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Agro-Waste Reinforced Kombucha Bacterial Cellulose Composites for Sustainable Woven Craft Materials

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Abstract

The global woven craft and material industry has faced increasing criticism for excessive water consumption, chemical pollution, microplastic release from synthetic fibres, and dependence on non-renewable petroleum-based resources. Kombucha bacterial cellulose (KBC), a biodegradable, high-purity biomaterial, shows promising potential; however, its suitability for woven craft applications remains underexplored. This study investigates the development of agro-waste reinforced KBC composites as functional biomaterials for woven craft applications, with reference to traditional *kasah* weaving in Sarawak, Malaysia. Pineapple leaf fibres and baby corn husk fibres were incorporated into regenerated KBC matrices to produce twelve composite formulations. The morphological characteristics of the composites were examined using scanning electron microscopy (SEM), while tensile behaviour and moisture resistance were evaluated to assess performance under weaving-related conditions. The results demonstrated that fibre reinforcement significantly improved the mechanical stability, fibre–matrix interaction, and structural integrity of KBC composites compared with pure KBC controls. Among the reinforced composites, pineapple fibre formulations exhibited superior mechanical performance, while the KBC-PS2 composite demonstrated the most balanced behaviour for woven craft applications by combining good tensile strength, tear resistance, and flexibility. The reinforced composites achieved a maximum tear strength of 25.447 MPa and exhibited improved tensile performance relative to pure KBC, indicating suitability for low-load woven craft and biomaterial applications while exceeding the tensile performance of traditional *kasah* bark reference materials. These characteristics provided enhanced resistance to weaving tension while maintaining sufficient flexibility for manipulation during weaving. This study highlights the potential of KBC-based composites as sustainable materials that support the integration of biomaterial innovation with culturally contextualised weaving practices.

Keywords: Kombucha Bacterial Cellulose, Agro-waste Reinforced Composites, Sustainable Materials, Woven Biomaterial Performance, Natural Fibre Reinforcement.

1. Introduction

The woven craft and materials industry globally has faced mounting criticism for its environmental impacts, including excessive resource consumption, waste generation, and the use of non-renewable resources. Traditional woven craft manufacturing often uses petrochemical fibres, which contribute significantly to microplastic pollution and environmental degradation. Consequently, sustainable and biodegradable materials have become a primary area of concern in materials science and sustainable fashion studies (Jali, 2022). There is growing interest in bio-

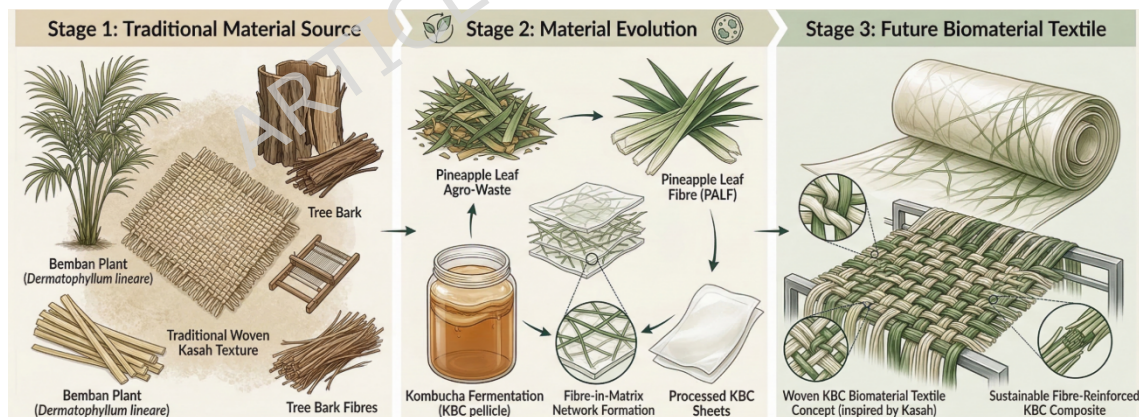
based materials derived from renewable sources as potential substitutes for traditional fibres, as they have a smaller ecological footprint and are biodegradable. Bacterial cellulose (BC) is an emerging biomaterial that has received significant attention for its structural and mechanical properties (Belkozhayev et al., 2025), owing to its high crystallinity, nanofibrillar network structure, flexibility, tensile strength, and biodegradability. Past studies have explored BC in applications such as biomedical scaffolds, food packaging, membrane filtration, and leather-like biomaterials (Shrivastav et al., 2022; Utoiu et al., 2024; Belkozhayev et al., 2025). There is comparatively little research on how to adapt BC to suit woven structures that demand flexibility, tensile strength, and surface properties compatible with weaving processes (Worku, 2025). Weaving processes impose mechanical requirements on materials, including tensile resistance, repeated bending tolerance, and frictional stability between interwoven strands (Jalil, 2025). Materials intended for woven craft and woven composite structures must have sufficient tensile strength, flexibility, and resistance to repeated bending to withstand interlacing during weaving. Previous studies on natural fibre-based woven materials have reported tensile strength ranges between approximately 5–30 MPa and elongation values between 3–15%, depending on fibre type, density, and structural configuration (Worku, 2025; Sethupathi et al., 2024). Therefore, reinforcement strategies are necessary to improve the structural performance of BC materials for woven biomaterial applications.



Figure 1. Original *kasah* woven mat product (author's archive)

Thus, additional reinforcement techniques are often needed to enhance the structural stability of BC materials when adapted for woven craft applications. The pineapple leaves, corn husks and other lignocellulosic residues used as agro-waste materials are sources of massive quantities of cellulose fibres that may be used as reinforcement components in composite materials (Sethupathi et al., 2024; Xiao et al., 2024). In addition to innovations in materials, the development of sustainable materials offers an opportunity to promote traditional crafts that depend on natural resources. Bidayuh people have a rich history of weaving traditional crafts from natural materials in Sarawak, Malaysia, including tree bark and rattan for *kasah* weaving, as shown in Figure 1 (Jalil & Robert, 2026). As Jalil and Alison (2026) stated, these resources are significant to the community's cultural life and material culture. Nonetheless, the growing scarcity of suitable bark sources and the environmental risks associated with the use of natural

resources led to concerns about the long-term sustainability of traditional *kasah* manufacturing. The creation of other bio-based materials that are analogous to traditional *kasah* in their functional characteristics may therefore help conserve traditional weaving activities and reduce ecological stress on natural forest resources. The combination of current biomaterial engineering and traditional craft expertise offers a promising avenue for sustainable material innovation that can simultaneously address environmental, cultural, and technological issues. Although BC has been widely researched in materials science, very few studies have examined its combination with agro-waste fibres for weaving into craft applications, especially in the context of indigenous craft systems. Previous research on BC materials has primarily focused on applications such as biodegradable packaging, biomedical scaffolds, hydrogels, and bio-based leather alternatives (Utoiu et al., 2024; Choi et al., 2022). BC films have attracted significant attention for sustainable packaging applications due to their biodegradability, high water retention, and favourable barrier properties (Catarino et al., 2025). Similarly, biofabrication studies have investigated BC sheets as leather-like materials for fashion accessories and experimental garments (Choi et al., 2022). Designers such as Suzanne Lee have explored BC as a biofabricated material for experimental fashion using fermentation-based production techniques, demonstrating the creative potential of microbial cellulose in sustainable fashion systems (Absharina et al., 2025; Jalil, 2022). However, most existing studies have concentrated on sheet-based BC materials intended for garment construction rather than structurally reinforced woven biomaterial applications. As a result, the remaining research gap is the ability to develop bio-based composite materials that have the structural benefits of BC, potential reinforcement from agricultural fibres, and address the functionality needs of weaving-based manufacturing.



(a) (b) (c)

Figure 2. Material evolution schematic: traditional fibre to sustainable agro-waste reinforced KBC composite (a) traditional natural materials, (b) agro-waste fibre and BC integration, (c) sustainable agro-waste reinforced KBC composite for woven applications

Thus, this research, as shown in Figure 2, will generate and assess an agro-waste-based reinforced KBC composite as a sustainable biomaterial for woven craft structures. This study examines the structural, mechanical, and morphological properties of regenerated BC matrices

modified with fibres from pineapple leaves and baby corn husks. It evaluates their performance and suitability as alternatives to traditional *kasah* weaving techniques.

2. Literature Review

2.1 Bacterial Cellulose as Sustainable Biomaterial

Bacterial cellulose is highlighted as an adaptable natural biomaterial with unique physical properties, including flexibility, high porosity, and good water-holding capacity, as well as chemical properties, including high crystallinity and purity. It also possesses biological characteristics such as biodegradability, biocompatibility, and non-toxicity (Shrivastav et al., 2022). Moreover, as Wu et al. (2023) explored, BC's hierarchical nanofiber network structure contributes to its extraordinary performance, making it suitable for high-strength structural materials, energy conversion and storage, bioelectronic interfaces, environmental remediation, and thermal management. BC is a biocompatible biomaterial with a unique macromolecular structure, consisting of self-assembled nanostructured fibres with high crystallinity (Utoiu et al., 2024). Advances in BC production focus on improving efficiency, productivity, and control, adapting to specific bacterial strains and industrial material applications. The biotechnological valorisation of plant biomass, particularly agricultural residues such as straw, stalks, and husks, for BC production is a growing area, as noted by Belkozhayev et al. (2025). These lignocellulosic feedstocks are abundant, renewable, and potential substrates for microbial fermentation (Belkozhayev et al., 2025). Key factors influencing BC bioprocesses include microorganism selection, substrate optimisation, and cultivation techniques. Catarino et al. (2025) stated that utilising alternative substrates, especially agro-industrial waste, can reduce production costs and improve the sustainability of biomaterial engineering.

2.2 Agro-Waste Fibres in Bio-Composite Materials

Agricultural waste residues are increasingly used to develop eco-friendly biocomposites due to their recyclability, abundance, and variable properties. Extraction, processing, chemical modification, and physical treatments significantly influence the physical, mechanical, and thermal properties of these fibres (Phiri et al., 2023). Siqueira et al. (2022) showed that Brazilian agro-industrial waste, which generates about 291 million tons yearly, is a significant source of natural fibres and polymers for biosorbents, structural bio-based materials, and composite reinforcement. Moreover, computational techniques are being used to design novel biocomposites from recycled PET and agro-industrial biomass, with pineapple peel fibres showing promising longitudinal stiffness (Díaz-Gómez et al., 2025). Pineapple leaf fibre (PALF) is a prominent natural fibre due to its rich cellulose content, cost-effectiveness, eco-friendliness, and good strength (Sethupathi et al., 2024). Research focuses on improving PALF reinforced composites by selecting different composite matrices and designing appropriate structures to enhance performance (Xiao et al., 2024). Arumugam et al. (2025) reported that pre-treated short PALFs, combined with ceramic powder and nano-SiO₂, can produce high-performance polyester hybrid nanobiocomposites with improved interfacial compression and tensile strengths for

industrial applications. Sustainable chemicals such as sodium bicarbonate and borax can modify PALF surfaces, thereby improving the strength, crystallinity, and thermal properties of PALF/poly(lactic acid) biocomposites and enhancing mechanical properties (Komal & Singh, 2022).

On the other hand, corn husk fibre has also been investigated in hybrid composites. Hazrol et al. (2023) showed that cornhusk fibre-reinforced corn starch-based hybrid composites exhibit improved thermal properties with increased cornhusk fibre loading and are biodegradable. However, research shows that PALF exhibits superior mechanical properties. Its tensile strength ranges from 180 to 753 MPa, which is higher than that of other fibres used in composite reinforcement (de Silva et al., 2025). In direct comparisons, PALF has shown higher flexural strength than corn husk fibre in certain composite formulations (Ramadina et al., 2026). When processed into nanocellulose, pineapple leaf nanocellulose (PLNc) significantly enhances the tensile strength of biocomposite films, with Siribanluehan and Wattanachai (2024) reporting a 220% increase. Moreover, corn husk fibre can also enhance the mechanical properties of composites, but not as much as PALF. Its incorporation into thermoplastic cornstarch-based biocomposite films has been shown to improve tensile strength and Young's modulus (Ibrahim et al., 2019). However, the successful extraction and utilisation of both corn husk and pineapple leaf for biocomposite films suggest that both can be processed into fine reinforcing agents (Siribanluehan & Wattanachai, 2024). Natural fibres in general are recognised for their ease of handling and processing compared to synthetic alternatives (Asim et al., 2015). Various green materials derived from agricultural by-products, including coconut fibre, kenaf fibre, rice bran, rice husk, rice straw, tea-leaf fibre, and peanut shell, are also being studied for their sound-absorbing properties. Jang (2023) stated that their structural effectiveness depends on thickness, density, and the presence of an air back cavity.

2.3 Biomaterials for Sustainable Woven Crafts

Bacterial cellulose biofabrication is a method for producing sustainable, eco-friendly structural biomaterials that addresses challenges such as low yields and high production costs by optimising cultivation conditions and using genetic engineering (Absharina et al., 2025). BC is a promising biomaterial for sustainable sensing applications, with studies focusing on its physical and mechanical properties and its potential for eco-friendly, biodegradable, flexible structures (Tyurin et al., 2023). Xu et al. (2025) showed that Mycelium-cellulose interface engineering creates robust woven bio-structures by integrating mycelium with cellulose fibres, forming a semi-interpenetrating network that enhances water resistance and strength while maintaining environmental stability. Biomaterials are increasingly used in advanced structural applications, with a focus on integration strategies and sustainable innovations to enhance material performance and efficacy (Roshima & Periyasamy, 2026). The sustainable materials sector is shifting from synthetic polymers to eco-friendly biopolymers, such as bacterial and plant-based nanocellulose, lignin, chitosan, alginate, gelatin, collagen, keratin, and PLA, for functionalizing woven craft materials, offering biodegradability and sustainability (Daget & Tassew, 2025). Eco-friendly finishing techniques using natural colours and bio-crosslinkers derived from organic

resources offer a sustainable solution to reduce environmental damage in the woven craft and materials industry (Shaharuddin et al., 2021). Sustainability in material engineering involves eco-friendly practices and materials, such as organic fibres, recycled matrices, and innovative biodegradable composites, to mitigate environmental impact and promote ethical production (Sawant et al., 2024). Shaharuddin et al. (2021) stated that sustainable material sourcing in the manufacturing supply chain is driven by the need to reduce environmental impact, improve social status, and adapt to conscious consumer needs, with trends heavily favouring organic fibres, recycling, and biodegradable structures.

2.4 Natural Materials in Weaving Systems from Ancient

The conventional materials industry is resource-intensive, leading to significant environmental burdens. Material recycling is crucial for sustainable resource management but faces challenges with natural, synthetic, and blended matrices (Worku, 2025). The rapid growth and renewability of bamboo offer an eco-friendly alternative to traditional fibres, but challenges remain in its use in woven crafts. Integrating bamboo into traditional weaving methods can enhance its uniqueness and preserve cultural heritage (Jalil, 2025). Modernisation, market dilution, and reduced youth participation challenge the survival of indigenous crafts, despite their sustainable, low-impact production rooted in local ecology (Lakra & Nayyak, 2025). The *Ainu*, indigenous people of Hokkaidō, are known for their traditional woven artefacts, which showcase ingenious techniques for transforming plant fibres into durable structural items (Palomino, 2024). Moreover, *Obom*, a traditional woven material of the Fan-béti in Cameroon, is made from tapered bark, which Kuate et al. (2024) stated that research aims to improve its properties to meet modern structural weaving standards while valorising biodegradable natural resources. The cultural sustainability of indigenous woven crafts, such as the *Àdìrẹ elékò* patterns among the Yoruba, is threatened by imitated versions and challenges in sourcing raw materials. Diyaolu (2025) stated that there is a need for governmental attention to policies that support and protect indigenous handicrafts and woven artefacts.

While BC is widely recognised as a sustainable biomaterial (Shrivastav, 2022; Utoiu, 2024), the literature does not extensively differentiate among or specifically focus on the unique properties, production challenges, or advantages of kombucha-derived BC for structural woven craft applications. Research often refers to BC in general, without delving into the specific characteristics imparted by the kombucha symbiotic culture of bacteria and yeast (SCOBY) on the performance of woven composite mats. The literature highlights the use of agro-waste fibres as reinforcement in various bio-composites, often with polymer matrices (Arumugam, 2025). However, there is a notable gap in detailed studies on optimal methods for directly incorporating specific agro-waste fibres, such as pineapple leaf fibre and corn husk fibre, into a BC matrix, particularly one derived from kombucha. While BC is recognised for its potential in sustainable woven biomaterials (Absharina, 2025), there is limited specific research detailing the mechanical properties (tensile strength, flexibility, bending tolerance, tear resistance) and aesthetic qualities (texture, feel, dyeability) of agro-waste reinforced KBC composites that are specifically tailored and evaluated for craft weaving applications.

The existing literature tends to focus on BC as a standalone material or in other forms, such as nonwovens. The provided literature does not include any direct studies or comparisons evaluating the performance, sustainability, cultural acceptance, or economic viability of agro-waste-reinforced kombucha BC composites compared with traditional materials. This represents a significant unexplored area for a specific research focus. Although the literature addresses the biotechnological valorisation of agricultural residues for BC production to reduce costs (Belkozhayev et al., 2025), there is a lack of comprehensive studies on the industrial scalability and economic feasibility of producing agro-waste-reinforced KBC composites for structural woven craft applications.

3. Materials and Methods

The methodology section has been divided into three phases: material preparation, composite fabrication, testing, and, finally, the weaving process.

3.1 Material Preparation and Extraction

The biomaterials developed in this study were derived from fermentation waste and agricultural by-products to investigate their potential application as sustainable woven biomaterial composites. The primary materials included KBC, pineapple leaf fibres, and baby corn husk fibres as follows.

Kombucha Bacterial Cellulose (KBC) waste was sourced from KIN Kombucha, a local kombucha producer in Kuching, Sarawak, Malaysia, where BC is generated as a by-product of the fermentation process. The approximate geographical coordinates of the production site are 1.553° N, 110.359° E. The collected KBC waste was thoroughly washed with distilled water to remove residual impurities and fermentation media before further processing and composite fabrication. The material was chosen for its high cellulose purity, biodegradability, and inherent nanofibrillar structure, all of which are relevant to the manufacturing of biomaterials. The BC in this paper was purified and processed before composite fabrication. To eliminate residual fermentation media and impurities, raw KBC pellicles were initially boiled in tap water for 30 minutes. For the chosen treatment groups, the cellulose was further treated with a 1% solution of sodium bicarbonate (NaHCO_3) to improve purification and fibre dispersion in the composite matrix. Another oxidative treatment with 3 per cent hydrogen peroxide (H_2O_2) was used in specific samples to bleach and eliminate organic residues. The purified BC sheets after chemical treatment were then mechanically mixed in an immersion blender until a homogeneous cellulose mesh was obtained. The suspension of blended cellulose was then cast into wooden moulds measuring 10 cm × 10 cm × 1.5 cm to produce flat composite sheets. The fabricated KBC composite samples were initially dried under ambient laboratory conditions ($27 \pm 2^\circ\text{C}$ and $65 \pm 5\%$ relative humidity) with fan-assisted air circulation for approximately 24 hours. The samples were subsequently dehydrated in a controlled drying oven at 45°C for 8 hours to ensure complete moisture removal and structural stabilisation. To enhance the durability, flexibility, and moisture resistance of the composites, the dried KBC sheets were coated with a natural wax formulation consisting of beeswax (40 wt.%), carnauba wax (20 wt.%), and coconut oil (40 wt.%). The wax blend was heated to $70\text{--}75^\circ\text{C}$ for 15–20 minutes until fully homogenised, then applied to the

KBC surface using a brush-coating technique. The average coating thickness was approximately 0.2–0.3 mm. The sheets were coated and allowed to dry at room temperature for 24 hours.

Agro-waste (Pineapple) - The agricultural waste used in this study was sourced from Bidayuh farming communities in Sarawak, Malaysia. Pineapple leaves were collected from *Ridung Campsite*, where two local varieties, *Nanas Paun* and *Nanas Sawit*, were identified. The approximate geographical coordinates of the collection site are 1.397° N, 110.397° E. This foliage is normally abandoned during farming maintenance and propagation. The extraction of pineapple leaf fibres used water retting and scraping due to the high volume of leaves to be extracted and the lack of access to mechanised processing equipment. The leaves were initially clipped to remove thorny edges and washed to remove surface contaminants. The washed leaves were then placed in water and allowed to undergo 9 days of water retting to soften the surrounding plant tissues. The outer surface of the leaves was scraped off by hand with a ceramic shard to dislodge the fibres after being retted. The fibres obtained were thoroughly washed, followed by boiling in tap water with 1 per cent sodium bicarbonate to remove impurities further and enhance their cleanliness. The fibres were then dried in the sun until the weight was constant. The extracted pineapple leaf fibres possessed an average fibre length of approximately 20–60 mm after manual extraction and drying. Pineapple leaf fibre is reported to contain approximately 70–82% cellulose, which contributes to its favourable tensile properties and suitability as a reinforcement in biodegradable composites (Asim et al., 2015; Hanyue et al., 2024).

Agro-waste (Baby corn husk) - Baby corn husks were obtained from local farms in *Kampung Peros*, Sarawak, Malaysia, where the husks are typically removed and discarded during corn harvesting. The approximate coordinates for this location are 1.416° N, 110.167° E. All plant materials were collected manually and cleaned before further processing. These agricultural residues were chosen for their availability, lignocellulosic fibre content, and compatibility with BC matrices for composite reinforcement. The treatment process was alkaline and used to separate the fibre. Fresh corn husks were thoroughly washed and cut into smaller pieces before alkaline treatment. The husks were immersed in a 0.4 wt% sodium hydroxide (NaOH) solution, prepared by dissolving 2 g of NaOH in 500 mL of distilled water (approximately 0.1 M). Approximately 25 g of husk material was treated in the solution using a water bath at 95°C for 30 minutes. The alkaline treatment was conducted to remove hemicellulose, lignin, waxes, and other non-cellulosic impurities while improving fibre surface roughness and fibre–matrix adhesion. The selected alkaline concentration and treatment duration were based on previous natural fibre treatment studies and preliminary optimisation trials to avoid excessive fibre degradation while enhancing fibre separation. After treatment, the fibres were rinsed repeatedly with distilled water until a neutral pH (approximately pH 7) was achieved, as confirmed using pH indicator measurements. The processed baby corn husk fibres exhibited irregular short-fibre morphology with estimated fibre lengths ranging from 10 to 40 mm. Corn husk fibres contain lignocellulosic components, including cellulose, hemicellulose, and lignin, which contribute to

their compatibility with biodegradable composite matrices and reinforcement behaviour (Xiao et al., 2024).

3.2 Composite Fabrication/Fibre Reinforcement

A biomaterial composite was produced by combining agricultural waste fibres with BC via blending and layered reinforcement methods, as shown in Figure 3. In the case of fibre-blended composites, pineapple or corn husk fibres were added to the BC slurry at different weight ratios relative to the wet KBC weight. The fibre loading levels were selected at 1 wt.% (low reinforcement), 3 wt.% (medium reinforcement), and 5 wt.% (high reinforcement) based on preliminary fabrication trials and previous studies on natural fibre-reinforced biocomposites (Bahlouli et al., 2023; Mochane et al., 2021; Sarifuddin et al., 2012). Lower fibre loading was expected to preserve flexibility and processability, while moderate loading was intended to improve mechanical reinforcement. Fibre loading above 5 wt.% was not investigated because preliminary observations indicated difficulties in fibre dispersion, increased fibre agglomeration, reduced matrix uniformity, and brittleness in the composite structure. The fibre-cellulose mixtures were homogenised using an immersion blender to ensure uniform dispersion. The fibre-cellulose mixtures were homogenised using an immersion blender to ensure uniform dispersion.

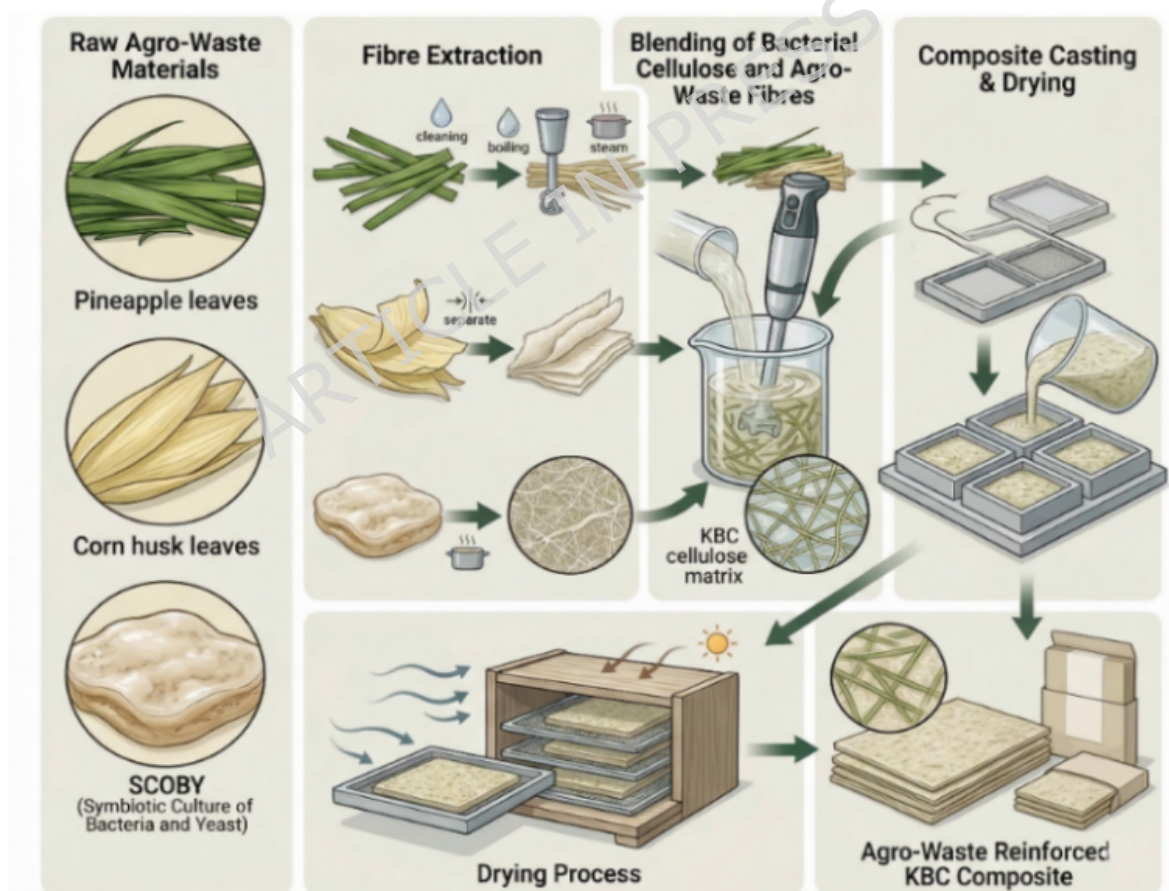


Figure 3. Composite fabrication process and structure of agro-waste reinforced BC

Mechanical blending and manual stirring were performed to improve fibre dispersion in the cellulose slurry before casting; however, complete control over fibre orientation and uniformity

was not achievable due to the random distribution of the natural fibres. For layered composites, an initial layer of blended BC slurry was first poured into the mould, followed by placement of dehydrated corn husks or randomly distributed pineapple fibres. A second layer of cellulose slurry was then added on top before drying, creating a sandwich-like reinforcement structure within the composite sheet. Random fibre orientation may have introduced local variations in fibre dispersion and mechanical performance. The 12 biomaterial samples were prepared to assess the impact of fibre type, fibre content, and chemical treatment on the structural and functional performance of the developed composites. The composite formulations reported in this paper are summarised in Table 1, which lists the fibre content, chemical treatments, and fabrication methods applied to create the BC-agricultural fibre composites. KBC Composite fabrication samples are depicted in Figure 4.

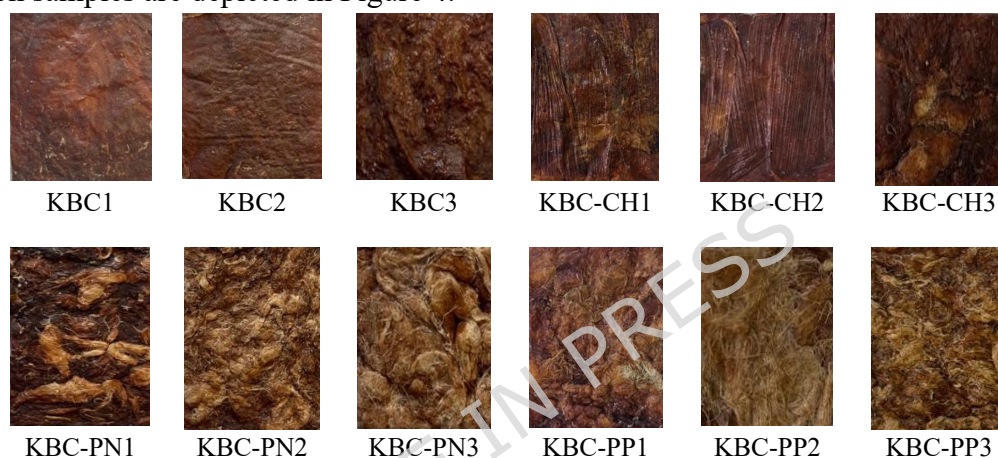


Figure 4. KBC Composite fabrication samples

Morphological characterisation - The surface morphology and microstructural characteristics of the developed biomaterials were analysed using Scanning Electron Microscopy (SEM). SEM observations were conducted using a JEOL JSM-6390LA scanning electron microscope equipped with Energy Dispersive Spectroscopy (SEM-EDS). The analysis enabled high-resolution visualisation of the native nanofibrillar network and surface roughness in the pure KBC matrix, as well as fibre dispersion and fibre–matrix interactions in the agro-waste reinforced composites. A total of 12 representative samples were examined, including pure BC sheets, pineapple fibre-reinforced composites, and corn husk reinforced composites. The SEM analysis provided insight into structural integration between the BC matrix and the incorporated agricultural fibres. Before SEM observation, all samples were oven-dried and sputter-coated with a thin layer of gold to improve surface conductivity and image clarity.

Mechanical testing - Tensile strength testing was performed to assess the mechanical performance of the developed biomaterials, focusing on their ability to resist pulling forces during use in craft materials and weaving processes. A tensile test was performed on a Shimadzu AGS-50kNX universal testing machine (Autograph AGS-X Series). A modified specimen dimension (1.3 cm × 6 cm) was adopted due to the limited size and fragility of the biomaterial

sheets, while maintaining the tensile testing principles described in ASTM D3039/D3039M, which is typically used to determine the tensile properties of composite materials. Although the specimen size differed from the ASTM D3039 standard dimensions, the tensile testing procedure and loading principles were consistently maintained across all samples to ensure a fair comparison. The crosshead speed was maintained at 5 mm/min. This test is used to determine the maximum stress of a material which is used in the weaving process. These mechanical parameters are important indicators of a material's durability and performance during the weaving process. To provide macrostructural context for these evaluations, the physical evolution of the raw materials into the finished woven structures is shown in Figure 5. As shown in Figure 5, incorporation of agricultural waste fibres altered the native nanofibrillar structure of BC by introducing fibre reinforcement into the matrix network.

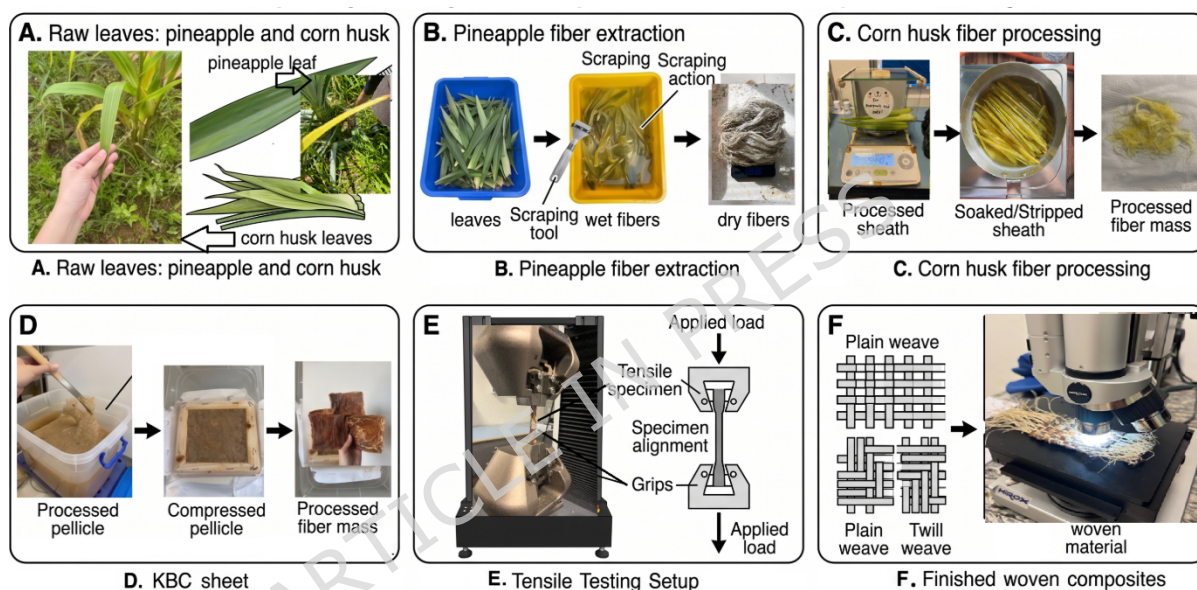


Figure 5. Macro-morphological stages of composite material development: (a) raw pineapple leaves, (b) extracted pineapple fibres, (c) corn husk fibres, (d) fabricated KBC sheets, (e) tensile testing setup showing specimen alignment, and (f) finished woven composite samples

Moisture resistance testing - This test was conducted to determine the water repellence performance of the developed biomaterials. The testing procedure used was based on AATCC TM79, which measures the liquid-absorption properties of biomaterial composites. All the samples were coated with a natural wax formulation before testing to replicate the protective finishing often used on conventional woven fabrics. The wax coating was made with carnauba wax, beeswax, and coconut oil in the ratio 1:0.5:1, with a slight addition of lavender and thyme essential oils. All coated samples maintained visible water droplets on the surface for more than 60 seconds with no observable penetration, indicating low surface wettability. The water droplets did not visibly penetrate the composites' internal structure and remained on the surface throughout the test duration. The wax mixture was melted, manually applied to the sample

surfaces, and allowed to harden using a hair dryer to ensure the wax penetrated and adhered to the surfaces. For the droplet test, 50 μL of distilled water was added using a micropipette 1 cm above the sample surface. Five measurements were taken on each 5 cm $\times$ 5 cm sample at five different locations to ensure measurement reliability. The behaviour of the water droplets was measured for 60 seconds to determine whether the liquid was absorbed into the material or remained on the surface, indicating hydrophobic behaviour and better moisture resistance. Water absorption percentage was calculated using:

$$\text{Water Absorption (\%)} = \frac{W_w - W_d}{W_d} \times 100$$

Where W_d is the initial dry weight, and W_w is the wet weight after exposure, following the ASTM D570 standard.

Figure 6 shows the traditional *kasah* woven structure featuring the newly developed agro-waste reinforced KBC composite material, which will be discussed in the following.



Figure 6. (a) Original *kasah* woven, (b) Traditional *kasah* woven structure featuring the newly developed agro-waste reinforced KBC composite material, (c) Fashion products with agro-waste reinforced KBC composite (designed and developed by the authors)

4. Results and Discussion

4.1 Morphological Structure Analysis

The surface morphology and microstructural characteristics of the developed KBC composites reinforced with agricultural waste fibres were analysed using SEM to evaluate fibre dispersion, network formation, and surface texture, which are associated with composite performance. Figure 5 shows the SEM micrographs of the pure KBC sheet and the fibre-reinforced composite samples. The pure KBC sample exhibited a compact three-dimensional nanofibrillar network with interconnected cellulose fibrils forming a continuous structure. The fibrillar arrangement appeared highly entangled, contributing to the inherent flexibility and structural integrity of the BC matrix. However, the absence of reinforcing fibres resulted in a smooth and homogeneous morphology.

In contrast, the pineapple leaf fibre-reinforced composites exhibited a more heterogeneous microstructure, with visible fibre bundles embedded in the cellulose matrix. The fibres appeared well dispersed throughout the matrix, indicating effective fibre integration during composite fabrication. Mechanical interlocking between the cellulose nanofibrils and the lignocellulosic fibre surfaces was also observed, which may contribute to improved structural stability and load distribution within the composite. Similarly, the baby corn husk fibre composites exhibited a rougher surface morphology with partially exposed fibres distributed throughout the BC network. The increased surface roughness suggests enhanced interfacial interaction between the agricultural fibres and the cellulose matrix, which may improve frictional resistance and structural stability in woven biomaterial applications. Full SEM images for all 12 samples, as presented in Figure 4, showed surface morphology. To clearly compare the three components of composite samples, Figure 7 shows the interconnections and morphology at a closer view. This structural modification contributed to enhanced surface roughness and fibre–matrix interlocking, which are beneficial for improving composite durability and handling performance in woven craft and biomaterial applications.

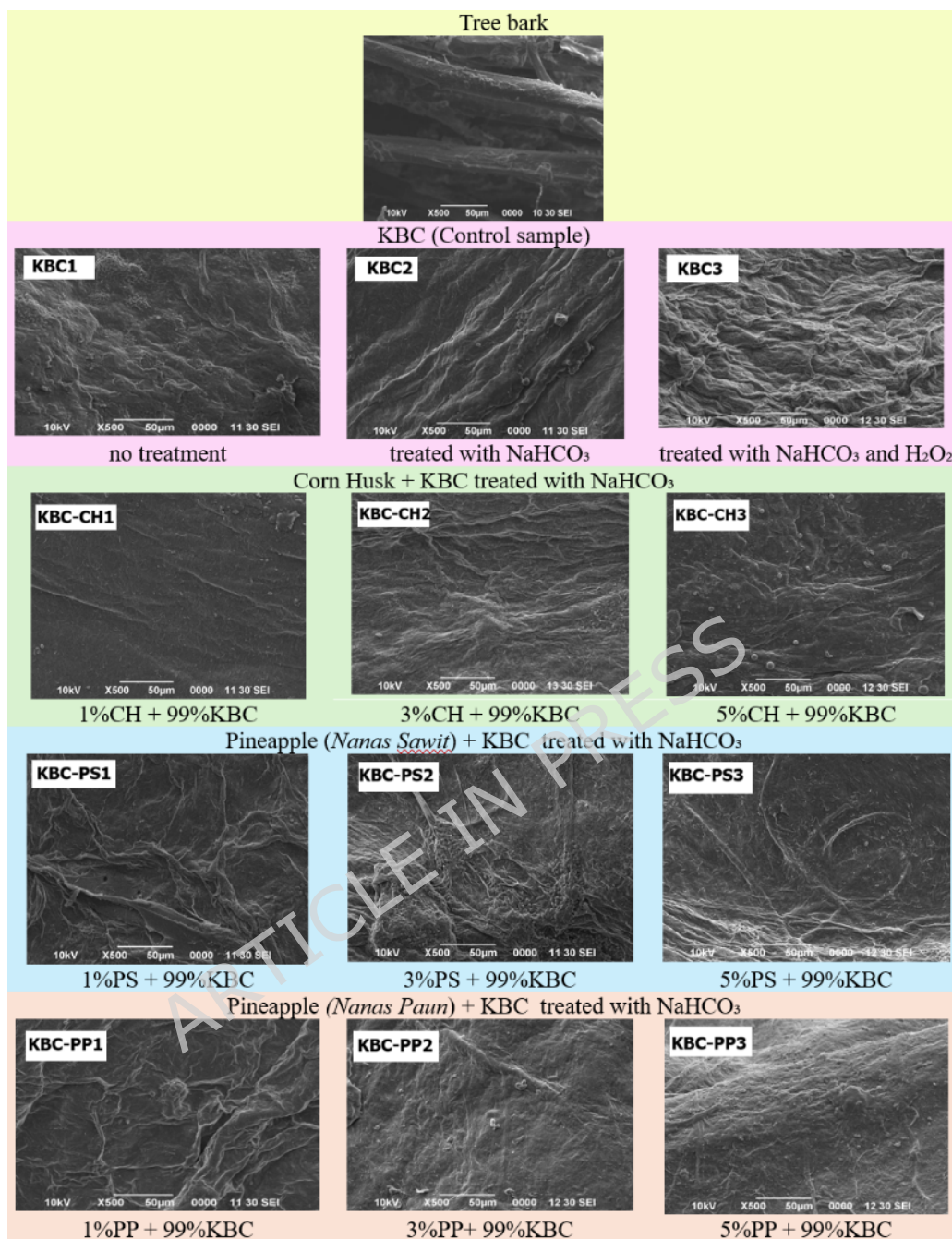


Figure 7. SEM results of the developed biomaterial sample composites

The morphological examination established that the addition of agro-waste fibres significantly altered the internal structure of the regenerated KBC composites. SEM analysis revealed interlocking microfibrillar networks characteristic of BC matrices, which form the fundamental structural framework of the composite material. These nanofibrillar networks are well known for their high crystallinity, water retention capacity, and mechanical stability, which distinguish BC from plant-derived cellulose fibres (Wu et al., 2023; Shrivastav et al., 2022). Previous studies have reported that BC forms an ultrafine three-dimensional nanofibrillar network, which

contributes to high tensile strength and structural integrity (Catarino et al., 2025; Utoiu et al., 2024; Mehrotra et al., 2023).

SEM observations indicated that fibre incorporation increased surface roughness and promoted interfacial bonding between the fibre reinforcement and the cellulose matrix. These morphological modifications improved mechanical performance by enhancing stress transfer between the matrix and reinforcing fibres. Similar structural behaviour has been reported in natural fibre-reinforced biocomposites, where fibre dispersion and interfacial adhesion strongly influence composite strength, stiffness, and durability (Szatkowski et al., 2025; Phiri et al., 2023). Among the tested fibres, with a closer view in Figure 8, pineapple leaf fibres exhibited particularly favourable dispersion within the regenerated cellulose matrix. Pineapple leaf fibre, a lignocellulosic material known for its high cellulose content and favourable fibre aspect ratio, has previously been identified as an effective reinforcement material for biodegradable composites due to its excellent mechanical properties and biodegradability (Szatkowski et al., 2025). The fibrous morphology observed in the pineapple-reinforced samples contributed to improved structural interlocking within the composite matrix, thereby enhancing tensile performance.

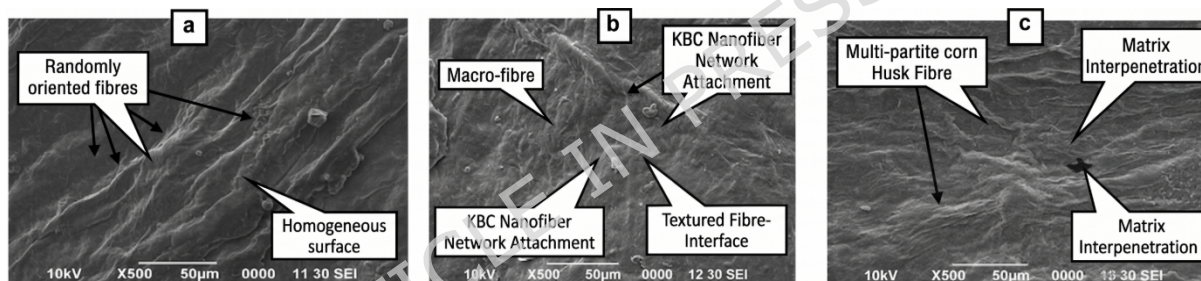


Figure 8. Comparative SEM morphology of Composites: (a) pure KBC (KBC2), (b) pineapple fibre composite (KBC-PP2), and (c) corn husk fibre composite (KBC-CH2)

4.2 Mechanical Performance and Deformation Profiles

To assess the mechanical appropriateness of the developed biomaterial composites for woven craft applications, tensile strength, elongation, and elastic stiffness were evaluated. Tensile testing is used to determine a material's resistance to pulling forces that typically arise during weaving and fabric handling. The findings demonstrated that fibre reinforcement significantly improved the mechanical performance of the BC composites. To further elucidate the mechanical deformation mechanisms under tensile loading, representative stress-strain curves for the key formulations (KBC3, KBC-PS2, KBC-PP2, and KBC-CH1) are shown in Figure 9. The corresponding Elastic Modulus (Young's Modulus) values, calculated directly from the initial linear elastic region of these stress-strain pathways, are compiled in Table 1.

As observed in Figure 9, the distinct trajectories of the stress-strain curves clearly reflect the structural variations introduced by different fibre treatments and biological sources. Sample KBC3 exhibited a prominent elastoplastic deformation profile with an extended elongation at

break (14.819%), achieving a high tensile strength of 5.147 MPa and a calculated Young's modulus of 85.6 MPa. This behaviour highlights the dense, cohesive nature of the chemical-treated pure matrix. Upon the introduction of agro-waste fibres, the stress-strain profiles transitioned based on the fibre type and loading. The pineapple-reinforced composite KBC-PS2 demonstrated a balanced elastoplastic trajectory, where the initial linear slope yielded a Young's modulus of 42.1 MPa, combining stable tensile strength (1.416 MPa) with high elongation (11.305%). Conversely, KBC-PP2 showed a very high Young's modulus.

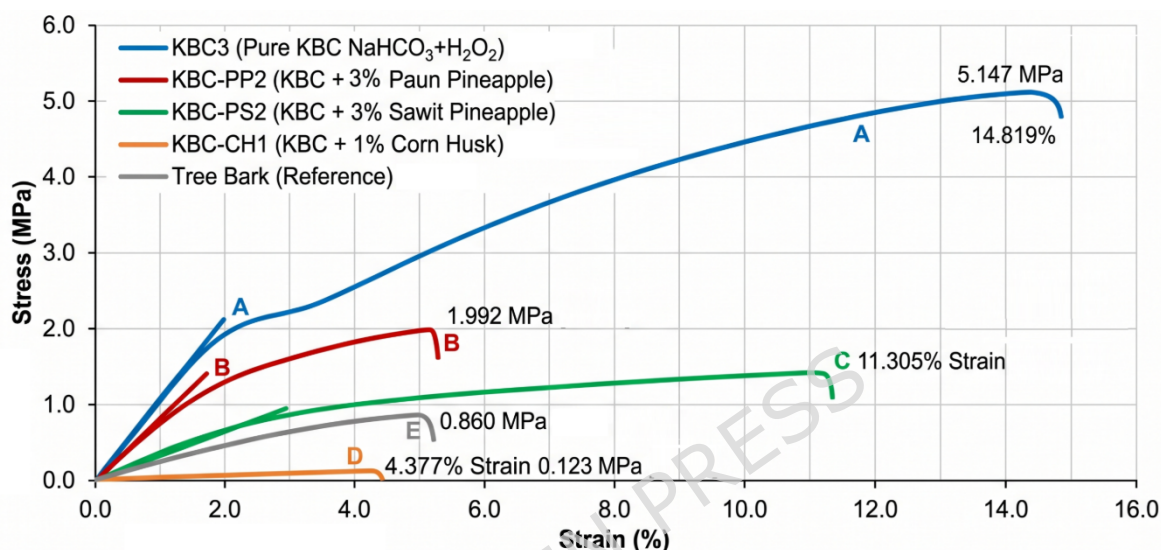


Figure 9. Representative stress-strain curves of selected composite formulations exhibiting distinct mechanical behaviours under tensile load

At the same time, KBC-PP3 exhibited the highest stiffness among all reinforced composites, indicating superior stiffness and efficient matrix-to-fibre stress transfer up to its brittle failure point at 5.385% elongation. In contrast, the corn husk composite KBC-CH1 exhibited a highly compliant profile, characterised by a lower initial slope (Young's modulus of 14.8 MPa) and a protracted, irregular plastic deformation zone extending to 12.547% elongation, indicating matrix microcracking and progressive fibre pull-out due to weaker interfacial adhesion.

Pineapple fibres are characterised by large amounts of cellulose and a moderately strong lignocellulosic structure, which provides the composite matrix with increased load-bearing capacity. On the same note, the tensile performance of corn husk fibre reinforcement was also better than that of pure KBC, but the increase was a little less than that observed with the pineapple fibre composites. Differences in fibre morphology, cellulose content, and fibre stiffness can explain this disparity. In general, the findings validate that agricultural fibre reinforcement can improve the mechanical stability of BC composites, making them more applicable in applications that require mechanical stability. According to the tensile strength, elongation at break, and tear strength findings presented in Table 1, the mechanical performance of the composites differs significantly with the type of reinforcement fibre and fibre content. The

raw KBC samples show that the raw material is moderately flexible and has low mechanical strength. The tensile strength (5.147 MPa) and tear resistance (66.916 MPa) are the highest in KBC3, indicating that changes in fabrication or structure can affect performance. Nevertheless, in general, the lack of reinforcing fibres results in lower structural properties than those of fibre-reinforced composites.

Table 1. Mechanical properties of bacterial cellulose–agricultural fibre composites

Sample Code	Composite Type	Fibre Content (%)	Tensile Strength (MPa)	Elastic Modulus (MPa)	Tear Strength (MPa)	Elongation at Break (%)	Performance Interpretation
Tree Bark	-	NA	0.860	25.4	11.285	4.813	Reference
KBC1	Pure KBC Untreated	0	1.500	35.2	19.507	9.991	Flexible material, low reinforcement
KBC2	Pure KBC NaHCO ₃	0	0.419	12.5	5.448	5.418	Lowest performance, weak integrity
KBC3	Pure KBC NaHCO ₃ +H ₂ O ₂	0	5.147	85.6	66.916	14.819	High tensile/tear strength, plastic look
KBC-PS1	KBC + <i>Sawit</i> Pineapple	1	0.478	18.5	6.219	4.877	Slight reinforcement, limited improvement
KBC-PS2	KBC + <i>Sawit</i> Pineapple	3	1.416	42.1	18.414	11.305	Balanced strength and flexibility
KBC-PS3	KBC + <i>Sawit</i> Pineapple	5	2.211	78.4	28.750	9.149	Highest tensile strength, reduced flexibility
KBC-PP1	KBC + <i>Paun</i> Pineapple	1	0.865	22.8	11.242	9.016	Moderate reinforcement, improved flexibility
KBC-PP2	KBC + <i>Paun</i> Pineapple	3	1.957	92.5	25.447	5.385	Significant tensile/tear improvement
KBC-PP3	KBC + <i>Paun</i> Pineapple	5	1.992	105.3	25.896	5.192	Highest structural stability, lower elasticity
KBC-CH1	KBC + Corn Husk	1	0.123	5.4	1.605	4.377	Weak reinforcement, low loading
KBC-CH2	KBC + Corn Husk	3	0.395	48.2	5.130	1.596	Higher stiffness, limited tensile performance due to brittle fibre–matrix interaction

KBC-CH3	KBC + Corn Husk	5	0.540	14.8	7.025	12.547	Stronger structure, ductile deformation behaviour
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The homogenization of *Sawit* pineapple fibre increases the mechanical properties of the composite. The increase in fibre content improved stress resistance by increasing load transfer between the fibre reinforcement and the matrix. The tensile strength (2.211 MPa) is the highest in KBC-PS3 (5%) in this group. Nevertheless, greater fibre loading results in a slight decrease in elongation, indicating a change in material behaviour: it becomes less flexible and more rigid. This indicates that a moderate fibre content (roughly 3 per cent) provides the best balance between strength and flexibility.

Paun pineapple fibre is highly reinforced in the KBC matrix. High values of tensile strength are recorded in KBC-PP2 and KBC-PP3 (1.957 MPa and 1.992 MPa). The tear strength exceeds 25 MPa, indicating that it is very resistant to mechanical breakdown. But at increased fibre content, elongation reduces slightly. This shows that *Paun* pineapple fibre enhances the structural stability and has reasonable flexibility. Corn husk fibres give partial reinforcement but reduced mechanical improvement compared to pineapple fibres. The tensile strengths are rather low across all corn husk samples. CH3 (5%) exhibits greater elongation, which indicates greater flexibility. Tear strength, however, is low, indicating weak bonding between the fibre and the matrix.

Overall, corn husk fibre is a reinforcement source with lower efficiency than pineapple fibres. Comparing all the composites, a few conclusions can be made: the highest tensile strength is KBC-PS3 (2.211 MPa), the highest tear strength is KBC3 (66.916 MPa), and the most balanced composite, KBC-PS2, exhibited the most balanced performance, providing good tensile strength, high tear resistance, and sufficient flexibility for woven craft applications. Of the fibres assessed, pineapple fibres (*Sawit* and *Paun* types) are superior fibre reinforcers, as they have a stronger fibre structure and are more effective with the composite matrix than corn husk fibres. The data also show that the fibre content is a decisive factor in determining mechanical behaviour. Although fibre loading increases tensile strength and tear resistance, excessive fibre loading can make the material less flexible and more brittle. Thus, a fibre content of about 3% seems to offer the best balance between strength, flexibility, and durability and is therefore the best composition for sustainable applications of composite products.

In comparison with the tensile strength of the developed composites in Table 1, where fibre reinforcement was applied, tensile performance improved significantly over that of pure BC. The fibre-reinforced composites had a higher surface grip and structural durability than pure BC. These properties are valuable for weaving applications that require friction between the fibres and structural stability under loom tension. The resulting biomaterials exhibited mechanical flexibility and surface characteristics comparable to traditional *kasah* bark materials used in

indigenous woven craft applications, particularly in terms of structural handling and surface grip during weaving processes (Jalil & Robert, 2026; Palomino, 2024) (Table 2).

Table 2. Weaving suitability matrix

Material	Flexibility	Surface Grip	Moisture Resistance	Weaving Suitability
Tree bark (<i>kasah</i> reference)	Medium	High	High	Suitable
Pure KBC	High	Low	Moderate	Limited
Pineapple fibre Composite	Medium	High	High	Suitable
Corn Husk Fibre Composite	Medium	Medium-High	High	Suitable

Mechanical testing results demonstrated that fibre reinforcement improved the tensile strength of the regenerated KBC composites compared with pure BC controls. While pure KBC samples exhibited high flexibility, their tensile strength remained moderate, potentially limiting their use in structures subjected to continuous mechanical loading. The incorporation of agro-waste fibres improved the load-bearing capacity of the composites by enabling more efficient stress distribution throughout the material structure. Among the developed composites, a clear distinction must be made between raw structural rigidity and practical weaving suitability. While KBC-PP2 provides the highest stiffness and structural reinforcement, its lower elongation (5.385%) makes it significantly stiffer and more brittle. In contrast, KBC-PS2 emerges as the best-balanced composite for woven craft applications, where material flexibility is extremely important. KBC-PS2 offers an optimal combination of tensile strength (1.416 MPa) and tear strength (18.414 MPa), along with a high elongation rate (11.305%), which was higher than the tensile strength reported for traditional bark-based *kasah* materials (11.285 MPa) used in indigenous woven craft applications (Jalil & Robert, 2026). This high elongation translates to excellent flexibility, making KBC-PS2 the superior choice for meeting the dynamic bending and interlacing demands of woven crafts.

This improvement can be attributed to enhanced fibre–matrix interaction observed in SEM analysis, in which the fibres were evenly dispersed and strongly integrated into the regenerated cellulose matrix. Surface treatment with sodium bicarbonate may also have improved fibre wettability and compatibility with the cellulose matrix, facilitating stronger interfacial bonding (Komal & Singh, 2022). Additionally, samples containing higher fibre loading exhibited greater porosity and occasional fibre clustering. Excessive fibre loading may introduce structural defects that reduce mechanical stability by forming voids and weak bonding regions. Similar behaviour has been reported in natural fibre-reinforced composites, where over-reinforcement can result in fibre agglomeration, stress concentration zones, and non-uniform fibre distribution, thereby weakening the composite structure (Szatkowski et al., 2025; Siribanluehan & Wattanachai, 2024). These findings suggest that optimal fibre loading is essential to balance tensile strength, flexibility, and structural uniformity in reinforced BC composites.

4.3 Moisture Resistance Performance

Moisture resistance is an important factor in evaluating the durability of woven biomaterials, particularly in humid or wet environments where natural fibres may absorb moisture and

gradually deteriorate. Based on ASTM D570 calculations, all wax-coated composite samples exhibited relatively low water absorption, indicating improved hydrophobicity and reduced surface wettability after the surface finishing treatment, as shown in Table 3. The developed biomaterial samples (KBC3, KBC-CH3, KB-CPS3, and KBC-PP2) retained water droplets on the surface for more than 60 seconds without visible penetration.

Table 3. Water absorption performance of selected composites

Sample	Water Absorption (%)	Observation
KBC3	2.1 ± 0.3	No visible penetration
KBC-PS3	1.8 ± 0.2	Hydrophobic surface
KBC-PP2	1.5 ± 0.2	Stable droplet retention
KBC-CH3	2.4 ± 0.4	Slight edge absorption

Among the tested samples, KBC-PP2 and KBC-PS3 exhibited the lowest water absorption behaviour, which may be associated with improved fibre–matrix integration and reduced pore permeability within the regenerated BC structure. The incorporation of lignocellulosic fibres and structural densification of the BC matrix likely contributed to limiting water infiltration. These findings suggest that the developed composites exhibit moisture resistance comparable to that of traditional bark-based *kasah* materials and may therefore be suitable for woven craft applications in humid environments.

4.4 Weaving Suitability of the Composite Materials for Woven Craft Applications

Some of the main material properties that determine a material's suitability for weaving are tensile strength, flexibility, surface friction, and moisture resistance. As shown in Figure 6 in the methodology section, the agro-waste-reinforced composites developed in this research, used to make fashion products, exhibited good workability across the required parameters. The weaving processes are especially beneficial for the controlled surface roughness observed in SEM analysis. Minor surface roughness enhances friction between fibres during interlacing, reducing slip and improving structural stability in the woven craft. This is a particularly significant property of materials designed to capture the performance of traditional *kasah* made from bark. Moreover, the hydrophobic finishing treatments enhanced the composites' moisture resistance, thereby making them more applicable in moist environments. Traditional *kasah* materials are usually exposed to the environment and subjected to water and other treatments during weaving and use. Thus, an important performance criterion of alternative materials is moisture durability. This implies that the developed composites have the mechanical and structural properties required for weaving systems, owing to enhanced tensile strength, controlled porosity, and fibre-matrix bonding (Table 4).

Table 4. Weaving suitability matrix

Composite	Flexibility	Tensile Strength	Moisture Resistance	Weaving Suitability
Pure KBC	High	Moderate	Low–Moderate	Suitable for lightweight woven applications

Pineapple Composite	Moderate–High	High	High	Highly suitable for woven craft structures
Corn Husk Composite	Moderate	Low–Moderate	Moderate–High	Suitable for flexible, low-load woven applications

In addition to mechanical performance, the constructed biomaterial composites support overall sustainability goals by converting agricultural waste into economic value. Agricultural by-products such as pineapple leaves and baby corn husks are usually discarded, yet they contain useful lignocellulosic fibres that can be used to reinforce a composite. The exploitation of such agro-waste products promotes a circular material system by transforming low-value residues into useful biomaterials. Moreover, alternative *kasah* weaving materials can be developed, thereby reducing the utilisation of forest-tree bark. Bark extraction by the aborigines may exert pressure on forest ecosystems when harvesting practices are poorly managed. This research provides a direction for conserving traditional woven craft practices and mitigating harmful environmental impacts by offering a sustainable material alternative derived from renewable agricultural waste and microbial cellulose fermentation. The combination of biomaterial engineering and indigenous craft systems, in this respect, represents a new approach to developing sustainable woven crafts. Interdisciplinary material innovations can not only support environmental sustainability but also help preserve traditional craft knowledge in local communities in Sarawak. Overall, as shown in Table 5, the mechanical performance of the developed composites was strongly influenced by fibre type and fibre loading. Among all samples, KBC3 exhibited the highest overall tensile and tear strength, indicating that chemical treatment significantly enhanced the structural integrity of the pure BC matrix. Among the fibre-reinforced composites, KBC-PS3 demonstrated the highest tensile strength, while KBC-PP3 exhibited the greatest stiffness due to improved fibre–matrix interaction and structural densification. However, for woven craft applications requiring a balance between strength, flexibility, and handling performance, KBC-PS2 demonstrated the most balanced overall behaviour, combining stable tensile strength, high elongation, and good tear resistance. The findings further indicate that a moderate fibre loading of approximately 3% provides the optimal balance between reinforcement efficiency and material flexibility, whereas excessive fibre loading may increase rigidity and reduce ductility.

Table 5. Suitable agro-waste reinforced KBC composites in different places

Property	Best Sample
Highest tensile strength overall	KBC3 (5.147 MPa)
Highest tensile strength among fibre-reinforced composites	KBC-PS3 (2.211 MPa)
Highest elastic modulus/stiffness	KBC-PP3 (105.3 MPa)
Highest tear strength overall	KBC3 (66.916 MPa)
Best flexibility among reinforced composites	KBC-CH3 (12.547%)
Best balance for woven craft application	KBC-PS2 or KBC-PP2

Several limitations should be acknowledged in this study. First, the developed composites were primarily evaluated for low-load woven craft applications rather than for conventional fabric production, as the materials were fabricated in sheet form rather than processed into continuous yarn structures. Second, although mechanical blending and manual stirring were used to improve fibre dispersion, complete control over fibre orientation and uniformity within the BC matrix was not achievable, potentially introducing local variations in mechanical behaviour. In addition, the study focused on small-scale laboratory fabrication, and therefore, the scalability, long-term durability, and industrial processing feasibility of the developed biomaterials were not fully investigated. The moisture resistance evaluation was conducted under controlled, short-term conditions; further studies involving prolonged environmental exposure, repeated wetting cycles, and ageing performance are recommended. Finally, only pineapple leaf fibre and baby corn husk fibre were investigated as reinforcement materials; therefore, future studies may explore other agricultural residues, fibre treatments, and hybrid reinforcement strategies to optimise further the structural and functional performance of KBC-based woven biomaterials.

5. Conclusion

This study developed agro-waste-reinforced KBC composites as eco-friendly biomaterials for utilisation in woven craft structures. The incorporation of pineapple leaf and corn husk fibres significantly improved the structural stability, tensile behaviour, and fibre–matrix interaction of regenerated BC compared with pure KBC controls. Among the developed composites, pineapple fibre-reinforced formulations demonstrated superior overall mechanical performance, while the KBC-PS2 composite exhibited the most balanced behaviour for woven craft applications by combining good tensile strength, flexibility, tear resistance, and structural handling performance. These properties are especially suitable for woven biomaterial applications that require resistance to weaving tension and repeated manipulation during interlacing processes. The use of agro-waste fibres also supports sustainable material development by valorising agricultural residues while reducing dependence on bark harvesting for traditional *kasah* production. By integrating biomaterial engineering with Indigenous craft traditions, this study demonstrates the potential of BC composites as environmentally responsible materials for culturally contextualised woven craft innovation. Future research should further investigate large-scale fabrication, long-term structural durability, environmental ageing performance, and the broader application of these biomaterials in sustainable fashion and craft manufacturing.

Declarations

Ethical Approval

This study received ethical approval from the Ethics Committee of the Faculty of Applied and Creative Arts, Universiti Malaysia Sarawak (UNIMAS). The research procedures were conducted in accordance with the ethical guidelines and regulations of Universiti Malaysia Sarawak and followed internationally accepted standards for research involving human participants.

Declaration of AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author used ChatGPT as a language assistant to rephrase and refine the text. After using this tool, the author reviewed and edited the content as necessary, taking full responsibility for the publication's accuracy.

Consent to Participate: Not applicable.

Consent for Publication: Not applicable.

Data availability: The data is available upon request from the corresponding author.

Clinical trial number: Not applicable

Ethical Approval and Accordance: This study did not involve human participants or human data. Therefore, ethical approval is not applicable.

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Author's contribution: **MHJ** - Conceptualisation, Methodology, Software, Data curation, Visualisation, Writing – original draft, Supervision, Funding acquisition, Project administration. **AIAR** - Conceptualisation, Investigation, Resources, Formal analysis, Visualisation.

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