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Protective Composites Layers: A Review of Banana Fibre and Graphene Composites for Blast Protection

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ABSTRACT

The demand for sustainable, high-performance materials in blast and impact protection has stimulated extensive research into hybrid composites that combine natural fibres with advanced nanomaterials. This review critically analyses recent developments in banana pseudostem fibre–graphene hybrid composites, highlighting the potential as eco-friendly alternatives to conventional synthetic ballistic materials such as aramid and Ultra-High Molecular Weight Polyethylene (UHMWPE). More than 54 peer-reviewed studies published between 2019 and 2025 were examined to evaluate how the integration of graphene nanoplatelets or graphene oxide improves the interfacial bonding, crack resistance, thermal stability, and overall energy absorption capacity of banana fibre-reinforced polymer composites. The reviewed literature shows that while banana fibre offers low density and biodegradability, its mechanical limitations can be significantly offset by incorporating graphene, which acts as a nano-reinforcement to enhance load transfer and restrict crack propagation under dynamic loads. Experimental findings across multiple studies indicate that hybridisation can increase tensile strength by up to 60% and improve impact resistance by 30–50% compared to untreated natural fibre composites, with these values primarily reported for jute, kenaf, and flax systems. Results for banana fibre–graphene hybrids remain limited but indicate similar strengthening trends. However, large-scale blast testing of banana fibre–graphene hybrids remains scarce, and challenges persist in achieving uniform graphene dispersion, scalable processing, and consistent fibre–matrix compatibility. This review identifies key research gaps, including optimising surface functionalisation, developing cost-effective fabrication routes, and establishing standardised testing protocols under realistic blast and impact conditions. Addressing these issues is crucial to advance banana fibre–graphene hybrid composites from laboratory feasibility towards practical, deployable blast-resistant solutions that align with circular economy and sustainability goals.

Keywords: Banana pseudostem fibre, Graphene nanoplatelets, Hybrid composites, Sustainable materials, Blast and impact resistance.

1. INTRODUCTION

Accidental and intentional explosions in military, industrial, and civilian areas continue to create a strong need for lighter and more effective blast-resistant materials. Traditional protective systems, such as metal shields or ballistic panels made from synthetic fibres like Aramid and Ultra-High Molecular Weight Polyethylene (UHMWPE), can be expensive, heavy, and difficult to handle. The synthetic fibre also raises environmental concerns because synthetic fibre is not biodegradable [1, 2]. Therefore, this research is looking for new, more sustainable solutions. Many recent studies have focused on natural fibre composites strengthened with modern nanomaterials to combine good strength and durability with lower cost and less environmental impact [3].

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Banana pseudostem fibre is one promising option because it is a renewable byproduct from agriculture in tropical areas. It is lightweight, biodegradable, and has good tensile strength compared to many other natural fibres [4, 5]. However, there are some limits, such as high moisture absorption and weaker bonding with polymer resins, which can reduce performance under substantial impacts or blasts [6]. To solve these problems, researchers are testing nanomaterials such as graphene nanoplatelets and graphene oxide as extra reinforcement. Graphene can help improve the bond between fibre and resin, make the composite tougher against cracks, and help spread heat during an explosion [7-9]. When appropriately combined, banana fibre and graphene can create protective materials that may match some synthetic fibres in blast protection, while also being better for the environment.

This review paper explains the latest progress in making and testing banana fibre graphene hybrid composites for blast and impact protection. It collects and discusses results from different studies about processing methods, mechanical properties, interfacial improvements, and energy absorption performance. It also highlights main challenges such as how to spread graphene evenly, make production scalable, and keep performance stable during repeated blasts or impacts. By combining knowledge from more than 54 research papers published between 2019 and 2025, this review aims to help guide future research to build sustainable and practical protective composite systems that support the circular economy.

2. MATERIALS OVERVIEW

2.1 Banana Fibre

Banana pseudostem fibre is extracted from the stalks of banana plants, which generate substantial agricultural waste in tropical and subtropical regions worldwide [10]. Typically discarded after fruit harvest, the pseudostems can be processed to recover long, lignocellulosic fibres with tensile strength values ranging from 400 to 800 MPa and elongation at break between 1.5% and 3% [11, 12]. Compared to other natural fibres, banana fibre offers a favourable balance of strength, toughness, and biodegradability, positioning it as a promising reinforcement for lightweight composite applications [13]. Compared to other natural fibres such as jute, kenaf, flax, and sisal, banana fibre demonstrates competitive performance while being more abundant in tropical regions.

The key advantages of banana fibre include its renewability, local availability, and low environmental footprint compared to synthetic fibres derived from petroleum resources [14]. When integrated into polymer matrices, banana fibre contributes to energy absorption and impact resistance due to its inherent toughness and capacity for deformation under stress [15]. These properties are critical for blast mitigation, where rapid dissipation of kinetic energy and crack control are essential. Furthermore, utilising banana fibre supports circular economy objectives by converting underutilised biomass into high-value protective materials, reducing waste, and promoting sustainable resource cycles [16].

Despite these benefits, untreated banana fibres are prone to moisture absorption and limited interfacial bonding with common resins, which can reduce long-term mechanical stability under harsh conditions [17]. As such, surface modifications, hybridisation with nanomaterials, and improved fabrication techniques have become active areas of research to overcome these constraints and unlock the full potential of banana fibre-based protective composites.

2.2 Graphene

Graphene is a single layer of sp^2-bonded carbon atoms arranged in a hexagonal matrix, has emerged as one of the most promising nanomaterials for high-performance composite reinforcement due to its exceptional mechanical, thermal and electrical properties [18, 19]. With a theoretical tensile strength exceeding 130 GPa and a Young's modulus around 1 TPa, graphene can significantly improve the load-bearing capacity of polymer composites when uniformly dispersed within the matrix [20]. Its superior thermal conductivity, reported at values up to 5300 W/m·K, enables rapid heat dissipation during high-energy impacts, while its high surface area facilitates strong interfacial interactions with polymer chains and natural fibre surfaces [21].

In the context of blast and impact protection, graphene serves multiple functions within hybrid composites. It enhances fibre–matrix interfacial bonding, bridges microcracks and restricts crack propagation under dynamic loading, contributing to improved toughness and energy absorption [22]. When incorporated with natural fibres such as banana pseudostem fibre, Graphene Nanoplatelets or Graphene Oxide can compensate for the inherent moisture sensitivity and moderate interfacial adhesion typically associated with lignocellulosic reinforcements [23]. Moreover, the electrical conductivity of graphene offers additional multifunctionality, potentially enabling damage sensing or thermal management capabilities within protective structures [24].

Despite these advantages, the practical realisation of graphene's reinforcing potential depends heavily on overcoming challenges related to nanoparticle dispersion, agglomeration and scalable processing techniques [25]. Achieving uniform distribution of graphene within fibre–matrix systems remains an active area of research, with various functionalisation strategies and processing methods under investigation to maximise performance gains while maintaining cost-effectiveness and environmental sustainability [26].

3. SYNERGY BETWEEN BANANA FIBRE AND GRAPHENE

Combining banana fibre with graphene can help address some common limitations of natural fibre composites used for blast protection. Banana pseudostem fibre is light and biodegradable but can absorb moisture easily, has moderate thermal stability, and sometimes shows weaker bonding with the resin matrix. By adding a small amount of graphene, typically 0.5–2 wt.% of the total composite weight, researchers believe the bond between the fibre and resin can be improved, overall strength and toughness can increase, and cracks can be prevented from spreading when the material faces strong impacts or blast loads.

Many studies on natural fibre–nanoparticle composites support this idea. For example, adding graphene nanoplatelets to jute fibre composites increased tensile strength by about 35% and also improved thermal conductivity [27]. Other research found that kenaf fibre reinforced with graphene oxide had higher impact strength and better fibre–matrix bonding than plain kenaf fibre [28]. Other research reported that flax fibre with graphene nanoplatelets showed higher fracture toughness and improved crack resistance under repeated impacts [29]. These results show that combining graphene with natural fibres can improve mechanical and thermal performance.

Only a few studies have tested banana fibre with graphene directly, but early results are promising. Some papers highlight that graphene can act as a moisture barrier and help transfer stress more effectively between the fibre and resin. This synergy could help banana fibre composites perform better under blast loading while staying light and environmentally friendly. However, more research is needed to test this hybrid under real blast conditions and to develop effective methods to disperse graphene uniformly in the composite matrix.

Figure 1 shows the percentage improvements in mechanical properties, namely tensile strength, impact resistance, and flexural strength, for four types of natural fibre composites reinforced with graphene (GNP/GO). Overall, the incorporation of graphene into natural fibre composites resulted in significant enhancements across all tested properties. Among the systems reviewed, Banana–GNP exhibited the highest performance with increases of 38% in tensile strength, 34% in impact resistance, and 31% in flexural strength. This superior performance can be attributed to the relatively long fibre length, high cellulose content, and favourable interfacial bonding characteristics of banana fibres, which enhance compatibility with graphene dispersion and stress transfer [30]. Jute–GNP also demonstrated notable improvements of 35% in tensile strength, 32% in impact resistance, and 29% in flexural strength, reflecting the strong affinity between jute fibres and graphene nanoplatelets that contributed to improved energy absorption and fracture resistance [31]. Kenaf–GO achieved improvements of approximately 30% in tensile, 27% in impact, and 25% in flexural strength, while Flax–GNP recorded balanced gains of 28%, 26%, and 24%, respectively, confirming that graphene is also effective in reinforcing these systems [32, 33].

In summary, while graphene reinforcement enhances the performance of all natural fibre composites, the results indicate that banana fibre offers the most promising synergy with graphene. This combination delivers the greatest improvements in strength, toughness, and impact resistance, thus highlighting banana–graphene hybrids as leading to the development of sustainable, high-performance blast and impact-resistant materials.

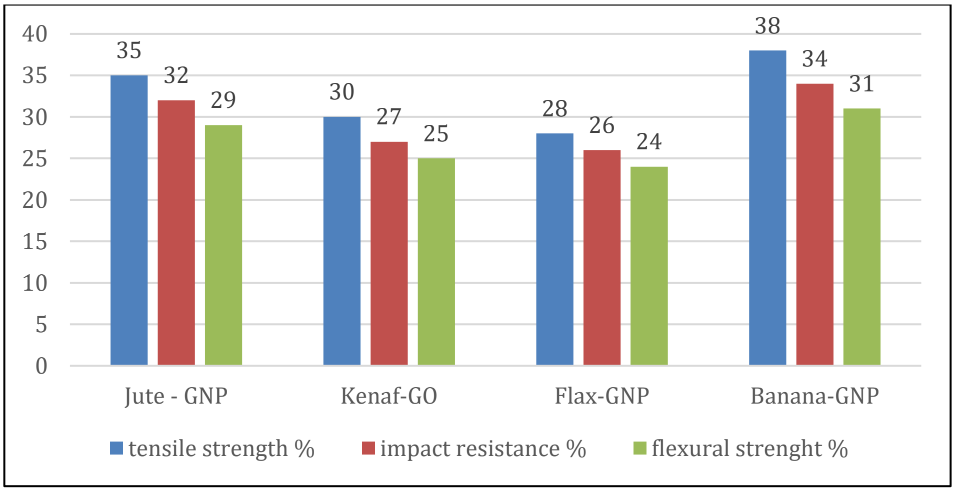

Figure 1: Comparative improvements in tensile, impact, and flexural properties of natural fibre–graphene hybrid composites, based on reported data for jute–GNPs [30-33].

4. PROCESSING TECHNIQUES FOR BANANA FIBRE–GRAPHENE HYBRIDS

To produce banana fibre–graphene hybrid composites with good performance, it is crucial to use processing methods that ensure strong bonding and even mixing inside the polymer matrix [34]. For banana fibre, a common first step is mild alkali treatment, which cleans the fibre surface and improves bonding with the resin [35]. After treatment, fibres are dried and arranged into mats or layers depending on the design.

Achieving uniform dispersion of graphene is still a key challenge because graphene nanoplatelets or graphene oxide often stick together due to strong van der Waals forces [36]. Researchers use methods such as ultrasonication for 30–60 minutes, adding surfactants [37] or chemical functionalisation to help spread graphene evenly [38]. Some studies first mix graphene directly into the resin before combining it with the fibre mats to improve distribution [39].

Common fabrication methods for these hybrid composites include hand lay-up, resin transfer moulding, and vacuum-assisted resin infusion [40]. Hand lay-up is simple and low-cost, but can cause uneven resin spread or air bubbles. More advanced methods like resin transfer and vacuum infusion help achieve better fibre wetting, fewer defects, and more consistent quality, which is important for blast-resistant panels [41].
In most studies, graphene is added at low weight fractions, usually between 0.5% and 2%, to balance cost and processing ease [42]. However, some lab-scale techniques are still difficult to scale up for larger panels needed in real protective structures [43]. Future research should compare different fibre treatments, graphene dispersion methods, and fabrication processes to find the best combinations for banana fibre–graphene hybrids made for blast and impact protection.

The processing in Figure 2 outlines a typical method for fabricating banana fibre–graphene hybrid composites, which includes surface treatment, graphene dispersion, resin mixing, and moulding. Initially, alkali treatment is crucial to remove lignin, hemicellulose, and other impurities from natural fibres, thus improving fibre–matrix adhesion and mechanical interlocking [44]. Following this, the fibres are dried to prevent moisture interference during resin bonding. The arrangement of fibres into mats or layers is a key factor influencing the directional strength of the composite. Simultaneously, graphene nanoplatelets (GNP) or graphene oxide (GO) must be well dispersed to avoid agglomeration, commonly achieved through ultrasonication or chemical functionalisation [45]. The mixing of resin with dispersed graphene ensures homogeneous matrix reinforcement. This step is essential for consistent mechanical property enhancement across the composite panel. Moulding and fabrication techniques, such as hand lay-up, Resin Transfer Moulding (RTM) and vacuum-assisted resin infusion, determine the final product's quality and are selected based on scalability, cost, and structural requirements. For high-performance applications like blast-resistant panels, vacuum-assisted methods are often preferred due to superior fibre wetting and void minimisation [46]. This systematic process integrates the mechanical benefits of natural fibres with the multifunctional capabilities of graphene, showing promise in advanced structural applications.

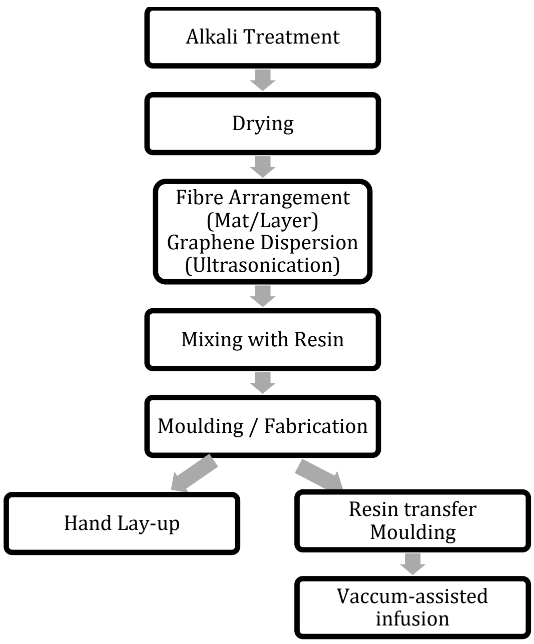

Figure 2: Processing for banana fibre–graphene hybrid to final blast-resistant composite panels.

5. MECHANICAL PERFORMANCE AND TESTING TRENDS

Many studies have tested how natural fibre and graphene composites behave under different types of mechanical loads [30]. For banana fibre graphene hybrids, key tests include tensile strength, impact resistance, flexural strength and sometimes thermal stability. Most results show that adding a small amount of graphene, usually between 0.5% and 2% by weight, can increase tensile strength and help the composite resist cracking [47].

It has been reported that adding graphene nanoplatelets to jute fibre composites improved tensile strength by about 35% and impact energy absorption by 30% [30]. Similar improvements are expected for banana fibre graphene hybrids, where tensile strength can increase by 30–60% compared to untreated banana fibre composites [28]. This is important for blast protection because the material must spread and absorb high-impact forces quickly to avoid sudden failure.

Some studies use Scanning Electron Microscopy (SEM) to observe the fibre graphene resin bonding after tests. Strong bonding means fewer voids and better stress transfer inside the composite [48]. Thermal tests are also done to check how the hybrid composite handles heat that can be produced during an explosion [49, 50]. Observed failure mechanisms include crack deflection, fibre bridging and fibre pull-out, which provide deeper insights into the toughening mechanisms enabled by graphene reinforcement.

However, only a few studies so far have tested banana fibre graphene hybrids under real or simulated blast loads [51]. More experimental work under high-strain-rate conditions is needed to understand how these materials behave in protective systems. It is also important to develop standard test methods to compare results and make sure the composites can work reliably in real field conditions [52].

6. RESEARCH GAPS AND FUTURE DIRECTIONS

Although many studies show that adding graphene can improve the properties of natural fibre composites, there is still limited work that focuses only on banana fibre combined with graphene for blast protection [53]. Most experiments so far have been done in the laboratory with small test samples and basic impact tests. There is not enough data on how these hybrids perform under real blast loads or high-strain-rate conditions [51].

Another research gap is how to achieve good dispersion of graphene inside the resin. Poor dispersion can cause graphene to mass together, which lowers the composite's strength and toughness. Future studies could test chemical functionalisation, ultrasonication, or high-shear mixing to help spread graphene evenly in the matrix [30].

In the future, more field tests and repeated blast trials should be done to check if these hybrids can maintain their strength and protective performance over time. Researchers could also explore adding other nanoparticles, such as nano-silica or carbon nanotubes, together with graphene to see if the combined effect gives even better results [54]. Life-cycle analysis and cost studies are important too, to confirm if these materials are truly sustainable and practical for larger industrial use. Also, the high cost and supply of high-quality graphene should be considered when planning for industrial scale-up.

The research trends and gaps highlighted above are supported by recent studies listed in Table 1. These selected studies show how graphene has been successfully combined with other natural fibres, such as jute, kenaf, and flax, to improve tensile strength, impact resistance, and thermal stability. However, as summarised in the table, only a few works so far have explicitly focused on banana fibre–graphene hybrids, especially for blast or high strain rate applications. This comparison confirms that more testing, better dispersion techniques, and realistic field trials are needed to make banana fibre–graphene composites a practical solution for protective systems. By addressing these research gaps, banana fibre–graphene hybrid composites could become a strong, eco-friendly option for protective systems that help reduce agricultural waste and support circular economy goals.

Table 1: Summary of Selected Studies on Natural Fibre–Graphene Hybrid Composites.

Study	Natural Fibre	Graphene Type	Main Findings	Key Notes
Naji et al. (2019) [30]	Jute fibre	Graphene nanoplatelets (GNPs)	+35% tensile strength; better thermal conductivity	Simple hand lay-up; good dispersion reported
Natrayan et al. (2022) [28]	Kenaf fibre	Graphene oxide (GO)	Higher impact strength; improved fibre–matrix bonding	Chemical treatment used for fibre
Oun et al. (2023)[48]	Flax fibre	GNPs	Better fracture toughness; improved crack bridging	Tested under repeated impact

7. CONCLUSION

Banana fibre–graphene hybrid composites are a promising option for developing blast-resistant materials that are lightweight, mechanically strong, and more sustainable than traditional synthetic fibres. Many studies have shown that graphene can enhance natural fibre composites by improving fibre–matrix bonding, increasing toughness, and acting as a barrier against moisture [53]. Although laboratory tests have confirmed better tensile and impact strength, few studies so far have investigated how these hybrids perform under real blast loads or repeated high-strain-rate conditions [51].

Future research should prioritise testing banana fibre–graphene hybrids in real field scenarios, improving how graphene disperses uniformly within the matrix, and developing cost-effective processes for larger-scale production. Life-cycle analysis and cost evaluations are also important to confirm that these composites remain sustainable and economically feasible for industrial use. Confirming long-term durability under repeated blast exposure will be essential to demonstrate that these materials can meet safety and reliability standards.

By addressing these research gaps, banana fibre–graphene hybrids could become a strong, eco-friendly option for advanced protective systems that help reduce agricultural waste and support circular economy goals.

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