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Bio-hybrid carbon fibre/OPFF epoxy composites: mechanical, interfacial, and thermal performance

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Abstract

The development of sustainable lightweight composites with reliable structural integrity is important for transportation and construction applications. This study investigates a bio-hybrid sandwich composite comprising carbon fibre skins and Oil Palm Frond Fibre (OPFF) as a natural porous core, with emphasis on improving interfacial integrity through chemical modification. The primary objective is to evaluate the effectiveness of sequential NaOH and H_2O_2 treatment in enhancing mechanical performance, interfacial bonding, and thermal stability of the composite system. Hybrid composites were fabricated using an epoxy matrix, combining carbon fibre reinforcements with untreated and chemically treated OPFF cores in various fibre configurations. Mechanical properties were assessed under tensile, flexural, and impact loading, while interfacial morphology and thermal behaviour were examined using microscopy and thermal analysis. The results demonstrate that NaOH + H_2O_2 treatment improves composite performance, with treated unidirectional hybrids exhibiting the highest tensile and flexural strengths. Microscopic observations reveal a substantial reduction in fibre pull-out, debonding, and skin–core delamination, indicating enhanced interfacial integrity and more efficient load transfer. In addition, treated composites show improved thermal stability. The novelty of this work lies in demonstrating that chemically treated OPFF can function as a sustainable sandwich core, where improved interfacial bonding plays a decisive role in suppressing delamination and enhancing overall composite performance.

Keywords:
Hybrid composite, oil palm frond fibre, carbon fibre, alkali–peroxide treatment.

1 Introduction

The global demand for lightweight, high-strength, and environmentally responsible materials has accelerated the development of advanced composite technologies across transportation, construction, and energy-related sectors [1]. In particular, polymer matrix composites reinforced with natural fibres have attracted increasing attention as viable alternatives to fully synthetic fibre systems, owing to their renewability, lower density, reduced carbon footprint, and potential for biodegradability [2], [3]. These attributes align closely with current sustainability targets and circular-economy principles in materials engineering. However, despite their environmental advantages, natural fibre–reinforced composites often struggle to meet the stringent mechanical and durability requirements demanded by high-performance structural applications.

Carbon fibre–reinforced polymer composites remain the benchmark for structural efficiency due to their exceptional tensile strength, high elastic modulus, and outstanding fatigue resistance. Consequently, rather than replacing carbon fibre entirely, recent research has increasingly focused on hybrid composite concepts that integrate natural fibres with carbon fibres to achieve an optimised balance between mechanical performance, weight reduction, cost efficiency, and environmental sustainability. Hybridisation enables the complementary characteristics of each reinforcement type to be exploited: carbon fibres provide load-bearing capacity and stiffness, while natural fibres provide ductility, impact resistance, and ecological benefits [4]–[6].

Among various hybrid composite configurations, sandwich composite architectures have emerged as a particularly effective strategy for maximising stiffness-to-weight and strength-to-weight ratios. A typical sandwich structure consists of two thin, stiff skins separated by a lightweight core, allowing bending loads to be carried primarily by the skins while the core resists shear deformation and stabilises the structure. This structural concept offers superior efficiency compared to monolithic laminates, particularly under flexural and dynamic loading conditions [7]. When properly designed, sandwich composites can achieve high energy absorption, improved vibration damping, and enhanced impact resistance, making them attractive for aerospace, automotive, and lightweight structural applications [8]–[10].

Despite these advantages, selecting suitable core materials remains a critical challenge in sandwich composite design. Conventional synthetic cores, such as polymer foams or honeycomb structures, offer excellent mechanical performance but raise concerns related to cost, recyclability, and environmental impact. Natural fibre–based cores offer a promising alternative due to their low density, renewable origin, and energy-absorption capacity. However, their broader adoption has been limited by inherent drawbacks, including relatively low mechanical strength, pronounced moisture sensitivity, and weak interfacial bonding with polymer matrices, which can ultimately compromise long-term structural integrity [11], [12].

Interfacial adhesion between natural fibres and polymer matrices is another persistent limitation. The hydrophilic nature of lignocellulosic fibres contrasts with the typically hydrophobic character of polymer matrices, leading to poor wettability and inefficient stress transfer at the interface. This deficiency often manifests as fibre pull-out, interfacial debonding, and premature mechanical failure [13], [14]. Consequently, chemical surface treatments—most notably alkali-based treatments—have been widely investigated as a means of modifying fibre surfaces, removing hemicellulose and lignin, increasing surface roughness, and enhancing fibre–matrix compatibility [15].

Parallel to these developments, there has been growing interest in the utilisation of agricultural waste fibres as reinforcements in polymer composites. Such fibres are derived from residues that would otherwise be underutilised or disposed of, thereby adding value to agricultural by-products while mitigating environmental burden [11], [16]. Moreover, the lightweight nature of these composites supports energy efficiency and emission reduction in transportation applications [17].

Oil palm biomass is among the most abundant agricultural residues in palm-oil-producing countries, particularly in Southeast Asia. Components such as oil palm fronds, Empty Fruit Bunches (EFB), and trunks possess high cellulose content and favourable microstructural characteristics that make them attractive as reinforcing fibres. Previous studies have reported improvements in tensile, flexural, and impact properties of polymer composites reinforced with oil palm fibres [8], [18]. However, most existing

studies emphasise particulate or short-fibre reinforcements rather than exploiting oil palm fibres as functional core materials in sandwich composite architectures.

A critical research gap, therefore, exists in the systematic integration of OPFF as a functional core material in hybrid composites combined with high-performance carbon fibre skins. The challenges associated with moisture sensitivity, interfacial bonding, and processing compatibility become even more pronounced at the core–skin interface, where inadequate adhesion can lead to delamination and significant loss of structural efficiency [12], [19]. In addition, the combined mechanical, interfacial, and thermal responses of such bio-hybrid sandwich systems remain insufficiently explored.

In this context, chemical modification of OPFF with alkali (NaOH) followed by oxidative treatment (H_2O_2) offers a promising approach to enhance fibre quality and interfacial performance. Alkali treatment removes amorphous components such as hemicellulose and lignin, increasing surface roughness, while peroxide treatment further reduces residual lignin and improves surface cleanliness. The combined treatment is therefore expected to improve wettability, interfacial adhesion, and load transfer efficiency, addressing key limitations of untreated natural fibres.

Based on these considerations, the present study investigates hybrid sandwich composites comprising chemically treated OPFF as a porous natural core and carbon fibre as high-strength external skins, bonded with an epoxy matrix. The primary objective of this work is to develop and characterise a bio-hybrid composite system based on carbon fibre and chemically treated OPFF. The study systematically examines the effects of fibre treatment and configuration on mechanical properties (tensile, flexural, and impact), interfacial morphology and failure mechanisms, and thermal degradation behaviour. By condensing the background discussion and sharpening the research focus, this work positions OPFF-based hybrid sandwich composites as a viable route toward sustainable high-performance structural materials.

2 Methods

2.1 Materials

OPFF used in this study was obtained from an oil palm plantation located in Kuaro District, Paser Regency, East Kalimantan, Indonesia. The selected biomass represents an abundant agricultural residue with high potential for value-added composite applications. Sodium hydroxide (NaOH) and hydrogen peroxide (H_2O_2), both of Analytical Reagent (AR) grade, were supplied by Sigma-Aldrich (USA) and used as chemical treatment agents without further purification. The polymer matrix consisted of a bisphenol-A-based epoxy resin combined with a compatible hardener (Eposchon B). This epoxy system was selected for its high mechanical stability, good thermal resistance, and well-documented compatibility with both carbon fibres and chemically treated natural fibres.

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2.2 Fibre extraction and preparation

OPFF was extracted from the basal region of the oil palm frond, which is known to possess higher fibre density and more uniform morphology compared to the distal sections. The fronds were cut into segments of 200 mm length, after which the hard outer epidermal layer was carefully removed using a sharp blade to expose the fibrous tissue beneath. The prepared frond segments were then soaked in water at 26 ± 2°C for 72 h. This retting process facilitated the loosening of hemicellulose–pectin bonding and reduced the content of extractives, enabling easier fibre separation.

After soaking, the softened fronds were manually flattened and cleaned to separate individual fibres. The extracted fibres were thoroughly washed with running water to remove residual impurities and subsequently air-dried until a stable moisture content of approximately 9–10% was achieved. This controlled moisture level was maintained to ensure consistency prior to chemical treatment and composite fabrication.

2.3 Chemical fibre treatment

Chemical treatment of OPFF was performed to improve fibre quality and enhance fibre–matrix interfacial adhesion, while untreated fibres served as control specimens. The treatment consisted of two sequential steps. In the first step, dried fibres were immersed in a 4% NaOH aqueous solution for 60 min at room temperature with periodic stirring. Alkali treatment is known to remove surface impurities such as lignin, hemicellulose, and waxy substances, thereby increasing surface roughness and improving mechanical interlocking with the epoxy matrix [16], [20].

Following alkali treatment, the fibres were rinsed repeatedly with distilled water until the pH was neutral. In the second step, the alkali-treated fibres were immersed in a 4% H_2O_2 solution for 60 min under the same conditions. Hydrogen peroxide acts as an oxidative and bleaching agent, further reducing residual lignin and enhancing surface cleanliness, thereby improving wettability and interfacial bonding [21]. After treatment, the fibres were again thoroughly washed and oven-dried at 50°C for 2 h to restore a stable moisture content of 9–10%.

The selected NaOH concentration and treatment duration were chosen based on the literature, which indicates that moderate alkali concentrations and treatment times of approximately 1 h effectively enhance tensile strength and modulus without causing fibre degradation [22].

2.4 Composite fabrication

Hybrid composites were fabricated using the hand lay-up technique with the prepared epoxy resin system. This method was selected for its flexibility in controlling layer arrangement and its suitability for integrating carbon fibre skins with natural fibre cores in sandwich configurations [8]. The resin-to-hardener ratio was maintained according to the manufacturer's recommendations, and the total resin content was kept constant for all composite variants to isolate the effects of fibre treatment and configuration.

The reinforcement system consisted of carbon fibre layers serving as the external skins and Oil Palm Frond Fibre (OPFF) as the core reinforcement. Four composite configurations were prepared based on fibre treatment and arrangement. The first configuration, Without Treated OPFF–Carbon OPFF Straight denoted (WT–COS), comprised carbon fibre skins combined with untreated OPFF arranged in a long, unidirectional configuration. The second configuration, Without Treated OPFF–Carbon OPFF Random (WT–COR), employed untreated OPFF distributed in a short random orientation. The third configuration, NaOH + H_2O_2 treated OPFF–Carbon OPFF Straight (NH–COS), consisted of carbon fibre skins and OPFF treated sequentially with NaOH and H_2O_2 arranged in a long unidirectional configuration. The fourth configuration, NaOH + H_2O_2 treated OPFF–Carbon OPFF Random (NH–COR), utilised chemically treated OPFF in a short random configuration. For all composite variants, the fibre-to-matrix ratio was controlled using a weight-fraction approach to ensure consistency and reproducibility across specimens.

2.5 Testing and characterisation

Mechanical testing and characterisation were conducted to evaluate the influence of fibre treatment and configuration on composite performance. For each composite variant, five identical specimens were prepared, and the reported values represent average results.

2.5.1 Single-fibre tensile strength

Single-fibre tensile properties were evaluated in accordance with ASTM D3379-75 to ensure methodological consistency and comparability. Individual oil palm frond fibres were mounted on cardboard frames with a gauge length of 10 mm using epoxy resin as an adhesive. The grip sections were reinforced with tape to prevent slippage and premature failure during loading. Prior to testing, fibre diameters were measured using a digital microscope

to determine the initial cross-sectional area. Tensile tests were performed at room temperature using a single-fibre tensile testing machine at a constant crosshead speed of 2 mm/min. Multiple specimens were tested for each treatment condition to ensure data reliability and reproducibility.

2.5.2 Tensile properties of hybrid carbon–OPFF composites

Tensile tests were performed in accordance with ASTM D638 using a Universal Testing Machine (UTM) type M1 (Comtech) with a maximum load capacity of 20 kN. Specimens were tested with a gage length of 150 mm at a crosshead speed of 2 mm/min until failure. Tensile strength was calculated from the maximum applied load and the initial cross-sectional area of the specimen.

2.5.3 Flexural properties of hybrid carbon–OPFF composites

Flexural properties were evaluated using a three-point bending configuration in accordance with ASTM D790, employing the same UTM system at room temperature with a loading rate of 2 mm/min. The load was applied at the mid-span between two symmetric supports, and flexural strength was calculated based on specimen geometry and span length.

2.5.4 Impact properties of hybrid carbon–OPFF composites

Impact resistance was assessed using the Charpy impact test following ASTM D256 standards. A Zwick/Roell Charpy impact tester (model 727676) was used to determine the energy absorbed during fracture, which was calculated from the pendulum energy and the notched cross-sectional area.

2.5.5 Scanning Electron Microscopy (SEM)

Interfacial morphology and failure mechanisms were examined using SEM. Fractured composite surfaces were coated with a thin gold layer to enhance surface conductivity and observed using a HITACHI SU3500-A SEM at an accelerating voltage of 3 kV. SEM analysis focused on identifying fibre pull-out, voids, delamination, and differences in interfacial quality between untreated and treated composites.

2.5.6 Thermogravimetric and differential thermal analysis (TGA/DTA)

Thermal stability was analysed using TGA and DTA with Mettler Toledo TGA/DSC1 and Mettler Toledo 3+ HT/1600 instruments (Switzerland). Approximately 10 mg of each composite sample was placed in an alumina crucible and heated from 30 to 900°C at 10°C/min under a nitrogen atmosphere to prevent oxidation. Mass loss and thermal events were continuously recorded to identify degradation stages and assess the influence of chemical treatment on thermal behaviour.

3 Results and discussion

3.1 Single-fibre tensile strength and elastic modulus of OPFF

The tensile behaviour of single OPFF exhibited a pronounced dependence on chemical treatment. Fibres treated with NaOH followed by H_2O_2 showed a substantial increase in tensile strength compared with untreated fibres. As shown in Fig. 1(a), the NaOH–H_2O_2-treated sample exhibits a markedly higher tensile strength (150.302 MPa) compared with the untreated condition (76.691 MPa), indicating a substantial improvement in load-bearing capacity after treatment. The maximum tensile strength of treated OPFF reached 150.302 MPa, nearly twice that of untreated fibres. This improvement indicates that the applied chemical treatment effectively enhanced the fibres' intrinsic load-bearing capacity.

The observed increase in tensile strength is attributed to alkali treatment, which removes lignin and hemicellulose from the fibre surface, thereby promoting better alignment of cellulose fibrils along the loading direction and improving microfibril interlocking. The subsequent H_2O_2 treatment primarily served as an oxidative and bleaching agent, reducing residual lignin and increasing the structural homogeneity of the fibres. While the direct mechanical contribution of H_2O_2 is relatively limited, its role in surface purification supports the overall improvement achieved by the combined treatment. The results are consistent with the general observation that moderate alkali concentrations provide optimal enhancement of fibre strength. In contrast, excessive alkali exposure can lead to cellulose depolymerisation and a reduction in strength [23], [24].

In addition to tensile strength, chemical treatment significantly influenced the stiffness of OPFF. Treated fibres exhibited a Young's modulus of 3.752 GPa, compared with 2.084 GPa for untreated fibres (Fig. 1(b)). This increase in elastic modulus reflects the enhanced rigidity of the treated fibres and their improved resistance to elastic deformation under applied load.

The increase in stiffness is attributed to the reduction of non-cellulosic components, particularly lignin and hemicellulose, following alkali treatment. The removal of these amorphous constituents increases the relative fraction of ordered cellulose and promotes fibril orientation, resulting in higher crystallinity and more efficient load transfer within the fibre microstructure. The combined NaOH–H_2O_2 treatment further supports modulus enhancement by reducing residual lignin and improving surface uniformity, in agreement with reported trends for chemically treated lignocellulosic fibres [25], [26].

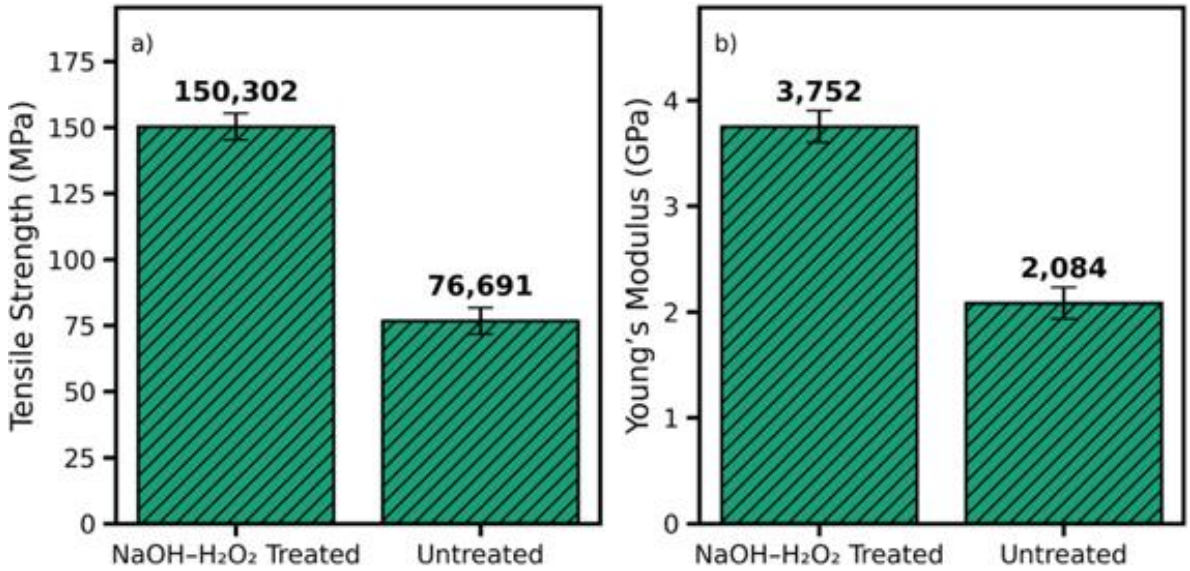


Fig. 1. Tensile strength (a) and Young's modulus (b) of NaOH–H_2O_2 treated and untreated samples of OPFF.

3.2 Tensile and flexural properties of hybrid carbon–OPFF composites

The tensile performance of hybrid carbon–OPFF composites was strongly affected by both fibre treatment and reinforcement configuration. Among all tested variants, the NH–COS composite, consisting of carbon fibre skins and NaOH + H_2O_2-treated OPFF arranged in a long unidirectional configuration, exhibited the highest tensile strength of 112.91 MPa. In contrast, the lowest tensile strength of 68.55 MPa was recorded for the WT–COR composite, which employed untreated OPFF in a short random configuration.

Fig. 2 presents the tensile test results of the hybrid carbon–OPFF composites, illustrating the comparative tensile behaviour and strength of each composite configuration. These results demonstrate a clear trend: chemical treatment enhances fibre–matrix adhesion, leading to improved tensile performance. Furthermore, the COS configuration provided superior stress distribution and more effective load transfer along the fibre direction than random short-fibre arrangements. This behaviour is consistent with the literature, which reports that unidirectional fibre orientations can yield significantly higher tensile strength than random configurations due to alignment with the principal loading direction [27].

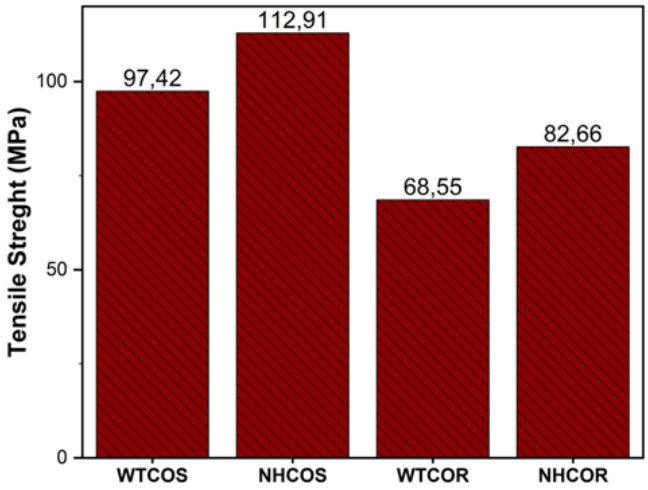


Fig. 2. Tensile strength of composites.

Flexural testing under three-point bending conditions further highlighted the benefits of chemical treatment and fibre orientation. The highest flexural strength was obtained for the NH–COS composite, reaching 109.98 MPa, while the WT–COR composite exhibited the lowest value of 36.49 MPa. The substantial difference between these two configurations underscores the critical role of interfacial bonding and reinforcement architecture in governing flexural behaviour.

Fig. 3 compares the flexural test results for the hybrid carbon–OPFF composites. Composites incorporating treated OPFF showed a marked improvement in flexural deformation resistance, reflecting enhanced stiffness and more efficient load transfer between the core and the skins. The COS configuration consistently delivered the best flexural performance, confirming that aligned long fibres are more effective at supporting bending loads than randomly oriented short fibres, which tend to promote stress concentration and premature failure.

Chemical treatment of OPFF with NaOH, followed by H_2O_2, emerges as the dominant factor responsible for the enhanced composite performance. Alkali treatment effectively removes lignin, hemicellulose, and surface impurities that act as barriers to adhesion, while simultaneously increasing surface roughness and reducing the fibres' hydrophilic character. These changes promote improved wettability and mechanical interlocking between OPFF and the epoxy matrix, which is further supported by the oxidative and cleaning action of H_2O_2. Such improvements in fibre–matrix interfacial bonding are widely recognised as critical for effective load transfer and enhanced mechanical performance in sandwich composites [28]–[30].

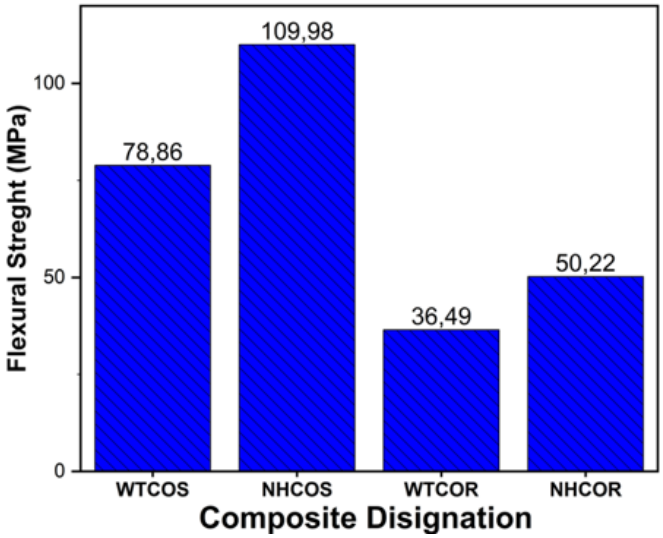


Fig. 3. Flexural strength of composites.

The superior tensile strength (112.91 MPa) and flexural strength (109.98 MPa) observed for the NH–COS configuration can be attributed to the synergistic interaction between chemically treated fibres and a unidirectional reinforcement architecture. In this configuration, fibres are aligned with the principal load direction, enabling more uniform stress distribution and minimising stress concentrations within the composite. Strong interfacial bonding ensures that applied loads are efficiently transferred from the epoxy matrix to the OPFF core and carbon fibre skins, thereby delaying the onset of damage and improving load-bearing capacity. This interpretation is consistent with established findings that unidirectional fibre arrangements typically outperform random orientations under tensile and flexural loading due to their superior load-transfer efficiency [23].

In contrast, untreated and randomly oriented composites (WT–COR) exhibited significantly lower tensile (68.55 MPa) and flexural strength (36.49 MPa). These reductions are attributed to weak interfacial bonding, non-uniform stress distribution, and premature damage initiation. The presence of untreated lignocellulosic components on the fibre surface limits epoxy wetting and adhesion, resulting in inefficient load transfer and early interfacial failure. Random fibre orientation further exacerbates this effect by introducing stress concentrations and reducing the effective contribution of fibres aligned with the loading direction. Similar trends have been reported in hybrid sandwich systems, where inadequate interface quality and suboptimal stacking sequences significantly compromise mechanical performance [31], [17].

3.3 Impact properties

The impact resistance of the hybrid composites, evaluated using the Charpy method, exhibited a narrower range of variation compared to tensile and flexural properties. Impact energy values ranged from 15.6 to 17.25 kJ/m across all composite variants. The highest impact energy absorption was recorded for the NH–COR composite, with a value of 17.25 kJ/m.

Fig. 4 presents the impact strength of the composites, enabling direct comparison of energy absorption among all composite variants. Although the differences among the variants were relatively small, chemically treated composites consistently demonstrated a positive trend in impact performance. This behaviour suggests that improved fibre–matrix interfacial bonding enables more effective energy dissipation during impact loading, particularly in random fibre configurations, where crack deflection and fibre pull-out can contribute to energy absorption [32].

Impact performance showed a narrower range of variation (15.6–17.25 kJ/m) compared with tensile and flexural properties,

reflecting the different damage mechanisms governing impact loading. Nevertheless, treated composites—particularly NH–COR (17.25 kJ/m)—showed improved energy absorption. This behaviour can be attributed to enhanced interfacial integrity, which allows progressive damage mechanisms such as controlled fibre pull-out, matrix deformation, and crack deflection, rather than abrupt brittle fracture. Random fibre configurations are often advantageous under impact loading due to their more isotropic response and ability to dissipate energy over a wider damage zone [28], [33].

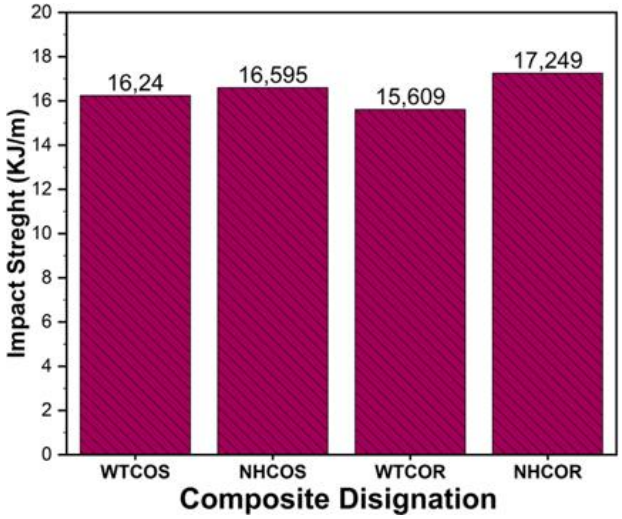


Fig. 4. Impact strength of composites.

3.4 Macroscopic evaluation of failure mechanisms

Macroscopic examination of the fractured specimens revealed distinct differences in failure mechanisms between untreated and treated composites. Untreated carbon–OPFF composites were predominantly characterised by fibre pull-out and fibre–matrix debonding, indicating weak interfacial adhesion. In the WT–COR composite, the fracture surfaces exhibited extensive fibre pull-out, with extracted fibre lengths of approximately 35 mm, accompanied by clear debonding at the fibre–matrix interface. These failure features hindered efficient stress transfer, resulting in a relatively low tensile strength of 68.55 MPa.

In contrast, composites reinforced with chemically treated OPFF (NH–COS) exhibited a pronounced shift in failure behaviour. As shown in Fig. 5, fibre pull-out was significantly reduced to only a few millimetres, and interfacial debonding was largely absent. The improved fibre–matrix adhesion enabled more efficient stress transfer, contributing directly to the higher tensile strength of 112.91 MPa observed in the NH–COS composite. Overall, macroscopic fracture analysis confirms that the NaOH + H_2O_2 treatment effectively strengthens the interface and shifts the dominant failure mode toward more controlled fracture behaviour.

Macroscopic fracture analysis provides direct evidence linking interfacial quality to mechanical performance. Untreated composites displayed extensive fibre pull-out, with extracted fibre lengths reaching approximately 5 mm, accompanied by clear fibre–matrix debonding. These failure modes indicate inefficient stress transfer and are characteristic of composites with weak interfacial adhesion, explaining the relatively low tensile and flexural strengths observed. Conversely, chemically treated OPFF composites showed markedly reduced fibre pull-out, often limited to only a few millimeters, and an absence of debonding. This transition in dominant failure mode confirms the effectiveness of NaOH + H_2O_2 treatment in strengthening the fibre–matrix interface and directly accounts for the improved mechanical performance [24], [30].

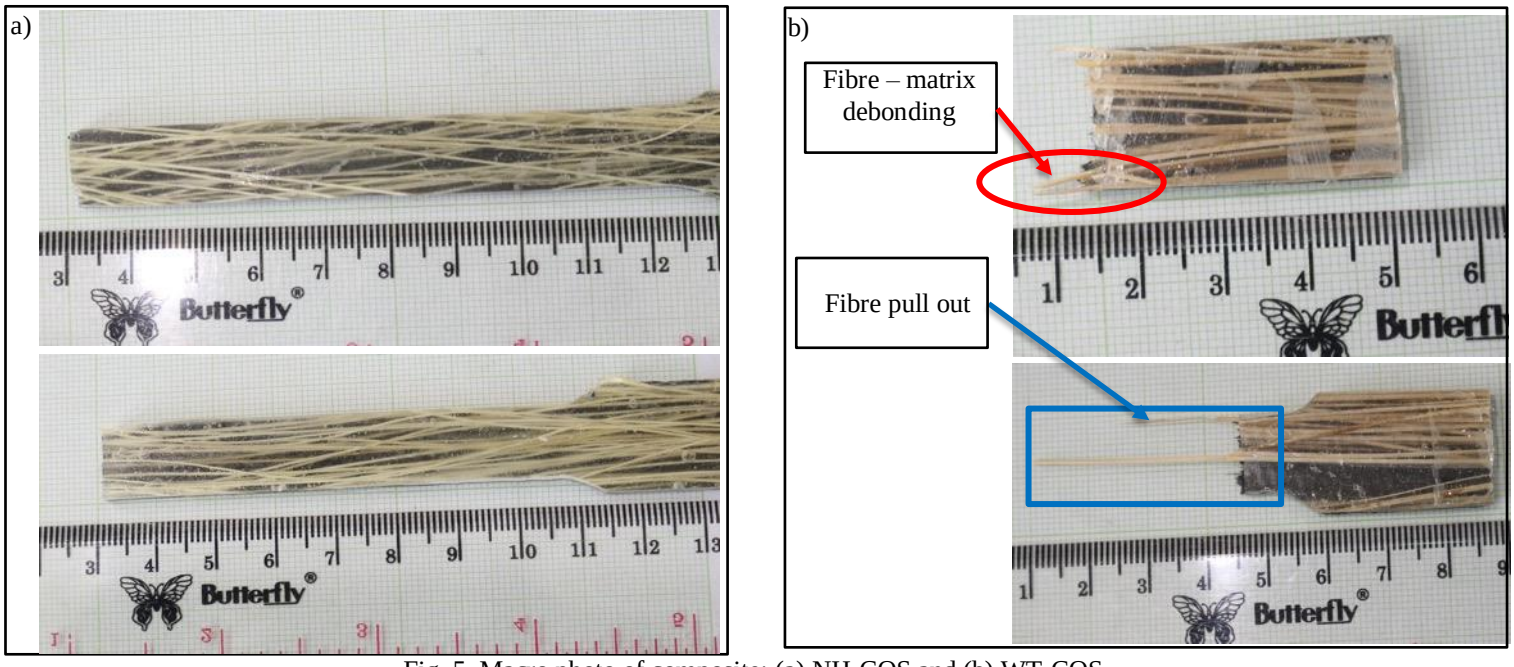


Fig. 5. Macro photo of composite: (a) NH-COS and (b) WT-COS.

3.5 SEM analysis of interfacial morphology

SEM analysis provided further insight into the interfacial quality of the hybrid composites. SEM micrographs of the WT–COS composite revealed pronounced interlayer delamination at the skin–core interface, frequent fibre pull-out, and the presence of voids and interfacial gaps within the matrix. These features are indicative of weak interfacial bonding and correlate with the inferior mechanical performance of untreated composites.

In contrast, SEM images of the NH–COS composite showed a compact and homogeneous fibre–matrix interface with no significant voids or large gaps. No interlayer delamination was observed in the examined regions, and fibre fracture at the failure plane was evident without signs of fibre pull-out. The OPFF fibres were uniformly embedded and well-coated by the epoxy matrix, confirming the effectiveness of chemical treatment in enhancing interfacial adhesion.

Fig. 6 compares the interfacial morphologies of untreated and treated composites, highlighting reduced defects and fewer fibre fractures in the treated specimens. SEM further reinforces the macroscopic observations by revealing clear differences in interfacial morphology. SEM images of WT–COS specimens, Fig. 6(a)-Fig. 6(b), showed interlayer delamination at the skin–core interface, numerous voids, and pronounced fibre pull-out, all of which act as stress concentrators and accelerate crack propagation.

These microstructural defects are well known to degrade stiffness and strength in sandwich composites. In contrast, NH–COS specimens exhibited dense and homogeneous interfacial regions, with OPFF (Fig. 6(c)-Fig. 6(d)), fibres well embedded in the epoxy matrix and no visible delamination. The presence of fibre fracture rather than pull-out at the failure plane indicates that the interface strength exceeded the intrinsic fibre strength, providing strong evidence of effective stress transfer [22], [26]. Moreover, the treated fibre composites showed clear signs of fibre breakage, accompanied by localised debonding between the fibres and the epoxy matrix, further confirming strong interfacial adhesion. Consequently, the mechanical performance of the treated fibre composites was markedly enhanced compared to that of the untreated fibre composites [34].

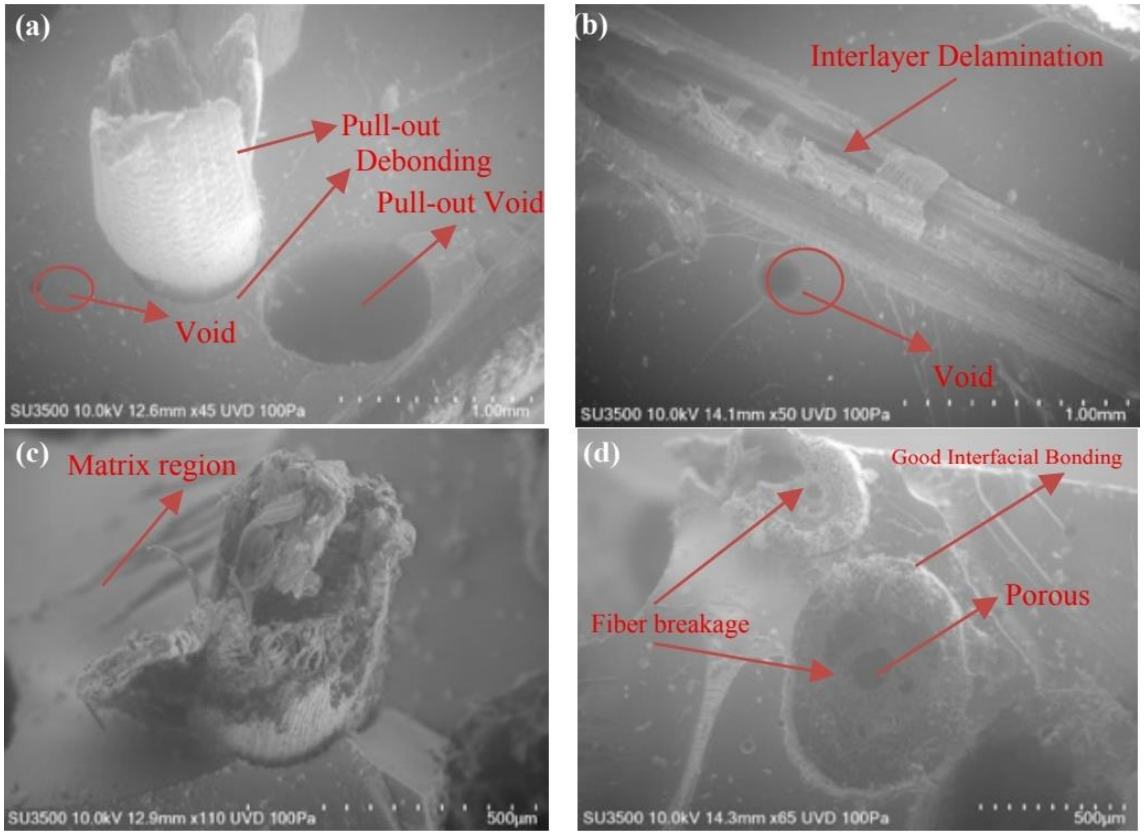
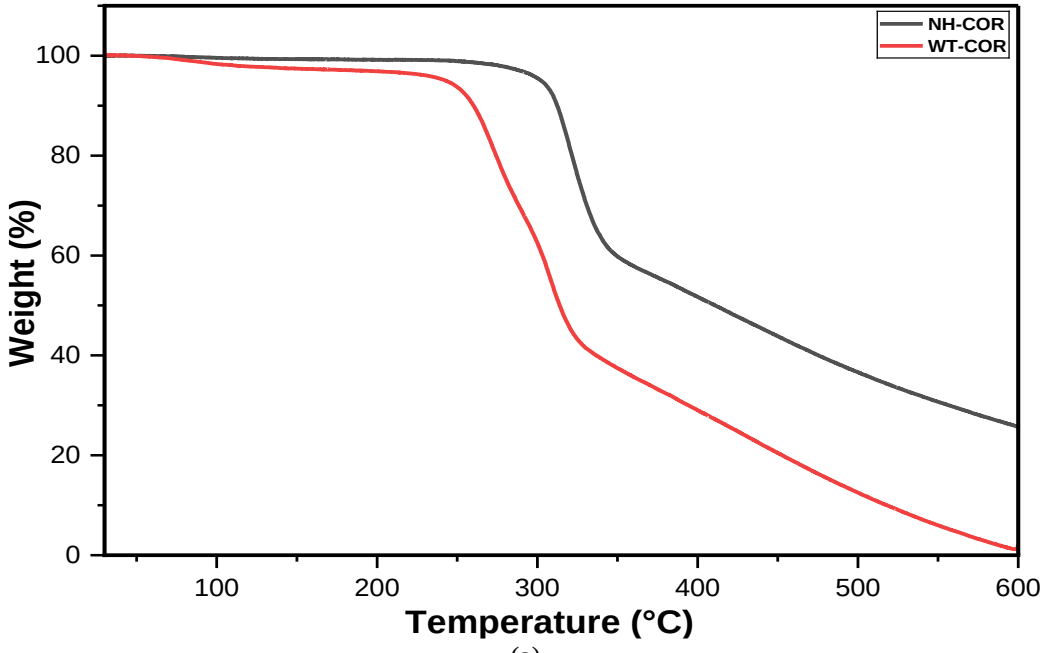


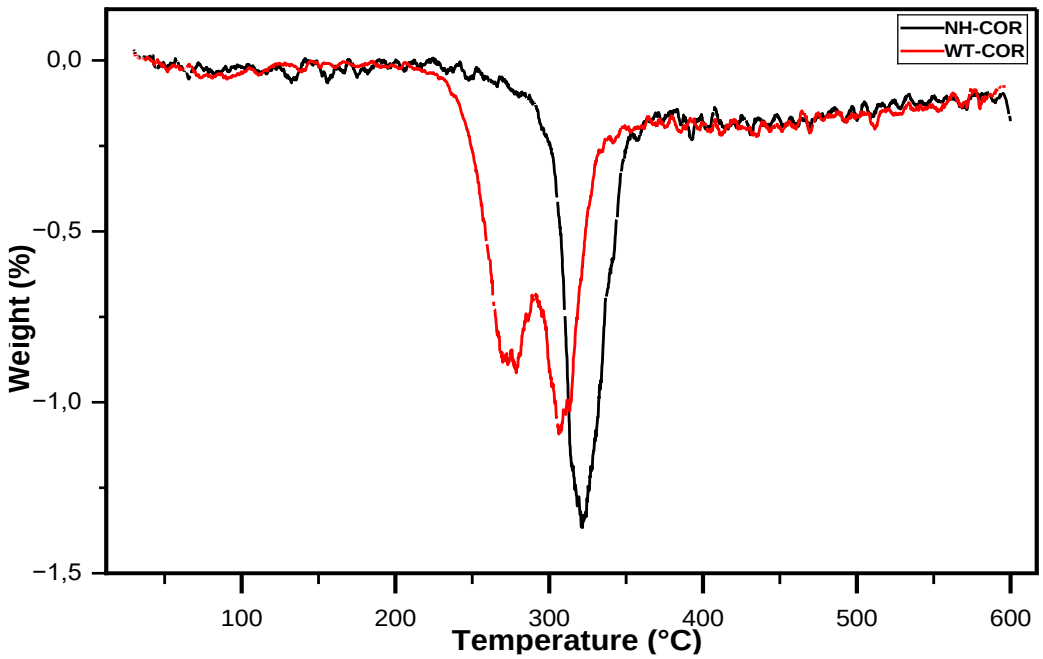
Fig. 6. SEM images of fractured tensile samples of prepared composites: WT–COS (a–b) and NH–COS (c–d).

3.6 Thermal analysis results

The matrix and fibres in the composites have a significant impact on their thermal stability. Fig. 7(a) and Fig. 7(b) illustrate the thermal stability curves of the NH-COR and WT-COR composites, in which NH-COR comprises carbon-fibre skins with an OPFF core subjected to NaOH+H_2O_2 treatment. At the same time, WT-COR employs the same hybrid configuration with an untreated OPFF core. From the thermogravimetric responses, the onset of pronounced mass loss (Ti) for WT-COR is observed at a lower temperature (≈275.6°C) than for NH-COR (≈321.6°C), indicating that chemical modification of the OPFF reinforcement effectively delays the initiation of thermal decomposition. Accordingly, the TGA/DTG-derived indices, namely the onset (Ti), the temperature associated with the maximum rate of degradation (Tm), and the endset of major decomposition (Tf), collectively indicate that the NaOH+H_2O_2 route promotes superior thermal endurance in the hybrid system.



(a)



(b)

Fig. 7. Thermogravimetric analysis and DTG curve of prepared composites.

The overall mass-loss evolution can be interpreted in terms of successive physicochemical processes. At relatively low temperatures (approximately up to 150°C), the measured weight reduction is primarily attributable to desorption of absorbed moisture and the release of low-molecular volatiles/extractives. As the temperature increases toward the intermediate regime (around 200–250°C), progressive scission of thermally labile linkages associated with non-cellulosic constituents becomes more pronounced, particularly those linked to the hemicellulose and lignin fractions. At higher temperatures, the dominant decomposition is driven by the breakdown of cellulose-rich domains and the thermal deterioration of the epoxy matrix. Importantly, the higher initial mass-loss temperature observed for NH-COR indicates that the alkaline/oxidative treatment successfully removes constituents that would otherwise decompose readily at lower temperatures, thereby elevating the initial decomposition threshold through altered fibre chemistry and composition [35]. Moreover, the mass-loss steps of the treated composite are shifted toward slightly higher temperatures than those of WT-COR within the mid-to-high temperature domains, suggesting enhanced thermal stability that can be rationalised by more effective elimination of non-cellulosic fractions, an increased relative cellulose content, and improved thermal robustness of the fibre phase. In parallel, the treated configuration is commonly associated with higher material ductility and improved composite integrity relative to untreated counterparts, implying a strengthened and more uniform load-bearing architecture that is less susceptible to thermally induced degradation [35], [36]. Finally, the carbon-fibre skins are expected to preserve dimensional stability and heat resistance further, thereby complementing the treated OPFF core and reinforcing the thermal resilience of the NH-COR hybrid sandwich structure under elevated-temperature exposure.

4 Conclusions

This study demonstrates that chemically modified OPFF can serve as an effective, sustainable core reinforcement in carbon-fibre-skinned epoxy hybrid sandwich composites. The treatment strategy of sequential NaOH and H_2O_2, significantly enhanced intrinsic fibre properties, as reflected in increased single-fibre tensile strength (150.302 MPa) and elastic modulus (3.752 GPa), which improved composite-level performance. The treated unidirectional configuration (NH–COS) exhibited the best structural response, achieving tensile and flexural strengths of 112.91 MPa and 109.98 MPa, respectively, confirming that strong interfacial bonding combined with aligned reinforcement maximises load-transfer efficiency. Failure analysis provided clear mechanistic validation: untreated composites showed extensive fibre pull-out and interfacial debonding, whereas treated composites exhibited only limited pull-out and negligible debonding, consistent with the compact, void-suppressed interfaces observed by SEM. Thermal performance was also enhanced by chemical treatment, as indicated by the emergence of a higher-temperature degradation event at approximately 321.6°C in treated composites. These findings expand the design framework of bio-hybrid sandwich composites by introducing OPFF as a value-added, agricultural-waste-based core material and by establishing a clear relationship between processing, interface, and properties.

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