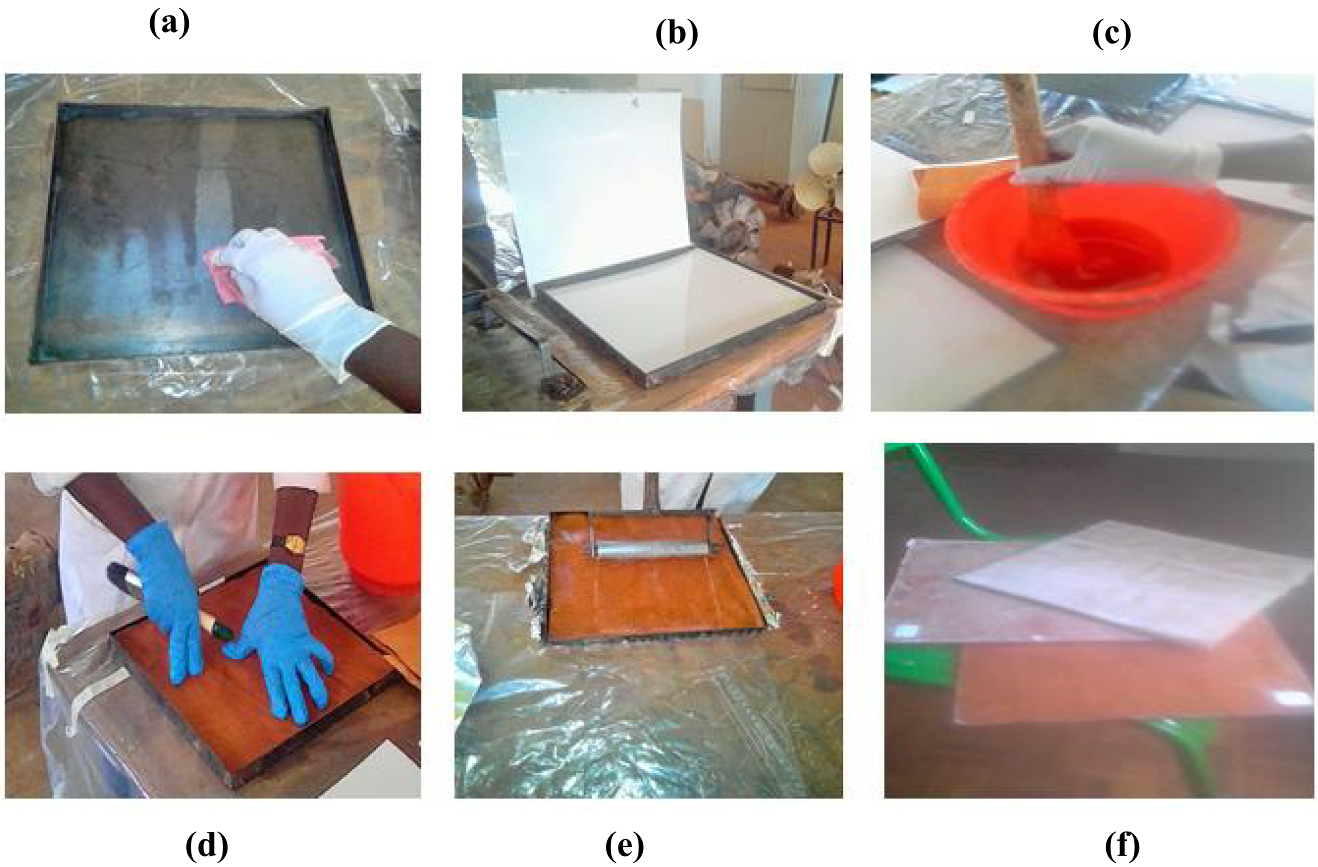

FIGURE 2 | Composite fabrication (a) cleaning mold; (b) mold set up; (c) mixing resin and catalyst; (d) laying reinforcements and resin impregnation; (e) bubble removal and squeezing out excess resin using a roller prior to drying; (f) fabricated composites.

TABLE 3 | Experimental design for producing the different composite sample types.

Composite sample types	Fiber weight fraction (%)	Weight of fibers (g)	Resin weight (g)	Catalyst weight (g)	Composite designation	Reinforcement stacking sequence
1	15	92.7	520.1	5.2	3B1	B-B-G-B
2	25	107.8	320.2	3.2	3B2	B-B-G-B
3	15	134.6	755.1	7.6	3G1	G-G-B-G
4	25	138.0	409.9	4.1	3G2	G-G-B-G
5	20	88.2	349.3	3.5	B	B-B-B-B
6	20	159.2	630.5	6.3	G	G-G-G-G
7	20	104.0	411.9	4.1	BG1	B-G-B-G
8	20	109.0	431.7	4.3	BG2	B-G-G-B
9	20	113.1	447.9	4.5	BG3	G-B-B-G
10	20	132.5	524.8	5.2	BG4	B-B-G-G

is important for assessing the material's resistance to tension and stretching forces, which is relevant for applications where the composites will undergo pulling or stretching stresses.

Compressive strength tests were performed following ASTM D3410M, also using the Universal Testing Machine (Model UT-10; S/No: 2015/12) with a 100 kN capacity at a crosshead speed of 5 mm/min. Specimens were prepared with a length of 40 mm, a width of 25 mm, and a gauge length of 40 mm. This test measures the composite's ability to withstand compressive forces and eliminates the possibility of buckling, which is critical for evaluating the performance of the composites in load-bearing applications.

Impact strength was measured using an impact tester (Model HLE; S/No: 2015/15) according to ISO 179-1:2000 standards. The impact test was conducted with a 15 J hammer, and the specimens had a length of 60 mm, a width of 10 mm, and a span length of 40 mm. All the specimens were un-notched to evaluate their natural resistance to impact. Impact strength is an essential

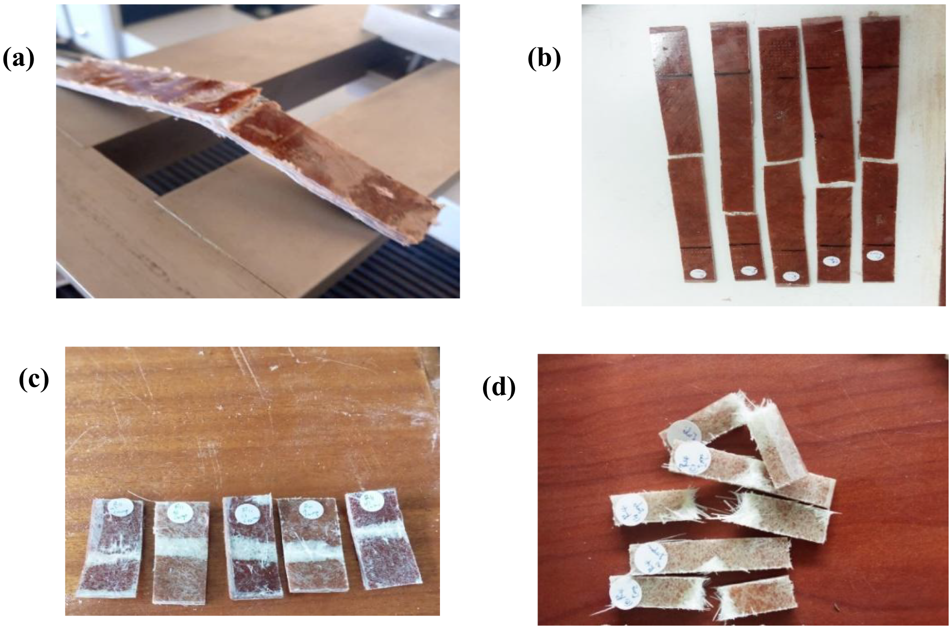

FIGURE 3 | Failed composites after mechanical tests (a) after flexural test; (b) after tension test; (c) after compression test; (d) after impact test.

measure of a material's ability to absorb energy and resist sudden forces, which is especially important for safety-critical applications such as in the automotive industry.

For all mechanical tests, five specimens were tested for each composite type, and the average values were reported. These mechanical tests are vital for understanding the overall performance of the hybrid composites and determining their potential for use in various engineering applications.

2.5 | Statistical Analysis

The experimental data obtained from the mechanical tests were statistically analyzed to determine the significance of the effects of fiber weight fraction and hybrid ratio on the mechanical properties of the composites. One-way analysis of variance (ANOVA) was used to assess the significance of differences in the flexural, tensile, compressive, and impact strengths of the various composite samples. The ANOVA was performed at a 95% confidence level, with a p-value of less than 0.05 considered statistically significant. The F-values and p-values were reported for each mechanical property to quantify the influence of the composite parameters. This statistical analysis provided a robust evaluation of the experimental results, identifying which factors had a significant effect on the performance of the bark cloth/glass fiber hybrid composites.

2.6 | Surface Morphology Analysis

The scanning electron microscopy (SEM) analysis was performed to investigate the surface morphology and cross-sectional structure of hybrid composites with various stacking sequences of bark cloth (B) and glass fibers (G). The samples were prepared with sequences G-G-B-G, B-G-B-G, and B-G-G-B. Small sections were cut from each composite for analysis. SEM images were taken using a VEGA3 TESCAN SEM at an accelerating voltage of 5.0 kV, with magnifications set at 250× for surface analysis and 2.00k× for cross-sectional analysis. The images provided insights into fiber pull-out, microvoids, and the fiber-matrix interaction, highlighting areas of poor resin impregnation and bonding. This methodology enabled a detailed assessment of the structural integrity and mechanical behavior of the composites.

3 | Results and Discussion

The mechanical properties of the bark cloth and glass fabric hybrid composites were analyzed based on flexural, tensile, compressive, and impact strength tests. The effects of varying fiber weight fractions and hybrid ratios (bark cloth to glass fabric) on these properties were investigated to evaluate the performance of the composites. Composite thickness ranged from 4.0 to 5 mm. Figure 3 depicts the failed composites after undergoing the necessary named tests. As seen, most composites failed within acceptable levels.

3.1 | Flexural Strength

The flexural strength of the bark cloth and glass fiber hybrid composites was significantly influenced by the hybrid ratio and fiber weight fractions of 15%, 20%, and 25%, as shown in Figure 4. Composites with a higher proportion of glass fiber consistently exhibited superior flexural performance compared to those with a higher proportion of bark cloth. This improvement is attributed to the higher stiffness and load-bearing capacity of glass fibers, which dominate bending resistance when placed in outer layers where tensile and compressive stresses are maximum. Bark cloth, being more compliant, contributes primarily to energy absorption rather than load carrying. The superior performance at a 1:3 bark cloth–glass fiber ratio reflects a positive hybrid effect, where the stiff glass fibers provide primary load resistance while bark

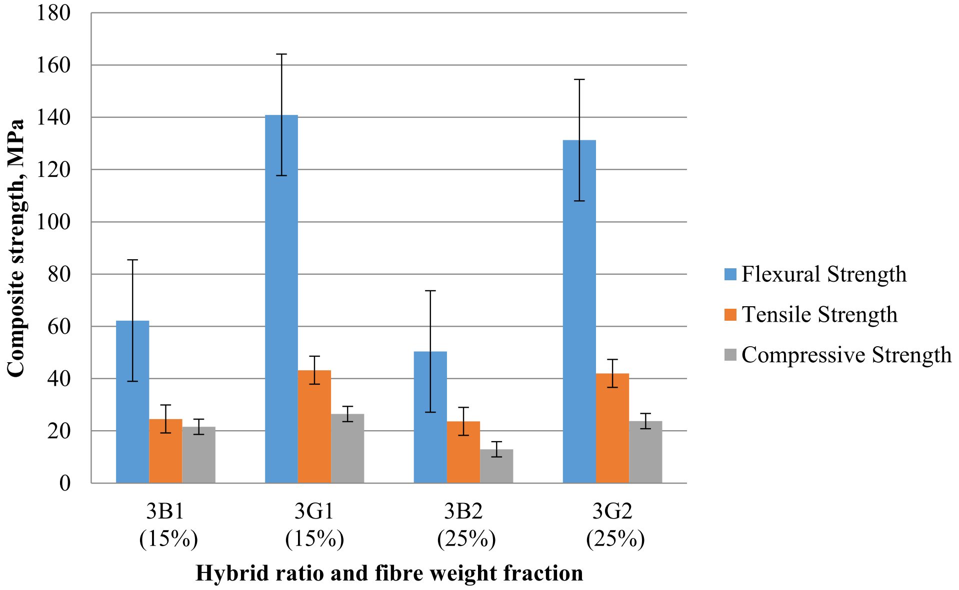

FIGURE 4 | Flexural, tensile, and compressive strengths as a function of hybrid ratio at 15% and 25% fiber weight fraction.

cloth enhances crack deflection and energy dissipation, consistent with hybrid laminate theory.

Similar improvements in flexural strength with increased glass fiber content were reported by researchers, who observed that glass-dominated outer plies significantly enhance bending stiffness. However, unlike their work using jute fibers, the present study demonstrates that bark cloth, due to its woven textile structure, offers superior interlaminar crack bridging. For instance, Hanifawati et al. [46] reported a notable improvement in tensile and flexural strength when glass fiber was added to a banana fiber/polyester matrix. Similarly, Bindal et al. [47] demonstrated that hybrid composites made from natural and synthetic fibers, such as jute/glass, exhibited improved flexural properties compared to pure natural fiber composites.

At 20% fiber weight fraction, composites showed better overall flexural performance than the 25% fiber weight fraction composites, but they were still slightly inferior to the 15% weight fraction composites, suggesting that 20% provides a balanced performance when fiber content and resin wetting are optimized. The observed poor performance at 25% fiber weight fraction is likely due to insufficient resin for fiber wetting, leading to poor fiber-matrix adhesion. Studies like Shahzad and Nasir [54] corroborate this observation, reporting that fiber agglomeration at higher content can lead to a decrease in mechanical properties due to inefficient load transfer between fibers. Additionally, Rachchh and Trivedi [55] found that increasing the natural fiber content beyond optimal levels in glass/natural fiber composites leads to decreased tensile and flexural strength, further supporting our results. The ANOVA results (Table 4) for flexural strength indicated significant differences across hybrid ratios at all fiber weight fractions (15%, 20%, and 25%), with *p*-values lower than 0.05. The 20% fiber weight fraction composites showed improved performance compared to the 25% composites, likely due to better fiber distribution and resin penetration.

Flexural performance is governed mainly by stacking sequence and fiber distribution. Composites with glass fibers in the outer layers exhibited superior flexural strength since maximum bending stresses occur at the laminate surfaces, where stiff glass fibers effectively resist deformation. Bark cloth performs better near the neutral axis, contributing to shear resistance and energy dissipation. The high flexural strength achieved in the optimized hybrid confirms that partial replacement of glass fibers with bark cloth can maintain structural performance while improving sustainability.

3.2 | Tensile Strength

Tensile strength results mirrored the flexural strength trend, with higher glass fiber content improving the tensile strength of the hybrid composites (Figure 4). The observed increase in tensile strength with increasing glass fiber content is attributed to the higher stiffness and tensile modulus of glass fibers, which dominate load transfer along the loading direction. However, beyond 20 wt% fiber loading, tensile strength declined, likely due to insufficient resin wetting and fiber agglomeration, which impair interfacial bonding and reduce effective stress transfer from matrix to fibers. This behavior aligns with findings reported by Misri et al. [56], who reported that the inclusion of glass fiber in sugar palm composites increased tensile strength by 59.20%. The highest tensile strength was observed at 15% fiber weight fraction, while the 20% fiber weight fraction composites performed better than those with 25%. The superior tensile performance at 15% can be attributed to better resin penetration and more uniform fiber distribution. Composites with a 1:3 hybrid ratio and glass fibers in higher proportion, such as composite BG3, exhibited the best tensile performance at 20% fiber weight fraction due to improved load transfer from the glass fibers.

Similar observations were made by Hemalatha and Ramesha [57], who found that hybrid composites with higher synthetic fiber content, such as jute/glass composites, showed enhanced tensile performance due to better load transfer and fiber-matrix adhesion. In contrast, the 25% fiber weight fraction composites, such as 3B2 (B-B-G-B), exhibited reduced tensile strength, which

TABLE 4 | Analysis of variance for effect of hybrid ratio on bark cloth and glass fabric reinforced polyester composites.

Mechanical property	Fiber weight fraction	Source of variation	SS	df	MS	*F*	*p*
Flexural strength	15%	Between groups	15,335.84	1	15,335.84	42.50619	0.000184
		Within groups	2886.326	8	360.7908		
		Total	18,222.17	9			
	20%	between groups	100,503.2	5	20,100.63	14.54638	1.34E-06
		Within groups	33,163.92	24	1381.83		
		Total	133,667.1	29			
	25%	Between groups	16,341.81	1	16,341.81	70.74337	3.04E-05
		Within groups	1848.01	8	231.0012		
		Total	18,189.82	9			
Tensile strength	15%	Between groups	870.1158	1	870.1158	35.66891	0.000334
		Within groups	195.1539	8	24.39424		
		Total	1065.27	9			
	20%	Between groups	3329.748	5	665.9497	60.79107	7.7E-13
		Within groups	262.9135	24	10.95473		
		Total	3592.662	29			
	25%	Between groups	841.6228	1	841.6228	131.7509	3.01E-06
		Within groups	51.10388	8	6.387985		
		Total	892.7266	9			
Compressive strength	15%	Between groups	60.12304	1	60.12304	0.496407	0.501076
		Within groups	968.9316	8	121.1165		
		Total	1029.055	9			
	20%	Between groups	3847.087	5	769.4174	10.87158	1.5E-05
		Within groups	1698.559	24	70.77329		
		Total	5545.646	29			
	25%	Between groups	290.8445	1	290.8445	45.23302	0.000149
		Within groups	51.43932	8	6.429915		
		Total	342.2838	9			
Impact strength	15%	Between groups	5.21284	1	5.21284	0.387706	0.55084
		Within groups	107.5627	8	13.44534		
		Total	112.7756	9			
	20%	Between groups	398.1756	5	79.63512	8.52665	9.43E-05
		Within groups	224.1493	24	9.339555		
		Total	622.3249	29			
	25%	Between groups	23.13441	1	23.13441	1.398344	0.270952
		Within groups	132.3532	8	16.54415		
		Total	155.4876	9			

could be attributed to insufficient resin and poor wetting of the fibers. According to Kumar and Singh [58], higher natural fiber content increases matrix absorption, reducing resin availability for fiber wetting, which is a critical factor in tensile performance. The ANOVA results (Table 4) for tensile strength at all fiber weight fractions (15%, 20%, and 25%) showed statistically significant differences ($p < 0.05$), confirming that the hybrid ratio and fiber content played a crucial role in determining the tensile behavior of the composites.

The tensile behavior of the hybrid composites is strongly influenced by fiber type, fraction, and stacking sequence. Increasing glass fiber content significantly improves tensile strength due to its higher stiffness and load-bearing capacity compared to bark cloth. The optimal performance observed at the 1:3 bark cloth–glass fiber ratio demonstrates a positive hybrid effect, where glass fibers carry the primary load while bark cloth contributes to stress redistribution and crack deflection. At higher fiber contents (25 wt%), tensile strength decreases due

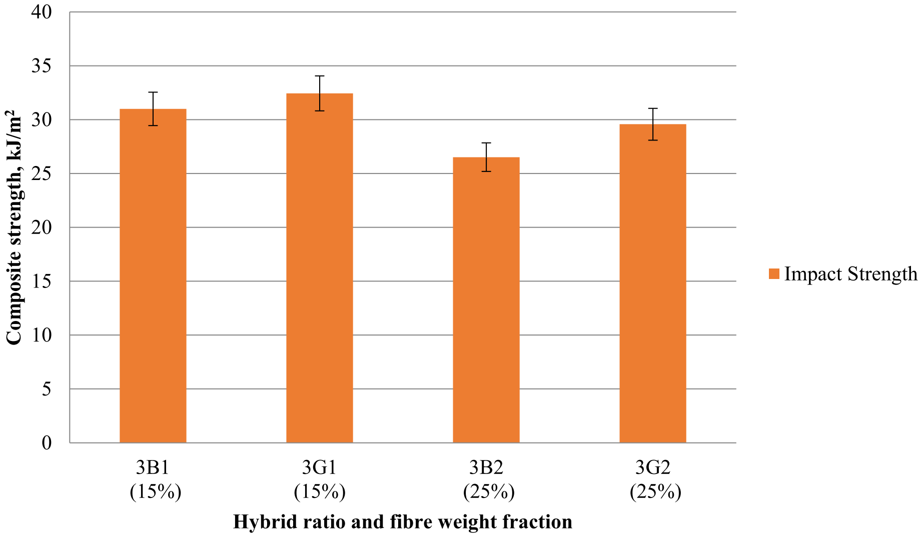

FIGURE 5 | Impact strength as a function of hybrid ratio at 15% and 25% fiber weight fraction.

to poor resin wetting and fiber agglomeration, which weaken the fiber–matrix interface and reduce load transfer efficiency. These properties indicate suitability for semi-structural automotive components.

3.3 | Compressive Strength

The compressive strength tests revealed that hybrid composites with higher glass fiber content exhibited superior performance (Figure 4), which aligns with the findings of Misri et al. [56], who reported that glass fibers provide superior resistance to compressive forces in hybrid composites. The 1:3 hybrid ratio composites showed the highest compressive strength at both 15% and 20% fiber weight fractions, with the latter providing a balanced performance. Composites with a 20% fiber weight fraction outperformed those with 25%, likely due to fewer agglomeration issues and better resin penetration. At 25% fiber weight fraction, composites suffered from reduced compressive strength due to inadequate resin distribution and fiber agglomeration, which hindered uniform load distribution.

The reduction in compressive strength at 25% fiber weight fraction can be attributed to fiber agglomeration and poor fiber-matrix adhesion, as observed in previous studies [54]. In glass/natural fiber hybrid composites, Rachchh and Trivedi [55] reported that exceeding an optimal natural fiber content led to reduced compressive strength due to uneven fiber distribution and resin starvation.

The ANOVA results (Table 4) for compressive strength indicated significant differences at both 20% and 25% fiber weight fractions, with p-values below 0.05, confirming the importance of hybrid ratio and fiber content in determining compressive performance.

3.4 | Impact Strength

The impact strength of the hybrid composites increased with the inclusion of glass fibers, consistent with findings from Satheeskumar [59], who noted that good fiber-matrix adhesion improves impact resistance. At 20% fiber weight fraction, composite BG4 (B-B-G-G) exhibited the highest impact strength of 27.50 kJ/m^2, surpassing the performance of 25% composites. The presence of glass fibers in the outer layers facilitated effective load transfer during impact, allowing the composite to absorb and dissipate energy more efficiently.

Similar trends were reported by Mohanta and Acharya [60], where hybrid composites with synthetic fibers in the outer layers showed superior impact resistance compared to natural fiber composites. The impact performance of the 25% fiber weight fraction composites was lower due to fiber agglomeration and insufficient resin penetration, as noted by Shahzad and Nasir [54], and Rachchh and Trivedi [55].

At 20% fiber weight fraction, hybrid composite BG4 (B-B-G-G) exhibited the highest impact strength of 27.50 kJ/m^2 (Figure 5), outperforming the 25% composites but slightly underperforming compared to the 15% composites. The presence of glass fibers in the outer layers facilitated effective load transfer during impact, resulting in better energy absorption and distribution. This improvement in impact resistance is similar to the findings of Satheeskumar [59], where good fiber-matrix adhesion improved impact strength.

The ANOVA results (Table 4) for impact strength at 20% fiber weight fraction revealed significant differences ($p < 0.05$), confirming that hybridization and fiber arrangement contributed to the improved impact resistance of the composites. The 20% composites performed better than the 25% composites due to better fiber-matrix bonding and fewer fiber agglomeration issues.

Hybrid composites showed enhanced impact resistance due to the complementary behavior of bark cloth and glass fibers. Bark cloth improves energy absorption through fiber pull-out and crack deflection, while glass fibers limit excessive deformation and structural collapse. The best impact performance occurred at intermediate fiber contents, reflecting an optimal balance between stiffness and ductility. This makes the hybrid composites

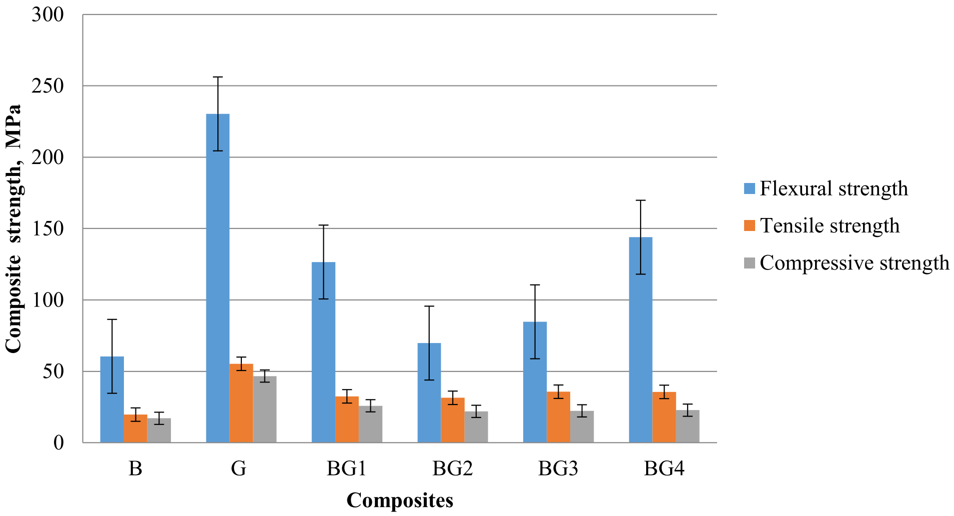

FIGURE 6 | Flexural, tensile, and compressive strengths as a function of varying reinforcement stacking sequence.

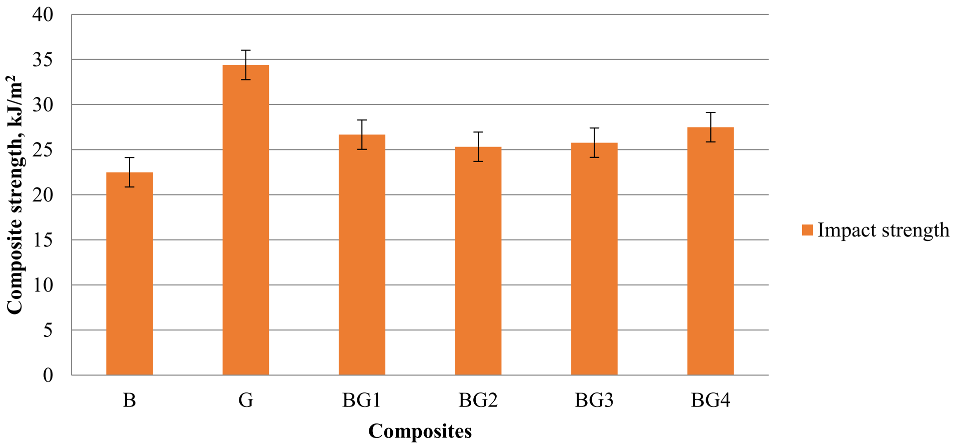

FIGURE 7 | Impact strength of composites as a function of varying stacking reinforcement stacking sequence.

suitable for automotive components requiring impact tolerance and lightweight design.

3.5 | Effect of Stacking Sequence

The stacking sequence had a profound impact on the mechanical performance of the hybrid composites, particularly at 20% fiber weight fraction. As seen in Figure 6, composites with glass fibers in the outer layers exhibited higher mechanical properties across flexural, tensile, and compressive strengths. The importance of the stacking sequence in enhancing the mechanical properties of natural fiber-based composites has been reported in previous studies [40, 48]. In this study, composite BG3 (G-B-B-G) at 20% fiber weight fraction showed the best tensile strength, which can be attributed to the advantageous placement of glass fibers in the outer layers, improving load distribution. Similarly, composite BG4 (B-B-G-G) exhibited the highest impact strength (Figure 7), benefiting from the glass fibers on the outer side, which facilitated effective load transfer during impact.

At 20% fiber weight fraction, the stacking sequence played a crucial role in optimizing the balance between the rigidity provided by glass fibers and the flexibility and sustainability of bark cloth. The 20% composites outperformed the 25% composites due to better fiber distribution and fewer agglomeration issues. When glass fibers were placed as the outer layers, as in BG3 and BG4, the composites showed significant improvements in mechanical performance compared to configurations where bark cloth was in the outer layers, such as B-G-G-B.

The results also showed that hybrid composites with alternating layers of bark cloth and glass fiber outperformed pure bark cloth composites in all mechanical properties. For instance, the flexural strength of hybrid composites increased by 137.98%, tensile strength by 81.59%, and compressive strength by 51.58% compared to pure bark cloth composites. These findings align with studies such as Santhanam et al. [26], which found that stacking sequence had a more substantial effect on flexural and impact strength than tensile strength.

The ANOVA results (Table 4) for the effect of stacking sequence on flexural, tensile, compressive, and impact strengths at 20% fiber weight fraction confirmed significant differences ($p < 0.05$). The F-ratio values were higher than the F-criteria values, indicating that the stacking sequence significantly affected the

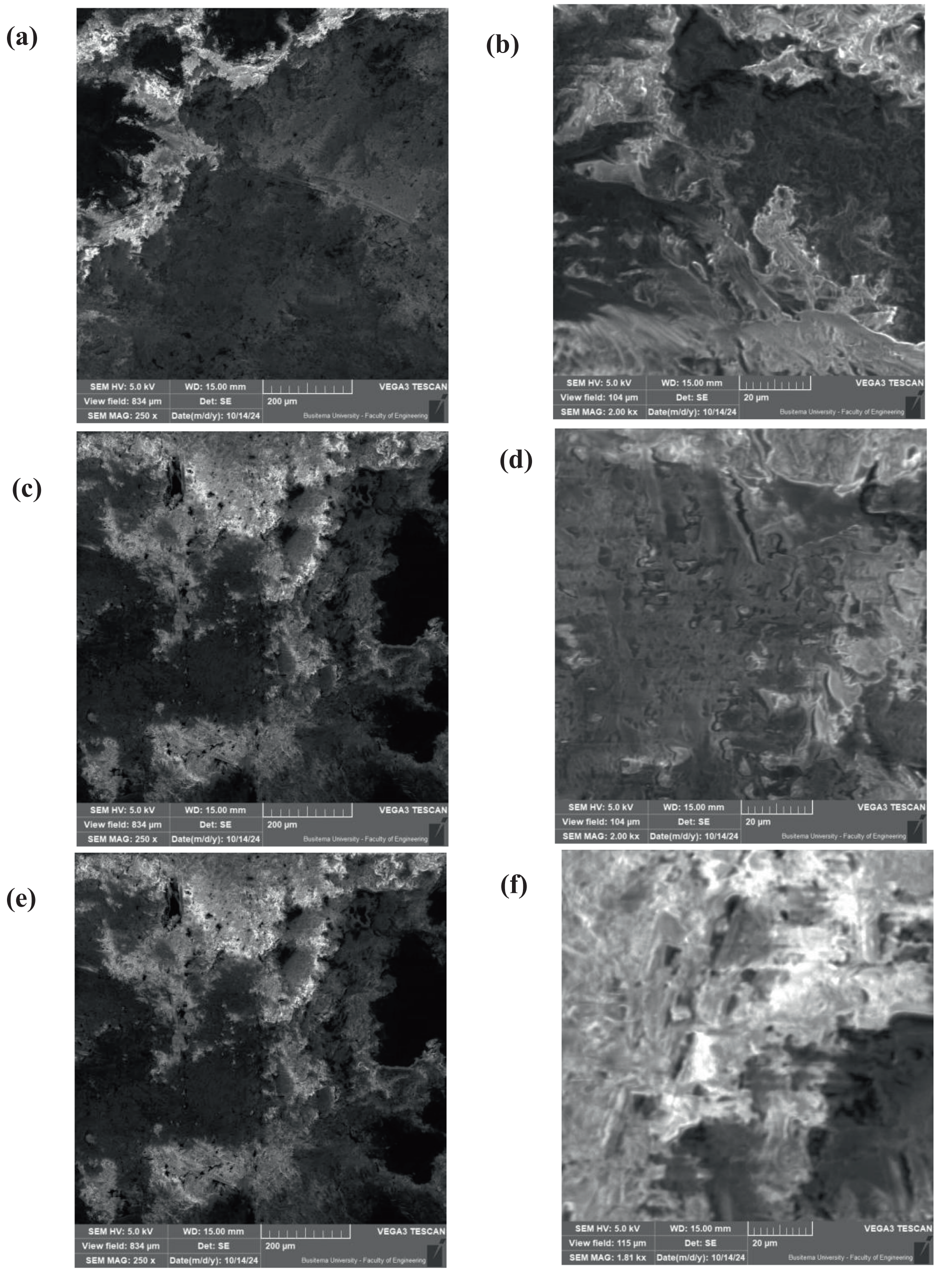

FIGURE 8 | Surface morphology and cross-section SEM analysis of hybrid composite; (a, b) B-G-G-B hybrid; (c, d) B-G-B-G hybrid; (e, f) G-G-B-G hybrid.

performance of the composites. The highest mechanical properties were consistently observed in composites with glass fibers in the outer layers, such as BG3 and BG4.

The stacking sequence significantly influences the mechanical performance of hybrid composites. Placing glass fiber layers at the outer surfaces is particularly beneficial because the outer plies experience the highest tensile and compressive stresses during bending and impact loading. Due to their higher stiffness and strength, glass fibers effectively carry these stresses, enhancing flexural rigidity, impact resistance, and surface durability. In contrast, bark cloth fibers, being less stiff and more moisture-sensitive, are better suited for the core region where shear dominates. This configuration also improves environmental resistance and surface integrity, which are critical for automotive applications. Further optimization of stacking sequences through symmetric layups, functionally graded laminates, and application-specific designs can significantly enhance the overall performance and durability of hybrid composites.

3.6 | Surface Morphology and Cross-Section Analysis

The SEM analysis of the B-G-G-B hybrid composite highlights both surface and cross-sectional features that provide insights into the material's structure and performance. In the surface morphology at 250× magnification (Figure 8a), roughness and fiber pull-out are visible, indicating regions of incomplete resin impregnation. These voids and surface irregularities suggest that the bonding between the matrix and fibers, especially in the bark cloth layers, may not be sufficient, which could lead to stress concentration points and reduced mechanical integrity.

In the cross-sectional view at 2.00k× magnification (Figure 8b), the glass fiber layers are well integrated, showing a more uniform bond with the matrix. However, the bark cloth layers exhibit fiber pull-out and weaker bonding, with voids observed between the fibers and the matrix. This indicates potential flaws in the resin impregnation process, particularly in the natural fiber regions. These imperfections could act as points of failure under mechanical stress, compromising the overall durability of the composite [50].

For the B-G-B-G hybrid composite, the SEM analysis also reveals rough surface morphology (Figure 8c), with significant fiber pull-out and voids, again suggesting incomplete resin impregnation. The bark cloth fibers show weaker bonding compared to the glass fibers. In the cross-section (Figure 8d), glass fibers appear more consistently bonded to the matrix, while the bark cloth layers are less integrated, with visible fiber pull-out and voids that could reduce mechanical strength.

Finally, for the G-G-B-G hybrid composite, surface analysis shows a similar roughness, with some regions exhibiting fiber pull-out (Figure 8e). In the cross-section (Figure 8f), the glass fibers are well embedded, but the bark cloth layers show weaker bonding and void formation, indicating potential weaknesses in fiber-matrix adhesion. These defects highlight the need for improved resin infiltration and fiber alignment to enhance the composite's overall structural integrity and mechanical performance.

SEM analysis revealed more pronounced fiber pull-out and voids in bark cloth layers compared to glass fiber layers, indicating weaker fiber–matrix interfacial bonding and less compact microstructure. These defects can adversely affect long-term durability by promoting crack initiation, moisture ingress, and interfacial degradation under environmental exposure. In humid conditions, voids facilitate water diffusion into the hydrophilic bark cloth fibers, leading to swelling, interfacial debonding, and progressive loss of mechanical integrity. Under thermal cycling, these poorly bonded regions act as preferential sites for fatigue damage due to differential thermal expansion between constituents. Nevertheless, the incorporation of glass fiber layers significantly mitigates these effects by enhancing load redistribution, restricting crack propagation, and improving dimensional stability, thereby enabling the hybrid composites to remain viable for semi-structural automotive applications.

3.7 | Performance and Structure–Property Relationships

The mechanical performance of the bark cloth–glass fiber hybrid composites is governed by the synergistic interaction among fiber type, hybrid ratio, stacking sequence, and fiber weight fraction. Bark cloth contributes to weight reduction, sustainability, and energy absorption, while glass fibers provide the primary load-bearing capacity due to their superior stiffness and strength. The superior performance observed at the 1:3 bark cloth-to-glass fiber ratio confirms that an appropriate balance between natural and synthetic reinforcements can simultaneously enhance mechanical efficiency and material sustainability.

Composites with glass fiber outer layers consistently exhibited higher flexural and impact strengths, attributed to their ability to withstand surface tensile and compressive stresses during bending and dynamic loading. In contrast, bark cloth-rich laminates showed more fiber pull-out and voids in SEM images, explaining their comparatively lower tensile and flexural properties due to weaker interfacial bonding and reduced load transfer efficiency.

Fiber weight fraction further influenced mechanical behavior, with 20 wt% fiber content yielding superior properties compared to 25 wt%, where resin starvation and fiber agglomeration impaired matrix wetting and interfacial adhesion. This demonstrates that mechanical performance is not solely dependent on fiber content but critically on the quality of fiber–matrix interaction and structural integrity.

Hybridization with glass fibers effectively mitigated the inherent limitations of bark cloth fibers, including lower mechanical strength and moisture sensitivity. Glass fibers act as efficient stress carriers and crack-bridging agents, significantly enhancing tensile, flexural, and compressive strengths. For instance, the 1:3 hybrid achieved tensile and flexural strengths of 43.24 and 140.94 MPa, respectively, far exceeding those of bark cloth-only composites. Moreover, the reduced hydrophilic content and denser microstructure in hybrid composites limit moisture ingress, contributing to improved durability and structural stability.

These results demonstrate that controlled hybridization and stacking sequence optimization are effective strategies for tailoring composite performance for lightweight automotive components, where a balance between strength, impact resistance, durability, and sustainability is essential.

4 | Conclusion

This study successfully demonstrated the potential of bark cloth–glass fiber hybrid composites as sustainable and high-performance materials for automotive and lightweight structural applications. By systematically varying fiber ratio, stacking sequence, and fiber weight fraction, the structure–property relationships governing the mechanical behavior of the composites were clearly established. The hybridization of bark cloth with glass fibers significantly enhanced tensile, flexural, compressive, and impact properties compared to bark cloth-only composites, confirming the effectiveness of combining natural and synthetic reinforcements. Among the investigated configurations, the 1:3 bark cloth-to-glass fiber ratio exhibited optimal mechanical performance, achieving a favorable balance between load-bearing capability, toughness, and sustainability. The superior properties of this hybrid system were attributed to efficient stress transfer through glass fibers, complemented by crack deflection and energy dissipation mechanisms introduced by bark cloth. The stacking sequence was found to play a critical role, with glass fibers positioned in the outer layers providing enhanced resistance to bending and impact loads due to their ability to sustain surface stresses. Additionally, an optimal fiber weight fraction of 20 wt% was identified, beyond which mechanical performance deteriorated due to resin starvation, fiber agglomeration, and weakened interfacial bonding, as confirmed by SEM analysis. This work highlights hybridization and stacking sequence optimization as effective strategies for overcoming the limitations of natural fiber composites while maintaining environmental benefits. The findings provide a valuable framework for designing lightweight, mechanically efficient, and sustainable hybrid composites suitable for automotive interior panels, semi-structural components, and impact-resistant parts. Future studies should focus on long-term durability, moisture resistance, fatigue behavior, and life-cycle assessment to further validate the industrial applicability and environmental advantages of bark cloth–glass fiber hybrid composites.

Author Contributions

Frances Alibet: conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft, writing – review and editing. **Paul Wambua:** supervision, resources, funding acquisition, writing – review and editing. **David Njuguna Githinji:** validation, resources, writing – review and editing, funding acquisition. **Samson Rwahwire:** funding acquisition, supervision, writing – review and editing, resources, validation. **Ocident Bongomin:** writing – review and editing, methodology, visualization, formal analysis, validation, writing – original draft.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Peer Review

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