Fibers and Polymers
https://doi.org/10.1007/s12221-026-01312-z

Online ISSN 1875-0052
Print ISSN 1229-9197

REVIEWS

Silane-Treated Glass Fibre-Reinforced Thermoplastic Composites: A Review of Nanofillers and Fibre Configurations

Anahar Nurul Aina[1,2] · Muhammad Asyraf Muhammad Rizal[1,2,3] · Muhamad Fauzi Abd Rased[1,2] · Desmond Daniel Chin Vui Sheng[2] · Rohah A. Majid[1,4] · Haris Ahmad Israr Ahmad[2] · Mohd Radzi Ali[3] · Noryani Muhammad[5] · Mochamad Asrofi[6] · Mugahed Amran[7] · Qahtan Al-Shami[8]

Received: 25 August 2025 / Revised: 18 December 2025 / Accepted: 1 January 2026

Abstract

Thermoset composites, commonly used in aerospace applications, offer excellent mechanical strength but face challenges related to repairability, recyclability, and limited energy absorption. As industries increasingly shift towards sustainable and damage-resistant materials, glass fibre-reinforced thermoplastics incorporating nanofillers, such as graphene, have attracted growing attention for their ability to enhance mechanical performance and durability under demanding service conditions. The main objective of this review is to evaluate and optimise glass fibre-reinforced thermoplastic composites modified with silane treatment and nanofillers through the implementation of a quasi-isotropic stacking sequence mechanism. This study reviews and analyses previous research that primarily involved the extrusion of thermoplastics with graphene nanofillers, followed by mechanical (tensile and impact) and thermal evaluations, as well as morphological assessments using scanning electron microscopy to examine the effects of fibre treatment, mesh configuration, and nanofiller dispersion. Findings from these studies reveal that the inclusion of graphene nanofillers in glass fibre-reinforced thermoplastic composites can enhance tensile strength by approximately 16%, improve impact resistance by 37–78%, and increase thermal stability by 15–20%. Overall, this review concludes that the addition of graphene significantly improves mechanical strength, thermal stability, and energy absorption, addressing performance and sustainability concerns in high-demand sectors. The insights presented also highlight potential pathways for future work aimed at refining composite composition, improving durability, and broadening industrial applications.

Keywords Silane · Glass fibre · Thermoplastic · Graphene · Quasi-static isotropic stacking mechanisms

1 Introduction

Composite materials are engineered by combining two or more distinct constituents to achieve superior properties unattainable by individual materials. Amongst various composites, polymer matrix composites (PMCs) have gained prominence for their versatility, lightweight nature, and adaptability to structural needs [1, 2]. Applications range from reinforced concrete in infrastructure [3] to PMCs in electronics [4] and wind turbine blades [5]. In aerospace, PMCs like glass fibre-reinforced polymers (GFRP) have demonstrated considerable promise due to their high strength-to-weight ratios and durability under operational stresses [6].

In recent years, thermoplastic composites have gained substantial attention as next-generation materials for sustainable structural applications. Unlike thermoset matrices that harden irreversibly and are difficult to recycle, thermoplastics offer the advantages of reprocessability, weldability, and high impact resistance, making them promising alternatives in sectors seeking greener manufacturing solutions [7]. Within this context, thermoplastic composites such as acrylonitrile butadiene styrene (ABS) are being explored as sustainable alternatives to thermosets, which face challenges in recyclability and environmental compliance [7]. To enhance the mechanical performance of glass fibre/thermoplastic composites, hybridization with graphene has been introduced. Owing to its exceptional tensile strength, stiffness, and multifunctional characteristics, graphene significantly improves the overall performance of thermoplastic composites [8–10]. The hybridised system offers benefits

Extended author information available on the last page of the article

including improved fatigue life, impact resistance, and load-bearing capability, rendering it ideal for aerospace and structural applications [11, 12]. This combination of glass fibre, graphene, and thermoplastic presents a promising composite solution for modern engineering challenges. However, previous studies have largely focussed on conventional stacking arrangements or randomly oriented fibre systems, leaving limited insight into how structural design, particularly stacking sequence, affects the energy absorption behaviour of these hybrid composites.

Previous researchers have employed various fabrication and characterisation techniques to investigate these systems. Typically, glass fibres were treated with silane coupling agents to enhance fibre–matrix adhesion and interfacial bonding. The thermoplastic matrix, primarily acrylonitrile butadiene styrene (ABS), was melt-compounded with graphene nanoplatelets (GNPs) through twin-screw extrusion to achieve homogeneous dispersion. Laminates were subsequently fabricated using compression moulding or hot pressing, with glass fibre mats stacked in orientations such as [0°/±45°/90°] to obtain quasi-isotropic properties. The resulting composites were then evaluated via tensile, flexural, and impact tests (ASTM D638, D790, and D256), thermal analyses using TGA and DSC, and morphological examinations by SEM to study fibre–matrix interfaces and fracture behaviour [13–16].

Despite their superior mechanical performance, hybridised graphene glass fibre/thermoplastic composites exhibit limitations in energy absorption capacity, particularly under complex loading scenarios. Although graphene and glass fibre reinforcement enhance strength and stiffness, its ability to dissipate impact energy efficiently remains a challenge in crash-sensitive or high-strain-rate applications. Traditional unidirectional or simple layup arrangements do not offer sufficient resistance to multi-axial loads, which leads to inadequate energy dissipation. The quasi-isotropic stacking sequence has therefore been proposed as a promising structural design to overcome these shortcomings. By arranging the fibres symmetrically in different orientations, this approach improves mechanical consistency in all directions, potentially boosting both energy absorption and overall structural integrity [13, 14]. However, the combined effects of nanofillers, such as graphene hybridization and quasi-isotropic stacking in glass fibre/thermoplastic composites, remain underexplored. This study aims to address this research gap by investigating how quasi-isotropic stacking can mitigate the observed decline in energy absorption performance, thereby offering a novel pathway to enhance composite toughness and reliability.

Energy absorption refers to a material's capacity to dissipate energy when subjected to impact or deformation, an essential property for critical applications in aerospace, automotive, and defence sectors. Mechanical performance includes key characteristics, such as tensile strength, flexural modulus, and fatigue life. In hybridised graphene glass fibre/ABS composites, energy absorption is influenced by several factors, including the fibre layout, matrix–reinforcement bonding, and stacking configuration. A quasi-isotropic stacking sequence, involving fibre layers at 0°, ±45°, and 90°, provides near-uniform mechanical properties in the in-plane directions. This arrangement increases resistance to delamination, crack growth, and residual stress concentration [15, 16]. Such a configuration ensures better energy dissipation under impact by distributing loads more evenly and delaying failure [17]. When employed alongside graphene nanoplatelets, which improve stiffness and load transfer, the synergistic effect contributes to improved energy dissipation and mechanical robustness. Thus, the integration of quasi-isotropic stacking within hybridised composites promises a balanced enhancement of both energy absorption and structural integrity.

The key reason for employing a quasi-isotropic stacking sequence is its ability to replicate isotropic behaviour in materials that are naturally anisotropic. Traditional layups, like unidirectional or angle-ply, often suffer from directional weaknesses, particularly under off-axis or transverse loading. In contrast, quasi-isotropic laminates with their symmetric fibre orientation would ensure that stress is uniformly distributed, reducing peak stress concentrations and improving delamination resistance [13]. As reported by Modi et al. [13], symmetric laminates have a 25.39% greater inter-laminar shear strength (ILSS) compared to asymmetric laminates. In demanding applications such as aerospace or crash-intensive environments, this translates to greater damage tolerance and longer service life. When combined with graphene reinforcement, the stacking sequence complements the enhanced stiffness and bonding provided by nanofillers, leading to improved structural stability under multi-directional loading. Thus, the quasi-isotropic stacking strategy is not only technically sound but also highly effective in enhancing mechanical performance and energy absorption.

From a mechanical perspective, the quasi-isotropic stacking sequence modifies how internal stresses are distributed and how deformation occurs within the composite. By layering glass fibre sheets in orientations such as [0°/±45°/90°], the composite achieves a more uniform stiffness and strength across the plane, unlike traditional layups where stress is concentrated along specific fibre directions [16]. This uniformity minimises von Mises stress peaks and suppresses crack initiation and delamination [15]. Moreover, this configuration minimises interfacial debonding between the matrix and reinforcement, further enhancing the material's energy absorption under dynamic loading [17]. The presence of nanofiller enhances these effects by strengthening the fibre–matrix interface and increasing overall stiffness, resulting in noticeable improvements in modulus, impact

resistance, and fatigue life. Experimental results by Bharathi et al. [16] also show that quasi-isotropic stacking reduces indentation damage and post-impact residual stresses, validating its effectiveness in real-world scenarios. Hence, the quasi-isotropic sequence acts as a design-level reinforcement, strategically complementing material-level enhancements provided by graphene.

With the growing demand for high-performance, lightweight, and damage-tolerant materials in the aerospace and automotive industries, the exploration of novel composite configurations has become essential. Whilst hybridised composites reinforced with graphene and glass fibres show significant potential, the optimization of their stacking sequences has not been sufficiently explored, particularly in thermoplastic matrices. Although numerous studies have investigated woven fibre systems, mesh reinforcements, and nanofillers, few have systematically examined how quasi-isotropic layups influence energy absorption and mechanical behaviour when integrated with these reinforcements [10, 12]. This review is motivated by the need to examine the complex interplay between material architecture and reinforcement mechanisms, and to identify the current research gaps that hinder progress in developing next-generation structural composites. The main objective is to evaluate the effectiveness of quasi-isotropic stacking sequences in enhancing the mechanical properties and energy absorption capabilities of hybridised graphene–glass fibre/ABS composites. Ultimately, this review aims to propose design guidelines for future composite systems that are better suited to withstand multi-directional loading in demanding engineering environments.

2 Fibre as Reinforcing Components in Composites

Fibre-reinforced thermoplastic composites are high-performance materials that combine the advantageous characteristics of thermoplastics with the strength of fibres, making them suitable for a wide range of applications, particularly in the automotive and aerospace sectors. These composites consist of fibres embedded within a matrix. Whilst the fibres provide strength and rigidity, the polymer matrix contributes to flexibility and ease of moulding. The interface between the fibres and the matrix is distinct and plays a vital role in maintaining the structural integrity of the composite during processing [18]. Polymer composites typically comprise rigid, relatively hard fibres embedded in a matrix, which may be thermoset, thermoplastic, or elastomeric in nature. Commonly used reinforcing fibres include carbon, glass, aramid, and natural fibres [19].

2.1 Woven Glass Fibre

Woven glass fibre is a key material in the development of composites, particularly hybrid composites. Its structure offers excellent tensile strength and flexibility, enabling broad application across various sectors. When combined with fibres such as basalt, it significantly improves the mechanical behaviour of composites, particularly in terms of elasticity and viscous flow [20]. Additionally, woven glass fibre enhances thermal stability by restricting polymer chain mobility. Although hybridisation offers only marginal improvements in damping performance over single glass fibre-reinforced composites, all hybrid systems show enhanced damping characteristics compared to the unreinforced polyester matrix. Owing to its high strength-to-weight ratio and low density, woven glass fibre is widely employed in industries. Figure 1 illustrates the lamination process involving alternating layers of basalt and glass fibre plies.

The fabrication process involves cutting fibres into 300 mm lengths, layering them in a steel mould, compressing, applying resin, and allowing the composite to cure. This method is vital in producing high-performance hybrid composites for engineering and industrial applications. Woven glass fibre composites consist of interlaced glass fibres arranged in a fabric-like structure [21]. They are preferred for their combination of mechanical robustness and design

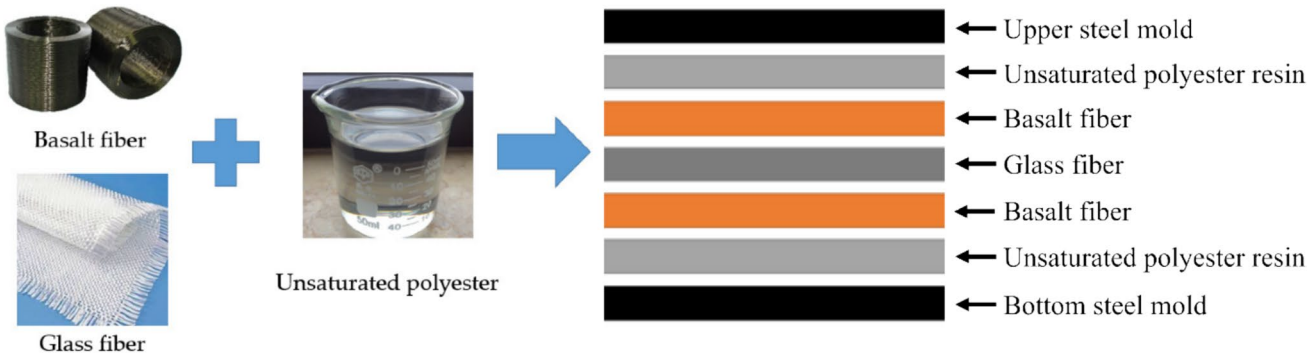

Fig. 1 Lamination sequence involving alternating layers of basalt and glass fibre plies (Haris et al. [20]) Creative Common CC BY license

flexibility. Studies have shown that whilst woven flax composites exhibit superior inter-laminar fracture toughness compared to conventional glass fibre composites, the hybridisation of glass and flax fibres further enhances these fracture properties. Acoustic emission analysis has been used to evaluate the failure mechanisms in such system. These composites are favoured in demanding sectors due to their lightweight nature and resilience under varying environmental conditions. The introduction of natural fibres like flax into glass fibre composites contributes to improved fracture resistance and sustainability.

Research into hybrid systems comprising basalt and glass fibres has demonstrated significant enhancements in mechanical performance. According to Sapuan et al. [22], a B22.5/G7.5 composite achieved a tensile strength of 213.92 MPa, considerably higher than that of unmodified unsaturated polyester resin. The inclusion of basalt fibre also improved flexural strength and modulus. Failure was mainly attributed to bending and shear mechanisms, indicating effective stress transfer from the matrix to the fibres. Scanning electron microscopy and SPSS software were used to analyse the fracture surfaces and validate the findings. In conclusion, woven glass fibre plays a crucial role in advancing high-performance hybrid composites due to its outstanding tensile strength, flexibility, and lightweight nature. When hybridised with basalt or natural fibres, these composites exhibit enhanced mechanical properties, thermal stability, and fracture toughness. The fabrication techniques and hybrid configurations discussed here highlight the promising role of woven glass fibre-reinforced composites in structural and engineering applications.

2.2 Glass Fibre Wire Mesh Fibre

The integration of glass fibre with metal wire mesh as a hybrid reinforcement in polymer composites has shown considerable promise in enhancing structural performance and resistance to damage. Glass fibre is widely employed due to its high tensile strength, low density, and cost-effectiveness. However, its brittleness and vulnerability to impact and delamination limit its effectiveness under severe structural conditions. To overcome these limitations, metallic wire meshes are incorporated to improve toughness, crack-arresting ability, and energy absorption [23]. This hybrid approach combines the rigidity and lightweight nature of glass fibres with the ductility and impact resistance of wire mesh, making it especially suitable for demanding applications.

Gokuldass et al. [24] highlighted the mechanical behaviour of hybrid composites composed of glass and Kevlar fibres, reinforced further with nanosilica and micro-rubber particles. The combination of E-Glass and Kevlar within an epoxy matrix enhances mechanical properties through efficient load transfer and strong interfacial bonding. The addition of nanosilica and micro-rubber toughens the epoxy, resulting in composites with improved tensile strength and flexural modulus compared to fibre reinforcement alone. This study underscores the critical role of fibre stacking sequences and careful selection of reinforcement materials in optimising composite performance.

The influence of mesh material, orientation, and surface treatment on the mechanical efficiency of wire mesh-reinforced composites has also been emphasised. In one study, two types of wire mesh, aluminium wire mesh (AWM) and copper wire mesh (CWM), were incorporated into hybrid natural fibre composites at orientations of 45° and 90° [25]. Both meshes enhanced the composites' mechanical properties, with a 45° alignment notably improving stiffness, strength, and ductility. The wire meshes were cleaned with deionised water to promote optimal bonding, whilst chemical surface treatments were applied to enhance adhesion at the fibre–mesh interface. Figure 2 illustrates the orientation of jute fibres and the configurations of the aluminium and copper wire meshes.

Liu et al. [26] examined the use of 304 stainless-steel wire mesh (SWM), with a tensile strength of 800 MPa, as reinforcement in 3D concrete printing. The mesh was provided in sizes of 400 mm × 100 mm and 100 mm × 100 mm and was embedded in multiple layers within the printed concrete to ensure optimal contact and reduce delamination risk. Their results showed significant improvements in mechanical performance, maximum load capacity, and deflection behaviour, outperforming random steel fibre reinforcements in shear strength and structural efficiency. Consequently, SWM is considered an effective reinforcement strategy for 3D-printed concrete structures. Table 1 summarises various applications of fibreglass and wire meshes in composite materials.

3 Configurations and Designs of Hybrid Composites

A composite comprising two or more types of fibre embedded within a single polymer matrix is generally referred to as a hybrid fibre composite. The development of such composites requires the careful selection and treatment of fibres to optimise both cost and performance [31]. Studies have shown that incorporating glass fibres with natural fibres, such as jute, Napier, abaca, hemp, or banana, significantly enhances the mechanical properties compared to composites reinforced with a single-fibre type [32–35]. Various industries have adopted the hybridisation of natural fibres in the fabrication of composite products. For example, Flex Form technology employed hemp/kenaf hybrid composites in the production of door panels for the Chrysler Sebring [31]. Swolfs et al. [36] highlighted that fibre hybridisation in polymer composites can effectively improve the toughness and strength of the material.

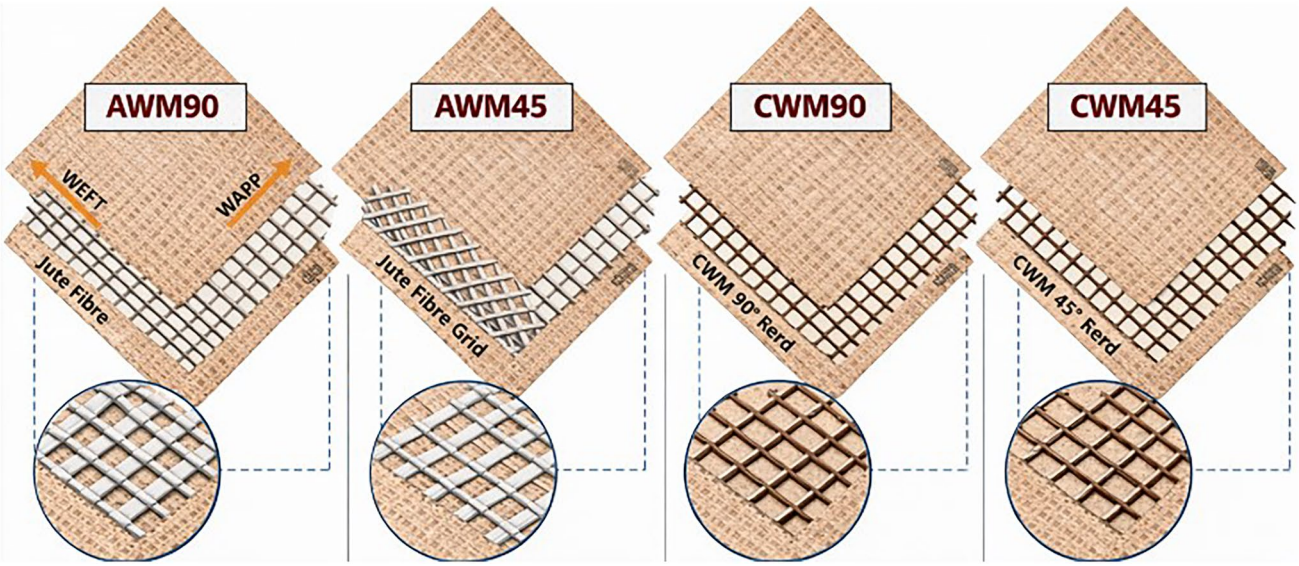

Fig. 2 Hybrid configurations of AWM and CWM composites

In recent years, hybrid composites have attracted considerable attention due to their superior mechanical characteristics, including improved strength, stiffness, and impact resistance. By blending different fibre types—such as glass, basalt, or natural fibres—these composites can take advantage of the distinct benefits of each constituent, resulting in better overall performance than single-fibre systems [37]. Hybrid composites are formed by integrating multiple reinforcing fibres into a single polymer matrix to elevate the composite's performance. The resulting combination may lead to either a synergistic enhancement or a reduction in properties, depending on the compatibility and arrangement of the fibres. Typically, hybrid fibres can be configured in one of three main ways: (1) interlayer, (2) yarn-by-yarn, and (3) fibre-by-fibre, as illustrated in Fig. 3.

4 Fibre Reinforcement and Its Configurations

Reinforcing fibres, such as carbon, glass, and aramid, provide exceptional strength, stiffness, and fatigue resistance to composites. Unlike the more ductile matrix, which deforms under load, the fibres bear most of the applied stress [38]. The interplay between the flexible matrix and the rigid fibres provides a well-balanced combination of strength and durability. Whilst the matrix is responsible for absorbing and dissipating impact energy, the fibres maintain the composite's structural integrity, thereby preventing failure [39]. A key factor influencing the mechanical behaviour of fibre-reinforced composites is the fibre stacking sequence in which the specific arrangement and orientation of fibre layers within the matrix [40]. This structural configuration significantly affects properties, such as tensile strength, stiffness, and resistance to environmental degradation. The manner in which fibre layers are stacked determines how loads are distributed and absorbed throughout the material, making it a critical design consideration in applications where reliability and long-term performance are essential. To achieve optimal mechanical performance, stacking sequences are carefully designed to meet specific engineering requirements. Common configurations include unidirectional layers for maximum strength along a single axis, cross-ply arrangements to enhance strength in perpendicular directions, and quasi-isotropic sequences that mimic the uniformity of isotropic materials [41, 42]. These arrangements ensure that the composite structure can effectively resist varied loading conditions without compromising its integrity.

The choice of stacking sequence is typically tailored to suit the composite's intended application. For instance, in aerospace engineering, cross-ply and quasi-isotropic layups are frequently used to balance stiffness and flexibility under multi-directional stress [43]. In contrast, automotive and sports equipment industries often employ optimised stacking strategies to maximise performance whilst reducing overall weight, emphasising the importance of precise fibre orientation [44]. Ultimately, the superior properties of fibre-reinforced composites are the result of the synergistic relationship between the matrix and the fibres. The matrix not only facilitates stress transfer and ease of manufacturing but also protects the fibres from environmental exposure. Meanwhile, the fibres provide the composite with its primary mechanical strength and stiffness. A summary of the

Table 1 Fibreglass mesh/wire mesh utilisation in fibre-reinforced polymer composites

Type of mesh	Loadings	Mechanical properties' improvement	Morphological surface improvement	Ref
Stainless steel wire mesh embedded in glass fibre-reinforced epoxy	*Weight fraction:* Woven glass fibre is 50% of mass fractions Epoxy resin is 40% of mass fractions SSWM is 10% of mass fractions	The GFRP-SSWM laminate significantly enhances tensile properties, elevating the strength of GFRP from 86 to 110 MPa. The integration of SSWM in the core boosts the laminate's tensile properties, resulting in increased strength and flexibility	The upper mesh, central mesh, and lower mesh are laminates exhibiting varying strengths and tensile stresses. The upper mesh exerts negligible disruptive effect on the fibre structure, the intermediate mesh causes significant fibre disturbance, and the lower mesh experiences substantial tensile stress due to wire-induced deformation	[27]
Steel wire mesh embedded in glass fibre-reinforced epoxy	*Weight fraction:* 50, 52.5, 55, 57.5, 60 wt.% of Woven glass fibre, SSWM uniformly maintained at 10 wt.%	The investigation indicates that S4 has the greatest load and displacement capacity, possessing an ultimate tensile strength that is 16.1% superior to that of standard GFRP. S4 and S5 exhibit superior flexural strength attributable to a reduced fibre fraction and inadequate epoxy resin wetting. S4 and S5 absorb greater energy owing to their stacking sequence and interfacial bonding. S4 has a 22% increase in shear strength	Increased fibre accumulation and a thin epoxy coating enhance adhesion between the matrix and reinforcement, but flexural load induces inter-laminar delamination and fibre pull-out, resulting in voids due to inadequate interfacial bonding	[28]
Stainless steel wire mesh embedded in glass fibre-reinforced epoxy	*Volume ratio:* Epoxy and glass fibre/stainless-steel wire mesh was 60:40 *Wire diameter:* 151 µm *Mesh opening size:* 282 µm	Energy absorption under low-velocity impact: *3 m/s*: predominantly matrix cracking and fibre breakage *4 m/s*: delamination and with occasional penetration *5 m/s*: perforation of the indenter	The SEM images of the treated surface of the SS mesh was found to be macroscopically featureless	[29]
Fibreglass mesh embedded in kenaf fibre-reinforced ABS	*Mesh sizes:* 1 mm^2 3 mm^2 5 mm^2	The KGFM-5 configuration, featuring kenaf fibre-reinforced ABS, offers a maximum flexural strength of 76.1 MPa, making it suitable for load-bearing applications. Its smooth curve ensures effective stress distribution and absorption until failure	Through SEM analysis, stacking KABS-A6 emerges as the configuration with the highest tensile stress because illustrates a robust fibre-matrix bonding	[30]

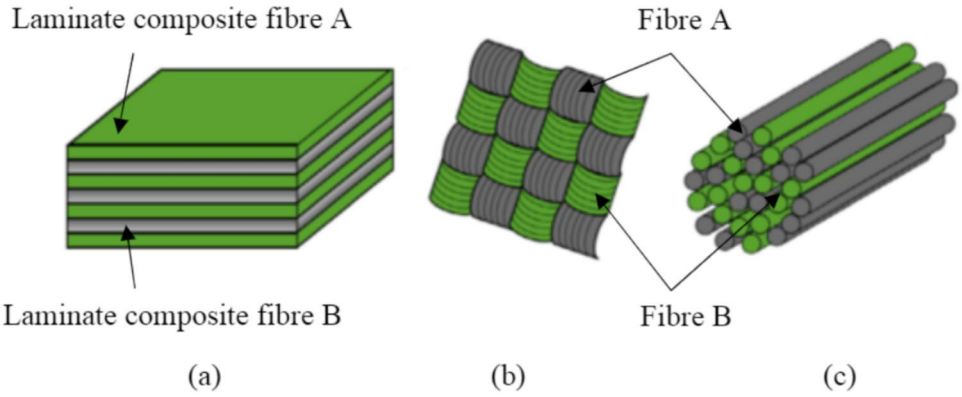

Fig. 3 Hybrid fibre configurations: **a** interlayer; **b** yarn-by-yarn; and **c** fibre by-fibre Reproduced with permission from [36]. Copyright 2014 Elsevier

Table 2 Effect of fibre orientations in fibre-reinforced polymer composites

Fibre orientation & fibre content	Fibre + matrix	Mechanical properties' improvement	Ref
0–1 with 0.1 steps 10 wt%, 20 wt%, 30 wt%, 40 wt%	E-Glass fibre-reinforced polypropylene	Tensile strength escalates with fibre content and alignment, although diminishes with anisotropy. Enhanced fibre orientation leads to elevated tensile strength, but anisotropic composites reduce strength by 10%	[45]
0° (unidirectional) 90° (transverse directional) 0°/90° (bidirectional) 45°/45°	E-Glass fibre-reinforced epoxy	The composite exhibited a significant ultimate tensile strength of 747.86 ± 10.1 MPa for [0°] s fibre, with notable improvement in 0° and 0°/90° orientations. The maximum tensile modulus was 14.23 ± 8.16 GPa at a 0° fibre orientation, whereas the maximum flexural strength was 129.74 ± 12.2 MPa	[46]
0/90° 0/45°	Bi-woven glass fibre-reinforced resin Graphite fibre-reinforced polymer	Laminates with a 0/45° orientation demonstrated exceptional flexural strength	[47]
0° 45° 90°	Continuous E-glass fibre-reinforced epoxy Discontinuous E-glass fibre-reinforced epoxy	The impact strength is influenced by the angle of inclination, ranging from a minimum of 90° to a high of 0°, with a constant at 45°	[48]
For square tubes S1 and S2: (0°, 50°, − 50°, 0°, − 50°, 50°, 0°) (mat, − 45°, 0°, 45°, mat) *For C1 and C2 circular tubes:* (0°, 56°, − 56°, 0°, − 56°, 56°, 0°) (0°, 71°, − 71°, 0°, − 71°, 71°, 0°)	Pultruded glass fibre-reinforced polymer (PFRP) tubes reinforced polyester and resin	The compressive strength of the S2 square tube exceeds that of S1 by 14.3%, attributable to a reduced plate slenderness ratio. S1 square tube specimens exhibit elevated tensile stress and modulus. Circular tubes possess marginally greater load capacity and compressive strength	[49]

fibre orientations and contents adopted from previous studies is presented in Table 2.

4.1 Quasi-isotropic Stacking Sequence Mechanism

Quasi-isotropic fibre stacking is a structural design methodology in composite materials intended to replicate the uniform mechanical properties of isotropic materials, such as metals. In contrast to unidirectional or cross-ply laminates that focus on loading orientations, quasi-isotropic stacking provides uniform strength and stiffness in all in-plane directions by arranging fibre layers at various angles which typically at 0°, ± 45°, and 90° [50]. This approach is especially advantageous for components exposed to multi-axial stresses or erratic loading conditions, as it provides a uniform response to pressures exerted from any direction.

The correlation between quasi-isotropic stacking and the 50/40/10 rule is essential for attaining optimal performance. In a quasi-isotropic laminate, around 50% of the fibres are aligned with the principal load direction (0°), 40% are orientated at ± 45° to address shear stresses, and 10% are positioned perpendicular to the primary load direction (90°) to enhance stability and counteract transverse forces [51]. This equitable distribution guarantees consistent mechanical characteristics and improves the composite's resistance to prevalent failure modes, including delamination, buckling, and fatigue. This rule's application guarantees that quasi-isotropic designs optimise material efficiency whilst maintaining structural integrity.

Quasi-isotropic stacking is extensively utilised in industries where performance under multi-directional loads is essential. In aerospace, aircraft fuselage panels and wing

components frequently utilise quasi-isotropic laminates to manage the intricate stresses during flight [52]. In vehicle engineering, body panels and structural components similarly benefit from this methodology by preserving durability whilst reducing weight [53]. In maritime applications, where wave-induced forces fluctuate significantly, quasi-isotropic composites offer a resilient alternative for hulls and undersea structures [54]. This design versatility highlights the usefulness and adaptability of quasi-isotropic stacking across several technical domains.

Recent advancements in manufacturing techniques, such as automated fibre placement (AFP) and 3D weaving, have further enhanced the precision and efficiency of producing quasi-isotropic laminates [55]. These methods allow for accurate fibre alignment and layer placement whilst minimising material waste, thus ensuring consistent quality and performance. Additionally, computational modelling tools have become indispensable for optimising quasi-isotropic designs, enabling engineers to simulate complex multi-axial loading scenarios and refine stacking sequences accordingly. As composite technologies continue to evolve, the integration of quasi-isotropic stacking with advanced manufacturing and simulation techniques will remain central to the development of high-performance, structurally efficient materials.

4.2 50/40/10 Rule

The fibre stacking sequence mechanism is essential in composite material design, as the arrangement and orientation of fibre layers dictate the material's mechanical properties. This technique guarantees optimal load distribution and structural integrity in diverse situations. A prevalent principle in stacking design is the 50/40/10 rule [56], which offers a framework for equilibrating strength, stiffness, and stability across various loading orientations.

The 50/40/10 rule dictates that around 50% of the fibres in a laminate should be aligned with the major load-bearing direction, 40% with secondary directions, and the remaining 10% with shear-resisting orientations. This distribution guarantees that the composite is optimum for both uniaxial and multi-axial loads, hence minimising the danger of delamination and failure [57]. In cross-ply designs, this principle may be used to layer orientations like [0°, ± 45°, 90°], ensuring the requisite strength for various operational situations [58]. This criterion is essential in practical applications for industries like aerospace and automobile manufacturing, where weight reduction and structural integrity are critical. Using the 50/40/10 rule, engineers can design fibre stacking sequences that ensure uniform stress distribution whilst preserving the composite's durability against fatigue and environmental factors. The regulation additionally facilitates quasi-isotropic design, which is especially beneficial for components subjected to intricate loading conditions.

With the advancement of composite production, automated technologies and sophisticated simulation tools are employed to accurately apply the 50/40/10 rule in fibre stacking processes. These advancements improve the uniformity and efficacy of composite manufacturing, allowing for materials with customised qualities to satisfy the requirements of advanced applications. This method closely resembles quasi-isotropic designs, wherein fibre orientations replicate isotropic characteristics by uniformly spreading layers across various directions, hence assuring uniform strength and stiffness throughout the composite structure.

5 Fibre Structure and its Modifications via Coupling Agent

The structural characteristics of reinforcing fibres are critical to the mechanical performance and reliability of fibre-reinforced thermoplastic composites. Both internal features including molecular alignment and crystallinity [59] as well as external attributes such as surface morphology [60], govern how fibres interact with the matrix and respond under mechanical stress. Fibres are typically composed of highly aligned molecular chains or crystallites, which contribute to their tensile strength, stiffness, and dimensional stability [61, 62]. The degree of alignment and crystallinity differs across fibre types, significantly influencing their reinforcement efficiency within the composite. However, the internal structure alone does not determine fibre effectiveness. The external surface characteristics of the fibres are equally vital, particularly in establishing a strong fibre–matrix interface. A well-bonded interface ensures efficient stress transfer between the fibre and matrix, which is essential for optimising the mechanical integrity of the composite [63]. Fibres with smooth or chemically inert surfaces often demonstrate poor interfacial bonding, leading to weak load transfer and reduced durability of the composite [64, 65].

To address this limitation, surface modification techniques are widely employed to enhance fibre–matrix adhesion. These include chemical treatments, such as alkali or silane functionalisation, plasma activation, and mechanical abrasion [66]. Each method aims to alter the fibre surface either by introducing reactive functional groups, increasing surface roughness, or improving wettability. Such modifications are designed to strengthen the chemical and mechanical interactions between the fibre and the thermoplastic matrix, ultimately improving tensile properties, impact resistance, and long-term stability of the composite material [67]. Moreover, the role of coupling agents becomes increasingly important in promoting

fibre–matrix compatibility, especially for thermoplastic systems. In these composites, the matrix acts not only as a binder but also as a medium for stress transfer between fibres. Effective surface treatments, particularly with the aid of coupling agents such as silanes for glass fibres or other chemical modifiers for carbon and aramid fibres, can create covalent or hydrogen bonds at the interface. These bonds facilitate better load distribution and reduce the likelihood of interfacial failure, resulting in a more robust and durable composite [68, 69].

Coupling agents play a vital role in enhancing this interface. By improving interfacial bonding, they ensure efficient stress transfer and increase the durability of the composite under various conditions. Untreated fibres generally exhibit poor adhesion to the thermoplastic matrix due to mismatches in surface chemistry and physical properties [70]. For instance, glass fibres are inherently hydrophilic, whereas thermoplastic matrices are often hydrophobic, leading to weak interfacial bonding and ineffective load transfer [71]. The importance of coupling agents becomes even more evident when considering the structural features and functional demands of different fibres. Whether dealing with the high rigidity of carbon fibres or the quasi-isotropic nature of glass fibres, effective stress transfer is essential for optimal performance. Coupling agents facilitate this by creating a cohesive interfacial layer that not only enhances mechanical properties but also increases resistance to environmental factors such as moisture ingress [63]. Additionally, coupling treatments address issues related to fibre surface morphology. Rough or porous fibre surfaces contribute to mechanical interlocking, whilst chemical modifications further strengthen adhesion at the molecular level [72]. This synergy between the thermoplastic matrix, fibre architecture, and surface treatment allows for the fabrication of composites with tailored properties. A well-designed interface incorporating appropriate coupling agents enables the reconciliation of differing material properties, enhancing both mechanical strength and environmental resilience. In summary, the integration of coupling agents in fibre treatment is a key strategy in the development of fibre-reinforced thermoplastic composites. This approach not only maximises composite performance but also opens avenues for more sustainable, versatile, and innovative material solutions across various industries. To further illustrate these improvements, Table 3 provides a summary of previous research on the use of silane coupling agents in hybrid fibre-reinforced polymer composites. In brief, the mechanical performance of fibre-reinforced thermoplastic composites is governed by a combination of internal fibre structure, surface characteristics, and interfacial chemistry. Continuous advancements in fibre modification techniques, defect control, and coupling agent technologies are driving the development of high-performance composites tailored for demanding applications in sectors.

6 Thermoplastic Matrix

Thermoplastic polymers have gained popularity as matrix materials for fibre-reinforced composites due to several advantages over thermosetting resins. Their ability to soften and be reshaped when heated offers excellent reprocessability, impact resistance, and environmental durability. Moreover, their notable fracture toughness and shorter processing times make them well suited for applications requiring rapid production and recyclability. Common thermoplastics used in composites include acrylonitrile butadiene styrene (ABS), polypropylene (PP), polyether ether ketone (PEEK), and polyethylene terephthalate (PET), each with unique performance characteristics. Thermoplastics can be softened and melted upon heating, enabling faster manufacturing compared to thermoset materials. They exhibit superior ductility and impact resistance and can be joined through various welding techniques. The properties of thermoplastic matrix composites depend significantly on the choice of matrix and fibre reinforcements, with E-glass fibres often preferred for their cost-effectiveness. In the automotive sector, short, randomly oriented fibres are commonly employed; however, this may affect the composite's isotropy. The incorporation of fibres and fillers into thermoplastic matrices enhances mechanical strength, improves thermal stability, and reduces mould shrinkage, making these composites ideal for a broad range of automotive applications.

The fabrication of thermoplastic polymer composites (PPCs) involves diverse methods, such as film stacking and compression moulding, each with specific processing parameters that strongly influence the mechanical performance. Processing pressure plays a vital role in achieving optimal fibre–matrix adhesion whilst minimising issues like fibre relaxation and shrinkage. Similarly, compaction temperature is critical; higher temperatures generally improve the flexural modulus, although excessive heat can degrade mechanical properties if not carefully controlled. The mechanical and thermal performance of thermoplastic PPCs is influenced by factors, including the polymer's molecular weight, morphology, and the fabrication technique employed. As noted by Qiao et al. [83], thermal stability is particularly important for applications involving elevated temperatures, with processing methods directly affecting the final properties.

Thermoplastic matrices offer key advantages in processability and recyclability. Unlike thermosets, which harden permanently, thermoplastics can be remoulded and reprocessed using heat. This not only simplifies manufacturing techniques like injection moulding, compression moulding, and thermoforming, but also supports material recovery and

Table 3 Silane coupling agent treated on hybrid fibre-reinforced polymer composites

Type of silane	Conc. used	Mechanical improvement	Morphological surface improvement	Refs
3-aminoprophyltriethoxysilane treated on Kenaf and Glass Fibre-Reinforced Epoxy	0.5 wt% 0.75 wt% 1 wt%	The integration of Silane CNT into kenaf and hybrid composite systems improved compressive properties, yielding a 73.25% increase in compressive modulus and a 20.15% rise in strength. This resulted in a 7.73% improvement in compressive strength and modulus	The compressive performance of Kenaf (k) composites and hybrid G/K composites is affected by the incorporation of glass fibres, leading to insufficient bonding and brittleness, with diverse applications in automotive components	[73]
(3-aminopropyl) triethoxysilane (APTES) treated on Glass fibre-reinforced epoxy	20 g	The research revealed enhanced mechanical properties and increased tensile strength in fracture specimens of MGF that exhibited no surface cracks or voids	The surface shape of GF stays unaltered following APTES alteration; nevertheless, the amount of carbon, oxygen, and nitrogen increases, thereby demonstrating effective grafting. The hydrophilicity of GF marginally increases, likely attributable to APTES grafting and the presence of oxygen and nitrogen components	[74]
(1) Aminoethylaminopropyltrimethoxysilane (Silane 6020) both treated on Glass fibre-reinforced polysulfone (PSU) (2) Aminopropyltriethoxysilane (Silane 6011)) both treated on Glass fibre) reinforced polysulfone (PSU)	1 wt%	Silane treatment improves the mechanical properties of glass fibre-reinforced composites by enhancing interfacial adhesion amongst constituents. The tensile strength, Young's modulus, and flexural strength of these composites significantly exceed those of the original glass fibre	The carbon content in salinized glass fibre rises due to CH2 bonding, whilst composites reinforced with silane 6011-treated glass fibre have improved tensile strength due to the formation of hydrogen and covalent bonds	[75]
(1) Methacryloxypropyltrimethoxysilane (MPS) treated on Glass fibre-reinforced epoxy (2) Aminopropyltriethoxysilane (APS) treated on Glass fibre-reinforced epoxy (3) Glycidoxypropyltrimethoxysilane (GPS) treated on Glass fibre-reinforced epoxy	0.2 wt%	The glass fibre and silane coupling agent exhibit improved hydrogen bonding, however MPS-treated glass fibres possess the maximum surface free energy due to their increased specific component	The adhesion is enhanced following treatment with a silane coupling agent	[76]
γ-Aminopropyl silane treated on Glass fibre-reinforced epoxy	0.1 wt% 1 wt% 3 wt%	Nanoindentation studies indicated that the percentage difference in penetration depth between the interphase and the epoxy matrix increased from 8.33% at 3.0% APS to 42.86% at 5.0% APS	The thickness of the interphase escalates with the degree of surface treatment, demonstrating commendable repeatability. Interphase measurements indicate values below 8% and 4%, as silane concentration escalates from 0 to 888 nm	[77]
3-aminopropyltrimethoxysilane treated on Glass fibre (chopped strand mat) reinforced epoxy	10.8 ml	The use of silane-treated OMMT significantly enhances the stiffness of E/GF composites, increasing their flexural modulus by 13%. The flexural strength of E/GF/silane-treated OMMT composites exceeds that of E/GF composites by 10%, due to enhanced interfacial contact	The coarse glass fibre surface of E/GF/silane-treated organoclay indicates improved interfacial interaction between the glass fibre and modified organoclay, leading to significant increases in flexural modulus and strength	[78]
(1) γ-aminopropyl triethoxy silane (APS) treated on Glass fibre (chopped strand mat) reinforced epoxy (2) γ-glycid oxypropyl trimethoxy silane (GPS) treated on Glass fibre (chopped strand mat) reinforced epoxy	1 wt%	The flexural properties of the composite film treated with the APS coupling agent are superior. The previously mentioned result indicates that APS-treated glass fibre exhibits strong compatibility with the fluorene acrylate and urethane acrylate matrix resins	APS and GPS exhibit strong adhesion to the surface of glass fibre. This signifies an enhancement in the interfacial adhesion of the glass composites. The results may be attributed to the increased presence of hydroxyl groups, which enhances hydrogen bonding at the interfaces between the glass fibre and the silane coupling agent	[79]

Table 3 (continued)

Type of silane	Conc. used	Mechanical improvement	Morphological surface improvement	Refs
3-aminopropyltryethoxysilane (3-APE) treated on Short glass fibre-reinforced polybutylene terephthalate (PBT)	–	The retention of tensile strength in treated SGF-PBT has increased to 76.8%, in contrast to the untreated SGF-PBT at 59.3%	The influence of 3-APE silane coupling agent on enhancing interfacial bonding quality is apparent from the surface characteristics of the SGF. The efficacy of stress transmission from the PBT matrix to the SGF has improved with the inclusion of 3-APE	[80]
N-phenyl-1-aminopropyltrimethoxysilane	0 wt% 0.5 wt% 1 wt% 1.5 wt% 2 wt% 2.5 wt%	The fixation increases with decrease in silane concentration	The increased thickness of silane coating prevents the bonding via siloxane linkage to the glass fibre surface	[81]
Triethoxy-silane treated on Pineapple leaf fibre-reinforced polyester resin	–	Tensile properties improve with fibre length up to 20 mm in polyester composites, likely due to uneven distribution within the matrix. PALF composites demonstrate a peak tensile strength of 57.4 MPa and exhibit low wear resistance. At 25 mm, tensile strength diminishes due to complications at the resin-fibre contact, impairing stress transmission efficiency	The SEM morphology of the cracked surface of PALF composite samples exhibited a uniformly smooth surface, signifying quick crack propagation and decreased fracture toughness	[82]

reuse at end-of-life. The combination of high mechanical performance and recyclability positions these composites as a sustainable alternative to traditional materials, addressing increasing environmental demands. For instance, ABS is a widely used thermoplastic known for its durability, ease of manufacturing, and aesthetic appeal. It is a copolymer composed of acrylonitrile, butadiene, and styrene, each contributing distinct properties: acrylonitrile improves chemical and thermal resistance, butadiene enhances toughness and impact strength, and styrene provides rigidity whilst facilitating processing. Despite its favourable properties, ABS has certain limitations, particularly its relatively low heat distortion temperature, which ranges between 100 °C and 110 °C. This can adversely affect its mechanical performance at elevated temperatures, as noted by Tambrallimath et al. [84]. However, incorporating nanofillers like graphene can significantly enhance its characteristics. For example, the addition of a graphene-based additive (Sb-Mo/Br-rGO) to ABS has been shown to markedly improve its thermal stability, tensile strength, and elastic modulus which yielding a 31% increase in tensile strength and a 73% increase in elastic modulus.

Such improvements not only boost the material's performance but also enhance its safety and adaptability across various applications [85]. Furthermore, the thermoplastic matrix in composites plays a vital role in stress transfer, ensuring that loads are evenly distributed across the fibres to prevent localised failure, which could otherwise compromise the material's structural integrity. The characteristics make ABS a preferred material across various industries, such as automotive, electronics, and consumer goods for applications, including vehicle parts, protective gear, and even LEGO bricks. Its lightweight nature, machinability, and ability to be moulded into complex shapes further contribute to its versatility for both industrial and everyday use.

7 Nanofillers as Additives in Composites

In aerospace technology, where the strength-to-weight ratio and toughness are paramount, incorporating nanofillers such as graphene nanoplatelets (GNPs) into fibre-reinforced composites has shown great promise. The nanofillers such as GNPs possess exceptional mechanical, thermal, and electrical properties, making them multifunctional additives that enhance composite performance [86]. When dispersed within the matrix, the nanofillers improve resin–fibre interfacial bonding, leading to better load transfer and increased resistance to crack initiation and propagation. According to Iqbal et al. [87], the presence of nanofiller such as GNPs delays critical crack formation and extends the fatigue life of composites, which is especially valuable in structural applications.

7.1 Graphene

Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, is renowned for its exceptional mechanical, electrical, and thermal properties. It is approximately 200 times stronger than steel by weight, making it a highly effective reinforcement for thermoplastic composites. When incorporated into fibre-reinforced thermoplastics, graphene significantly improves mechanical performance by enhancing interfacial bonding due to its large surface area, which promotes better load transfer between fibres and matrix. Beyond mechanical strength, graphene also provides excellent electrical conductivity, making graphene composites ideal for electronics, electromagnetic shielding, and sensor applications. Its superior thermal conductivity aids heat dissipation, protecting components from overheating and extending their lifespan in harsh thermal environments. Graphene also improves environmental resistance by protecting composites from UV degradation, moisture, and temperature fluctuations. Additionally, it enhances fatigue resistance, allowing composites to withstand repeated loading, which is critical for automotive and wind turbine parts. Overall, the integration of graphene enables the development of lightweight, durable, and multifunctional composites suited for demanding industries. Ongoing research continues to expand their potential, driving advances in sustainable, high-performance materials. Table 4 shows the summaries of graphene from previous research.

The addition of 0.2 wt.% GNP to GFRP and carbon fibre-reinforced polymer (CFRP) composites has been shown to increase tensile strength and modulus of elasticity, confirming GNP's effectiveness as a reinforcing agent [94]. Conversely, the same GNP content in aramid fibre-reinforced polymer (AFRP) composites did not produce a similar improvement in tensile strength, indicating a distinctive interaction between aramid fibres and GNP. The inclusion of GNP also increased the carbon content in the composites, likely due to its presence.

Hashim et al. [95] investigated the mechanical behaviour of unidirectional basalt fibre composites reinforced with hybrid graphene nanoplatelet-nanosilica fillers. Their results demonstrated that these hybrid nanofillers significantly enhanced both flexural modulus and strength. Amongst the tested composites, the variant labelled FRP-H0.2 exhibited superior performance, attributed to reduced nanofiller agglomeration and improved dispersion. The study also revealed that unidirectional basalt fibre composites possess a specific modulus approximately 28% higher than glass fibre composites. These findings suggest that hybrid nanofillers can substantially improve the mechanical properties of basalt fibre composites, positioning them as a promising alternative to traditional glass fibre composites. Figure 4 compares the specific modulus and specific strength of various FRP composites based on literature and the current study's results. As shown in Fig. 4, basalt fibre stands out as a beneficial reinforcement material due to its high specific stiffness and strength. The incorporation of hybrid nanofillers further enhances the specific stiffness of both basalt and glass fibre composites, thanks to their low density. Notably, the specific modulus of basalt fibre exceeds that of glass fibre by 28%.

8 Energy Absorption and Failure Mechanisms

Understanding the energy absorption capacity and failure behaviours of fibre-reinforced composites is vital for evaluating their performance under dynamic loading conditions, such as impact, crash, or ballistic events. These characteristics dictate the extent to which a material can dissipate energy without compromising structural integrity [96]. Energy absorption in such composites is predominantly governed by the interaction between fibres and the polymer matrix, which dictates crack propagation, interfacial bonding, and overall deformation behaviour. Hosseini and Raji [97] demonstrated that incorporating graphene nanoplatelets (GNPs) into glass fibre-reinforced ABS composites significantly enhanced their energy absorption under axial loading. By varying graphene content from 0 to 1.5 wt%, they observed that 1 wt% GNP yielded the highest specific energy absorption (6.48 kJ/kg), outperforming the control sample (4.12 kJ/kg). This improvement was attributed to enhanced matrix stiffening, crack arresting, and increased friction during progressive crushing. However, excess GNPs led to agglomeration, diminishing performance. This finding underlines the importance of optimising nanofiller content for maximising crashworthiness.

Complementary research by Erkek et al. [98] further validated the role of nanofillers. They fabricated crash boxes using hybrid composites of glass, aramid, and carbon fibres with 0.25–0.50% graphene. Amongst the configurations, carbon-fibre composite with 0.50% graphene (C0.50 g) recorded the highest peak force (8.52 kN) and specific energy absorption (10.08 J/g). Notably, aramid-based composites also exhibited considerable improvements, attributed to enhanced interfacial adhesion due to graphene. These studies confirm that combining nanofillers with carefully designed fibre architectures significantly improves impact resilience. However, a common shortfall in the literature is the omission of composite mass data that is an important factor in weight-sensitive applications, such as aerospace and automotive components. Composite materials also exhibit a variety of failure mechanisms that affect their energy absorption capability and structural integrity. Amongst the most critical is delamination, which involves the separation of laminate layers. This can arise from manufacturing defects, impact loading, inter-laminar stresses,

Table 4 Graphene nanofiller in glass fibre-reinforced polymer composites

Type of graphene	Loadings percentage	Mechanical properties improvement	Thermal properties improvement	Morphological surface improvement	Refs
Nanoplatelets treated in glass fibre-reinforced epoxy	0 wt% 0.125 wt% 0.25 wt%	The integration of graphene into GFRP specimens increased tensile strength by 14.79%, enhanced fracture toughness, and strengthened inter-laminar shear strength (ILSS). The peak ILSS was achieved with 0.25 wt% graphene loading, enhancing interfacial adhesion between glass fibres and epoxy. Moreover, the flexural strength of graphene increased by 14.06% and 25.15%, respectively	The addition of graphene in epoxy boosts the conductivity of the GFRP laminates, which enables easy heat transfer	The incorporation of graphene into the polymer matrix markedly enhanced the quality of the machined surface by diminishing these flaws	[88]
Nanoplatelets treated in S-glass fibre mat reinforced epoxy	0.1 wt% 0.6 wt% 1 wt%	The mechanical strength of 0.2 wt% GnPs improved the ultimate tensile strength (UTS) by 14%, 56%, and 114% due to higher interfacial adhesion between glass fibre and epoxy resin	Low concentrations of UVO-treated GnP (2 wt%) elevated the glass transition temperature and flexural modulus whilst decreasing the electrical resistivity of EPCs by a factor of 5.5×10^6	The investigation indicates that 0.2 wt% of the material demonstrates uniform dispersion as a result of sonication, whilst 0.6 wt% develops a network of entangled GnPs due to surface roughness and covalent bonding	[89]
Graphene oxide treated in carbon/glass fibre-reinforced epoxy	0.1 wt% 0.25 wt% 0.5 wt%	The tensile properties of composites, both with and without graphene oxide, differ, exhibiting variations in strength and modulus. The strength diminishes with increasing GO content, although remains superior to that of unaltered composites. The modulus progressively increases with the addition of GO concentration, with 0.35 wt% yielding a superior modulus	–	Enhanced bonding strength, reduced slippage, and increased fibre surface roughness improve the tensile characteristics of fibre-reinforced composite materials, mitigating pull-out occurrences and the manifestation of brittle fractures	[90]
Graphene nanoplatelets treated in glass fibre-reinforced epoxy	0.5 wt% 1 wt% 1.5 wt% 2 wt%	The use of nanoparticles into polymer composites significantly enhances tensile and compressive strength. The ultimate tensile strength increases by 10.25% with the incorporation of 0.5% nanoparticles, whilst the compressive strength enhances by 16.26% with 1% nanoparticles and by 18.64% with 2% nanoparticles	–	SEM examination demonstrated uniform GONP dispersion at 0.5% and 1% nanoparticle weight, but agglomerates formed at 1.5% and 2% due to cohesive forces amongst GONP	[91]

Table 4 (continued)

Type of graphene	Loadings percentage	Mechanical properties improvement	Thermal properties improvement	Morphological surface improvement	Refs
Graphene nanoplatelets treated in glass fibre-reinforced polypropylene	5 wt% 10 wt% 20 wt%	The incorporation of GNPs and GFs as reinforcements enhanced the Young's modulus of polypropylene, with GFs yielding a more significant enhancement. GNPs at the junction of PP and GFs enhanced interfacial stress transmission. The hybrid system exhibited a threefold increase in Young's modulus and decreased fracture stress; yet, samples containing glass fibres had superior tensile strength at failure	–	Graphene nanoplatelets (GNPs) were uniformly distributed at low concentrations; however, at the greatest concentration (20 wt% GNP), they congregated on the fracture surface and within voids	[92]
Graphene oxide treated in glass fibre-reinforced epoxy	–	The tensile characteristics of composites enhanced due to the dispersion of fGO, which diminished fracture propagation and improved fibre-matrix interactions, leading to a 17.6% increase in tensile strength at 1 wt% fGO	–	The integration of fGO flakes into GFRE composites significantly enhanced thermal stability, increasing the degradation temperature by 11.8 and 12.4 °C, respectively, based on the selected weight percentage and effective adhesion after spraying and drying	[93]

environmental exposure, or mismatched ply orientations. Wisnom [99] and Colombo et al. [100], highlighted how delamination, especially near the surface, drastically reduces fatigue life and bending stiffness in GFRP composites. Their modelling and experimental approaches revealed that transverse matrix cracks initiate and propagate delamination, significantly undermining long-term durability.

Another major failure mode is debonding, particularly in sandwich structures with composite skins and honeycomb cores. Miou and Fan [101] employed ultrasonic C-scan (Fig. 5) and bond strength tests to study failure at the skin–core interface. Their findings indicated that extended holding times during bonding degraded the adhesive, causing debonding, especially in hybridised FRP structures. Tearing on the surface mirrored subsurface debonding, and maintaining a holding period below 6 h was recommended to preserve bond integrity.

Environmental ageing also contributes to degradation. Haider et al. [102] examined the effect of UV, humidity, and thermal cycling on nanofiller-reinforced radome composites. Although dielectric performance remained stable, progressive interfacial deterioration was observed. Accelerated ageing of SiO_2-reinforced GFRP led to interlayer degradation from polymer plasticisation and internal stress (Fig. 6), though the materials retained sufficient mechanical performance for microelectronic applications.

Shear failure, a brittle and often sudden form of failure, occurs when forces act parallel to the material surface. It is especially problematic in impact and ballistic applications. Yooprasertchai et al. [103] found that GFRP-reinforced concrete beams were susceptible to shear or punching shear failure. By incorporating GFRP rods and optimising reinforcement geometry such as radial arrangements, brittle failures were transformed into more ductile flexural modes, improving impact resistance and suggesting updates to ACI design codes. In high-velocity impacts, shear plugging becomes prominent. This failure mode involves the formation and ejection of a plug-like laminate segment due to concentrated impact energy. [104]. Choudhury et al. [105] found that the number of failed layers, ambient temperature, and impact energy influenced plug thickness and failure progression. The GNPs were shown to enhance inter-laminar toughness and shear resistance, thereby increasing the energy absorption capacity. Similarly, Saleh et al. [106] noted that shorter concrete beams were more prone to shear plugging under impact, but strategic placement of reinforcements transformed brittle failures into more controlled responses. Symmetric shear failure, marked by fibre breakage and matrix cracking, can be effectively modelled using progressive damage theories and validated by finite-element methods [107].

Shear plugging and delamination are particularly detrimental in radome applications, where electromagnetic

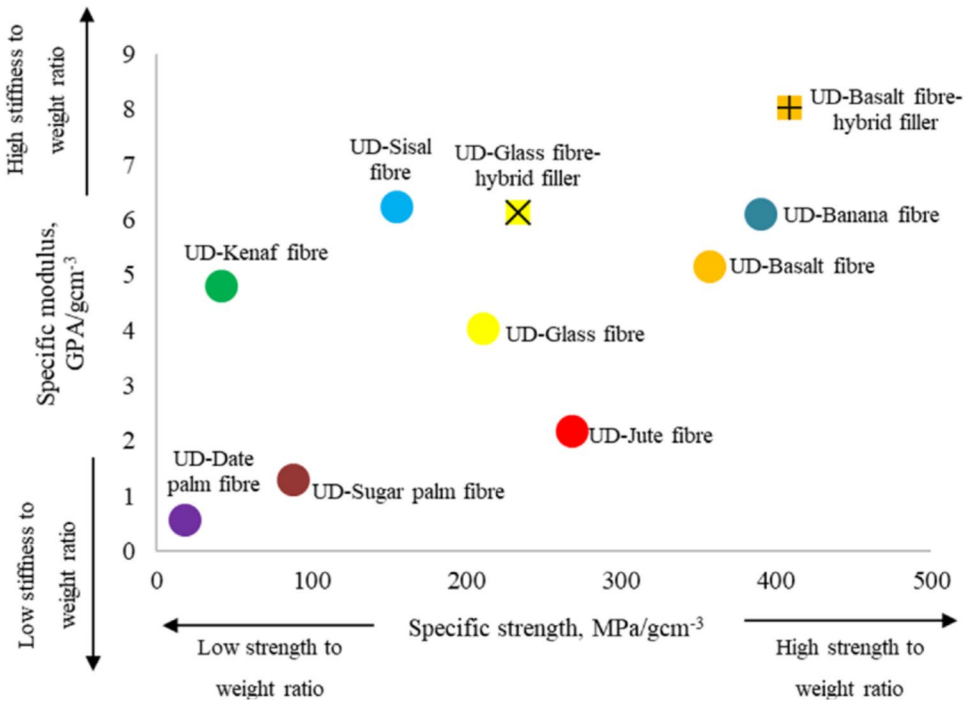

Fig. 4 Comparison of specific modulus and specific strength for natural fibre composites versus GFRP composites (Hashim et al. [95]) Creative Common CC BY license

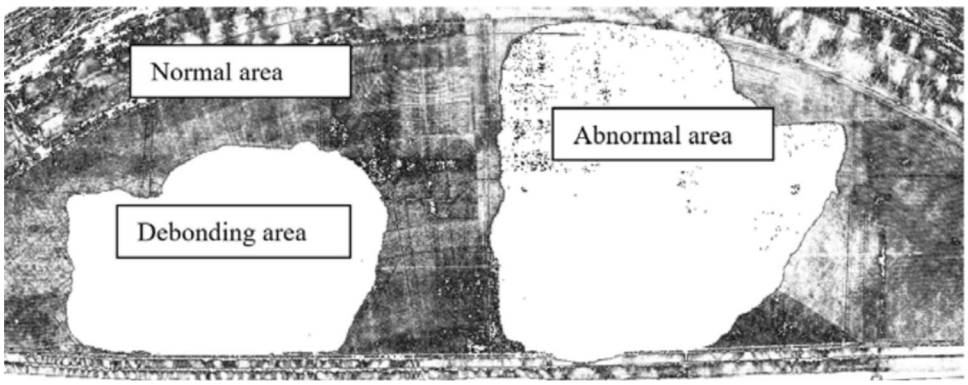

Fig. 5 Failure modes experienced FRP composites via ultrasonic c-scan inspection (Miao et al. [101]) Creative Common CC BY license

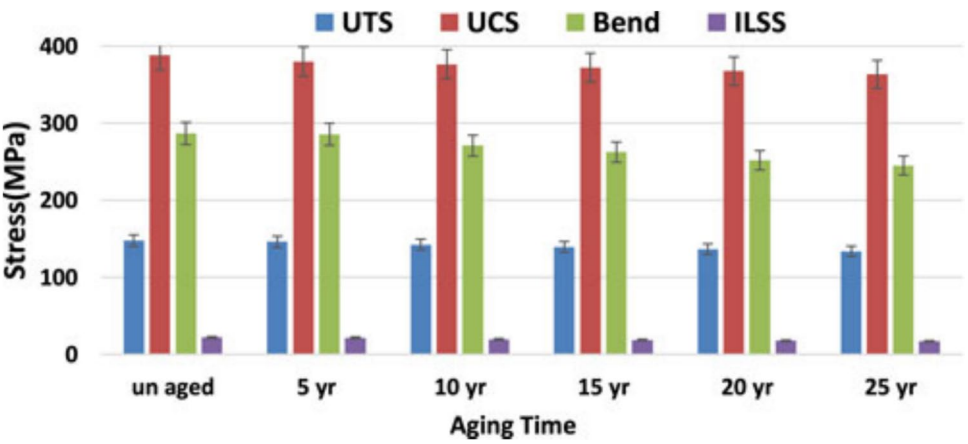

Fig. 6 Mechanical properties of the hybrid nanocomposites upon accelerated ageing (Haider et al. [102]) Creative Common CC BY license

transparency and mechanical stability are essential. Impact forces, such as bird strikes or hail, can initiate failure at the impact site, propagating through the laminate and affecting dielectric function. Improvements in inter-laminar bonding, matrix selection, and fibre architecture are crucial to mitigate such failures. Hence, the energy absorption capacity and failure mechanisms of fibre-reinforced composites are closely linked to the material's internal architecture, fibre–matrix interactions, and external environmental conditions. The incorporation of nanofillers has shown significant promise in enhancing crashworthiness and shear resistance, particularly when optimally distributed within hybrid composite systems. However, the occurrence of failure modes, such as delamination, debonding, and shear plugging, remains a major concern, especially under dynamic loading and ageing conditions. Addressing these issues requires strategic design approaches, such as improved interfacial bonding, precise control of processing parameters, and the integration of toughening agents. This effort would ensure long-term durability and structural reliability of the composite system.

9 Conclusion

This review examines the hybridisation of nanofiller such as graphene within glass fibre-reinforced thermoplastic composites, focussing on the influence of quasi-isotropic stacking sequences on enhancing composite performance. It highlights critical aspects in optimising composite performance, including graphene loading, silane surface preparation, fibre–matrix compatibility, and stacking sequence. Quasi-isotropic stacking, characterised by non-uniform fibre orientations, exhibits enhanced in-plane property homogeneity and superior energy absorption compared to traditional layups. The integration of surface-treated fibres and nanofillers inside a thermoplastic matrix facilitates the development of composites with balanced mechanical strength, enhanced thermal stability, and multi-axial stress resistance. The integration of configuration structure and composition material represents a significant advancement in the sustainable design of durable composite systems.

Thermoplastic-based hybrid composites are increasingly relevant in accordance with worldwide trends favouring recyclable, repairable, and high-performance materials, especially within the aerospace, automotive, and defence industries. Initiatives by industry and government aimed at sustainability have prompted a transition from thermoset to thermoplastic systems, with ABS emerging as a likely matrix. To achieve ideal thermal performance, literatures reveal that incorporation of graphene should be confined to a specific range of 0.2–0.5 wt%, as this ensures superior dispersion, reduces agglomeration, and enhances thermal conductivity whilst preserving structural integrity. Reviews on silane coupling agents such as APTES, show efficacious in fibre surface treatment; nevertheless, concentrations must be meticulously restricted generally not surpassing 1 wt% to prevent surface oversaturation and interfacial degradation. Furthermore, quasi-isotropic stacking sequences are favoured due to their multi-directional strength and damage resistance, making them ideal for components subjected to diverse stress situations. Their fibre orientations in symmetry improve stress distribution and cracking resistance, making them ideally suited for future structural applications that demand reliability, weight reduction, and energy absorption.

Acknowledgements The authors would like to thank to Ministry of Higher Education (KPT), Malaysia for financial support under Fundamental Research Grant Scheme (FRGS) Project under Grant No FRGS/1/2024/TK04/UTM/02/1. The authors also would like to express gratitude to Universiti Teknologi Malaysia (UTM) through Centre for Advanced Composites Materials (CACM) and Faculty of Mechanical Engineering for providing facilities to conduct the work.

Author Contributions A.N.A., and M.A.M.R. did the investigation and methodology on the subject matter. M.A.M.R. did the funding acquisition and project administrations. M.A.M.R., and A.N.A. wrote the main manuscript text. M.F.A.R., R.A.M., and D.D.C.V.S. supervised the manuscript. H.A.I.A., M.R.A., M.A., N.M., M.A., and Q.A-S. Review the project.

Funding Open access funding provided by The Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia. This work is funded by the Ministry of Higher Education (KPT), Malaysia through Fundamental Research Grant Scheme (FRGS) Project (Grant No. FRGS/1/2024/TK04/UTM/02/1).

Data availability All data and materials are available within this research article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

1. M. Sanjay, B. Yogesha, Studies on natural/glass fiber reinforced polymer hybrid composites: an evolution. Mater. Today Proc. **4**, 2739–2747 (2017). https://doi.org/10.1016/j.matpr.2017.02.151
2. M. Boopalan, M. Niranjanaa, M.J. Umapathy, Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites. Compos. Part B Eng. (2013). https://doi.org/10.1016/j.compositesb.2013.02.033
3. H. Afshari, W. Hare, S. Tesfamariam, Constrained multi-objective optimization algorithms: review and comparison with application in reinforced concrete structures. Appl. Soft Comput. **83**, 105631 (2019). https://doi.org/10.1016/j.asoc.2019.105631
4. N. Forintos, T. Czigany, Multifunctional application of carbon fiber reinforced polymer composites: electrical properties of the reinforcing carbon fibers: a short review. Compos. Part B Eng. **162**, 331–343 (2019). https://doi.org/10.1016/j.compositesb.2018.10.098
5. S. Yousef, J. Eimontas, K. Zakarauskas, N. Striūgas, Recovery of styrene-rich oil and glass fibres from fibres-reinforced unsaturated polyester resin end-of-life wind turbine blades using pyrolysis technology. J. Anal. Appl. Pyrolysis **173**, 106100 (2023). https://doi.org/10.1016/j.jaap.2023.106100
6. M.K. Egbo, A fundamental review on composite materials and some of their applications in biomedical engineering. J. King Saud Univ. Eng. Sci. **33**, 557–568 (2021). https://doi.org/10.1016/j.jksues.2020.07.007
7. B. Yildiz Zeyrek, B. Aydoğan, E. Dilekcan, F. Öztürk, Recycle potential of thermoplastic composites. Ömer Halisdemir Üniversitesi Mühendislik Bilim Derg **12**, 919–925 (2023). https://doi.org/10.28948/ngumuh.1258388
8. A. Kordi, S. Adibnazari, A. Imam, M. Najafi, Effects of two- and three-dimensional graphene-based nanomaterials on the fatigue behavior of epoxy nanocomposites. Mater. Today Commun. **24**, 101194 (2020). https://doi.org/10.1016/j.mtcomm.2020.101194
9. M. Song, X. Li, S. Kitipornchai, Q. Bi, J. Yang, Low-velocity impact response of geometrically nonlinear functionally graded graphene platelet-reinforced nanocomposite plates. Nonlinear Dyn. **95**, 2333–2352 (2019). https://doi.org/10.1007/s11071-018-4695-y
10. K. Malik, F. Ahmad, N.A. Yunus, P.S.M.M. Yusoff, B. Guan, N. Nosbi, S. Ali, T. Nakato, E. Mouri, The effects of graphene hybridization on mechanical properties of GFRP composites. p. 020023 (2021). https://doi.org/10.1063/5.0072598
11. F. Zaccardi, E. Toto, F. Marra, M.G. Santonicola, S. Laurenzi, Hybrid carbon nanocomposites made of aerospace-grade epoxy showing synergistic effects in electrical properties and high processability. Polymers (Basel) **15**, 1163 (2023). https://doi.org/10.3390/polym15051163
12. S. Hassanifard, K. Behdinan, Fatigue response of multiscale extrusion-based additively manufactured acrylonitrile butadiene styrene-graphene nanoplatelets composites. Compos. Part B Eng. **279**, 111464 (2024). https://doi.org/10.1016/j.compositesb.2024.111464
13. V. Modi, K.K. Singh, R. Shrivastava, Effect of stacking sequence on interlaminar shear strength of multidirectional GFRP laminates. Mater. Today Proc. **22**, 2207–2214 (2020). https://doi.org/10.1016/j.matpr.2020.03.301
14. M.R.M. Asyraf, A. Syamsir, N.M. Zahari, A.B.M. Supian, F. Usman, Z. Itam, Effect of stacking sequence on long-term creep performance of pultruded GFRP composites. Polymers (Basel) **14**, 4064 (2022). https://doi.org/10.3390/polym14194064
15. A. Cutolo, A.R. Carotenuto, S. Palumbo, L. Esposito, V. Minutolo, M. Fraldi, M. Fraldi, E. Ruocco, Stacking sequences in composite laminates through design optimization. Meccanica **56**, 1555–1574 (2021). https://doi.org/10.1007/s11012-020-01233-y
16. A.U. Bharathi, V. Arumugam, C.S. Kumar, Experimental investigation on the effect of stacking sequence on damage resistance and post-indentation performance of glass/epoxy laminates under different loading planes using acoustic emission monitoring. Mater. Res. (2023). https://doi.org/10.1590/1980-5373-mr-2022-0325
17. Y. Li, J. Zhong, K. Fu, Low-velocity impact and compression-after-impact behaviour of flax fibre-reinforced composites. Acta Mech. Solida Sin. **33**, 431–448 (2020). https://doi.org/10.1007/s10338-019-00158-8
18. H. Awais, Y. Nawab, A. Amjad, A. Anjang, H. Akil, M.S. Zainol, Composites part C: open access environmental benign natural fibre-reinforced thermoplastic composites: a review. Compos. Part C Open Access **4**, 100082 (2021). https://doi.org/10.1016/j.jcomc.2020.100082
19. S. Waghmare, S. Shelare, K. Aglawe, P. Khope, A mini review on fibre-reinforced polymer composites. Mater. Today Proc. **54**, 682–689 (2022). https://doi.org/10.1016/j.matpr.2021.10.379
20. N.I.N. Haris, R.A. Ilyas, M.Z. Hassan, S.M. Sapuan, A. Afdzaluddin, K.R. Jamaludin, S.A. Zaki, F. Ramlie, Dynamic mechanical properties and thermal properties of longitudinal basalt/woven glass fiber reinforced unsaturated polyester hybrid composites. Polymers (Basel) **13**, 3343 (2021). https://doi.org/10.3390/polym13193343
21. E.H. Saidane, D. Scida, M.-J. Pac, R. Ayad, Mode-I inter-laminar fracture toughness of flax, glass and hybrid flax-glass fibre woven composites: failure mechanism evaluation using acoustic emission analysis. Polym. Test. **75**, 246–253 (2019). https://doi.org/10.1016/j.polymertesting.2019.02.022
22. S.M. Sapuan, H.S. Aulia, R.A. Ilyas, A. Atiqah, T.T. Dele-Afolabi, M.N. Nurazzi, A.B.M. Supian, M.S.N. Atikah, Mechanical properties of longitudinal basalt/woven-glass-fiber-reinforced unsaturated polyester-resin hybrid composites. Polymers (2020). https://doi.org/10.3390/polym12102211
23. A.A. Megahed, F. Abd El-Wadoud, A. Wagih, A.M. Kabeel, Effect of incorporating aluminum wire mesh on the notched and un-notched strengths of glass fiber/epoxy composites. Compos. Struct. **263**, 113695 (2021). https://doi.org/10.1016/j.compstruct.2021.113695
24. R. Gokuldass, R. Ramesh, Mechanical strength behavior of hybrid composites tailored by glass/Kevlar fibre-reinforced in nano-silica and micro-rubber blended epoxy. SILICON **11**, 2731–2739 (2019). https://doi.org/10.1007/s12633-018-0064-1
25. P. Krishnasamy, G. Rajamurugan, M. Thirumurugan, Performance of fiber metal laminate composites embedded with AL and CU wire mesh. J. Ind. Text. (2020). https://doi.org/10.1177/1528083720935570
26. M. Liu, Q. Zhang, Z. Tan, L. Wang, Z. Li, G. Ma, Investigation of steel wire mesh reinforcement method for 3D concrete printing. Arch. Civ. Mech. Eng. **21**, 24 (2021). https://doi.org/10.1007/s43452-021-00183-w
27. M. Sakthivel, S. Vijayakumar, Influence of stainless-steel wire mesh on the mechanical behaviour in a glass-fibre-reinforced epoxy composite. Mater. Tehnol. **51**, 455–461 (2017). https://doi.org/10.17222/mit.2016.063
28. M. Sakthivel, S. Vijayakumar, B.V. Ramnath, Investigation on mechanical and thermal properties of stainless steel wire mesh-glass fibre-reinforced polymer composite. SILICON **10**, 2643–2651 (2018). https://doi.org/10.1007/s12633-018-9801-8
29. N. Karunagaran, G. Bharathiraja, A. Muniappan, K. Yoganandam, Energy absorption and damage behaviour of surface treated glass fibre/stainless steel wire mesh reinforced hybrid composites. Mater. Today Proc. **22**, 1078–1084 (2020). https://doi.org/10.1016/j.matpr.2019.11.305

30. M.R.M. Asyraf, S.A. Hassan, T. Khan, M. Fitri, M. Fauzi, R.A. Ilyas, T. Khan, Hybrid Kenaf Fibre/fibreglass meshes reinforced thermoplastic ABS composites based on quasi-isotropic mechanism: a brief review. J. Nat. Fibre Polym. Compos. **2**, 2821–3289 (2023)
31. M. Jawaid, H.P.S. Abdul Khalil, Cellulosic/synthetic fibre-reinforced polymer hybrid composites: a review. Carbohydr. Polym. **86**, 1–18 (2011). https://doi.org/10.1016/j.carbpol.2011.04.043
32. B. Vijaya Ramnath, S. Junaid Kokan, R. Niranjan Raja, R. Sathyanarayanan, C. Elanchezhian, A. Rajendra Prasad, V.M. Manickavasagam, Evaluation of mechanical properties of abaca-jute-glass fibre-reinforced epoxy composite. Mater. Des. **51**, 357–366 (2013). https://doi.org/10.1016/j.matdes.2013.03.102
33. R.A. Braga, P.A.A. Magalhaes, Analysis of the mechanical and thermal properties of jute and glass fiber as reinforcement epoxy hybrid composites. Mater. Sci. Eng. C **56**, 269–273 (2015). https://doi.org/10.1016/j.msec.2015.06.031
34. R. Bhoopathi, M. Ramesh, C. Deepa, Fabrication and property evaluation of banana-hemp-glass fiber reinforced composites. Procedia Eng. **97**, 2032–2041 (2014). https://doi.org/10.1016/j.proeng.2014.12.446
35. M.J.M. Ridzuan, M.S. Abdul Majid, M. Afendi, K. Azduwin, N.A.M. Amin, J.M. Zahri, A.G. Gibson, Moisture absorption and mechanical degradation of hybrid Pennisetum purpureum/glass-epoxy composites. Compos. Struct. **141**, 110–116 (2016). https://doi.org/10.1016/j.compstruct.2016.01.030
36. Y. Swolfs, L. Gorbatikh, I. Verpoest, Fibre hybridisation in polymer composites: a review. Compos. Part A Appl. Sci. Manuf. **67**, 181–200 (2014). https://doi.org/10.1016/j.compositesa.2014.08.027
37. H.P.S. Abdul Khalil, S. Hanida, C.W. Kang, N.A. Nik Fuaad, Agro-hybrid composite: the effects on mechanical and physical properties of oil palm fiber (EFB)/glass hybrid reinforced polyester composites. J. Reinf. Plast. Compos. **26**, 203–218 (2007). https://doi.org/10.1177/0731684407070027
38. J.I. Perry, S.M. Walley, Measuring the effect of strain rate on deformation and damage in fibre-reinforced composites: a review. J. Dyn. Behav. Mater. **8**, 178–213 (2022). https://doi.org/10.1007/s40870-022-00331-0
39. H.K. Dalfi, K. Jan, Z. Yousaf, M. Peerzada, Improving the impact resistance and damage tolerance of fibre-reinforced composites: a review. J. Compos. Mater. **57**, 4479–4500 (2023). https://doi.org/10.1177/00219983231209718
40. M.Y. Salim, M.F.M. Fitri, M.A.M. Rizal, A.B.M. Supian, M.H. Dzulkifli, R.A. Ilyas, S.A. Hassan, Layering sequences of fibreglass meshes: effects on the quasi-static indentation and flexural properties of kenaf/acrylonitrile butadiene styrene composites. Fibers Polym. **26**, 2057–2068 (2025). https://doi.org/10.1007/s12221-025-00941-0
41. M.Y. Salim, M.F.M. Fitri, M.A.M. Rizal, R.A. Ilyas, M.H. Dzulkifli, S.A. Hassan, A.B.M. Supian, M.R. Razman, Energy absorption and mechanical performance of kenaf yarn/fibreglass mesh/acrylonitrile butadiene styrene composites: influence of mesh density. J. Mater. Res. Technol. **36**, 6890–6901 (2025). https://doi.org/10.1016/j.jmrt.2025.04.291
42. M.F.M. Fitri, M.R.M. Asyraf, S.A. Hassan, R.A. Ilyas, Unveiling the physico-mechanical properties of kenaf yarn fiber-reinforced <scp>acrylonitrile butadiene styrene</scp> composites: effect of quasi-isotropic lay-up sequences. Polym. Compos. **45**, 9362–9375 (2024). https://doi.org/10.1002/pc.28414
43. R. Maier, A.-C. Mandoc, Investigation on layering hybridization of glass/carbon fibre woven reinforced composites subjected to low-speed impact. J. Compos. Sci. **7**, 83 (2023). https://doi.org/10.3390/jcs7020083
44. M.F. Muhammad Fitri, M.R. Muhammad Asyraf, S. Abu Hassan, Hybridizing kenaf and glass fibres as reinforcement in ABS composites: current trends, properties and potential application in aircraft radome. J. Kejuruteraaan **36**, 2075–2096 (2024). https://doi.org/10.17576/jkukm-2024-36(5)-25
45. J.W. Kim, H.S. Kim, Study on fibre orientation and fibre content of glass fibre-reinforced polymer. Mater. Res. Innov. **18**, S2482–S2487 (2014). https://doi.org/10.1179/1432891714Z.000000000450
46. T. Seshaiah, K. Vijaya Kumar Reddy, Effect of fiber orientation on the mechanical behavior of E-glass fibre-reinforced epoxy composite materials. Int. J. Mech. Prod. Eng. Res. Dev. **8**, 379–396 (2018). https://doi.org/10.24247/ijmperdaug201840
47. G. Rathnakar, H.K. Shivanand, Fibre orientation and its influence on the flexural strength of glass fibre and graphite fibre-reinforced polymer composites. Int. J. Innov. Res. Sci. Eng. Technol. **2**, 548–552 (2013)
48. S. Singh, P. Kumar Gupta, Effect of fiber orientation on mechanical properties of jute/carbon/glass hybrid composite. Mater. Today Proc. **68**, 2574–2580 (2022). https://doi.org/10.1016/j.matpr.2022.09.419
49. A.U. Al-saadi, T. Aravinthan, W. Lokuge, Effects of fibre orientation and layup on the mechanical properties of the pultruded glass fibre-reinforced polymer tubes. Eng. Struct. **198**, 109448 (2019). https://doi.org/10.1016/j.engstruct.2019.109448
50. X. Xu, X. Sun, M.R. Wisnom, Initial R-curves for trans-laminar fracture of quasi-isotropic carbon/epoxy laminates from specimens with increasing size. Compos. Sci. Technol. (2021). https://doi.org/10.1016/j.compscitech.2021.109077
51. K. Grigoriou, A.P. Mouritz, Comparative assessment of the fire structural performance of carbon-epoxy composite and aluminium alloy used in aerospace structures. Mater. Des. **108**, 699–706 (2016). https://doi.org/10.1016/j.matdes.2016.07.018
52. K. Alblalaihid, S. Aldoihi, S. Alblihed, H. Algaan, S.S. Alsaleh, B.A. Alshammari, I.A. Alshunaifi, A. Almuqhim, K. Khormi, M. Abuobaid, A. Alshamikh, Optimizing in-plane strength of honeycomb structures to achieve quasi-isotropic performance. Mater. Des. (2025). https://doi.org/10.1016/j.matdes.2025.114381
53. H. Alshahrani, A. Ahmed, Enhancing impact energy absorption, flexural and crash performance properties of automotive composite laminates by adjusting the stacking sequences layup. Polymers (2021). https://doi.org/10.3390/polym13193404
54. S.E.L. Garouge, M. Tarfaoui, O. Hashim Hassoon, H.E.L. Minor, A. Bendarma, Effect of stacking sequence on the mechanical performance of the composite structure under slamming impact. Mater. Today Proc. **52**, 29–39 (2021). https://doi.org/10.1016/j.matpr.2021.10.109
55. P. Zivkovic, *The Investigation of Interleaved Automated Fibre Placement Composite Laminates* (University of Bristol, UK, 2020)
56. S. Lin, A.M. Waas, The effect of stacking sequence on the LVI damage of laminated composites; experiments and analysis. Compos. A Appl. Sci. Manuf. (2021). https://doi.org/10.1016/j.compositesa.2021.106377
57. V. Shankar, M.H. Nguyen, R.J. D'mello, A.M. Waas, Progressive failure analysis and open-hole compressive (OHC) strength prediction of laminates. AIAA Sci. Technol. Forum. Expo AIAA Sci. Tech. Forum. (2025). https://doi.org/10.2514/6.2025-0200
58. M. Yuan, H. Zhao, S. Liu, H. Ren, B. Zhang, J. Chen, Prediction of matrix-cracking-induced stiffness degradation of cross-ply laminates based on data-driven method. Compos. Sci. Technol. (2022). https://doi.org/10.1016/j.compscitech.2022.109716
59. N. Mittal, F. Ansari, V. Gowda Krishne, C. Brouzet, P. Chen, P.T. Larsson, S.V. Roth, F. Lundell, L. Wagberg, N.A. Kotov, L.D. Soderberg, Multiscale control of nanocellulose assembly:

transferring remarkable nanoscale fibril mechanics to macroscale fibers. ACS Nano **12**, 6378–6388 (2018). https://doi.org/10.1021/acsnano.8b01084
60. Z.X. Ooi, C.Y. Ewe, K.L. Chan, Y.P. Teoh, H. Ismail, Tensile evaluation and thermal characteristics of polyvinyl alcohol film with varying oil palm ashes content. Polym. Polym. Compos. **29**, 65–72 (2021). https://doi.org/10.1177/0967391120902946
61. M.R.M. Asyraf, L.F. Ng, P.S. Khoo, M.Y. Yahya, S.A. Hassan, E. Madenci, T. Khan, Lignocellulosic abaca fibre-reinforced thermoplastic composites as future sustainable structural materials: a bibliometric analysis and literature review. Cellulose (2024). https://doi.org/10.1007/s10570-024-05921-w
62. P.S. Khoo, M.A. Muhammad Rizal, A.H. Nordin, W. Ashraf, K.Z. Hazrati, S.H. Lee, M. Rafidah, Thermoplastic-based composites from treated *Arenga pinnata* (Wurmb.) Merrill. fibers: a bibliometric analysis and literature review on dynamic mechanical analysis. Polym. Compos. (2025). https://doi.org/10.1002/pc.29560
63. P.S. Khoo, M.A.M. Rizal, R.A. Ilyas, M.A.M. Yajid, S.A. Hassan, M.Y. Yahya, M.U. Wahit, Unveiling favorable mechanical properties of lignocellulosic wood-reinforced thermoplastic composites as future green and sustainable materials. Fibers Polym. **26**, 1425–1448 (2025). https://doi.org/10.1007/s12221-025-00874-8
64. S.A. Hashim, J.A. Nisar, An investigation into failure and behaviour of GFRP pultrusion joints. Int. J. Adhes. Adhes. **40**, 80–88 (2013). https://doi.org/10.1016/j.ijadhadh.2012.06.002
65. R. Sepe, F. Bollino, L. Boccarusso, F. Caputo, Influence of chemical treatments on mechanical properties of hemp fiber reinforced composites. Compos. Part B Eng. **133**, 210–217 (2018). https://doi.org/10.1016/j.compositesb.2017.09.030
66. P.S. Khoo, M.A.M. Rizal, K.Z. Hazrati, H.A. Aisyah, A.B.M. Supian, N.H. Hassan, M. Mahardika, M.R. Razman, T. Khan, T.A. Sebaey, Sustainable chemically treated lignocellulosic pineapple leaf fibre-reinforced polymer composites: mechanical properties, environmental aspects and applications. Cellulose **32**, 4101–4142 (2025). https://doi.org/10.1007/s10570-025-06519-6
67. A. Mali, P. Agbo, S. Mantripragada, L. Zhang, Surface-modified electrospun glass nanofibers from silane treatment and their use for high-performance epoxy-based nanocomposite materials. Materials (2023). https://doi.org/10.3390/ma16206817
68. P.R. Vieira, E.M.L. Carvalho, J.D. Vieira, R.D. Toledo Filho, Experimental fatigue behavior of pultruded glass fibre-reinforced polymer composite materials. Compos. Part B Eng. **146**, 69–75 (2018). https://doi.org/10.1016/j.compositesb.2018.03.040
69. A.E. Krauklis, C.W. Karl, A.I. Gagani, J.K. Jørgensen, Composite material recycling technology: state-of-the-art and sustainable development for the 2020s. J. Compos. Sci. (2021). https://doi.org/10.3390/jcs5010028
70. N.J. Sallehuddin, H. Ismail, Surface morphology of kenaf bast filled natural rubber latex foam. AIP Conf. Proc. **2267**, 020012 (2020). https://doi.org/10.1063/5.0016555
71. V.R.A. Prakash, S.J. Jaisingh, Mechanical strength behaviour of silane treated E-glass fibre/Al 6061 & SS-304 wire mesh reinforced epoxy resin hybrid composite. SILICON **10**, 2279–2286 (2018). https://doi.org/10.1007/s12633-018-9762-y
72. A. Nurnadia, R.A. Roshafima, A.L.N. Shazwani, A. Hafizah, W.M.Z.W. Yunus, R. Fatehah, Effect of silane treatment on rise straw/high density polyethylene biocomposites. J. Nat. Fibre Polym. Compos. **2**, 1–14 (2023)
73. N. Sapiai, A. Jumahat, M. Jawaid, A. Khan, Effect of MWCNT surface functionalisation and distribution on compressive properties of kenaf and hybrid kenaf/glass fibres reinforced polymer composites. Polymers (Basel) **12**, 1–18 (2020). https://doi.org/10.3390/polym12112522
74. M. Shariatmadar, S. Feizollahi, P. Gholamhosseini, Z. Abdorrezaee, S. Ghorbanzadeh, F.S. Hosseini, F.A. Shahraki, M. Mahdavian, Strengthening the mechanical characteristics and cathodic delamination resistance of fiber-reinforced polymer through chemical surface modification of glass fibers. Sci. Rep. **13**, 1–12 (2023). https://doi.org/10.1038/s41598-023-40555-1
75. G. Sherif, D.I. Chukov, V.V. Tcherdyntsev, A.A. Stepashkin, M.Y. Zadorozhnyy, Y.M. Shulga, E.N. Kabachkov, Surface treatment effect on the mechanical and thermal behavior of the glass fabric reinforced polysulfone. Polymers **16**, 864 (2024). https://doi.org/10.3390/polym16060864
76. S.J. Park, J.S. Jin, J.R. Lee, Influence of silane coupling agents on the surface energetics of glass fibers and mechanical interfacial properties of glass fiber-reinforced composites. J. Adhes. Sci. Technol. **14**, 1677–1689 (2000). https://doi.org/10.1163/156856100742483
77. C. Griswold, W.M. Cross, L. Kjerengtroen, J.J. Kellar, Interphase variation in silane-treated glass-fiber-reinforced epoxy composites. J. Adhes. Sci. Technol. **19**, 279–290 (2005). https://doi.org/10.1163/1568561054352649
78. N. Hamidah, M. Zulfli, C.W. Shyang, Flexural and morphological properties of epoxy/glass fibre/silane- treated organo-montmorillonite composites. J. Phys. Sci. **21**, 41–50 (2010)
79. H.-H. Kim, S.-Y. Kim, D.-H. Kim, C.-Y. Oh, N.-J. Jo, Effect of silane coupling agent on the flexural property of glass fiber reinforced composite film. J. Mater. Sci. Chem. Eng. **02**, 38–42 (2014). https://doi.org/10.4236/msce.2014.210006
80. Z.A. Mohd Ishak, A. Ariffin, R. Senawi, Effects of hygrothermal aging and a silane coupling agent on the tensile properties of injection molded short glass fiber reinforced poly(butylene terephthalate) composites. Eur. Polym. J. **37**, 1635–1647 (2001). https://doi.org/10.1016/S0014-3057(01)00033-7
81. N. Ikuta, I. Abe, T. Hori, H. Naitoh, Y. Kera, E. Nishio, Fixation of silane coupling agents to glass fiber in silane treatment process. Compos. Interfaces **1**, 455–462 (1993). https://doi.org/10.1080/156855493X00194
82. P.B. Anand, A. Lakshmikanthan, M.P. Gowdru Chandrashekarappa, C.P. Selvan, D.Y. Pimenov, K. Giasin, Experimental investigation of effect of fiber length on mechanical, wear, and morphological behavior of silane-treated pineapple leaf fiber reinforced polymer composites. Fibers **10**, 56 (2022). https://doi.org/10.3390/fib10070056
83. Y. Qiao, L.D. Fring, M.R. Pallaka, K.L. Simmons, A review of the fabrication methods and mechanical behavior of continuous thermoplastic polymer fiber–thermoplastic polymer matrix composites. Polym. Compos. **44**, 694–733 (2023). https://doi.org/10.1002/pc.27139
84. V. Tambrallimath, R. Keshavamurthy, S. D, P.G. Koppad, G.S.P. Kumar, Thermal behavior of PC-ABS based graphene filled polymer nanocomposite synthesized by FDM process. Compos. Commun. **15**, 129–134 (2019). https://doi.org/10.1016/j.coco.2019.07.009
85. G. Huang, S. Huo, X. Xu, W. Chen, Y. Jin, R. Li, P. Song, H. Wang, Realizing simultaneous improvements in mechanical strength, flame retardancy and smoke suppression of ABS nanocomposites from multifunctional graphene. Compos. Part B Eng. **177**, 107377 (2019). https://doi.org/10.1016/j.compositesb.2019.107377
86. F.S. da Luz, F.D.C. Garcia Filho, M.T.G. Del-Rio, L.F.C. Nascimento, W.A. Pinheiro, S.N. Monteiro, Graphene-incorporated natural fiber polymer composites: a first overview. Polymers (Basel) **12**, 1601 (2020)
87. A. Asif Iqbal, A.K.M. Parvez Iqbal, D.M. Nuruzzaman, A review on fatigue fracture characteristics in graphene reinforced nanocomposites. Ain Shams Eng. J. **15**, 102730 (2024). https://doi.org/10.1016/j.asej.2024.102730
88. R.K. Thakur, K.K. Singh, Evaluation of drilling characteristics to explore the effect of graphene nanoplatelets on glass

fiber reinforced polymer composite. Measurement **219**, 113233 (2023). https://doi.org/10.1016/j.measurement.2023.113233
89. N.T. Kamar, M.M. Hossain, A. Khomenko, M. Haq, L.T. Drzal, A. Loos, Interlaminar reinforcement of glass fiber/epoxy composites with graphene nanoplatelets. Compos. Part A Appl. Sci. Manuf. **70**, 82–92 (2015). https://doi.org/10.1016/j.compositesa.2014.12.010
90. H. Zhang, X. Gao, H. Li, W. Wu, S. Sun, Effect of graphene oxide on tensile and flexural properties of carbon/glass hybrid fiber-reinforced polymer composite. Polym. Compos. **42**, 5348–5360 (2021). https://doi.org/10.1002/pc.26228
91. B. VijayKiran, K.M. Rao, D. LingaRaju, An investigation on mechanical properties of E-Glass fiber reinforced polymer nanocomposites. Mater. Today Proc. **18**, 5454–5463 (2019). https://doi.org/10.1016/j.matpr.2019.07.575
92. D.G. Papageorgiou, I.A. Kinloch, R.J. Young, Hybrid multifunctional graphene/glass-fibre polypropylene composites. Compos. Sci. Technol. **137**, 44–51 (2016). https://doi.org/10.1016/j.compscitech.2016.10.018
93. M.A. Mahtar, I.A. Kinloch, M.A. Bissett, High-performance hybrid glass fibre epoxy composites reinforced with amine functionalised graphene oxide for structural applications. Compos. Part A Appl. Sci. Manuf. **185**, 108265 (2024). https://doi.org/10.1016/j.compositesa.2024.108265
94. T. Topkaya, Y.H. Çelik, E. Kilickap, Mechanical properties of fiber/graphene epoxy hybrid composites. J. Mech. Sci. Technol. **34**, 4589–4595 (2020). https://doi.org/10.1007/s12206-020-1016-4
95. U.R. Hashim, A. Jumahat, M. Jawaid, Mechanical properties of hybrid graphene nanoplatelet-nanosilica filled unidirectional basalt fibre composites. Nanomaterials **11**, 1468 (2021). https://doi.org/10.3390/nano11061468
96. L. Zhao, X. Qian, Y. Sun, M. Yuan, F. Tang, Y. Zhao, Q. Zhang, Y. Chen, Ballistic behaviors of injection-molded honeycomb composite. J. Mater. Sci. **53**, 14287–14298 (2018). https://doi.org/10.1007/s10853-018-2611-y
97. A. Hosseini, A. Raji, Improved double impact and flexural performance of hybridized glass basalt fiber reinforced composite with graphene nanofiller for lighter aerostructures. Polym. Test. **125**, 108107 (2023). https://doi.org/10.1016/j.polymertesting.2023.108107
98. B. Erkek, E. Kosedag, H. Adin, The impact of graphene filler on the energy absorption of hybrid composite crash boxes. Int. J. Mech. Mater. Des. **21**, 339–355 (2025). https://doi.org/10.1007/s10999-024-09739-z
99. M.R. Wisnom, The role of delamination in failure of fibre-reinforced composites. Philos. Trans. R. Soc. Lond. A Math. Phys. Eng. Sci. **370**, 1850–1870 (2012). https://doi.org/10.1098/rsta.2011.0441
100. C. Colombo, T. Bhujangrao, F. Libonati, L. Vergani, Effect of delamination on the fatigue life of GFRP: a thermographic and numerical study. Compos. Struct. **218**, 152–161 (2019). https://doi.org/10.1016/j.compstruct.2019.03.023
101. H. Miao, J. Fan, Debonding failure analysis of honeycomb sandwich composite radome. J. Phys. Conf. Ser. **1865**, 032068 (2021). https://doi.org/10.1088/1742-6596/1865/3/032068
102. I. Haider, I.H. Gul, S. Aziz, M.I. Faraz, M.A. Khan, S.H.I. Jaffery, D.W. Jung, Environmental aging of reinforced polymer composite radome: reliability and performance investigation. Front. Mater. (2024). https://doi.org/10.3389/fmats.2024.1427541
103. E. Yooprasertchai, R. Dithaem, T. Arnamwong, R. Sahamitmongkol, J. Jadekittichoke, P. Joyklad, Q. Hussain, Remediation of punching shear failure using glass fiber reinforced polymer (GFRP) rods. Polymers (Basel) **13**, 2369 (2021). https://doi.org/10.3390/polym13142369
104. T. Ju, C. Chen, M. Chang, K. Guo, E. Tang, Energy absorption model and damage behavior of GrNPs reinforced GFRP laminate composites under ballistic impact. Int. J. Impact Eng **201**, 105273 (2025). https://doi.org/10.1016/j.ijimpeng.2025.105273
105. S. Choudhury, C.S. Yerramalli, A. Guha, Analytical modeling of the ballistic impact performance of glass fabric: epoxy composites at low temperatures. Int. J. Impact Eng **176**, 104565 (2023). https://doi.org/10.1016/j.ijimpeng.2023.104565
106. Z. Saleh, M.N. Sheikh, A. Remennikov, A. Basu, Overload damage mechanisms of GFRP-RC beams subjected to high-intensity low-velocity impact loads. Compos. Struct. **233**, 111578 (2020). https://doi.org/10.1016/j.compstruct.2019.111578
107. L. Alonso, F. Martínez-Hergueta, D. Garcia-Gonzalez, C. Navarro, S.K. García-Castillo, F. Teixeira-Dias, A finite element approach to model high-velocity impact on thin woven GFRP plates. Int. J. Impact Eng **142**, 103593 (2020). https://doi.org/10.1016/j.ijimpeng.2020.103593

Authors and Affiliations

Anahar Nurul Aina[1,2] · Muhammad Asyraf Muhammad Rizal[1,2,3] · Muhamad Fauzi Abd Rased[1,2] · Desmond Daniel Chin Vui Sheng[2] · Rohah A. Majid[1,4] · Haris Ahmad Israr Ahmad[2] · Mohd Radzi Ali[3] · Noryani Muhammad[5] · Mochamad Asrofi[6] · Mugahed Amran[7] · Qahtan Al-Shami[8]

✉ Muhammad Asyraf Muhammad Rizal
muhammadasyraf.mr@utm.my

Anahar Nurul Aina
nurulaina@graduate.utm.my

Muhamad Fauzi Abd Rased
muhamadfauzi@utm.my

Desmond Daniel Chin Vui Sheng
daniel.chin@utm.my

Rohah A. Majid
r-rohah@utm.my

Haris Ahmad Israr Ahmad
harisahmad@utm.my

Mohd Radzi Ali
mohdradzi@upm.edu.my

Noryani Muhammad
noryani@utem.edu.my

Mochamad Asrofi
asrofi.teknik@unej.ac.id

Mugahed Amran
mugahed_amran@yahoo.com

Qahtan Al-Shami
qahtan.al-shami@gmail.com

[1] Centre for Advanced Composite Materials (CACM), Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

[2] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

[3] Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

[4] Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

[5] Fakulti Teknologi Dan Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

[6] Department of Mechanical Engineering, Faculty of Engineering, University of Jember, Kampus Tegalboto, 68121 Jember, East Java, Indonesia

[7] Department of Civil Engineering, College of Engineering, Taibah University, 42353 Medina, Saudi Arabia

[8] Department of Civil Engineering, Faculty of Engineering, Sana'a University, 9671 Sana'a, Yemen