DEVELOPMENT AND BALLISTIC EVALUATION OF CARBON FIBER-REINFORCED COCONUT-BASED HYBRID COMPOSITES FOR PROTECTIVE APPLICATIONS

Gambo, I., Akindapo, J.O. and Orueri, D.U.*

Department of Mechanical Engineering, Nigerian Defence Academy, Kaduna

*Corresponding email: danielorueri@nda.edu.ng

ABSTRACT

The increasing demand for lightweight, cost-effective, and sustainable ballistic protection materials has highlighted the limitations of conventional synthetic armor systems, particularly in terms of weight, cost, and environmental impact. This study aimed to develop and evaluate a novel hybrid composite system incorporating agro-waste reinforcements for potential application in lightweight ballistic protection. The composite architecture consisted of a carbon fiber (CF) strike face integrated with an epoxy matrix reinforced using alkali-treated coconut husk fiber (CHF), coconut shell powder (CSP), and lithium oxide (Li_2O). CHF was incorporated at varying loadings (10–30 wt.%) alongside fixed proportions of CSP and Li_2O, and the resulting composites were fabricated and subjected to mechanical characterization, including tensile, flexural, and impact testing. Ballistic performance was assessed using live-fire testing with 7.62 × 39 mm ammunition at a firing distance of 100 m. The results showed that the optimum formulation (10 g CHF, 30 g CSP, 10 g Li_2O, and 50 g epoxy) achieved the highest mechanical performance, with tensile strength of 27.14 MPa, flexural strength of 54.44 MPa, and impact strength of 0.294 J/mm. Ballistic evaluation demonstrated that a five-layer hybrid composite configuration effectively arrested the projectile, producing acceptable back-face deformation in the range of 8–12 mm. These findings indicate that coconut-based hybrid composites, when layered and combined with a carbon fiber strike face, can provide effective medium-range ballistic resistance. It is recommended that such hybrid systems be further optimized through thickness scaling and numerical impact modeling to support their adoption as sustainable alternatives to conventional synthetic armor materials.

Keywords: Coconut fiber; hybrid composites; ballistic protection; carbon fiber; epoxy resin; sustainable armor.

1 INTRODUCTION

The growing demand for lightweight, sustainable, and cost-effective ballistic materials has intensified research into alternatives to conventional synthetic fibers such as Kevlar® and Aramid, which, although highly effective, are associated with high production costs, energy-intensive manufacturing processes, and limited environmental sustainability [1, 2]. In response, natural fiber–reinforced composites have emerged as promising candidates for protective applications, offering advantages such as low density, renewability, biodegradability, reduced environmental footprint, and favorable specific mechanical properties [3, 4]. Natural fibers including coconut (coir), jute, hemp, flax, and sisal have been widely investigated as reinforcement materials in polymer composites due to their ability to absorb impact energy through mechanisms such as fiber pull-out, fracture, and matrix cracking [3, 4, 5].

Among these fibers, coconut fiber stands out because of its unusually high lignin content, which imparts superior toughness, resistance to microbial degradation, and enhanced energy dissipation capability under dynamic loading [5]. In addition, coconut fiber is abundantly available in tropical regions, making it an economically attractive and locally sustainable resource for composite fabrication. Despite these advantages, coconut fiber–based composites face several inherent challenges that limit their direct replacement of synthetic ballistic materials. These include moisture sensitivity, variability in fiber morphology and mechanical properties, weak interfacial bonding with polymer matrices, and generally lower ballistic resistance when compared to high-performance synthetic fibers [6, 7]. As a result, monolithic natural fiber composites often fail to meet the stringent requirements of modern ballistic protection systems. To overcome these limitations, recent research has increasingly focused on hybrid composite systems, where natural fibers are combined with synthetic fibers and particulate fillers to synergistically enhance mechanical strength, stiffness, impact resistance, and energy absorption capacity [8, 9]. Hybridization enables the retention of the environmental and cost benefits of natural fibers while leveraging the superior mechanical performance of synthetic reinforcements. Carbon fiber has gained attention due to its high strength-to-weight ratio, stiffness, and ability to distribute impact stresses efficiently within composite laminates. In parallel, the incorporation of particulate fillers such as coconut shell powder has been shown to further improve ballistic performance by increasing hardness, promoting projectile blunting, and enhancing microcrack deflection and energy dissipation mechanisms [10]. Mineral additives, including metal oxides, can also contribute to improved thermal stability, stiffness, and interfacial bonding within the composite matrix. However, the combined effect of coconut fiber, carbon fiber, coconut shell powder, and lithium oxide within a single epoxy-based hybrid composite system has not been sufficiently explored in the context of ballistic protection. Therefore, this study aims to develop and evaluate a novel hybrid composite comprising carbon fiber, coconut husk fiber, coconut shell powder, and lithium oxide dispersed in an epoxy matrix. The ballistic performance of the developed composite is assessed with reference to established standards, with the goal of advancing sustainable, high-performance materials suitable for lightweight armor applications.

2 LITERATURE REVIEW

Natural fibers have been extensively investigated as reinforcement materials in polymer composites due to their low cost, low density, renewability, and environmental benefits [11, 12]. Their ability to absorb energy through deformation, fracture, and interfacial debonding has made them attractive for applications involving impact and vibration resistance. Among various natural fibers, coconut fiber has received significant attention because of its high toughness, flexibility, and lignin-rich structure, which enhances its resistance to impact loading and crack propagation [13]. Several studies have explored the ballistic potential of coir-based composites, particularly in multilayered armor configurations. Risby *et al.* [14] demonstrated that coconut shell powder–reinforced epoxy panels, when combined with Twaron fabric, could withstand NIJ Level IIIA ballistic threats. Their findings highlighted the effectiveness of particulate fillers in promoting projectile deformation and energy dissipation. Similarly, Fernanda *et al.* [15] reported that coir fiber–reinforced epoxy composites performed comparably to Kevlar™ when used as a secondary layer in multilayered armor systems, emphasizing the viability of coconut fiber composites as supportive ballistic layers rather than standalone armor materials. Hybridization strategies have been widely adopted to enhance the mechanical and impact performance of natural fiber composites. Studies have shown that combining natural fibers with synthetic reinforcements such as glass or carbon fibers leads to improved tensile strength, flexural properties, and resistance to high-strain-rate loading [16, 17]. Carbon fiber provides high stiffness and load-bearing capability, enabling more effective stress redistribution during ballistic impact and delaying catastrophic failure of the composite laminate. The inclusion of particulate fillers has further been reported to improve the ballistic and mechanical performance of composite materials. Coconut shell powder, owing to its hardness and irregular particle morphology, enhances impact resistance by increasing frictional energy loss, inducing crack deflection, and promoting projectile blunting [18]. These mechanisms contribute to reduced penetration depth and improved overall energy absorption. However, the effectiveness of such fillers depends strongly on particle size, dispersion, and interfacial bonding within the polymer matrix.

Ballistic performance evaluation of composite armor materials is commonly conducted using standardized testing protocols such as NIJ 0101.06 and V50 ballistic limit testing [18, 19]. These standards provide reliable benchmarks for assessing penetration resistance, back-face deformation, and energy absorption under controlled impact conditions. Prior studies have consistently shown that layered and hybrid composite architectures outperform monolithic structures due to the presence of multiple delamination interfaces and diverse energy dissipation mechanisms [20, 21, 22]. Despite these advances, there remains a notable gap in the literature concerning the ballistic performance of coconut fiber composites hybridized simultaneously with carbon fiber and mineral fillers such as lithium oxide. The synergistic effects of these constituents on impact resistance, damage evolution, and energy absorption behavior are not yet well understood. This study seeks to address this gap by investigating a novel hybrid composite system designed to balance sustainability, mechanical robustness, and ballistic performance.

3 MATERIALS AND METHODS

3.1 Materials

Epoxy resin based on Bisphenol-A–co–chlorohydrine (Epochem A) and the corresponding hardener (Epochem B) were procured from Steeve Moore Chemicals and Scientific Equipment Limited, Zaria, Kaduna State, Nigeria. Coconut husks were obtained from local coconut vendors within Samaru, Zaria, Kaduna State. Carbon fibre mats were used as strike-face reinforcement for ballistic laminate fabrication, while lithium oxide and coconut shell powder served as hybrid fillers.

3.2 Equipment

The equipment utilized in this study included a laboratory milling machine for fibre size reduction, a compression moulding (hydraulic hot press) machine for composite fabrication, a universal testing machine for tensile and flexural testing, and a Resil impact tester for impact strength evaluation. A digital weighing balance was employed for accurate measurement of material constituents, while a microhardness tester was used for Vickers hardness determination. Thermal and morphological characterizations were conducted using a thermogravimetric analyzer (TGA) and scanning electron microscope (SEM), respectively. Chemical characterization was performed using a Fourier transform infrared (FTIR) spectrometer. A hot air oven was used for drying and conditioning of samples. Ballistic testing was carried out using an AK-47 rifle firing 7.62 × 39 mm live ammunition, with a standardized target board employed for impact assessment.

3.3 Composite Fabrication

Composite samples were prepared in accordance with ASTM D5687 guidelines for polymer composite processing. Coconut husk fibres (5.0 mm in length), lithium oxide, and coconut shell powder were incorporated into the epoxy matrix to form hybrid composites. Fibre content varied up to 50 wt.% at 10 wt.% intervals. The detailed formulation of the composites is summarized in Table 1.

Table 1. Formulation of Coconut Husk Fibre/Epoxy Composites

S/No	Sample	Coconut Husk Fibre (g)	Coconut shell Powder (g)	Lithium Oxide (g)	Epoxy Resin (g)
1.	A	-	-	-	100
2.	B	10	30	10	50
3.	C	15	25	10	50
4.	D	20	20	10	50
5.	E	25	15	10	50
6.	F	30	10	10	50

Neat epoxy samples (Sample A) were prepared by mixing epoxy resin and hardener in a 2:1 ratio by weight until a homogeneous mixture was achieved. The mixture was poured into a steel mould of dimensions 120 mm × 120 mm × 3.2 mm and cured in a hydraulic hot press at 120 °C and 2.5 MPa for 5 min, followed by post-curing at room temperature for 24 h. For hybrid composites (Samples B–F), 50 g of epoxy resin–hardener mixture was prepared and the hybrid fillers were added according to the prescribed formulations. The mixture was mechanically stirred for approximately 5 min to ensure uniform dispersion of fillers before being poured into moulds of dimensions 140 mm × 120 mm × 3.2 mm. Curing was conducted under identical temperature and pressure conditions as the neat epoxy samples. The process preparation is shown in Figure 1.

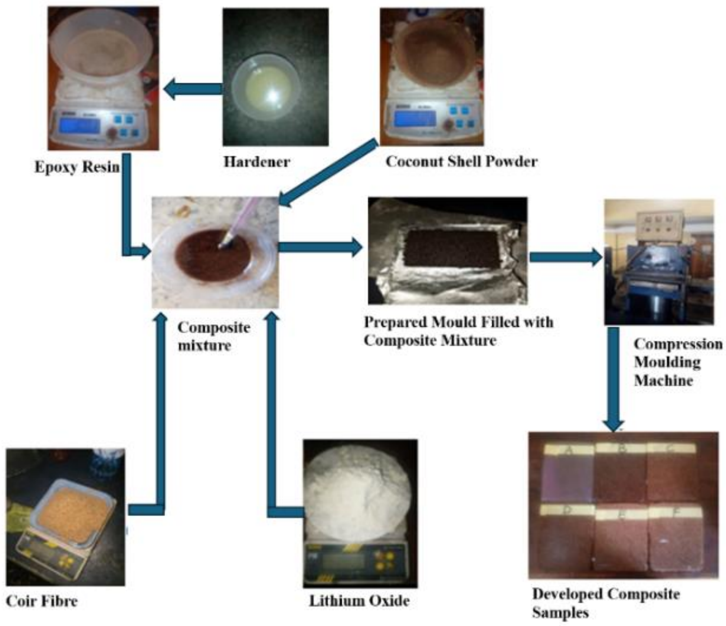


Figure 1. Sample Preparation Process

3.4 Fabrication of Ballistic Composite Plates

Ballistic laminate samples were fabricated using the optimal formulation (Sample B) as the matrix system, reinforced with varying layers of carbon fibre mat. Three ballistic configurations were prepared comprising 3, 4, and 5 carbon fibre layers, designated as Samples S1, S2, and S3, respectively, as shown in Table 2.

Table 2. Formulation for Ballistic Test Samples

S/No	SAMPLE	Coconut Husk Fibre (g)	Coconut shell Powder (g)	Lithium Oxide (g)	Epoxy Resin (g)	Carbon Fibre Mat (layer)
1	S1	10	30	10	50	3
2	S2	10	30	10	50	4
3	S3	10	30	10	50	5

Epoxy resin and hardener (2:1 ratio by weight) were mixed thoroughly, after which coconut husk fibre, coconut shell powder, and lithium oxide were added and stirred until a uniform mixture was obtained. The mixture was used to laminate the carbon fibre layers within a mould of dimensions 120 mm × 120 mm × 20 mm. The laminates were cured in a hydraulic hot press at 130°C and 5.0 MPa for 5 min, then demoulded and post-cured at room temperature for 24 h. The process is shown in Figure 2.

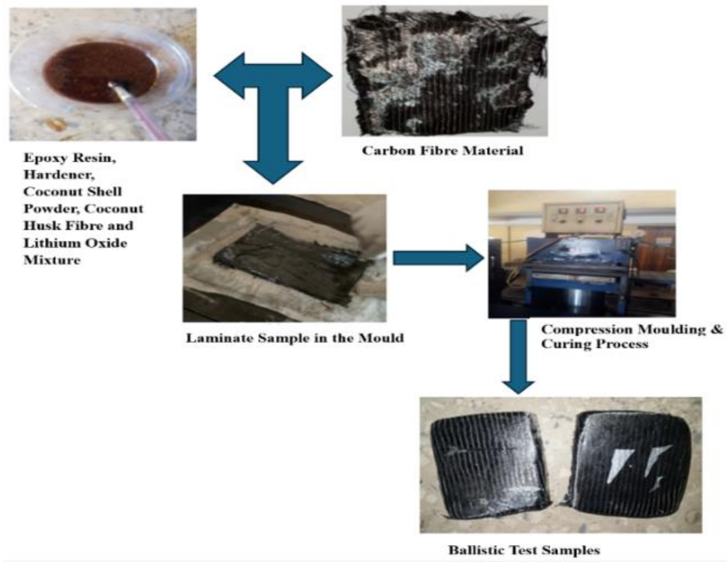


Figure 2. Schematics of the Ballistics Samples Preparation

3.5 Characterization Techniques

3.5.1 Fourier Transform Infrared (FTIR) Spectroscopy

FTIR analysis was conducted in accordance with ASTM E2224-10 using a Thermo Nicolet Nexus 870 spectrometer at Ahmadu Bello University, Zaria. Spectra were recorded over a wavenumber range of 4000–650 cm^{-1} to assess chemical functional groups and confirm the effectiveness of fibre surface treatment [13].

3.5.2 Tensile Testing

Tensile properties were evaluated following ASTM D638 using dumbbell-shaped specimens. Tensile strength, modulus, and elongation at break were recorded automatically by the universal testing machine software [23].

3.5.3 Impact Testing

Impact resistance was measured using the Izod impact method in accordance with ISO 179 / ASTM D256. Specimens of dimensions 80 mm × 15 mm × 5 mm were notched to initiate crack propagation. Impact strength was calculated from the absorbed energy and specimen thickness [24].

3.5.4 Micro-Hardness Testing

Vickers micro-hardness measurements were carried out in accordance with ASTM E384 using polished specimens of dimensions 30 mm × 30 mm × 5 mm. Indentations were made under loads ranging from 10–1000 gf with a dwell time of 10–15 s. The reported hardness values represent the average of three measurements per specimen [25].

3.5.5 Flexural Testing

Flexural properties were determined using a three-point bending configuration in accordance with ASTM D790. Specimens of dimensions 100 mm × 25 mm × 3.2 mm were tested over a support span of 80 mm, and flexural strength and modulus were calculated using standard equations [26].

3.5.6 Scanning Electron Microscopy (SEM)

Fracture surface morphology was examined using scanning electron microscopy following ASTM E986. Samples were sectioned, mounted on conductive stubs, and examined at various magnifications to identify failure mechanisms such as fibre pull-out, matrix cracking, and delamination [27].

3.5.7 Thermogravimetric Analysis (TGA)

Thermal stability was evaluated using thermogravimetric analysis in accordance with ASTM E1131. Approximately 12 mg of each sample was heated from 25°C to 800°C at a heating rate of 10°C/min under nitrogen and air atmospheres using a Q5000 IR thermo-analyzer [14].

3.5.8 Ballistic Impact Testing

Ballistic testing was conducted in accordance with ASTM E3005 using live 7.62 × 39 mm ammunition. Composite panels of dimensions 120 mm × 120 mm were mounted on a rigid frame and impacted at stand-off distances of 100, 75, 50, and 25 m. Penetration depth, back-face deformation (BFD), and failure modes, including fibre breakage, delamination, and matrix cracking, were recorded and analyzed. Ballistic performance was assessed with reference to NIJ Standard 0101.06 criteria for blunt trauma limits [28].

4 RESULTS AND DISCUSSION

The FTIR spectra of untreated and alkali-treated coconut husk fibres, along with the mechanical characterization results of the coconut-based composites, and the corresponding thermogravimetric (TGA) and scanning electron microscopy (SEM) analyses, are presented in Figures 3 to 13, as well as Plates 1 and 2.

4.1.1 Result of FTIR for Treated and Untreated Coconut Husk Fibres

Figure 3 presents the FTIR spectrum of untreated coconut husk fibre, exhibiting characteristic absorption bands typical of lignocellulosic materials. The broad band observed in the range 3300–3400 cm⁻¹ corresponds to O–H stretching vibrations associated with hydroxyl groups in cellulose, hemicellulose, and lignin [29]. Peaks near 2900 cm⁻¹ are attributed to C–H stretching of aliphatic groups, while strong absorptions between 1730–1745 cm⁻¹ are assigned to C=O stretching of ester linkages in hemicellulose and lignin [30, 31]. Additional bands around 1240–1260 cm⁻¹ are associated with C–O stretching of acetyl groups in hemicellulose, and those in the 1500–1600 cm⁻¹ region correspond to aromatic skeletal vibrations of lignin [32]. The FTIR spectrum of alkali-treated coconut husk fibre (Figure 4) shows distinct modifications arising from the removal of amorphous and non-cellulosic constituents. The disappearance of the 1730 cm⁻¹ band confirms effective removal of hemicellulose [33], while the reduced intensity of peaks near 1240 cm⁻¹ indicates cleavage of acetyl groups during alkaline treatment. A noticeable reduction in lignin-related aromatic bands (1510–1600 cm⁻¹) suggests partial delignification. In contrast, the O–H stretching band near 3330 cm⁻¹ becomes sharper, indicating increased exposure of cellulose hydroxyl groups following removal of surface impurities and extractives [34]. These spectral changes confirm that alkaline treatment enhances fibre crystallinity and surface roughness, thereby improving fibre–matrix adhesion, consistent with previous reports [35].

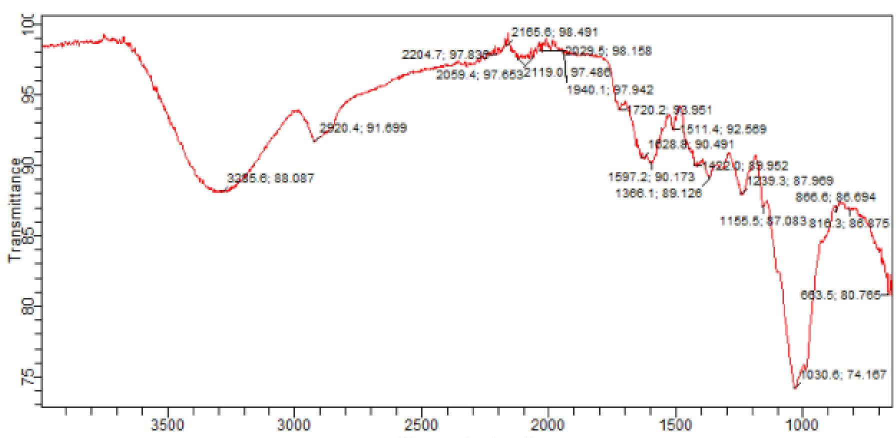


Figure 3. Fourier Transmission Infrared (FTIR) for Untreated Coconut Husk Fibre

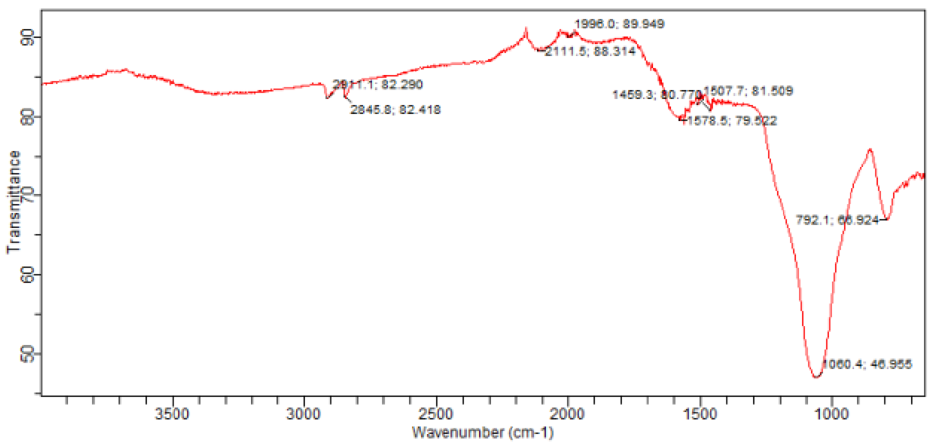


Figure 4. Fourier Transmission Infrared (FTIR) for Alkaline Treated Coconut Husk Fibre

4.1.3 Result of Tensile Strength Test

The tensile strength results of the developed composite plates (Samples A–F) are shown in Figure 5. Tensile strength varied significantly with composite formulation, ranging from 18.76 MPa (Sample F) to 27.14 MPa (Sample B). Neat epoxy resin (Sample A) exhibited a moderate tensile strength of 23.91 MPa, which increased upon incorporation of 10 g coconut husk fibre, 30 g coconut shell powder, and 10 g lithium oxide (Sample B). This improvement is attributed to effective stress transfer and mechanical interlocking between the epoxy matrix and the lignocellulosic reinforcements [36]. However, excessive fibre addition, as observed in Sample F (30 g fibre), resulted in a pronounced reduction in tensile strength due to fibre agglomeration, poor dispersion, and the formation of stress concentration sites [36].

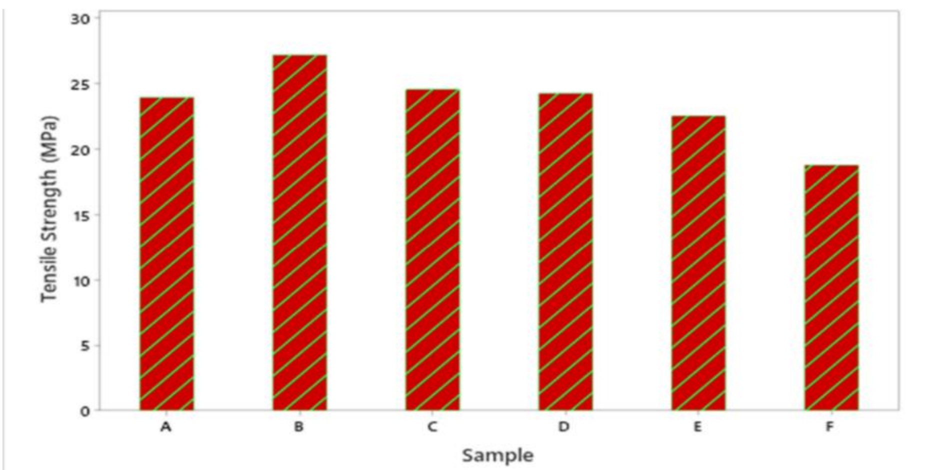


Figure 5. Tensile Strength Test Results for Produced Ballistic Plates

4.1.4 Result of Elastic Modulus Test

Figure 6 presents the elastic modulus of the developed composites, with values ranging from 144.94 MPa to 348.54 MPa. Sample C (15g coconut husk fibre, 25g coconut shell powder, and 10 g lithium oxide) exhibited the highest elastic modulus (348.54 MPa), exceeding that of neat epoxy (315.76 MPa). This enhancement reflects improved filler–matrix adhesion and the rigid nature of coconut shell powder, which restricts polymer chain mobility [37]. Conversely, excessive fibre loading led to reduced stiffness due to fibre pull-out and weak interfacial bonding, a common limitation in natural fibre composites beyond critical filler content [35].

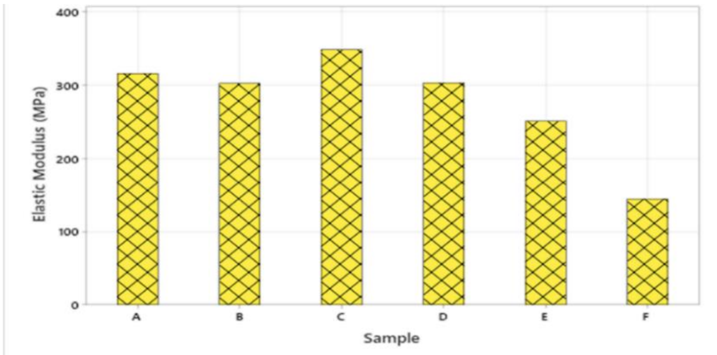


Figure 6. Elastic Modulus Test Results for Produced Ballistic Plates

4.1.5 Result of Elongation at Break Test

Elongation at break results (Figure 7) indicate a progressive decrease in ductility with increasing reinforcement content. Neat epoxy (Sample A) exhibited the highest elongation at break (11.59%), while heavily reinforced composites such as Sample F showed reduced ductility (7.20%). This trend reflects the inherently brittle nature of lignocellulosic fillers, which limit polymer chain mobility and strain energy absorption [37]. Sample B maintained a relatively high elongation (10.76%), demonstrating that balanced reinforcement can preserve ductility while enhancing strength.

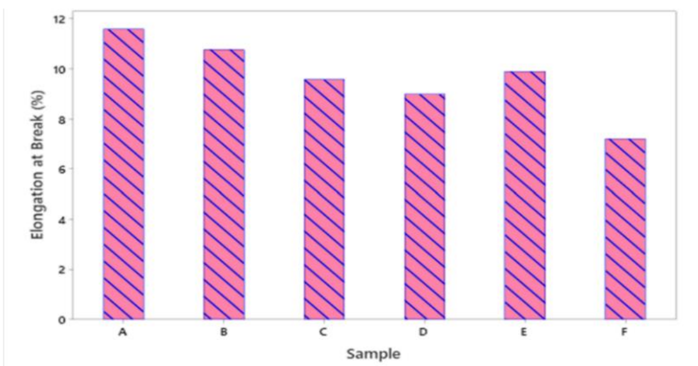


Figure 7. Elongation at Break Test Results for Produced Ballistic Plates

4.1.6 Result of Flexural Strength Test

Flexural strength results (Figure 8) followed a trend similar to the tensile strength, with Sample B exhibiting the highest value (54.44 MPa), surpassing neat epoxy (44.55 MPa). The improvement indicates effective stress redistribution under bending due to reinforcement incorporation, consistent with earlier findings on coconut shell powder–reinforced composites [38]. At higher filler loadings (Samples E and F), flexural strength decreased owing to agglomeration, void formation, and stress concentration effects.

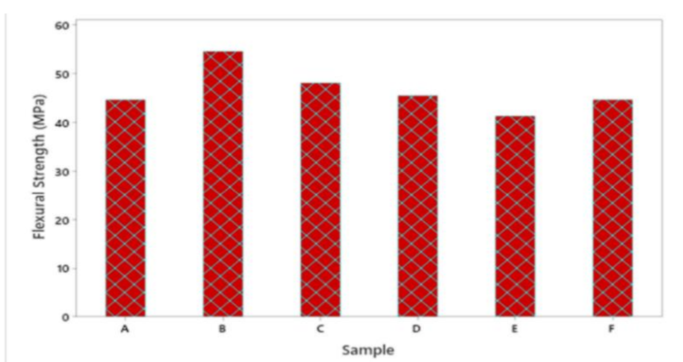


Figure 8. Flexural Strength Test Results for Produced Ballistic Plates

4.1.7 Result of Flexural Modulus Test

The flexural modulus results (Figure 9) show that neat epoxy possessed the highest modulus (2958.17 MPa), reflecting its inherent stiffness under bending. The reduction observed in reinforced samples, particularly Sample B (2147.56 MPa), is attributed to disruption of resin continuity by filler particles. Nevertheless, intermediate formulations (Samples C–E) retained adequate stiffness, highlighting the composition-dependent nature of reinforcement effects in natural fibre composites [36].

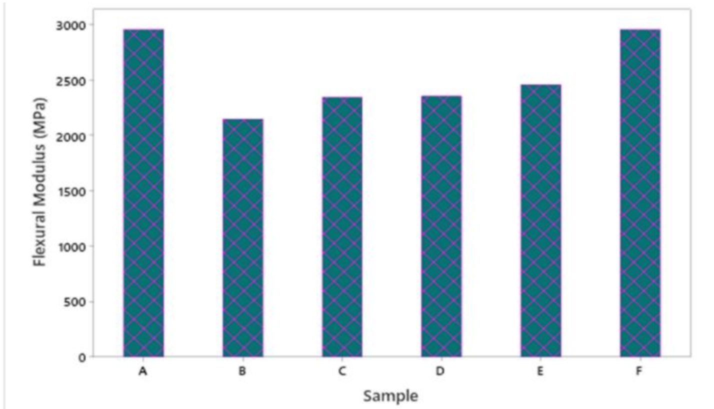


Figure 9. Flexural Modulus Test Results for Produced Ballistic Plates

4.1.8 Result of Impact Strength Test

Impact strength results (Figure 10) reveal that neat epoxy exhibited the lowest toughness (0.183 J/mm), confirming its brittle behaviour. Reinforced composites demonstrated enhanced impact resistance, with Sample B achieving the highest impact strength (0.294 J/mm). The synergistic combination of coconut husk fibre and coconut shell powder promoted crack deflection and energy dissipation mechanisms [38]. At higher fibre contents, impact strength declined due to agglomeration and weakened interfacial bonding, reducing resistance to crack propagation [39, 40].

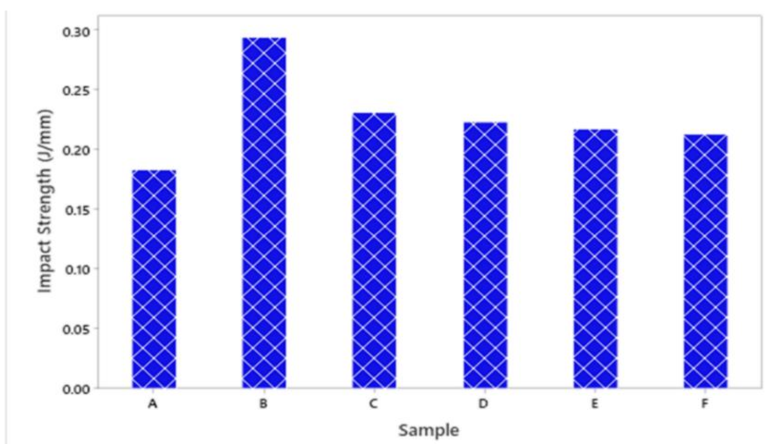


Figure 10. Impact Strength Test Results for Produced Ballistic Plates

4.1.9 Result of Hardness Test

Hardness results (Figure 11) show a steady increase with increasing fibre and shell powder content. Neat epoxy recorded the lowest hardness (40.63 HV), while Samples E and F exhibited the highest values (57.03 HV and 56.33 HV, respectively). This increase is attributed to the stiffening effect of lignocellulosic fillers, which enhance resistance to surface deformation [41]. The inverse relationship observed between hardness and impact strength is characteristic of fibre-reinforced composites and reflects the trade-off between stiffness and toughness [38].

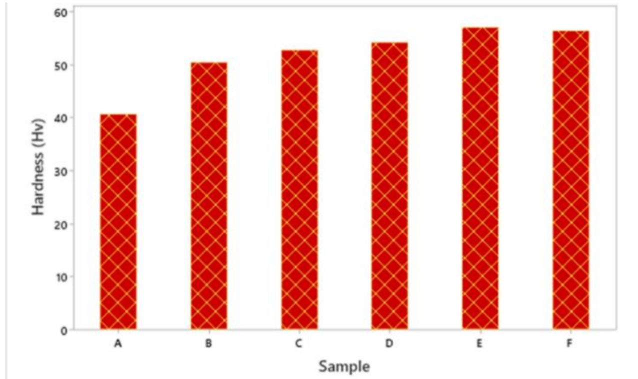


Figure 11. Hardness Test Results for Produced Ballistic Plates

4.1.10 Thermogravimetric Analysis Results

Figure 12 compares the TGA curves of neat epoxy (Sample A) and the reinforced composite (Sample B). Neat epoxy exhibited a single-stage degradation profile commencing between 300–400 °C, with a residual mass of 19.20%, typical of thermosetting polymers [42]. In contrast, Sample B displayed a multi-stage degradation behaviour initiated at lower temperatures due to moisture evaporation and early decomposition of hemicellulose and lignin components [43]. Notably, Sample B exhibited higher char yield at temperatures above 500°C, attributed to the synergistic effect of lignin-rich fillers and lithium oxide, which promote char formation through dehydration reactions and suppress flammable volatiles [44]. This enhanced char formation indicates improved thermal shielding and flame-retardant behaviour of the composite.

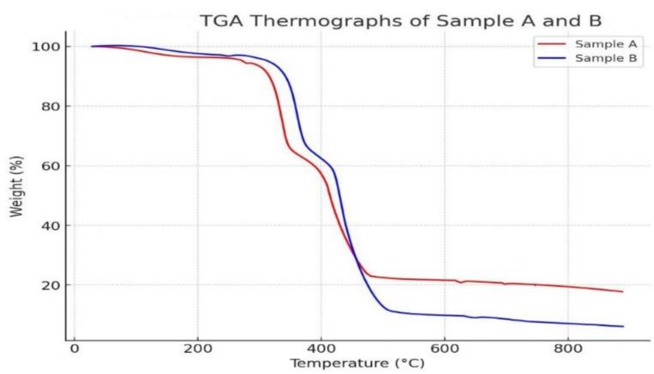
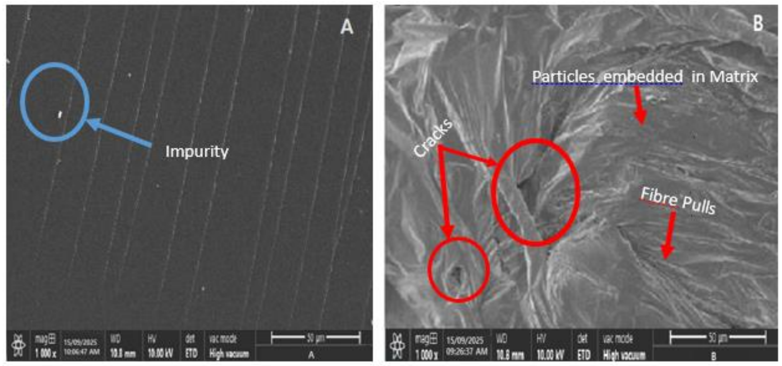


Figure 12. Thermogravimetric Analysis Test Results for Samples A and B Ballistic Plates

4.1.11 Scanning Electron Microscopy Results

SEM micrographs of Samples A and B (Figures 13a–b) reveal marked differences in fracture morphology. Neat epoxy displayed a smooth, homogeneous fracture surface, facilitating rapid crack propagation and explaining its low impact resistance [45]. In contrast, Sample B exhibited a heterogeneous microstructure with well-embedded coconut husk fibres and uniformly dispersed coconut shell powder particles, indicating effective wetting and interfacial bonding. These features enhance stress transfer and energy dissipation through fibre pull-out, crack deflection, and matrix cracking [46]. Single-shot ballistic impact tests conducted on three laminate configurations (Samples A–C) using 7.62 × 39 mm ammunition demonstrated a clear dependence of performance on laminate thickness and layering. Samples A (3 layers) and B (4 layers) failed to arrest the projectile at all tested distances (25–100 m), while Sample C (5 layers) successfully arrested the projectile at 100 m with a modest back-face deformation (≈8–12 mm). Partial penetration was observed at 75 m, shallow penetration at 50 m, and complete perforation at 25 m. The improved performance of Sample C is attributed to increased delamination interfaces, enhanced load spreading by the carbon-fibre strike face, and progressive energy dissipation by the coconut-based backing layers. Overall, the measured back-face deformation values (8–16 mm) for non-perforating impacts in Sample C are well below the NIJ allowable limit, indicating effective blunt trauma mitigation. The front views and rear views are shown in Plates 1 and 2. These findings are consistent with literature reports on multilayer natural fibre hybrid composites, which emphasize the need for increased layer count or ceramic/aramid hybridization to improve close-range ballistic resistance [47–51].



(a) (b)

Figure 13(a) and (b). Thermogravimetric Analysis Test Results for Samples A and B Ballistic Plates

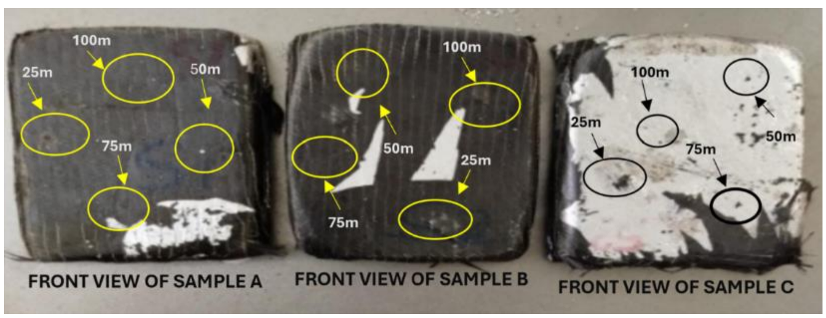


Plate 1. Front View of Tested Produced Ballistic Plate

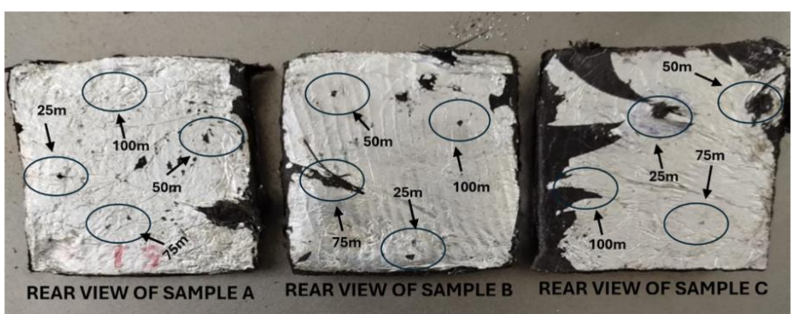


Plate 2. Rear View of Tested Produced Ballistic Plate

4.1 FTIR Analysis

4.1.12 Ballistic Performance

The ballistic performance for the single shot impact is shown in Table 3. P (Perforation): Complete penetration of the ballistic plate, resulting in a through-hole or projectile exit. PP (Partial Penetration): Projectile partially penetrates the plate but is arrested within the laminate, producing significant back-face deformation. NP (No Penetration): Projectile fully arrested with back-face deformation below the NIJ 0101.06 allowable limit (44 mm). *BFD values are reported only for NP and PP cases where projectile arrest or retention occurred. **Residual velocities are estimated values influenced by muzzle velocity variation, projectile deformation, laminate architecture, and shot placement. ***Residual velocity for PP cases is indicative only and represents potential post-impact velocity if shallow perforation occurs.

Table 3. Single-shot ballistic impact outcomes of composite samples at varying engagement distances

Sample	Distance (m)	Impact Outcome (Single Shot)	Back-Face Deformation, BFD (mm)*	Estimated Residual Velocity (m/s)**
Sample A (3 layers)	100	Perforation (P)	—	~320–430
	75	Perforation (P)	—	~350–470
	50	Perforation (P)	—	~400–520
	25	Severe perforation (P)	—	~430–560
Sample B (4 layers)	100	Shallow perforation (edge-case P)	—	~260–360
	75	Full perforation (P)	—	~320–450
	50	Severe perforation (P)	—	~360–500
	25	Severe perforation (P)	—	~420–560
Sample C (5 layers)	100	No penetration (NP)	8–12	—
	75	Partial penetration (PP); projectile retained with pronounced bulge	10–16	Possible-low residual-(~100–200) ***
	50	Partial penetration / shallow perforation	10–14	If-perforated: ~150–260
	25	Perforation (central hits)	—	~380–560

5 CONCLUSIONS

This study developed and validated a sustainability-oriented hybrid composite for ballistic protection through the multiscale integration of a carbon fiber strike face with a bio-based epoxy matrix reinforced by alkali-treated coconut husk fiber, coconut shell powder, and lithium oxide. The novelty of the system lies in the synergistic combination of renewable reinforcements with targeted inorganic modification to achieve mechanical robustness, thermal stability, and effective energy dissipation. The optimized formulation (10 wt.% CHF, 30 wt.% CSP, and 10 wt.% Li_2O) exhibited superior mechanical performance, achieving tensile strength of 27.14 MPa, flexural strength of 54.44 MPa, and impact resistance of 0.294 J/mm, exceeding that of neat epoxy and alternative compositions. Ballistic testing further demonstrated the practical viability of the design: a five-layer laminate successfully stopped 7.62 × 39 mm projectiles at a 100 m standoff distance, with back-face deformation limited to 8–12 mm, remaining well within accepted safety limits. These results confirm that natural-fiber-based hybrid composites, when strategically deployed as energy-absorbing backing layers behind a carbon fiber front face, can provide an effective balance between lightweight design, sustainability, and medium-threat ballistic resistance. Future work should focus on optimizing laminate architecture and interfacial bonding to enhance energy dissipation and damage tolerance. The incorporation of ceramic or ultra-high-molecular-weight polyethylene (UHMWPE) strike faces into ternary hybrid systems is recommended to address higher threat levels and reduced engagement distances. Additionally, multi-hit ballistic assessment and environmental durability studies are essential to evaluate long-term performance. Overall, this work establishes a robust framework for the development of sustainable, high-performance ballistic materials in advanced protective applications.

REFERENCES

1. Alvarez, V.A., Ruseckaite, R.A. and Vázquez, A. (2012). Mechanical properties and fracture behaviour of natural fibre composites. *Journal of Materials Science*, vol. 47, no. 8, pp. 2679-2690.
2. Alves, C., Ferrao, P.M.C., Silva, A.J., Reis, L.G., Freitas, M. and Rodrigues, L.B. (2012. Eco-design of automotive components making use of natural jute fibre composites. *Journal of Cleaner Production*, vol. 18, no. 4, pp. 313-327.

3. John, M. J. and Thomas, S. (2008). Biofibres and biocomposites. *Carbohydrate Polymers*, vol. 71, no. 3, pp. 343-364.

4. Shalwan, A. and Yousif, B.F. (2013). In state of art: Mechanical and tribological behaviour of polymeric composites based on natural fibres. *Materials and Design*, vol. 48, pp. 14-24.

5. Ahmad, J., Majdi, A., Al-Fakih, A., Deifalla, A.F., Althoey, F., El Ouni, M.H. and El-Shorbagy, M.A. (2022). Mechanical and durability performance of coconut fibre reinforced concrete: A state-of-the-art review. *Materials*, vol. 15, no. 10, 3601.

6. De Rosa, I.M., Kenny, J.M., Puglia, D., Santulli, C. and Sarasini, F. (2011). Morphological, thermal and mechanical characterization of okra fibres as potential reinforcement in polymer composites. *Composites Science and Technology*, vol. 71, no. 2, pp. 343-349.

7. Pickering, K.L., Efendy, M.A. and Le, T.M. (2016). A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*, vol. 83, pp. 98-112.

8. Jawaid, M., Khalil, H.P.S.A. and Bakar, A.A. (2010). Mechanical performance of oil palm empty fruit bunches/jute fibres reinforced epoxy hybrid composites. *Materials Science and Engineering: A*, vol. 528, pp. 5190-5195.

9. Sathishkumar, T. P., Satheeshkumar, S. and Naveen, J. (2014). Glass fibre–natural fibre hybrid composites: A review. *Journal of Reinforced Plastics and Composites*, vol. 33, no. 5, pp. 454-471.

10. Nayak, S.Y., Shenoy, S., Kini, C.R., Sultan, M.T.H. and Shahar, F.S. (2022). Experimental investigation into mechanical properties of coconut shell powder modified epoxy/3D glass composites. *Engineered Science*, vol. 20, pp. 306-320.

11. Ali, M., Shaker, K. and Nawab, Y. (2019). Mechanical properties of natural fibre composites: A review. *Journal of Materials Research and Technology*, vol. 2, pp. 586-607.

12. Faruk, O., Bledzki, A.K., Fink, H.P. and Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, vol. 37, no. 11, pp. 1552-1596.

13. Harish, S., Michael, D.P., Bensely, A., Lal, D.M. and Rajadurai, A. (2009). Mechanical property evaluation of natural fibre coir composite. *Materials Characterization*, vol. 60, no. 1, pp. 44-49.

14. Risby, M.S., Wong, S.V., Hamouda, A.M.S., Khairul, A.R. and Elsadig, M. (2008). Ballistic performance of coconut shell powder/Twaron fabric against non-armour piercing projectiles. *Defence Science Journal, vol. 58, no. 2, pp. 248-263.*

15. Fernanda Santos da Luz, S., Neves Monteiro, S., Sousa Lima, E. and Pereira Lima Júnior, É. (2017). Ballistic application of coir fibre reinforced epoxy composite in multilayered armour. *Materials Research*, vol. 20, no. 2, pp. 23-28.

16. Mallick, P.K. (2007). Fiber-Reinforced Composites: Materials, Manufacturing, and Design, *3rd ed. Boca Raton, FL: CRC Press*.

17. Strong, A.B. (2008). Fundamentals of Composites Manufacturing: Materials, Methods, and Applications, *2nd ed. Dearborn, MI: Society of Manufacturing Engineers*.

18. National Institute of Justice (2008). Ballistic Resistance of Body Armour, NIJ Standard-0101.06. *Washington, DC: U.S. Department of Justice*.

19. Crouch, I.G., Malbon, C.L. and Smith, A. (2010). Performance of ballistic-resistant body armour: A review of NIJ standards. *Defense Technology Journal*, vol. 15, no. 3, pp. 123-135.

20. Naveen, J., Jayakrishna, K., Mohamed, T.H. and Siti, M.A. (2020). Ballistic performance of natural fibre-based soft and hard body armour. *Frontiers in Materials*, vol. 7, 608139.

21. Orueri, D.U., Akndapo, J.O., Johnson-Anamemena, N. and Gideon, C.J. (2023) Modeling and Simulation of Laminate Composite Materials for use as Ballistic Protection. *Academy Journal of Science and Engineering*, vol. 17, no. 1, pp. 1-19.

22. Audu, M.U., Akindapo, J.O. and Orueri, D.U. (2025). Development and Comparative Study on the Mechanical properties of Alumina-Silicon Carbide and Boron Carbide Ceramic as Materials for Ballistic Application. *Nigerian Journal of Engineering Science and Technology Research*, vol. 11, no. 1, pp. 142-157.

23. Alkhatib, F., Mahdi, E. and Dean, A. (2021). *Design and evaluation of hybrid composite plates for ballistic protection: Experimental and numerical investigations*. *Polymers*, vol. 13, no. 9, Article 1450. https://doi.org/10.3390/polym13091450.

24. Charles, C.A., Ahmed, M.A. and Ibrahim, S. (2020). Mechanical properties of coir fibre-reinforced epoxy composites. *Materials Today: Proceedings*, vol. 27, pp. 1230-1237.

25. Renato, D., Silva, F.A.C., Monteiro, S.N. and Luz, F.S.D. (2018). Ballistic performance of multilayered armour systems reinforced with natural fibres. *Journal of Materials Research and Technology*, vol. 7, no. 2, pp. 233-243.

26. Shoafeng, L., Hang, Z. and Yao, W. (2019). Energy absorption behaviour of coconut fibres under dynamic loading. *Materials Science and Engineering A*, vol. 748, pp. 338-347.

27. Yaakob, M.Y., Jawaid, M. and Alothman, O.Y. (2020). Hybrid coir–synthetic fibre composites for ballistic protection. *Journal of Reinforced Plastics and Composites*, vol. 39, no. 5, pp. 150-162.

28. Stephen, A., Uchenna, O. and Wole, A. (2018). Mechanical characterization of coconut fibre composites for protective helmets. *The International Journal of Advanced Manufacturing Technology*, vol. 99, no. 3-4, pp. 789-798.

29. Poletto, M., Zattera, A.J. and Santana, R.M.C. (2014). Structural differences between wood species: Evidence from chemical composition, FTIR spectroscopy, and thermogravimetric analysis. *Journal of Applied Polymer Science*, vol. 132, no. 27, pp. 1-8.

30. Reddy, N. and Yang, Y. (2005). Biofibers from agricultural byproducts for industrial applications. *Trends in Biotechnology*, vol. 23, no. 1, pp. 22-27.

31. Kumar, R., Singh, S. and Singh, O.V. (2010). Bioconversion of lignocellulosic biomass: Biochemical and molecular perspectives. *Journal of Industrial Microbiology and Biotechnology*, vol. 37, no. 5, pp. 581-607.

32. Gupta, A., Sharma, A. and Kumar, R. (2013). Characterization of lignocellulosic fibers by FTIR and their utilization in polymer composites. *Journal of Reinforced Plastics and Composites*, vol. 32, no. 20, pp. 1542-1550.

33. Sgriccia, N., Hawley, M.C. and Misra, M. (2008). Characterization of natural fiber surfaces and natural fiber composites. *Composites Part A: Applied Science and Manufacturing*, vol. 39, no. 10, pp. 1632-1637.

34. Li, X., Tabil, L.G. and Panigrahi, S. (2007). Chemical treatments of natural fiber for use in natural fiber-reinforced composites: A review. *Journal of Polymers and the Environment*, vol. 15, no. 1, pp. 25-33.

35. John, M.J. and Thomas, S. (2008). Biofibres and biocomposites. *Carbohydrate Polymers*, vol. 71, no. 3, pp. 343-364.

36. Saba, N., Paridah, M.T. and Jawaid, M. (2015). Mechanical properties of kenaf fibre reinforced polymer composites: A review. *Construction and Building Materials*, vol. 76, pp. 87-96.

37. Pickering, K.L., Efendy, M.A. and Le, T.M. (2016). A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing,* vol. 83, pp. 98-112.

38. Prasad, R., Patel, V.K. and Kumar, S. (2020). Mechanical characterization of natural fibre reinforced composites: A review. *Materials Today: Proceedings,* vol. 28, pp. 255-260.

39. Akinyemi, B.A., Afolayan, J.O. and Oluwafemi, J.A. (2019). Effect of natural fibre loading on mechanical properties of polymer matrix composites. *Journal of Composite Materials Research,* vol. 11, no. 3, pp. 45-53.

40. Singh, R. and Deepak, D. (2021). Effect of fibre and filler hybridization on the mechanical properties of polymer composites. *International Journal of Composite Materials,* vol. 10, no. 4, pp. 95-104.

41. Oladele, I.O., Adewole, T.F. and Sadiku, R. (2020). Influence of agro-waste fibres on mechanical properties of reinforced epoxy composites. *Journal of Materials Science and Engineering,* vol. 9, no. 2, pp. 25-33.

42. Poletto, M., Zattera, A.J. and Santana, R.M.C. (2012). Thermal decomposition of wood: Kinetics and degradation mechanisms. *Bioresource Technology,* vol. 126, pp. 7-12.

43. Faruk, O., Sain, M. and Oksman, K. (2013). Biocomposites: Technology, environmental credentials and market forces. In *Biofiber Reinforcements in Composite Materials, Woodhead Publishing,* pp. 1-18.

44. Alongi, J., Camino, G. and Malucelli, G. (2013). Heating rate effect on char yield from silicon-based flame retardant polycarbonate. *Polymer Degradation and Stability,* vol. 98, no. 9, pp. 1626-1634.

45. Mohan, P. (2013). A critical review: The modification, properties, and applications of epoxy resins. *Polymer-Plastics Technology and Engineering,* vol. 52, no. 2, pp. 107-125.

46. Faruk, O., Bledzki, A.K., Fink, H.P. and Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science,* vol. 37, no. 11, pp. 1552-1596.

47. Nayak, S.Y., Shenoy, S., Kini, C.R., Sultan, M.T.H. and Shahar, F.S. (2022). Experimental investigation into mechanical properties of coconut shell powder modified epoxy/3D glass composites. *Engineered Science,* vol. 20, pp. 306-320.

48. Tepeduzu, B. and Karakuzu, R. (2019). Ballistic performance of ceramic/composite structures. *Ceramics International,* vol. 45, no. 2, pp. 1651-1660.

49. Penga, M.T., Zhang, X., Han, G., Xiong, W., Teneijid, M.A.I. and Guan, Z.W. (2022). Investigations of the ballistic response of hybrid composite laminated structures. *Defence Technology,* vol. 8, no. 8, pp. 1851-1863.

50. Love, K., Sarbjeet, S., Amar, P. and Narinder, K. (2020). A review on natural fiber reinforced composites. *Materials Today: Proceedings,* vol. 28, no. 3, pp. 1616-1621.

51. Santos da Luz, F., Monteiro, S.N., Sousa Lima, E.S. and Lima Júnior, É P. (2017). Ballistic application of coir fibre reinforced epoxy composite in multilayered armour. *Materials Research,* vol. *20*, no. 2, pp. 23-28.