PROGRESS IN AEROSPACE AND AVIATION TECHNOLOGY
e-ISSN: 2821-2924

PAAT

Vol. 5 No. 2 (2025) 17-29
https://publisher.uthm.edu.my/ojs/index.php/paat

Effect of Graphene on Pineapple Leaf Fiber (PALF)-Fiberglass Polymer Composite for Aerospace Application

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DOI: https://doi.org/10.30880/paat.2025.05.02.003

Article Info

Received: 20 June 2025
Accepted: 1 November 2025
Available online: 31 December 2025

Keywords

PALF, graphene, fiberglass, reinforcement, tensile test, SEM test, flexural test

Abstract

This study investigates the impact of incorporating graphene into a hybrid composite of pineapple leaf fiber (PALF) and fiberglass, specifically targeting aerospace applications. PALF, a natural and sustainable fiber, offers desirable mechanical properties but faces limitations in tensile and flexural strength, moisture resistance, and bonding efficiency with polymer matrices. To overcome these challenges, graphene and fiberglass are introduced as reinforcements. Graphene, known for its exceptional tensile strength, flexibility, and thermal conductivity, enhances the composite's mechanical properties, while fiberglass provides additional structural integrity due to its lightweight and durability. A sandwich layup method was employed for composite fabrication, and comprehensive mechanical testing, including tensile, flexural, and scanning electron microscopy (SEM) analyses, was conducted to evaluate their performance. Results from the tensile tests consistently demonstrated significant improvements in maximum stress, breaking stress, and strain as graphene content increased from 1% to 4%. For flexural tests, while the trends were less consistent across all percentages, a notable increase in maximum stress was observed at 4% graphene oxide. SEM analysis further revealed enhanced fiber-matrix interfacial bonding. Fiber breakage was observed more frequently than pullout, particularly with increased graphene content, indicating a tougher and more resilient interface. This research highlights the significant potential of PALF/graphene/fiberglass composites as sustainable alternatives for advanced aerospace materials, offering eco-friendly and high-performance solutions capable of meeting demanding structural requirements.

1. Introduction

Natural fibers, derived from plants, animals, or minerals, are renewable, biodegradable materials with properties like high strength, flexibility, and thermal insulation, making them a cost-effective and sustainable alternative to synthetic fibers. Pineapple leaf fiber (PALF), a natural and biodegradable material, shows significant potential as a reinforcement in composite materials due to its availability and high tensile strength. As industries seek sustainable alternatives to synthetic fibers, natural fibers have emerged as a promising option due to their abundance, low cost, and biodegradability [1]. PALF is a renewable resource sourced from agricultural waste, making it an eco-friendly material that supports the global movement to reduce dependence on non-renewable resources and minimize environmental impact by decreasing pollution [2]. With its high tensile strength, lightweight properties, and good stiffness, PALF offers an excellent alternative to synthetic fibers like glass or carbon fibers, enhancing the strength needed for various load-bearing structures [3]. Table 1 highlights the natural fiber's strength and stiffness versus the synthetic polymer's flexibility and lightweight characteristics, with PALF having the highest value of tensile strength among Jute and LLDPE.

Table 1 *Mechanical characteristics of jute, PALF, and LLDPE [4]*

Type	Tensile Strength (MPa)	Linear density (tex)	Tenacity (g/tex)	Breaking elongation (%)	Young's modulus (MPa)	Density (g/cm^3)	Moisture regains (%)
Jute	653.21 ± 6.31	2.02 ± 0.03	26.62 ± 0.21	1.04 ± 0.01	14783.12 ± 36.14	1.34 ± 0.01	13.70 ± 0.12
PALF	1572.32 ± 47.43	2.50 ± 0.06	100.08 ± 0.48	2.69 ± 0.04	6260.64 ± 47.39	1.53 ± 0.02	12.00 ± 0.11
LLDPE	86.1 ± 0.13	-	-	136.46 ± 0.56	146.72 ± 5.28	0.918 ± 0.01	-

However, PALF faces several limitations, including inconsistent tensile strength, low flexibility and impact resistance, and moisture absorption, which reduces its mechanical reliability and limits its applications, especially in critical industries like aerospace. To overcome these drawbacks, researchers have explored the incorporation of advanced materials such as graphene and glass fiber to enhance the mechanical performance of PALF-based composites [5]. When incorporated into polymer matrices, PALF reinforced high-density polyethylene (HDPE) composite showed improved tensile, flexural, and impact strength [4]. The aim of this study is to investigate the effects of graphene on the mechanical and morphological properties of a hybrid composite comprising pineapple leaf fiber (PALF) and fiberglass, with a focus on aerospace applications. The study seeks to determine whether increasing the proportion of graphene can strengthen the composite's structural integrity and mechanical performance. This study also seeks a lightweight, durable, and high-performance composite material that meets the mechanical demands of aerospace applications while promoting sustainability through the use of natural fibers like PALF.

Graphene is composed of single layers of carbon atoms arranged in a tightly packed, two-dimensional (2D) honeycomb crystal lattice [6], consisting of tightly packed carbon atoms with sp^2 hybridization [7]. It possesses unique chemical and physical properties, including high adsorption and storage capacity, exceptional thermal conductivity, outstanding shock energy absorption, and remarkable mechanical strength [8]. Composed of carbon atoms arranged in a hexagonal lattice, graphene has gained immense popularity in both academia and industry due to its exceptional structural, electrical, mechanical, thermal, and chemical properties, making it a focal point of research for diverse applications, offering significant advantages in industries where weight and strength are critical factors, such as aerospace, automotive, and structural engineering. Integrating graphene into cement-based materials improves impermeability and early mechanical strength, enhancing the sustainability and performance of building materials [7]. Graphene exhibits exceptional flexibility and elasticity, combined with its single-atom thickness, high carrier mobility, and outstanding mechanical strength [9]. It is one of the strongest materials known, with a tensile strength that is 100 times greater than that of steel [10]. Even small additions of graphene, typically 0.1–1 wt%, can increase the tensile strength of composites by up to 200%. These mechanical properties improve almost linearly as the graphene content increases [11]. Its flexibility and high elasticity allow it to withstand deformation while maintaining its structural integrity, making it ideal for applications requiring durability and resilience. The sp^2 hybridized carbon-carbon bonds in graphene create an exceptionally strong in-plane lattice, boasting an intrinsic tensile strength of 130 GPa [12] and a Young's modulus of 1 TPa [9, 12].

Glass fiber, also known as fiberglass, is a material made from extremely fine fibers of glass. It is produced by heating silica (sand) and other raw materials to a high temperature until they melt, then extruding the molten glass through fine holes to form thin, continuous fibers. These fibers are lightweight, strong, and highly flexible, making them an ideal reinforcement material. Glass fiber is commonly used in the production of composite materials, where it is combined with a polymer matrix to create fiberglass-reinforced plastics. These composites are prized for their excellent strength-to-weight ratio and resistance to corrosion [13]. Its flexural strength enables it to resist bending, with a tensile strength of 5.7 GPa [14]. In addition, glass fiber is also used for insulation, filtration, and various industrial applications due to its durability, non-flammable nature, and resistance to chemical damage. Glass fiber greatly improves the properties of fiber-reinforced polymers (FRPs), with the composites consisting of multiple phases, including fibers, resin, and an interfacial phase, making them stronger, lighter, and more durable [13]. GFRP is a multiphase composite material with anisotropic characteristics, where the mechanical properties of the resin matrix play a key role in determining the efficiency of load transfer between fibers, directly affecting the overall performance of the composite [13]. When embedded in a polymer matrix, glass fibers serve as reinforcement, enhancing the composite's tensile strength, flexural strength, and impact resistance, while offering an excellent strength-to-weight ratio along with superior corrosion resistance and chemical stability [15]. These combined properties make fiberglass perfect for applications in the aerospace, automotive, marine, communications, electronics, and safety equipment industries [16]. Table 2 presents the effect of graphene on PALF using a 70:30 ratio in the tensile test. The results indicate that the maximum stress of the specimen increased with the addition of graphene, while the maximum strain decreased. Additionally, the Young's modulus of the graphene-reinforced PALF improved. These findings suggest that reinforcing PALF with graphene can significantly enhance its mechanical properties.

Table 2 *Tensile test results for PALF/fiberglass and PALF/fiberglass with graphene reinforcement [17]*

PALF/fiberglass compositions	Maximum Stress (N/mm^2)	Maximum Strain (mm)	Breaking Stress (N)	Breaking Strain (%)	Young's Modulus (GPa)
70:30 + Graphene	55.854	3.445	55.882	3.449	16.211
70:30	54.6604	4.236	53.853	4.253	12.904

As shown in Table 3, the addition of graphene to the 70:30 PALF/fiberglass composite resulted in a slight reduction in both stress and strain values. This indicates that the unmodified 70:30 PALF/fiberglass sample exhibited higher maximum stress and strain compared to its graphene-reinforced counterpart. However, the difference is minimal, likely due to the low graphene content, which is only 1% by weight relative to the PALF/fiberglass composition. At this concentration, the influence of graphene on the composite's flexural strength appears limited, suggesting that a higher graphene loading may be necessary to achieve a more significant improvement in mechanical performance.

Table 3 *Flexural test results for PALF/fiberglass and PALF/fiberglass with graphene reinforcement [17]*

PALF/fiberglass compositions	Maximum Stress (N/mm^2)	Maximum displacement (mm)
70:30 + Graphene	102.62	3.52
70:30	108.466	3.733

Recently, there has been significant interest from both the scientific community and industrial sectors in various natural plant fibers (such as sisal, jute, flax, hemp, and coir) for a range of applications, including construction, automotive, sports, aerospace, and geotechnical engineering [18]. In aerospace applications, the mechanical properties of materials play a crucial role in ensuring structural integrity and optimal performance under extreme conditions. Among these properties, tensile strength and flexural strength are particularly important, as they determine a material's ability to withstand pulling forces and bending stresses, respectively. Tensile strength refers to the maximum force a material can endure when stretched before failing. This property is critical for components such as the fuselage, wings, and engine parts, which are subjected to significant pulling and tension forces during flight, takeoff, and landing. Materials used in aerospace applications are chosen for their exceptional properties, including high strength-to-weight ratios, thermal stability, corrosion resistance, and durability under extreme conditions. To determine whether this material is suitable for aerospace applications, the research proceeded by comparing its data with commonly used aerospace composites, as shown in Table 4. The selected reference materials for comparison were glass fiber reinforced plastic (GFRP) and carbon fiber reinforced polymer (CFRP).

Table 4 *Main properties of glass-fiber-reinforced plastic (GFRP) and carbon-fiber-reinforced polymer (CFRP) [19]*

Property	Glass-fiber-reinforced plastic (GFRP)	Carbon-fiber-reinforced polymer (CFRP)
Young's Modulus (GPa)	12.3	17
Ultimate Tensile Strength (MPa/N/mm^2)	90	110

The successful reinforcement of PALF composites with graphene and fiberglass could offer the aerospace industry a new alternative material that balances mechanical excellence and environmental responsibility. This research involves the fabrication of PALF-fiberglass composites with varying graphene content, using the sandwich layup method. The aim of this study is to investigate the effects of graphene on the mechanical and morphological properties of a hybrid composite comprising pineapple leaf fiber (PALF) and fiberglass, with a focus on aerospace applications. The study seeks to determine whether increasing the proportion of graphene can strengthen the composite's structural integrity and mechanical performance. The composites are subjected to a series of mechanical tests, including tensile and flexural testing, as well as morphological examination via Scanning Electron Microscopy (SEM). This study also seeks a lightweight, durable, and high-performance composite material that meets the mechanical demands of aerospace applications while promoting sustainability through the use of natural fibers like PALF.

2. Methodology

PALF is prepared through both traditional hand-scraping techniques and modern mechanical methods, including the use of a Pineapple Leaf Fiber Machine. Once extracted, the fibers undergo thorough cleaning and drying to ensure they are properly conditioned for composite fabrication. The preparation of graphene involves dispersing graphene nanofillers in ethanol, followed by sonication to achieve uniform dispersion, before being mixed with DGEBA epoxy resin. The resulting mixture is then carefully stirred, degassed to remove trapped air, and cured to form a strong and consistent composite material. For fiberglass, preparation includes the extrusion and attenuation of molten glass into fine strands, which are later processed into fibers and incorporated as a reinforcing component within the composite structure.

The approach involves the fabrication of PALF-graphene-fiberglass hybrid composites using the sandwich layup method shown in Fig. 1. This process starts with the preparation of PALF through combing to refine the fibers, improving resin absorption and uniformity. Graphene is carefully dispersed into the resin using mechanical stirring to ensure even distribution, which is critical to maximizing the composite's strength and conductivity. During the layup process, layers of PALF and fiberglass are alternately stacked, each saturated with the graphene-enhanced resin, before being compressed and cured under pressure to eliminate voids and ensure strong interlayer adhesion.

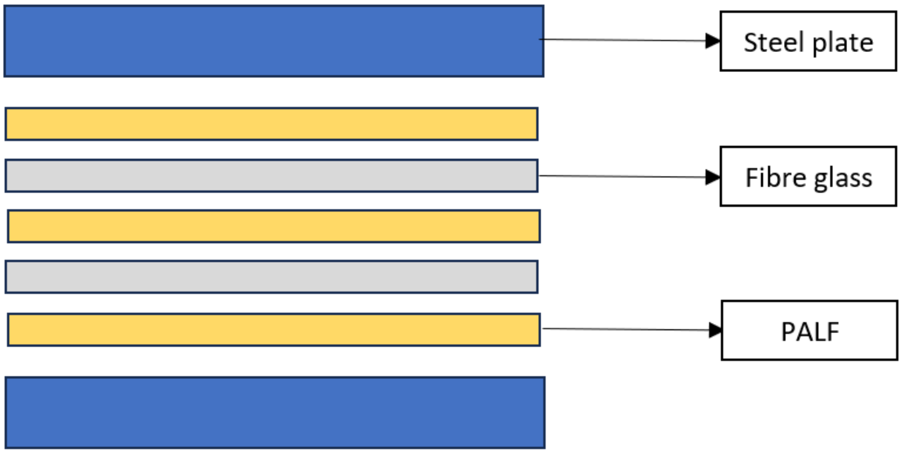

Fig. 1 *Sandwich layup method*

The composite samples are analyzed through mechanical testing and morphological evaluation. Tensile testing is conducted according to ASTM D3039 standards to assess strength, elasticity, and fracture behavior under direct tension. Flexural testing, following ASTM D790, evaluates the material's resistance to bending and its structural stiffness. Additionally, Scanning Electron Microscopy (SEM) is used to observe the fiber-matrix interface, graphene dispersion, and failure mechanisms at the microstructural level. These analyses ensure a comprehensive understanding of how graphene and fiberglass influence the performance of PALF composites, with the ultimate goal of developing a sustainable, high-performance material suitable for aerospace applications.

3. Results and Discussion

3.1 Tensile Test

Fig. 2 shows the stress-strain behavior of composites with 2%, 3%, and 4% graphene oxide under tensile loading. All samples display a steady increase in stress with strain, indicating good elastic behavior. The 4% graphene oxide composite shows the highest stress values, proving it has the best tensile strength. The 2% sample performs better than the 3% sample, which has slightly lower strength. Overall, adding 4% graphene oxide significantly improves the composite's mechanical performance. Table 5 shows the mechanical properties of composites with 2%, 3%, and 4% graphene oxide in a PALF/glass fiber matrix. As the graphene content increases, the material's strength and stiffness improve, especially at 4%. The maximum and breaking stress are similar at 2% and 3%, but at 4%, both rise sharply to 65.93 N/mm^2, showing a clear strength boost. Young's modulus also increases from 10.27 GPa at 2% to 12.42 GPa at 4%, indicating better stiffness. While strain slightly drops at 3%, it improves again at 4%, maintaining flexibility. Overall, 4% graphene oxide gives the best balance of strength and flexibility, making it ideal for high-performance use.

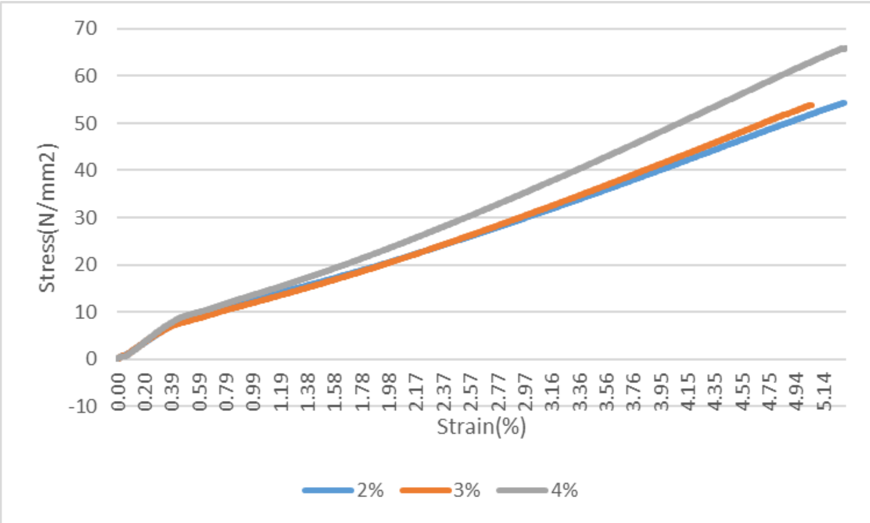

Fig. 2 *Graph of 50:50 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Table 5 *Graph of 50:50 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Percentage of graphene	Maximum Stress (N/mm^2)	Maximum Strain (%)	Breaking Stress (N/mm^2)	Breaking Strain (%)	Young's Modulus (GPa)
2%	54.28	5.28767	54.26	5.292	10.265
3%	53.875	5.04867	53.7725	5.062	10.671
4%	65.925	5.30833	65.925	5.30867	12.419

Fig. 3 shows the stress-strain behavior of composites with 2%, 3%, and 4% graphene oxide (60:40 PALF/fiber) under tensile loading. All samples exhibit elastic behavior, with stress increasing as strain rises. The 4% graphene oxide sample shows the highest stress, indicating the best tensile strength and stiffness. The 3% sample performs slightly lower but is still better than the 2%, which has the weakest performance. The biggest improvement is seen between 2% and 3%, with further gains at 4%, especially at higher strain. This confirms that more graphene oxide improves tensile strength. Table 6 shows how graphene oxide affects flexural performance. At 2%, the composite has moderate strength (52.89 N/mm^2), good flexibility (5.94% strain), and lower stiffness (8.90 GPa). At 3%, strength and stiffness improve significantly (65.57 N/mm^2, 12.80 GPa), but strain drops slightly to 5.12%. At 4%, the composite achieves the best overall performance: highest strength (71.50 N/mm^2), highest stiffness (12.97 GPa), and improved strain (5.51%). Overall, 4% graphene oxide offers the best balance of strength, stiffness, and flexibility for structural use.

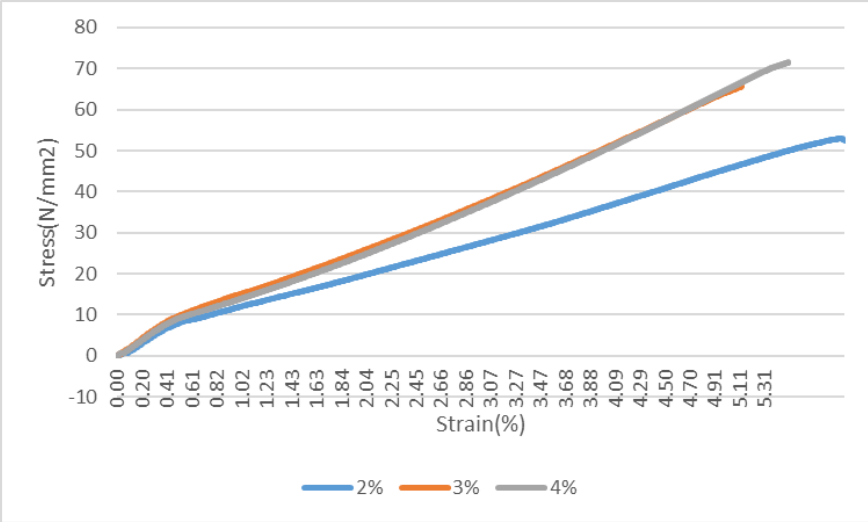

Fig. 3 *Graph of 60:40 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Table 6 *Graph of 60:40 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Percentage of graphene	Maximum Stress (N/mm^2)	Maximum Strain (%)	Breaking Stress (N/mm^2)	Breaking Strain (%)	Young's Modulus (GPa)
2%	52.8925	5.94433	52.535	5.97467	8.898
3%	65.57	5.12333	65.555	5.12667	12.798
4%	71.4975	5.51267	71.49	5.51333	12.97

Fig. 4 shows that all three composites initially follow a linear stress-strain path, indicating elastic behavior. As strain increases, the curves deviate, showing the start of plastic deformation. The 4% graphene oxide composite consistently reaches the highest stress levels, highlighting its superior strength and stiffness compared to the 2% and 3% samples. This suggests that increasing graphene oxide improves the mechanical properties of the 70:30 PALF/glass fiber composite. Table 7 supports this, showing that at 2% graphene, the composite has good stiffness (14.97 GPa) but lower flexibility. At 3%, both stress and strain increase slightly, though stiffness decreases a bit. At 4%, the composite achieves the best performance with the highest stress (81.60 N/mm^2), strain (5.74%), and a strong balance of stiffness (14.22 GPa). Overall, adding 4% graphene oxide provides the best improvement in strength, stiffness, and flexibility.

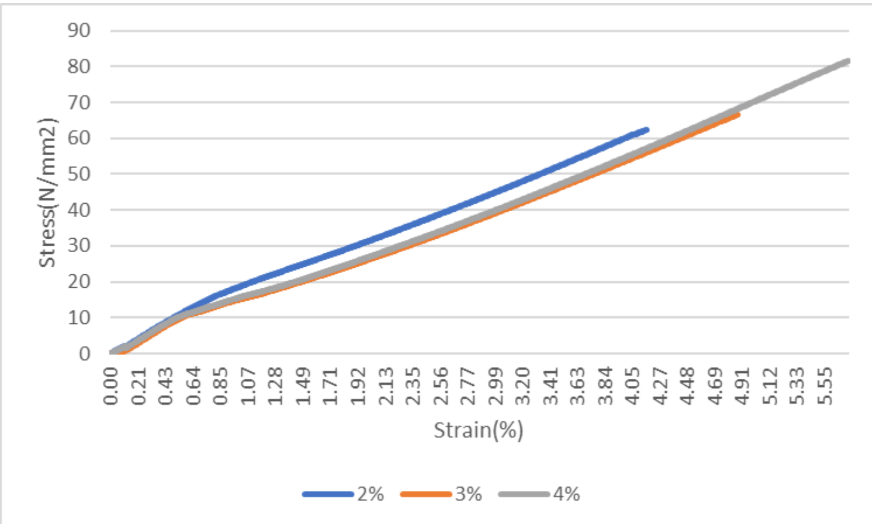

Fig. 4 *Graph of 70:30 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Table 7 *Graph of 70:30 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Percentage of graphene	Maximum Stress (N/mm^2)	Maximum Strain (%)	Breaking Stress (N/mm^2)	Breaking Strain (%)	Young's Modulus (GPa)
2%	62.3425	4.16533	62.3425	4.16533	14.967
3%	66.6475	4.87433	66.6475	4.87467	13.673
4%	81.6025	5.738	81.6025	5.738	14.221

3.2 Flexural Test

Fig. 5 and Table 8 show that adding 3% graphene oxide (GO) confers the composite its highest tensile strength (63 N/mm^2). The 2% sample is weaker but more ductile, while the 4% sample drops slightly in strength (61 N/mm^2) and fails more brittly, likely due to GO agglomeration. Strains are greatest at 2% GO (3.99%), fall at 3% (3.40%), and rise a bit at 4% (3.59%). Overall, 3% GO provides the best balance of high strength with reasonable ductility.

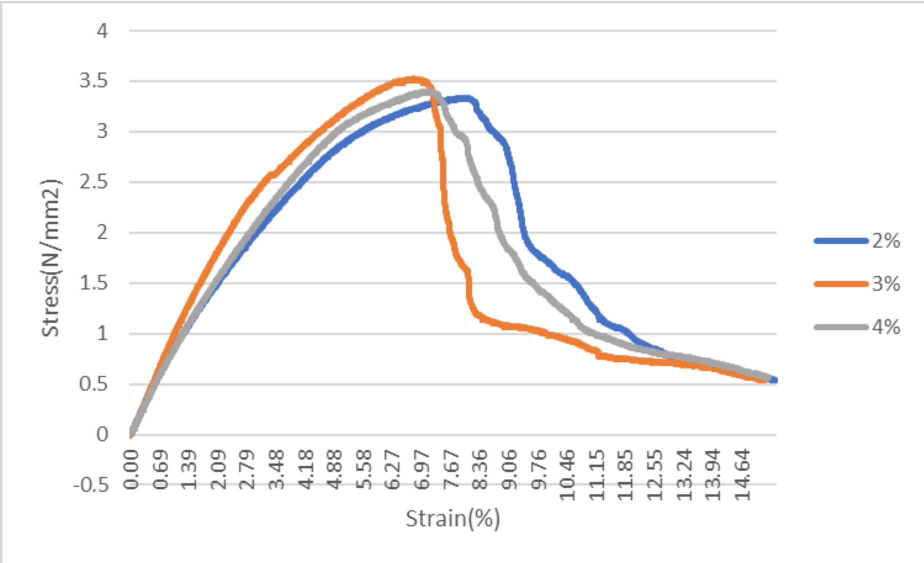

Fig. 5 *Graph of 50:50 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Table 8 *Graph of 50:50 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Percentage of graphene oxide	Maximum Stress (N/mm^2)	Maximum Strain (%)
2%	60.0300	3.98750
3%	63.4500	3.40250
4%	61.2900	3.59208

Fig. 6 shows the stress-strain behavior of a 60:40 PALF/glass fiber composite reinforced with 2%, 3%, and 4% graphene oxide. The 2% and 3% GO samples have similar peak stress (4.2 N/mm^2), but the 3% sample fails more suddenly, indicating a more brittle nature. The 2% sample, in contrast, shows a more gradual drop in stress, suggesting better ductility. The 4% GO sample has the lowest peak stress but stretches more, showing higher ductility and toughness. Table 9 confirms this trend, with maximum stress slightly increasing from 75.06 N/mm^2 at 2% GO to 76.55 N/mm^2 at 3% GO, then dropping sharply to 44.28 N/mm^2 at 4% GO, likely due to graphene agglomeration. Meanwhile, strain increases steadily from 3.14% to 3.50% as GO content rises, indicating improved flexibility. Overall, 3% GO provides the best balance of strength and ductility, while 4% enhances flexibility but reduces strength.

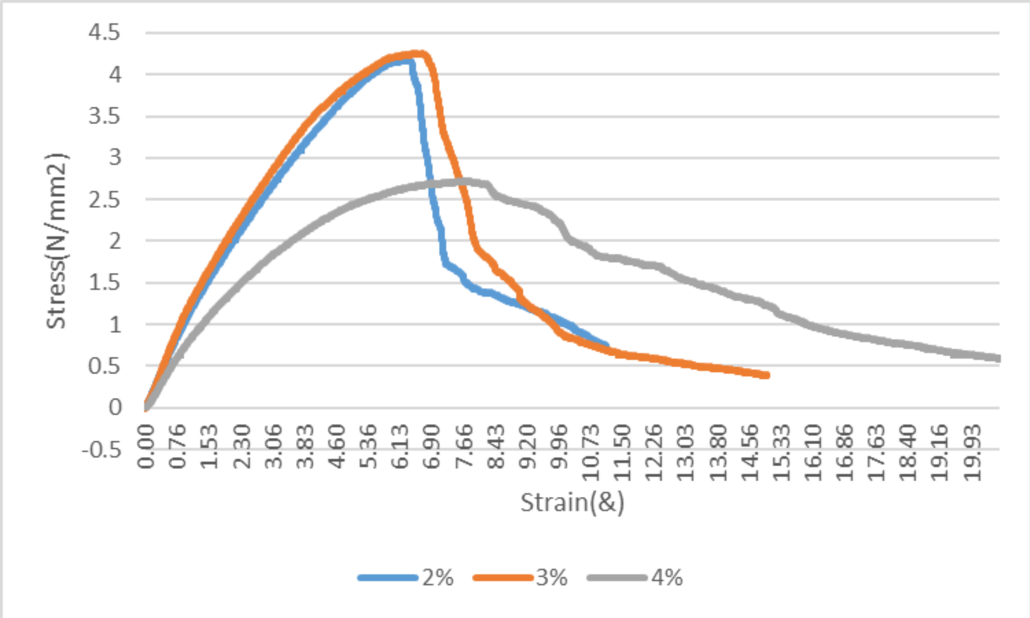

Fig. 6 *Graph of 60:40 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Table 9 *Graph of 60:40 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Percentage of graphene oxide	Maximum Stress (N/mm^2)	Maximum Strain (%)
2%	75.0600	3.13667
3%	76.5450	3.27958
4%	44.2800	3.49542

Fig. 7 and Table 10 show how graphene oxide (GO) content affects a 70:30 PALF/glass fiber composite. With 2% GO, the composite combines solid strength (79 N/mm^2) and good ductility (3.8% strain). Raising GO to 3% slightly lowers both strength and strain, offering no clear advantage. At 4% GO, strength jumps sharply to approximately 117 N/mm^2 by far the highest, but ductility falls to 2.6%, making the material much stiffer and more brittle. In short, 2% GO provides a balanced, more flexible composite, whereas 4% GO maximizes strength at the cost of elongation.

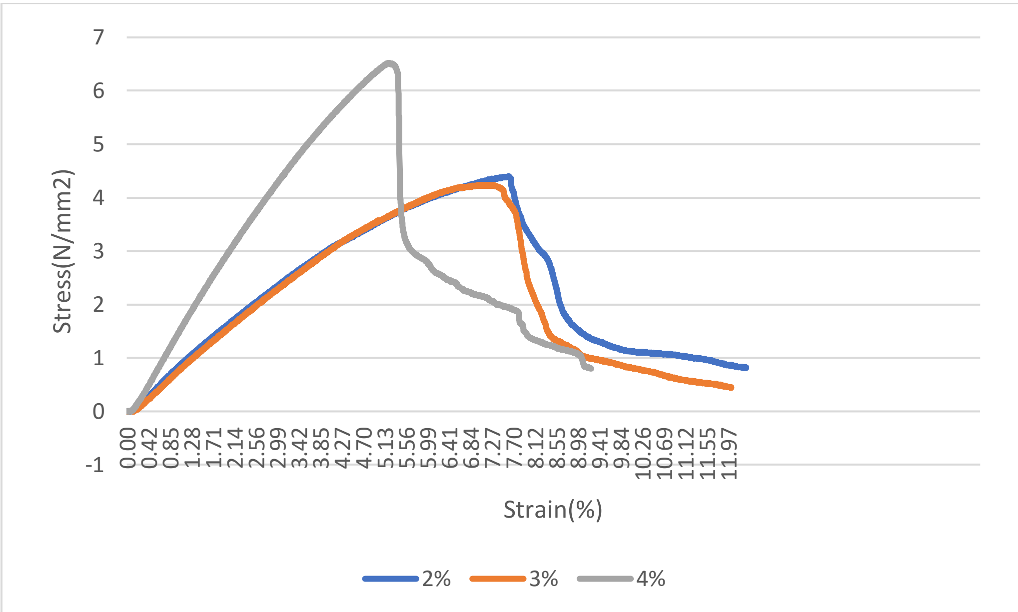

Fig. 7 *Graph of 70:30 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Table 10 *Graph of 70:30 ratio of PALF to glass fiber reinforced by 2%, 3%, and 4% of graphene oxide*

Percentage of graphene oxide	Maximum Stress (N/mm^2)	Maximum Strain (%)
2%	79.1100	3.79750
3%	76.1850	3.61417
4%	117.360	2.60292

3.3 SEM Test

Three SEM tests were carried out, beginning with a sample containing 2% graphene in a 70:30 PALF reinforced with glass fiber composite, followed by samples with 3% and 4% graphene. The purpose of these tests was to observe the microstructure of the specimens after tensile testing and identify any variations between them.

Fig. 8 and Fig. 9, showing SEM images at 250x magnification, reveal the microstructure of PALF composites reinforced with 2% and 4% graphene and glass fiber. The images show both fiber breakage and pullout, indicating mixed failure modes. The presence of fiber breakage suggests strong fiber-matrix bonding, especially improved by graphene's high surface area and strong interactions, which enhance adhesion and create a more uniform composite. However, many pulled-out fibers with clean ends point to weaker bonding in some areas, leading to less effective load transfer and reduced strength. Fig. 10 shows fibers easily pulled out without breaking, confirming weaker interfacial strength and premature failure. These issues may be caused by poor resin impregnation or uneven graphene dispersion, which can weaken tensile performance. Overall, while graphene reinforcement enhances the composite's toughness and durability, it necessitates improved fiber-matrix bonding and fabrication consistency. These graphene-enhanced composites have great potential for aerospace because they are lightweight and strong, able to handle mechanical stress, temperature changes, and impacts, which results in longer-lasting and more dependable aerospace parts.

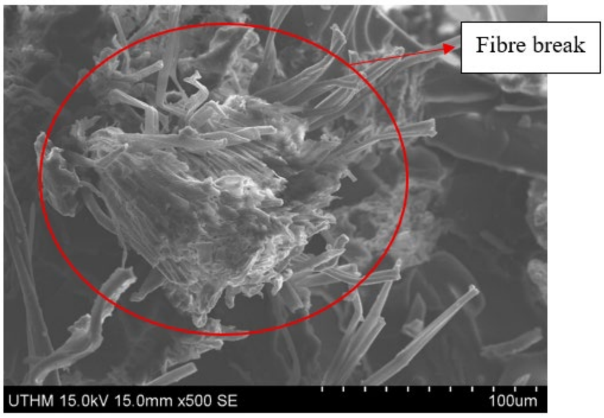

Fig. 8 *Fiber breakage observed at the fracture ends of the PALF/fiberglass reinforced with 2% of graphene at 500x magnification*

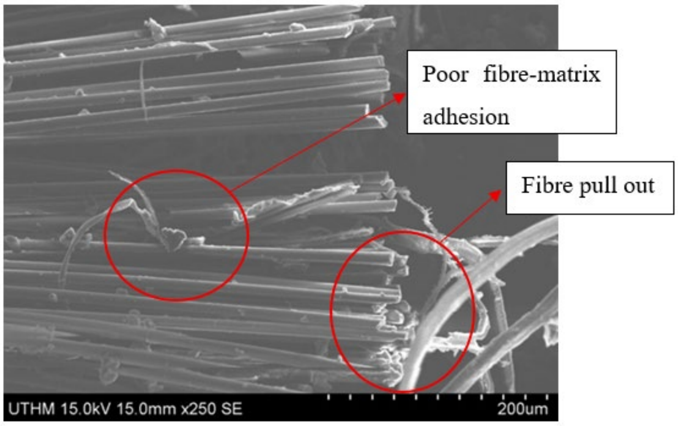

Fig. 9 *Weak fiber-matrix adhesion in the PALF/fiberglass reinforced with 4% of graphene observed at 250x magnification*

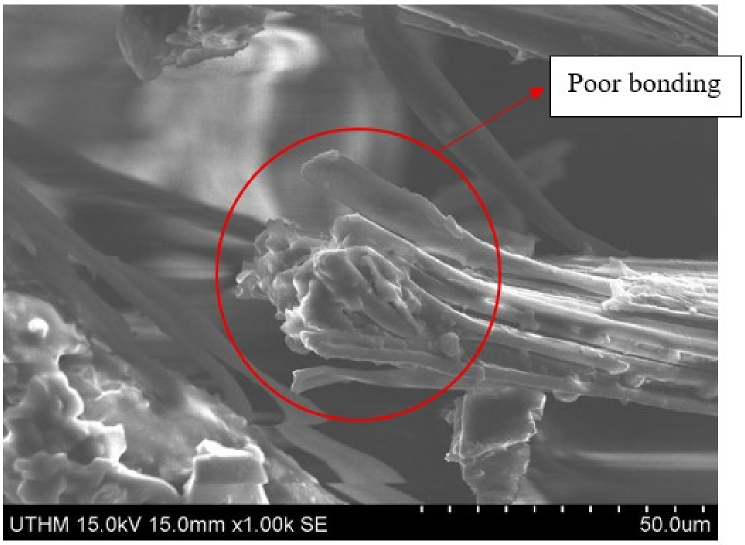

Fig. 10 *Poor bonding on PALF/fiberglass reinforced with 3% graphene at x1000 magnification*

3.4 Comparison with past research

Table 11 shows how adding graphene affects the tensile properties of 50:50 PALF/fiberglass composites. The composite without graphene is the stiffest, with a Young's Modulus of 17.445 GPa and a maximum stress of 62 N/mm^2. However, it is not as ductile. When 2% and 3% graphene are added, both strength and stiffness drop, while strain increases to over 5%, meaning the material becomes more flexible but weaker, likely due to poor dispersion or weak bonding. However, at 4% graphene, the composite performs best overall, with the highest strength (65.925 N/mm^2), improved strain, and a balanced Young's Modulus of 12.419 GPa. This suggests that 4% graphene provides the best mix of strength and flexibility for this composite.

Table 11 *Tensile test results for (50:50) PALF/fiberglass and PALF/fiberglass reinforced without graphene, 2%, 3%, and 4% graphene reinforcement*

Percentage of graphene	Maximum Stress (N/mm^2)	Maximum Strain (%)	Breaking Stress (N/mm^2)	Breaking Strain (%)	Young's Modulus (GPa)
Without graphene	62	3.554	61.96	3.555	17.445
2%	54.28	5.28767	54.26	5.292	10.265
3%	53.875	5.04867	53.7725	5.062	10.671
4%	65.925	5.30833	65.925	5.30867	12.419

Table 12 presents the flexural test results for 50:50 PALF/fiberglass composites with different amounts of graphene oxide. The sample without graphene shows a flexural stress of 61.045 N/mm^2 and a strain of 4.096%, serving as the reference. Adding 2% graphene slightly reduces both stress and strain, indicating weaker performance at this level. At 3% graphene oxide, the flexural stress improves significantly to 63.450 N/mm^2, the highest among all, though strain drops to 3.4025%, showing the material becomes stiffer but more brittle. With 4% graphene, the stress decreases slightly to 61.290 N/mm^2, but the strain increases to 3.592%, suggesting a better balance between strength and flexibility. In summary, 3% graphene oxide exhibits the best flexural strength, while 4% offers a good compromise between strength and ductility.

Table 12 *Flexural test results for (50:50) PALF/fiberglass and PALF/fiberglass reinforced without graphene, with 2%, 3%, and 4% graphene reinforcement*

Percentage of graphene oxide	Maximum Stress (N/mm^2)	Maximum Strain (%)
Without graphene	61.045	4.096
2%	60.0300	3.98750
3%	63.4500	3.40250
4%	61.2900	3.59208

Table 13 clearly shows that increasing the graphene content in the 70:30 PALF/fiberglass composite improves its tensile properties. The control sample without graphene has the lowest performance, with a maximum stress of 54.66 N/mm^2 and a Young's Modulus of 12.904 GPa. When 1% graphene is added, there is a slight increase in strength and a significant rise in stiffness, as the Young's Modulus jumps to 16.211 GPa. At 2% graphene, the composite shows a more noticeable improvement in strength, reaching 62.34 N/mm^2, while still maintaining good flexibility. The 3% graphene sample further improves strength and strain, achieving 66.65 N/mm^2 and 4.87% strain, indicating a better balance between strength and ductility. The best performance is seen at 4% graphene, where both the maximum and breaking stress reach 81.60 N/mm^2, the highest among all samples, along with the highest strain value of 5.74%. The Young's Modulus remains relatively high at 14.22 GPa, showing the material retains its stiffness. Overall, increasing the graphene content, especially up to 4%, significantly enhances the tensile strength, ductility, and stiffness of the composite, making it more suitable for structural applications.

Table 13 *Tensile test results for (70:30) PALF/fiberglass and PALF/fiberglass reinforced without graphene, with 1%, 2%, 3%, and 4% graphene reinforcement*

Percentage of graphene	Maximum Stress (N/mm^2)	Maximum Strain (%)	Breaking Stress (N/mm^2)	Breaking Strain (%)	Young's Modulus (GPa)
Without graphene	54.6604	4.236	53.853	4.253	12.904
1%	55.854	3.445	55.82	3.449	16.211
2%	62.3425	4.16533	62.3425	4.16533	14.967
3%	66.6475	4.87433	66.6475	4.87467	13.673
4%	81.6025	5.738	81.6025	5.738	14.221

Table 14 shows that adding small amounts of graphene oxide (1–3%) lowers the flexural strength of the PALF/fiberglass composite, dropping from the baseline 108 N/mm^2 to as low as 76 N/mm^2, while strain stays roughly the same. But at 4% graphene oxide the trend reverses: flexural strength jumps to about 117 N/mm^2, an 8% gain over the untreated composite, though the material becomes less flexible (strain falls to 2.6%). In summary, 4% graphene oxide seems to be the optimal level for enhancing bending strength, but it also increases the stiffness and brittleness of the composite, a factor that designers must consider in relation to the requirement for ductility.

Table 14 *Flexural test results for (70:30) PALF/fiberglass and PALF/fiberglass reinforced without graphene, with 1%, 2%, 3%, and 4% graphene reinforcement*

Percentage of graphene oxide	Maximum Stress (N/mm^2)	Maximum Strain (%)
Without graphene	108.466	3.733
1%	102.62	3.52
2%	79.1100	3.79750
3%	76.1850	3.61417
4%	117.360	2.60292

Table 15 compares the mechanical properties of traditional aerospace composites GFRP and CFRP with PALF (Pineapple Leaf Fiber) reinforced composites containing different amounts of graphene. GFRP has a Young's modulus of 12.3 GPa and a tensile strength of 90 N/mm^2, while CFRP performs better with 17 GPa and 110 N/mm^2. The PALF/fiberglass composites with graphene show promising results, outperforming GFRP in stiffness with Young's modulus values around 13.7 to 15 GPa and tensile strengths between 62 and 82 N/mm^2. This suggests that PALF-graphene composites could replace GFRP in some aerospace uses, offering good stiffness and environmental benefits thanks to natural fibers. However, compared to CFRP, PALF composites have similar or better stiffness but lower tensile strength, meaning they might be suitable only for applications where stiffness is more important than maximum strength. Before fully replacing GFRP or CFRP, other important properties like shear strength, compressive strength, and thermal behavior need to be tested and compared. Overall, PALF/fiberglass/graphene composites show potential as a sustainable option for certain aerospace parts, especially non-primary structures, but further refinements in materials and manufacturing are needed to match the highest performance demands.

Table 15 *Young's modulus and tensile strength for PALF/fiberglass reinforced with 2%, 3%, and 4% of graphene, glass-fiber-reinforced plastic (GFRP), and carbon fiber reinforced polymer (CFRP)*

Material	Young's modulus (GPa)	Tensile Strength (N/mm^2)
PALF/fiberglass reinforced with 2% of graphene	14.967	62.3425
PALF/fiberglass reinforced with 3% of graphene	13.673	66.6475
PALF/fiberglass reinforced with 3% of graphene	14.221	81.6025
Glass-fiber-reinforced plastic (GFRP)	12.3	90
Carbon fiber reinforced polymer (CFRP).	17	110

4. Conclusion

This research explored how adding graphene affects pineapple leaf fiber (PALF) and fiberglass polymer composites, focusing on their use in aerospace. The study found that adding graphene significantly improves the mechanical strength of these composites. Tensile tests indicated that increasing graphene from 1% to 4% raised the maximum stress, breaking stress, and strain, meaning the material can handle more pulling force and stretch more before breaking. Although the Young's Modulus varied slightly, overall tensile performance got better. For bending strength, 4% graphene oxide in the 70:30 PALF to fiberglass mix notably increased the material's resistance to bending. SEM images revealed better bonding between fibers and the matrix in graphene-enhanced samples, with fibers breaking rather than pulling out. This stronger connection helps transfer stress efficiently, which is important for aerospace use. In summary, adding graphene, especially at higher amounts, improves the strength, stiffness, and durability of PALF composites while keeping them sustainable. These improved composites show enormous promise as lightweight, strong, and eco-friendly materials for aerospace applications. This research offers helpful information about developing advanced, green composite materials for demanding engineering needs.

Acknowledgement

The authors are thankful for the financial support provided by Universiti Tun Hussein Onn Malaysia (UTHM) through the Tier 1 grant (vote Q496). The authors also wish to express sincere gratitude and acknowledge the support received from the Faculty of Mechanical and Manufacturing Engineering, UTHM.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to this manuscript as follows. ***Study conception and design:*** *Muhammad Hafizuddin Baderillah and Mohd Fadhli Zulkafli.* ***Data collection:*** *Muhammad Hafizuddin Baderillah.* ***Analysis and interpretation of results:*** *Muhammad Hafizuddin Baderillah and Mohd Fadhli Zulkafli.* ***Manuscript preparation:*** *Muhammad Hafizuddin Baderillah and Mohd Fadhli Zulkafli. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] M. Balasubramanian, R. Saravanan, and S. T., "Exploring natural plant fiber choices and treatment methods for contemporary composites: A comprehensive review," Dec. 01, 2024, *Elsevier B.V.* doi: 10.1016/j.rineng.2024.103270.

[2] M. J. Phiri, J. P. Mofokeng, M. M. Phiri, M. Mngomezulu, and Z. Tywabi-Ngeva, "Chemical, thermal and morphological properties of polybutylene succinate-waste pineapple leaf fibres composites," *Heliyon*, vol. 9, no. 11, Nov. 2023, doi: 10.1016/j.heliyon.2023.e21238.

[3] S. Nagaraja, P. B. Anand, H. D. Shivakumar, and M. I. Ammarullah, "Influence of fly ash filler on the mechanical properties and water absorption behaviour of epoxy polymer composites reinforced with pineapple leaf fibre for biomedical applications," *RSC Adv*, vol. 14, no. 21, pp. 14680–14696, May 2024, doi: 10.1039/d4ra00529e.

[4] H. Rahman, F. Yeasmin, T. Islam, M. Hasan, M. B. Uddin, and R. A. Khan, "Fabrication and investigation of the physico-mechanical properties of Jute-PALF reinforced LLDPE hybrid composites: Effect of gamma irradiation," *Heliyon*, vol. 8, no. 4, Apr. 2022, doi: 10.1016/j.heliyon.2022.e09287.

[5] B. Vinod and L. J. Sudev, "Effect of cryogenic treatment on mechanical behavior of PALF reinforced polymer composite," in *Materials Today: Proceedings*, Elsevier Ltd, Jan. 2022, pp. 330–337. doi: 10.1016/j.matpr.2022.04.692.

[6] A. K. M, J. LS, and R. CHANDRAN, "Enhanced Mechanical and Electrical Properties of Styrene Butadiene Rubber Nanocomposites with Graphene Platelet Nano-powder," *Journal of Polymer Materials*, vol. 40, no. 3–4, pp. 141–156, Mar. 2024, doi: 10.32381/JPM.2023.40.3-4.2.

[7] S. Wang, Y. Zhuge, Y. Liu, and Y. Lu, "Effect of mechanochemistry on graphene dispersion and its application in improving the mechanical properties of engineered cementitious composites," *Journal of Building Engineering*, vol. 95, Oct. 2024, doi: 10.1016/j.jobe.2024.110251.

[8] J. Xing, Y. Wang, L. Yi, and Y. Zhang, "Anisotropic and tunable mechanical properties of graphene based asymmetric carbon honeycomb," *Results in Engineering*, vol. 24, Dec. 2024, doi: 10.1016/j.rineng.2024.103296.

[9] Z. Ma, "Advances in graphene-assisted flexible substrate sensors for human motion monitoring," Sep. 01, 2024, *Elsevier B.V.* doi: 10.1016/j.ijoes.2024.100760.

[10] J. Ma *et al.*, "Effect of monovacancy defects on anisotropic mechanical behavior of monolayer graphene: A molecular dynamics study," *Diam Relat Mater*, vol. 148, Oct. 2024, doi: 10.1016/j.diamond.2024.111437.

[11] P. Shi, Y. Chen, T. Guo, Y. Tu, and J. Feng, "Folded graphene reinforced metal matrix nanocomposites with comprehensively enhanced tensile mechanical properties," *Advances in Engineering Software*, vol. 200, Feb. 2025, doi: 10.1016/j.advengsoft.2024.103829.

[12] P. Bose, N. Koratkar, and Y. Shi, "Simultaneous improvement in the elastic and fracture properties of graphene-epoxy nanocomposites–a computational perspective," *Carbon N Y*, vol. 229, Oct. 2024, doi: 10.1016/j.carbon.2024.119455.

[13] Y. Cao *et al.*, "Improving tensile properties of glass fiber-reinforced epoxy resin composites based on enhanced multiphase structure: The modification of resin systems and glass fibers," *Mater Today Commun*, vol. 40, Aug. 2024, doi: 10.1016/j.mtcomm.2024.110225.

[14] M. T. Rafat, T. Z. Shuchi, F. R. Evan, and M. A. Rahman, "Mechanical and absorption properties of carbon-basalt and glass fiber reinforced composites: A comprehensive study with implications for advanced manufacturing technology," *Results in Materials*, vol. 23, Sep. 2024, doi: 10.1016/j.rinma.2024.100615.

[15] Y. Cao *et al.*, "UV ageing of epoxy resin-based glass fiber-reinforced polymer composites incorporating with various curing agents," *Mater Today Commun*, vol. 40, Aug. 2024, doi: 10.1016/j.mtcomm.2024.110061.

[16] S. K. Devendrappa, M. Puttegowda, and S. Ballupete Nagaraju, "Enhancing wear resistance, mechanical properties of composite materials through sisal and glass fiber reinforcement with epoxy resin and graphite filler," *Journal of the Indian Chemical Society*, vol. 101, no. 10, Oct. 2024, doi: 10.1016/j.jics.2024.101349.

[17] N. E. N. bin Noor Azman, M. F. Zulkafli, and S. N. A. Safri, "Development and Characterization of Pineapple Leaf Fibre Reinforced with Graphene and Fibre Glass Composites for Aerospace Application," *Progress in Aerospace and Aviation Technology*, vol. 4, no. 1, Jun. 2024, doi: 10.30880/paat.2024.04.01.009.

[18] S. Rana and R. Fangueiro, "Advanced composites in aerospace engineering," *Advanced Composite Materials for Aerospace Engineering*, pp. 1–15, Jan. 2016, doi: 10.1016/B978-0-08-100037-3.00001-8.

[19] C. Scarponi, "Carbon–carbon composites in aerospace engineering," *Advanced Composite Materials for Aerospace Engineering*, pp. 385–412, Jan. 2016, doi: 10.1016/B978-0-08-100037-3.00013-4.