

Enhanced tensile and morphological properties of PET/graphene nanoplatelet composites for food packaging applications

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ABSTRACT

The development and evaluation of graphene nanoplatelet (GNP)-reinforced polyethylene terephthalate (PET) composites for use in food packaging is investigated in this work. For test specimens, composites with 0.1 wt. C%, 0.3 wt.% C, and 0.5 wt.% C GNPs were prepared using a ball milling technique, extruded into filaments, and then 3D printed. Tensile testing revealed that the addition of GNPs significantly enhanced the tensile strength of PET. The greatest improvement was achieved at 0.3 wt.% C loading, whereas particle agglomeration led to a plateau or slight decline at 0.5 wt.% C. These patterns were supported by fracture surface analysis using scanning electron microscopy (SEM), which revealed smoother brittle surfaces in neat PET and increasingly rougher morphologies with dimples and microvoids in GNP-reinforced samples, suggesting better energy absorption and crack resistance. Overall, this study demonstrates that the tensile and morphological properties of PET are significantly enhanced through controlled GNP incorporation, highlighting its strong potential for high-strength, sustainable food packaging applications.

Keywords: *Graphene; Polyethylene terephthalate; Composites; Tensile properties; Food packaging*

1. INTRODUCTION

Due to its outstanding mechanical strength, chemical resistance, and optical transparency, polyethylene terephthalate (PET) is used extensively in packaging and industrial applications. Its excellent intrinsic properties, including high tensile strength (50-70 MPa), stiffness (Young's modulus of 1700 MPa), a glass transition temperature of 69-115 °C, and a melting point of 255-256 °C, provide substantial resistance to deformation, making PET a highly attractive material for diverse engineering and industrial uses [1]. Despite these advantages, PET suffers from limited thermal stability, reduced barrier performance at elevated temperatures, and restricted applicability in advanced functional packaging, which necessitates the development of strategies to overcome these shortcomings. Therefore, researchers have enhanced the thermal stability of PET by incorporating nanomaterials like graphene. As a two-dimensional carbon allotrope with exceptional electrical, thermal, and mechanical properties, graphene actively improves the performance of polymer nanocomposites [2], [3]. Indeed, numerous studies have demonstrated that incorporating graphene into PET matrices significantly enhances gas

barrier performance, mechanical strength, and thermal stability.

The development of PET-graphene nanocomposites can be achieved through several methods, such as mechanical mixing, solution mixing [4], in situ polymerization [5], [6], and melt blending [7]–[9]. Recently, mechanical mixing such as ball milling has emerged as a promising technique for achieving uniform graphene dispersion in the polymer matrix. Ball milling exfoliates graphene layers and distributes them evenly within PET, offering simplicity, scalability, and good filler dispersion, which are key for enhancing composite properties [10], [11]. It also avoids solvent use, making it more environmentally friendly. This method has been successfully applied to prepare various nanocomposites, improving their mechanical, thermal, and in some cases, electrical properties.

PET is already widely used in food-contact packaging because it combines high transparency, mechanical robustness, and established regulatory acceptance, and thus it provides a practical baseline for assessing whether low-loadings of graphene nanoplatelets (GNPs) can deliver incremental performance gains in terms of strength and

barrier enhancement without compromising safety [12], [13]. Nevertheless, for any nano-enabled food-contact material the central justification must include consumer safety, because potential hazards are primarily linked to chemical migration of intentionally added substances or residuals into food and particle release that involves shedding of nanoscale fragments during converting, abrasion, or end of life [14]–[16]. In this context, the risk is mitigated when the nanofiller is strongly embedded within the polymer matrix and when processing yields good dispersion with minimal free particulate at surfaces. However, safety cannot be assumed and should be framed within established regulatory approaches for food-contact plastics. Regulatory agencies evaluate food-contact materials on a case-by-case basis using overall and specific migration concepts and toxicological thresholds, and specific nanomaterial considerations have been highlighted in guidance documents and scientific opinions. For instance, EFSA's guidance on risk assessment of nanomaterials in the food/feed chain and EU Framework Regulation (EC) No 1935/2004 with plastics implementation under (EU) No 10/2011; in the U.S., FDA's food-contact notification framework and its guidance on nanotechnology [16], [17]. Prior studies on polymer-graphene nanocomposites generally report low migration/limited particle release when graphene-based fillers are well immobilized in the polymer, but also emphasize that outcomes depend strongly on filler chemistry, loading, dispersion state, and the food simulant/temperature-time conditions; therefore, positioning PET/GNP systems for food packaging is scientifically compelling yet requires explicit acknowledgement of migration and release as critical safety endpoints alongside the performance motivation.

Therefore, graphene can be added to PET using ball milling equipment to enhance the material's qualities for use in packaging and other applications [18], [19]. Additionally, the ball milling method provides an environmentally friendly alternative to conventional composite fabrication techniques. Herein, a polyethylene terephthalate-graphene nanoplatelets (PET-GNPs) composite was developed with various GNP concentrations (0.1 wt.% C, 0.3 wt.% C, and 0.5 wt.% C) using a ball milling approach to investigate the tensile strength and morphological properties for food packaging applications. Although food packaging materials are commonly produced by conventional processes such as extrusion or thermoforming, additive manufacturing (AM) was used in this study as a research-oriented processing tool rather than a final industrial manufacturing method. AM allows precise control of processing parameters and filler dispersion, enabling systematic evaluation of the mechanical and morphological effects of graphene nanoplatelets in the PET matrix with minimal material usage. Moreover, the thermal and melt-processing conditions in AM are comparable to those in conventional packaging processes, making the obtained results relevant and transferable. Next, the prepared mixtures were

extruded into filaments using a mechanical extruder. Commercial-grade PET filaments served as the matrix material. High-purity GNPs were employed as the reinforcing material to enhance the thermal and strength properties. The developed PET/GNP composites were 3D printed for tensile testing and morphological characterization.

2. MATERIALS AND METHODS

Commercial-grade polyethylene terephthalate (PET) filaments were used as the matrix material. commercial name (CLEARTUF® or APET/RPET), manufacturer (M&G Polymers or Recron Malaysia), and supplier (DESU Plastic or Recron Malaysia) were specified. The matrix possessed a melting temperature of 245–260 °C, a bulk density of 1.37–1.38 g/cm³, and a melt flow index of 5–20 g/10 min (at 280 °C/2.16 kg). High-purity graphene nanoplatelets (GNPs) were utilized as the reinforcing material to enhance the thermal and mechanical strength properties of house wall structures. Graphene nanoplatelets (GNPs) were purchased from Ugent Tech (Malaysia), grade UGPRO880GNP. Manufacturer specifications include an average of 6–8 layers, a thickness of 3–8 nm, a lateral size of 5 µm, and a purity of >99%.

2.1. Preparation of PET Graphene Nanocomposites

A planetary ball milling procedure was used to generate the PET/graphene nanocomposites, as shown in Figure 1. This ensured that the graphene nanoplatelets (GNPs) were uniformly dispersed within the polymer matrix. First, commercial-grade PET filaments were cut into small pieces. Stainless-steel balls and jars were used during the milling process to prevent contamination. After that, high-purity GNPs were incorporated at concentrations of 0.1 wt.% C, 0.3 wt.% C, and 0.5 wt.% C. Stainless-steel milling media were utilized to prevent sample contamination. The balls-to-powder weight ratio was maintained at 10:1 to ensure sufficient milling energy for effective particle size reduction and homogeneous mixing. The milling process was conducted for 4 hours at a rotational speed of 350 rpm, producing a fine and homogeneous PET/GNP mixture.



Figure 1. Photographs of PET-graphene mixtures in the milling jar: (a) before milling and (b) after milling.

2.2. Extrusion of PET-Graphene Filaments

The extrusion process was employed as a key step in fabricating PET-graphene composite filaments, as shown in Figure 2. The PET-GNP mixtures obtained from the ball milling stage were heated to a controlled temperature range of 185–190 °C, allowing the polymer matrix to soften and become moldable. The molten mixture was then extruded through a die to produce filaments with a uniform diameter of 1.75 mm, suitable for subsequent 3D printing applications. Strict temperature control during extrusion was critical to ensure proper dispersion of GNPs within the PET matrix, as this directly influenced the mechanical and thermal properties of the composites. PET/GNP composite filaments containing 0.1 wt.% C, 0.3 wt.% C, and 0.5 wt.% C GNPs were successfully produced, as shown in Figure 3. Each composition extruded smoothly, maintaining consistent filament quality and uniformity in diameter. The effective dispersion of graphene at these concentrations ensured reliable performance of the filaments during 3D printing.



Figure 2. Extrusion process of PET-GNPs filament using a mechanical extruder.

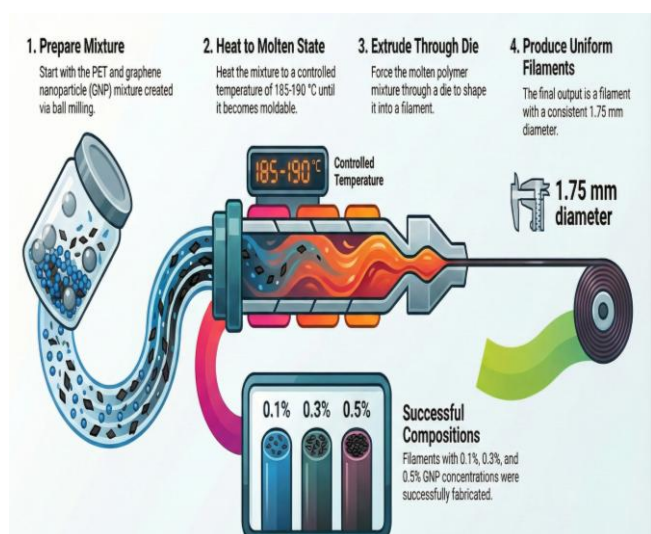


Figure 3. Fabricated PET-GNPs process and filament: (a) PET-0.1 wt.% C, (b) PET-0.3 wt.% C and (c) PET-0.5 wt.% C

2.3. 3D Printing of PET-Graphene Composite Filaments

The PET-Graphene composite filaments with 0.1 wt.% C, 0.3 wt.% C, and 0.5 wt.% C graphene concentrations were used to 3D print dog bone and square-shaped samples using a Crealty 3D printer for further characterization. To ensure optimal adhesion and print quality, the 3D printing process was performed with a nozzle temperature of 220 °C and a bed temperature of 90 °C. Specimens of dog bones were 3D-printed for tensile testing to assess the mechanical strength of each composition, and square-shaped samples were created for morphological characterization via SEM. These tests were conducted to determine the impact of different graphene concentrations on the mechanical strengths of PET-Graphene composite materials. Figure 4 shows the end-printed objects, which demonstrate the uniformity and integrity of printed shapes in all compositions.

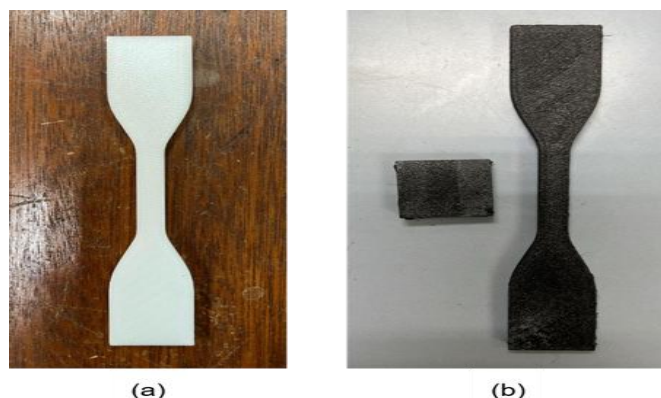


Figure 4. 3D-printed specimens of (a) neat PET and (b) PET-GNPs composites.

2.4. PET-Graphene Composite Characterization

Several critical analyses were conducted on PET-graphene nanocomposites to evaluate their mechanical and morphological characteristics. Mechanical properties were

determined through tensile testing of specimens fabricated via 3D printing into standard dumbbell-shaped geometries. The tensile strength obtained from these tests represents the composites' ability to withstand externally applied loads and their stiffness, respectively. Tensile tests of neat PET and PET/GNPs composites were conducted in accordance with ASTM D638 using Type I dog-bone specimens. Testing was performed at 23 ± 2 °C on a universal testing machine fitted with a 7 kN load cell. The crosshead speed was 5 mm/min. Prior to testing, specimens were conditioned for 24–48 h at 23 ± 2 °C and $50 \pm 5\%$ RH. For each formulation, at least five specimens ($n = 5$) were tested, and results are reported as mean $\pm$ standard deviation. The results provided quantitative insight into the influence of GNPs incorporation on the mechanical performance of the PET matrix. To understand the structural and mechanical interactions at the microscopic level, morphological fracture analysis was conducted using SEM. Samples were cut into small pieces and cryo-fractured after immersion in liquid nitrogen to obtain fresh brittle fracture surfaces. The fractured surfaces were mounted on aluminum stubs with carbon tape and sputter-coated with a thin Au layer to minimize charging. Imaging was performed under high vacuum at 5–10 kV using a secondary electron detector with a working distance of ~ 8 –10 mm, and representative micrographs were collected from multiple areas of each specimen.

3. RESULTS AND DISCUSSION

3.1. Tensile Properties

3.1.1. Tensile Strength

This study investigates the tensile strength of PET reinforced with varying concentrations of GNPs. The inclusion of graphene at different weight percentages (0.1 wt.% C, 0.3 wt.% C, and 0.5 wt.% C) aimed to evaluate its effect on the tensile properties of the composite material. Figure 5 shows the samples of PET and PET-graphene after tensile testing.

The tensile strength results for neat PET and PET reinforced with different concentrations of graphene nanoplatelets (GNPs) are presented in Figure 5. Adding 0.1 wt.% C graphene to PET resulted in a significant increase in tensile strength. Relative to neat PET, incorporating GNPs produced an immediate increase in tensile strength, rising to 5.6% improvement at PET-0.1 wt.% C and reaching 6.8% improvement at PET-0.3 wt.% C. A further increase of 6.6% improvement to PET-0.5 wt.% C is effectively comparable to the PET-0.3% formulation and suggests a plateau in reinforcement beyond PET-0.3 wt.% C within the investigated range. This rapid increase followed by saturation trend is commonly attributed to the establishment of an effective reinforcing/constraint network and improved stress transfer at low loadings (0.1–

0.3 wt.% C), whereas additional filler at higher loadings may yield diminishing returns due to reduced dispersion quality, the onset of agglomeration, and/or the introduction of local stress concentrators that offset further gains. The mean tensile strength of the composite in this case was 51.1 MPa, which is a remarkable improvement over pure PET. The improvement is due to the effectiveness of stress transfer from the PET matrix to the graphene fillers, resulting in a higher load-carrying capacity of the composite. At 0.3 wt.% C loading, its average tensile strength was 51.7 MPa. This small increase over the 0.1 wt.% C graphene composite shows that there is a plateau effect, which means that adding more graphene does not improve tensile strength in a straight line. It is likely that the different results were caused by differences in how well the graphene was distributed in the PET matrix. Accordingly, PET-0.3 wt.% C can be considered the optimal composition for maximizing tensile strength in this dataset, while PET-0.5 wt.% C provides no statistically meaningful additional improvement based on the reported mean values.

The average tensile strength decreased marginally to 51.6 MPa at the highest concentration of graphene tested (0.5 wt.% C). The slight fall in tensile strength compared to the 0.3 wt. % graphene composite reveals that at some concentration, graphene could not contribute much or may have even decreased the tensile strength. This is most likely due to agglomeration of the graphene particles, which can lead to sites of stress concentration and reduce overall material performance. The inclusion of graphene in PET increases its tensile strength, with the greatest improvement observed at lower loadings. An increase in inclusion above 0.3 wt.% C graphene does not yield proportional strength gains and can even result in a minor reduction. This trend emphasizes the necessity of maximizing filler content to achieve optimal property balance.

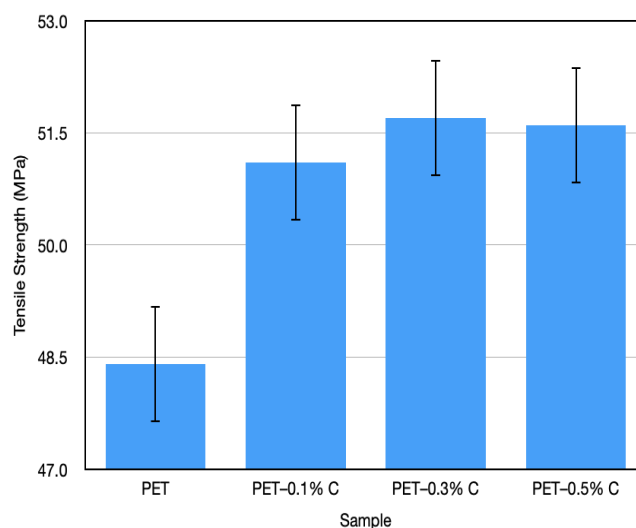


Figure 5. Tensile strength of PET and PET-GNPs

3.1.2. Stress-strain properties

Figure 6 shows the stress-strain graph for PET and PET-graphene composites, illustrating the relationship between the applied stress and the resulting strain until the point of fracture. For all materials, the initial linear portion of the curve represents elastic deformation, where the material will return to its original shape upon removal of the load. As stress increases, the curve deviates from linearity, indicating the onset of plastic deformation, followed by a peak point representing the material's ultimate tensile strength (UTS). Beyond this point, the material continues to elongate until failure.

For neat PET, the stress-strain curve shows a relatively steep initial slope, reflecting a high modulus of elasticity characteristic of rigid polymers. The curve then transforms into a non-linear one, which denotes the onset of plastic deformation. The maximum stress attained for pure PET corresponds to the peak of its tensile strength, after which there is a slow decrease in stress displaying the necking phenomenon before it fails. Necking is a peculiar feature of semicrystalline polymers with PET being one of them. This kind of response stems from the molecular chains of the material aligning and deforming under applied strains and stresses which is a property of tensile stress.

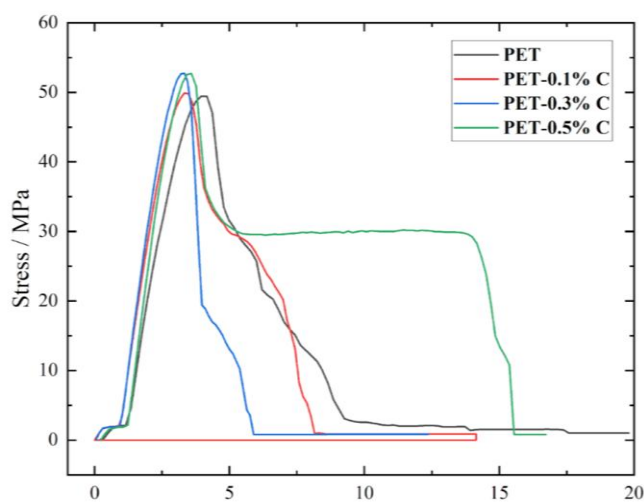


Figure 6. PET and PET-graphene composites' stress-strain curve

Graphene addition changes the stress-strain curve dramatically. For the graphene composites, the initial slope of the curve is higher compared to that of pure PET, reflecting a higher modulus of elasticity. This is because of the mechanical properties of the graphene and its ability to transfer stress onto the polymer matrix very efficiently. The increased stiffness of the composites over neat PET explains why such composites are perfect materials for use in applications where there is a need for a higher stiffness to deformation ratio.

Graphene's addition to the PET matrix demonstrates composite reinforcement, a process that uses a filler to improve specific properties. The enhanced tensile strength and toughness confirm graphene's reinforcing capabilities. Figure 7 presents the area under the stress-strain curves, which indicates the material's toughness and its capacity to absorb energy prior to failure.

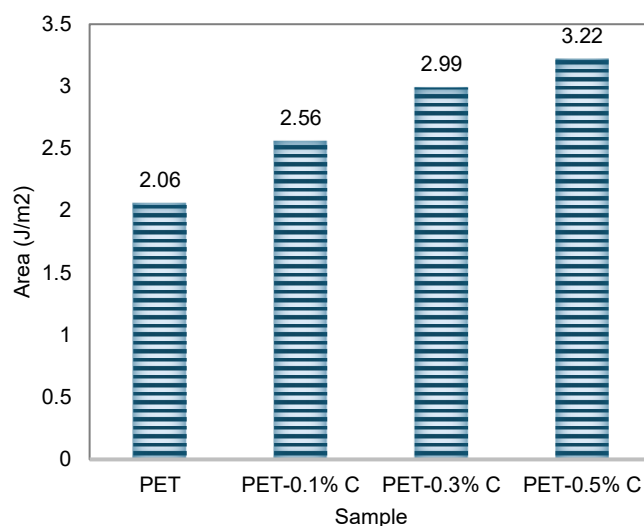


Figure 7. The area under the stress-strain graph of each sample

The area under the curve indicates that PET has the least toughness at a value of 2.06 J/m² and absorbs the least energy before failure. Referring to the introduction of 0.1 wt.% C, this eventually raises the toughness, suggesting that it has a better capacity of absorbing energy when compared to pure PET. The highest energy absorption was PET-0.5 wt.% C with the value of 3.22 J/m², meaning this material can withstand a larger amount of energy before failure, hence, it is the toughest of the tested samples. This sample is also highly tough, and significantly more than PET-0.3 wt.% C meaning that before fracturing it may absorb even more energy. The material with the highest toughness (PET-0.5 wt.% C) is best suited for applications where structural integrity is critical, as it can absorb more energy before breaking. This makes it ideal for applications subjected to impact or high strain. PET-0.3 wt. % also shows excellent toughness and may provide an optimal balance between structural strength and material flexibility. PET-0.1 wt.% C and pure PET have lower toughness, making them less suitable for high-energy or high-impact applications. The calculated areas indicate that carbon incorporation improves the toughness of PET, with PET-0.5 wt.% C showing the highest energy absorption and toughness. This material would likely provide the best structural integrity under stress. However, PET-0.3 wt.% C, which also performs well, could be a more cost-effective option with nearly optimal properties. These findings align with research showing that moderate carbon incorporation

enhances the mechanical properties of polymer composites.

However, the trade-off between strength and ductility is a critical consideration. While the reinforcement leads to increased strength and stiffness, excessive graphene can lead to brittleness, reducing the material's toughness. This balance is essential in designing composites for practical applications.

3.1.3. Tensile Modulus

Figure 8 shows the tensile modulus of neat PET and PET composites reinforced with varying GNPs filler content (0.1–0.5 wt.% C). The incorporation of GNPs as filler significantly enhances the tensile modulus, reaching an optimum at 0.3 wt. % C, after which a slight decrease is observed.

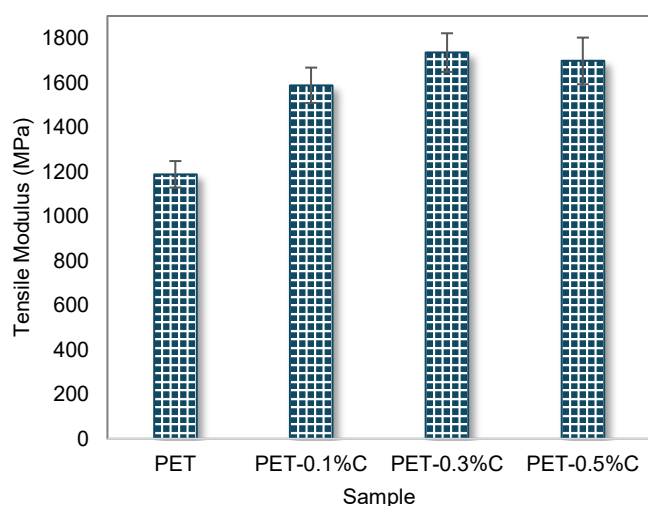


Figure 8. Tensile modulus of neat PET and PET composites reinforced with varying GNPs filler content (0.1–0.5 wt.% C).

The results demonstrate a clear and monotonic increase in the tensile modulus of PET as the concentration of GNPs-GNP filler rises, progressing from a baseline of 1188.64 MPa for neat PET to a maximum of 2098.02 MPa at a 0.5 wt. % C, representing a substantial 76.5% improvement in overall stiffness. This consistent reinforcement effect is attributed to the high intrinsic modulus of the GNPs filler, which effectively restricts the mobility of the PET polymer chains and facilitates efficient stress transfer from the flexible matrix to the rigid reinforcement phase. The steady upward trend in modulus indicates that the filler was well-dispersed within the polymer, successfully creating a reinforcing network that enhances the material's resistance to elastic deformation and makes it significantly more suitable for high-performance structural applications compared to the unfilled base polymer. The observed improvement in tensile modulus with increasing GNP filler content less than 0.5 wt.% C is consistent with previous studies by N. Azman et al. [20], which report that well-

dispersed graphene-based fillers enhance stiffness by restricting polymer chain mobility and improving interfacial stress transfer, while excessive filler loading may lead to agglomeration and reduced mechanical performance.

3.1.4. Yield Stress

Figure 9 represents the effect of GNPs filler concentration on the yield stress (MPa) of PET-matrix composites. Note the peak reinforcement at 0.3 wt.% C followed by a slight decline at 0.5 wt.% C due to potential particle agglomeration.

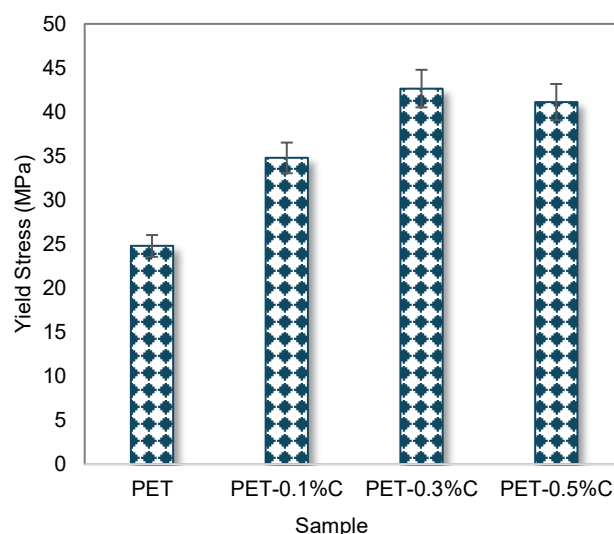


Figure 9. Effect of GNPs filler concentration on the yield stress (MPa) of PET-matrix composites.

The tensile yield stress of the PET-carbon composites demonstrates a significant reinforcement effect, increasing from a baseline of 24.8 MPa for neat PET to a peak of 42.6 MPa at a 0.3 wt. % C, representing a substantial 71.8% improvement in the material's resistance to permanent plastic deformation. This initial enhancement is attributed to the high interfacial adhesion between the carbon nanoparticles and the PET matrix, which facilitates efficient load transfer and restricts the long-range mobility of polymer chains. However, a slight decline in yield stress to 41.1 MPa was observed at 0.5 wt. % C. While stiffness typically continues to rise at this concentration, the yield strength diminishes due to microparticle agglomeration, where clusters act as localized stress concentrators and internal defects that facilitate premature yielding. Consequently, these results identify 0.3 wt. % C as the optimal filler loading for maximizing the structural integrity of the composite before the onset of particle-induced weakening. The UTS of the composites is increased with the incorporation of graphene and is maximum at 0.3 wt.% C graphene concentration. The improved UTS may be

due to the strong interfacial adhesion between the PET matrix and graphene for effective load transfer. In addition, the presence of graphene affects the ductile nature of the composites. Although the UTS is significantly increased, the strain at break behaves in a more intricate manner. At low graphene concentrations, the composites exhibit slightly higher ductility than pure PET, whereas, at higher concentrations, ductility is reduced because of the presence of agglomerates, which are known to act as stress concentrators and greatly reduce the ability to deform plastically. Similar to the results reported by Basheer A. Alshammari et al. [21] indicating that optimal tensile modulus is achieved when the nanofiller is uniformly dispersed, maximizing the interfacial area for stress transfer before the onset of particle clustering.

3.1.5. Maximum Stress

Figure 10 shows the impact of GNPs' filler concentration on the maximum stress also known as the ultimate tensile strength, of PET composites. The results indicate a peak strength at 0.3 wt.% C, with a subsequent reduction at 0.5 wt.% C due to filler-induced structural defects.

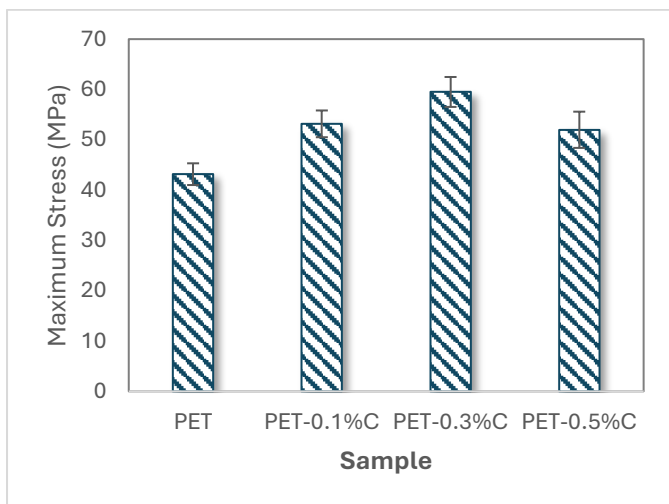


Figure 10. Impact of GNPs filler concentration on the maximum stress/ultimate tensile strength of PET composites.

The maximum stress (ultimate tensile strength) of the PET-carbon composites exhibits a significant reinforcement trend, increasing from 43.1 MPa for neat PET to a peak of 59.5 MPa at a 0.3 wt. % C, representing a 38% improvement in the material's peak load-bearing capacity. This enhancement is attributed to the effective dispersion of GNPs particles, which serve as rigid reinforcements that facilitate efficient interfacial load transfer from the polymer matrix. However, similar to the trend observed in yield stress, the maximum stress declines to 52.1 MPa at the 0.5 wt. % C, confirming that higher concentrations lead to nanoparticle agglomeration. These clusters create

localized stress concentrators and internal micro-defects that promote premature crack initiation, thereby limiting the maximum stress the composite can withstand before failure. Research by U. Habib et al. [22] highlights that while the modulus (stiffness) may continue to increase at higher filler loadings, the ultimate strength often decreases because large aggregates act as 'foreign bodies' or voids within the PET matrix, reducing the effective cross-sectional area that can support the load.

3.2. Morphological Characterization

The observations obtained from the dog bone samples after being subjected to tensile testing were distinct fracture characteristics across different PET-GNPs composites. The pure PET sample (Figure 11a) exhibited a relatively smooth fracture surface, indicative of typical polymeric failure. As the graphene content increased, the fracture surfaces became more irregular, with PET-0.1 wt.% C (Figure 11b) showing a slight increase in roughness. This trend continued with PET-0.3 wt. % C (Figure 11c) and PET-0.5 wt.% C (Figure 11d), where the fracture surfaces displayed more jagged edges and larger deformation zones. These observations suggest that the incorporation of graphene into the PET matrix alters the fracture mechanics, potentially enhancing toughness and resistance to brittle failure. Tensile strength is a critical property for materials subjected to mechanical loads, indicating the maximum stress a material can withstand while being stretched or pulled before breaking. Figure 11 displays photographs of the 3D-printed neat PET-GNPs' stress after undergoing a tensile testing.

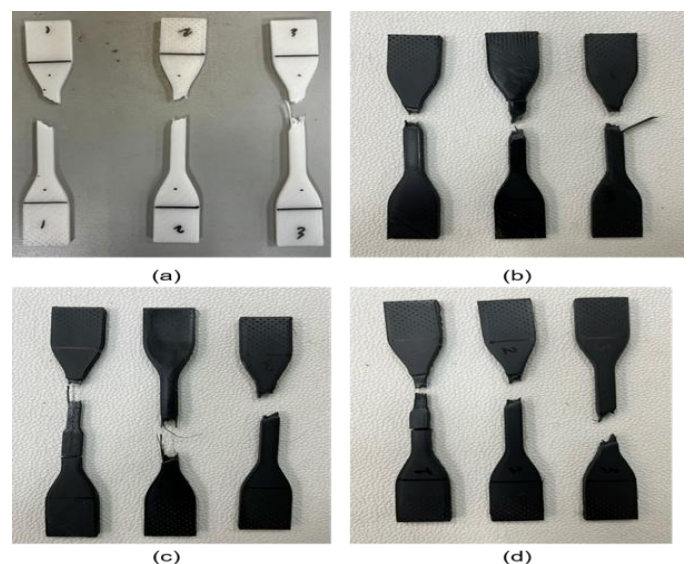


Figure 11. Photographs of 3D-printed with composition of PET and PET-Graphene material at different graphene concentrations after tensile testing: (a) PET, (b) PET-0.1 wt.% C (c) PET-0.3 wt.% C (d) PET-0.5 wt.% C

Figure 12 shows the detailed images of fractographic analysis shown in Figures 12a–d were performed on the transverse (cross-sectional) sections of PET-graphene composites at varying graphene concentrations (0 wt.% C, 0.1 wt. %, 0.3 wt.% C, and 0.5 wt.% C). These micrographs reveal the microstructural features that govern the mechanical behavior of the materials. In the case of neat PET, the SEM micrograph exhibits a relatively smooth and featureless fracture surface, which is characteristic of a brittle fracture. This agreed with the relatively smooth fracture surfaces of neat PET, suggesting a brittle fracture mode [23]. The absence of massive plastic deformation suggests low energy absorption before failure.

The addition of graphene to the PET matrix causes a noticeable change in the morphology of the fracture surface. At 0.1% graphene loading, the fracture surface begins to show rougher features with the presence of some dimples and microvoids, suggesting improved ductility. This is attributed to the improved distribution of stress and energy absorption by the graphene filler that impedes crack growth. The microvoids observed are local plastic deformations, which contribute to higher toughness of the composite [24], [25].

Increasing the content of graphene up to 0.3 wt.% C caused the fractographic observation images to reveal a rougher fracture surface with more dimpled morphologies. There is increased plastic deformation indicated, which means the composite can absorb more energy before failing, thus giving it higher fracture toughness. The graphene sheets provide a network to bridge cracks, hinder crack propagation, and increase the amount of work required to fracture the composite. For PET-0.3 wt.% C may arise from subtle microstructural differences, without evidence of significant particle agglomeration, ensuring uniform distribution of stress. At 0.5 wt.% C, SEM images exhibit mixed-mode fracture with some ductility and some brittleness. The fracture surface continues to have dimples from ductile modes next to cleavage as in brittle fracture. The mixed mode of fracture shows that graphene, while enhancing ductility could result in agglomeration when in excess. Such agglomerations may act as stress concentrators thereby reducing the composite capacity to plastically deform and therefore compromise toughness. The presence of these agglomerates can explain the observed slight decrease in tensile strength and fracture toughness at this concentration. SEM presents rather valuable information regarding fracture behavior of PET-graphene composites. The other visible microstructural features correspond with mechanical properties, confirming the importance of uniform nanofiller dispersion in enhancing fracture resistance. The analysis demonstrates the effectiveness of graphene nanoplatelets as a reinforcing agent, while underscoring that excess loading can be counterproductive due to agglomeration. The inclusion of graphene flakes into PET has significantly modified the fracture surface morphology. The SEM images

typically show a rough fracture surface in PET/graphene nanocomposites, indicative of improved energy dissipation mechanisms such as crack deflection, crack pinning, and graphene pullout.

The study by Choi revealed that a graphene monolayer incorporated into Al-doped ZnO (AZO) thin films on a PET substrate improved fracture toughness. SEM images demonstrated improved bending fracture resistance due to graphene's superior mechanical properties, with crack-initiating strain and fracture energy significantly enhanced compared to reference samples without graphene [26]. The graphene sheets caused crack deflection, crack pinning, debonding, fiber bridging, and pull-out, enhancing the overall fracture toughness [27]. The incorporation of uniform dispersion GNPs resulted in significant improvements of fracture toughness, elastic modulus, and ultimate strength of the nanocomposites, compared to pure epoxy [28]. The Py-LC-rGO showed better dispersion in the PET matrix than non-modified graphene. This enhanced nucleation ability led to thicker lamellar crystals and denser stacking of lamellae, considerably improving the impact toughness of the composite [29].

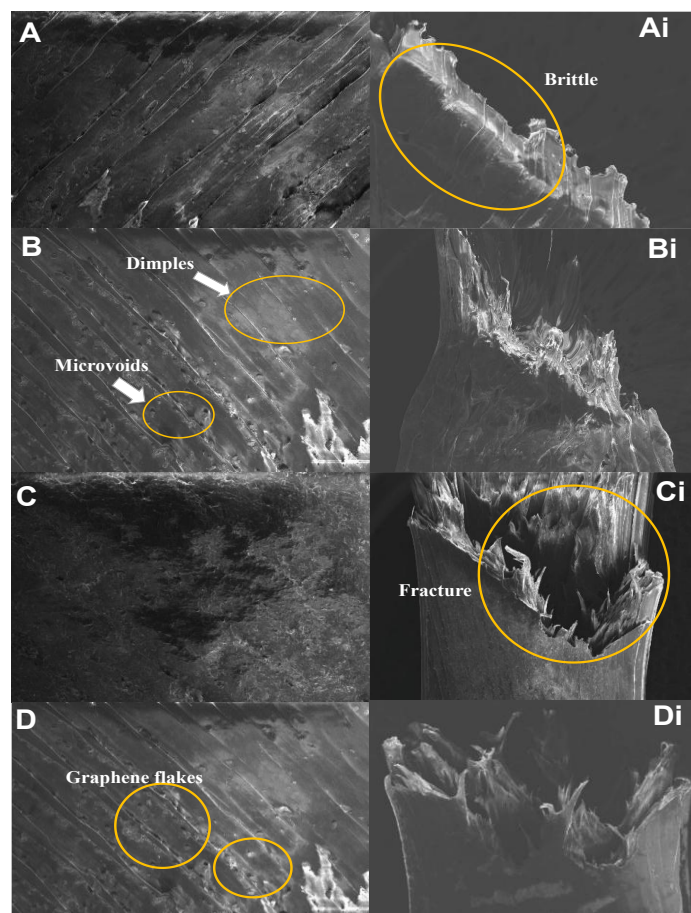


Figure 12. SEM micrographs of PET-Graphene composites at varying graphene concentrations: (A) 0 wt.% C, (B) 0.1 wt.% C, (C) 0.3 wt.% C, and (D) 0.5 wt.% C. Note: Left column (A–D): surface morphologies before fracture; right column (Ai–Di): corresponding fracture surfaces after fracture.

CONCLUSION

This study demonstrates that incorporating GNPs into PET significantly enhances mechanical strength while preserving ductility, making it a viable candidate for sustainable food packaging applications. The most pronounced tensile improvement occurred at 0.3 wt.% C GNP loading, whereas higher concentrations induced nanofiller agglomeration and a slight reduction in strength. SEM analysis supports these findings, revealing a transition from smooth brittle fracture surfaces in PET to rougher, dimpled morphologies in GNP-reinforced composites, signifying enhanced energy absorption and crack resistance. Indeed, these results show that controlled incorporation of GNPs yields PET composites with superior toughness, tensile strength, and crack propagation resistance, achieving an optimal balance between mechanical performance and processability. Moreover, in order to prevent GNP agglomeration at elevated loadings, maintaining homogeneous filler dispersion remains essential. These results not only demonstrate that PET/GNP composites are promising materials for robust food packaging, but they also emphasize how important it is to carefully adjust the amount of filler and the conditions of processing for large-scale industrial use.

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