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Low-Velocity Impact Properties of Hybrid PLA/Kenaf/Carbon Fiber Sandwich Bio-Composites Reinforced with Nanofillers

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ABSTRACT: The growing demand for lightweight and sustainable materials has driven increasing interest in biodegradable composites for structural applications. This study investigates the low-velocity impact response of hybrid PLA/kenaf/rayon-derived carbon fiber sandwich composites reinforced with graphene and nanoclay nanofillers. Skin layers were prepared with 1, 3, and 5 wt.% nanofiller loadings, while the core consisted of PLA modified with phenolic microspheres. Impact testing was conducted at 7 and 10 J to evaluate peak force, absorbed energy, and deformation behavior. Results indicate that 1 wt.% nanofiller loading generally provided higher absorbed energy compared to higher filler concentrations. Increasing filler loading to 5 wt.% did not result in further performance improvement. Graphene-filled laminates exhibited comparatively higher peak forces, whereas nanoclay-filled systems demonstrated greater displacement under impact. No full penetration occurred at the tested energy levels. The findings provide comparative insight into nanofiller effects on hybrid PLA-based sandwich composites under controlled low-energy impact conditions. Further microstructural characterization is recommended to validate dispersion and failure mechanisms.

KEYWORDS: Sandwich composite; polylactic acid; kenaf fiber; graphene; low-velocity impact

1 Introduction

The continuous search for materials that combine lightweight properties, high strength, and environmental sustainability has encouraged the development of advanced bio-based composites. In this context, sandwich structures have attracted growing attention due to their exceptional stiffness-to-weight ratio and capacity to absorb impact energy. A typical sandwich configuration comprises stiff and strong skin layers bonded to a low-density core, resulting in a material system that resists bending and absorbs energy efficiently under dynamic loading conditions. These structural advantages make sandwich composites

particularly suitable for applications in automotive body panels, aerospace interiors, marine decks, and other semi-structural components where energy absorption and damage tolerance are crucial [1].

Poly(lactic acid) (PLA) has emerged as one of the most promising thermoplastic matrices for sustainable composite development. Derived from renewable resources such as corn starch and sugarcane, PLA offers several desirable properties, including moderate strength, good transparency, and ease of processing. It also exhibits partial biodegradability, contributing to environmental sustainability objectives [2,3]. However, its inherent brittleness and low impact toughness limit its use in high-performance applications. Consequently, the reinforcement of PLA with fibers and nanofillers has become an effective strategy to enhance its toughness, strength, and thermal stability [4].

Among natural fibers, kenaf (*Hibiscus cannabinus*) has gained significant prominence as reinforcement for polymer composites. Extracted from the bast region of the stem, kenaf fiber possesses favorable structural and compositional characteristics that enable effective stress transfer between fiber and matrix [5]. Similar structure–property relationships have also been reported for other bast fibers, including okra and jute [6]. Kenaf fibers are lightweight, renewable, and biodegradable, offering an ecological advantage over conventional synthetic fibers. Nevertheless, natural fibers alone may not provide the strength and stiffness required for advanced structural applications. The hybridization of kenaf with carbon fiber has therefore been proposed as an effective method to balance mechanical performance with sustainability [7]. Furthermore, the successful incorporation of kenaf into PLA-based biocomposites supports its compatibility with biodegradable polymer matrices [8].

In addition to fiber reinforcement, the incorporation of nanofillers has been shown to further enhance interfacial adhesion, load transfer, and impact resistance in PLA-based composites. Graphene is particularly attractive because of its exceptional tensile strength, electrical and thermal conductivity, and atomic-level thickness that enables strong interfacial interaction with polymer matrices [9]. The carboxyl functionalization of graphene further improves compatibility with the PLA matrix, promoting uniform dispersion and improved stress transfer [10]. Nanoclay has demonstrated the potential to enhance mechanical stiffness, thermal stability, and flame retardancy at relatively low filler loadings [11,12]. When properly dispersed, nanoclay platelets can form intercalated or exfoliated structures within the polymer matrix, contributing to improved load transfer and reducing crack propagation [13]. The combined use of nanoclay and graphene within fiber-reinforced PLA systems can thus provide a synergistic effect, resulting in superior energy absorption and impact tolerance.

Previous research has reported improvements in static mechanical performance of hybrid PLA composites reinforced with natural and synthetic fibers as well as nanofillers [14,15]. However, studies addressing the dynamic response of such systems under low-velocity impact remain limited. Impact behavior is of particular importance for sandwich composites since they are often subjected to accidental or service impacts that may lead to internal damage such as delamination, fiber breakage, and matrix cracking. The complex interaction between the skin and the core during impact determines the overall energy absorption capability and damage tolerance of the structure. Recent studies have shown that impact energy, face-sheet characteristics, and core configuration significantly influence peak impact force, energy absorption, and damage morphology in sandwich composites [16]. Therefore, a comprehensive evaluation of low-velocity impact response is essential to ensure the reliability of hybrid biocomposites under service conditions.

This study developed a hybrid sandwich composite based on PLA reinforced with woven kenaf and carbon fibers as the skin layers and a lightweight core made from PLA mixed with phenolic microspheres. The PLA matrix in the skin was blended with nanofillers such as graphene and nanoclay at concentrations of 1, 3, and 5 wt.%, while the core was produced by adding phenolic microspheres at ratios of 1–5 wt.%. The inclusion of phenolic microspheres enhanced energy absorption, structural integrity, and reduced density, whereas the

nanofillers improved interfacial bonding and mechanical performance. The main objective of this work is to comprehensively evaluate the low-velocity impact behavior of hybrid PLA kenaf carbon fiber sandwich composites reinforced with nanofillers at different energy levels, focusing on impact force, absorbed energy, and failure morphology to support the development of sustainable materials for medium-load applications.

2 Materials and Methods

2.1 Materials

PLA pellets were used as the primary thermoplastic matrix. Graphene nanopowder and nanoclay were incorporated as nanofillers at loadings of 1, 3, and 5 wt.% for the skin laminates. Woven kenaf fiber mats served as natural reinforcement and were alkali-treated using an NaOH solution to improve fiber matrix adhesion. Rayon-derived carbon fiber fabric (0°/90° woven) was used as synthetic reinforcement in the hybrid skin layers. Phenolic hollow microspheres (Grade BJO-0840, Malayan Adhesive & Chemicals, Malaysia), synthesized from bio-based materials such as lignin, cellulose, and tannin, were incorporated into the PLA matrix at a loading of 4 wt.% to produce a lightweight core material.

2.2 Sandwiched Composites Fabrication

PLA pellets were dried at 80°C for 24 h prior to processing. Nanofillers were compounded with PLA using a twin-screw extruder at 160°C–180°C, with the formulations of the hybrid skin composites summarized in Table 1. The extrudates were pelletized and compression molded into thin films at 180°C under 5 MPa pressure. Hybrid skin laminates were fabricated by stacking carbon fiber and kenaf fiber layers alternately with PLA nanocomposite films. The laminates were consolidated via hot pressing at 180°C under 5 MPa pressure and subsequently cooled under pressure. The sandwich structure was assembled by placing the phenolic-microsphere-modified PLA core between two hybrid skin laminates, followed by consolidation under controlled temperature and pressure.

Table 1: Formulation of hybrid skin composites.

Sample Code	Nanofiller Types	Nanofiller Loading (wt.%)
HG1	Graphene	1
HG3	Graphene	3
HG5	Graphene	5
HN1	Nanoclay	1
HN3	Nanoclay	3
HN5	Nanoclay	5

Note: *H* = hybrid composite; *G* = graphene; *N* = nanoclay; the numbers (1, 3, and 5) indicate the nanofiller loading (wt.%).

For the fabrication of the skin composites, hybrid laminates were prepared by stacking woven kenaf and carbon fiber mats with the PLA nanocomposite films according to the configurations of carbon/kenaf/carbon/kenaf/carbon. The stacked layers were consolidated through hot-press molding at 180°C under 5 MPa pressure for 15 min and subsequently cooled under pressure to form uniform hybrid laminates. These laminates functioned as the outer skin layers of the sandwich structure. For the core fabrication, PLA pellets were blended with 4 wt.% phenolic microspheres before being compounded using the twin-screw extruder at 160°C–180°C, followed by hot pressing to produce lightweight core panels. The inclusion

of phenolic microspheres enhanced the energy absorption capability while reducing the density of the core material.

Finally, for the fabrication of the sandwich composites, the PLA/phenolic microsphere core was placed between two skin layers as illustrated in Fig. 1. The assembled structure was bonded and consolidated through hot pressing at 180°C under a pressure of 5 MPa for 10 min, followed by controlled cooling to room temperature under pressure to preserve dimensional stability and minimize residual stress. The fabricated sandwich composite panels were then cut into standard test specimens using a precision diamond saw for subsequent mechanical testing.

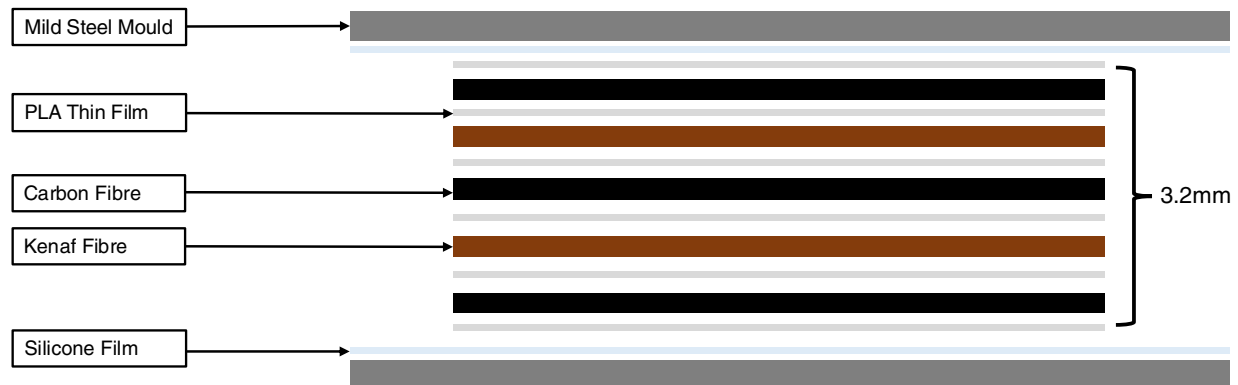


Figure 1: Concept of hybrid sandwich composite.

Laminated hybrid PLA/Kenaf/Carbon nanocomposites were prepared by alternately stacking five layers of reinforcement separated by thin PLA nanocomposite films, as shown in Fig. 2. Silicone release films were placed on both mold surfaces to prevent adhesion and produce smooth laminate surfaces. The lay-up was hot-pressed at 190°C under 20 t of pressure using a 26 mm × 26 mm × 3.2 mm mold, with 15 min of preheating followed by 15 min of pressing. The cured laminates were cooled to room temperature, demolded, and cut into test specimens.

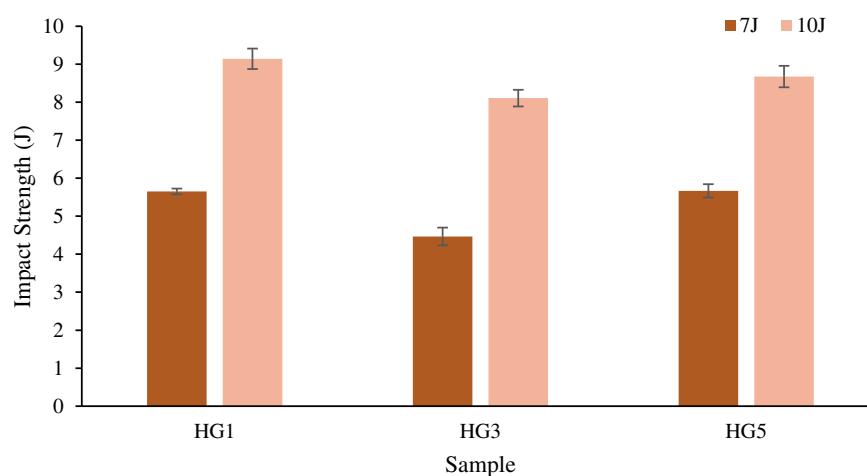


Figure 2: Impact strength of graphene-reinforced hybrid PLA/kenaf/carbon fiber sandwich composites at 7 and 10 J.

2.3 Low-Velocity Impact Testing

Low-velocity impact tests were conducted using a drop-weight impact tester in accordance with ASTM D7136. A stainless-steel impactor weighing 5.101 kg and equipped with a hemispherical nose of 12 mm diameter was released from predetermined heights to achieve incident impact energies of 7 and 10 J. Specimens measuring 150 mm × 100 mm × 3.2 mm were tested, with five specimens ($n = 5$) tested for each configuration. During impact, the rebound velocity of the impactor was measured using optical sensors, allowing the absorbed energy to be determined from the difference between the incident and rebound energies [17]. The impact energy (E) was calculated using the gravitational potential energy equation:

$$E = mgh$$

where E is the impact energy (J), m is the mass of the impactor (kg), g is the acceleration due to gravity (9.81 m/s^2), and h is the height (m) from which the impactor was released. The corresponding impact energy levels were set according to the parameters listed in Table 2.

Table 2: The value of impact energy and the striker height.

Impact Energy (J)	Height of Striker (m)
7	0.140
10	0.20

3 Results and Discussion

A limitation of the present study is the absence of neat PLA and intermediate control laminates (e.g., PLA/KF, PLA/CF, and PLA containing only phenolic microspheres), which would enable quantitative isolation of the individual contribution of each reinforcement component. Therefore, the present findings should be interpreted as comparative observations among the investigated hybrid sandwich composites rather than definitive evidence of the intrinsic reinforcing effect of the nanofillers. The low-velocity impact response of hybrid PLA/kenaf/carbon fiber sandwich composites reinforced with nanofillers was analyzed to assess the effect of graphene and nanoclay inclusion under different impact energies. The study focused on absorbed energy, peak impact force, deformation, and post-impact damage morphology to determine the influence of nanofiller type and loading on energy dissipation and damage evolution mechanisms. Two impact energy levels, 7 and 10 J, were selected to simulate low to moderate impact conditions typically encountered in semi-structural applications.

3.1 Impact Response of Graphene-Reinforced Composites

The low-velocity impact response of graphene-reinforced sandwich composites (HG1, HG3, and HG5) was evaluated at 7 and 10 J to assess the influence of nanofiller concentration on peak force and absorbed energy. At 7 J, all specimens exhibited non-perforated responses characterized by localized indentation and limited delamination. Among the tested formulations, HG1 demonstrated comparatively higher absorbed energy, whereas HG3 and HG5 showed reduced absorption trends.

The reduction in absorbed energy at higher graphene contents may be associated with reduced deformation tolerance at increased filler loading. Similar trends have been reported in graphene-reinforced polymer nanocomposites, where excessive graphene loading may promote nanoparticle agglomeration and increase composite stiffness, creating stress concentration sites that reduce energy dissipation through matrix

deformation and promote brittle fracture [18]. However, direct microstructural evidence was not obtained in the present study, and therefore interpretations remain based on mechanical response trends.

At 10 J, increased peak forces were observed relative to 7 J for all graphene-modified laminates. Although variations among HG1, HG3, and HG5 were recorded, the overall differences were moderate. The force–displacement curves indicated that increasing graphene concentration resulted in slightly reduced displacement at peak load, suggesting increased stiffness response under impact. No complete penetration occurred at either 7 or 10 J. Damage morphology primarily consisted of front-face indentation and limited back-face cracking. These findings indicate that, among the hybrid composites investigated, more prominently than total energy absorption under the tested impact conditions.

The data for these energy levels seem to be slightly different among other composites, which shows that the impact strength is not affected by the addition of graphene. Minor variations were observed among configurations; however, overall trends were consistent across repeated tests, which shows the impact strength did not vary significantly with increasing graphene content. By referring to Table 3, it may be remarked that for HG3 at an impact energy level of 10 J, the absorbed energy reached 10.82 J, the peak force reached 2.34 kN, and the peak deformation reached 10.09 mm, while the energy to peak deformation reached 10.09 mm, while the energy to peak deformation reached 10.82 J. At the 7 J impact energy level, HG1 recorded the highest energy to peak deformation (7.36 J) among the graphene-reinforced composites, followed by HG5 (7.12 J) and HG3 (5.74 J). As a result, the peak force reached 2.52 kN with a maximum deformation of 4.64 mm. Therefore, the absorbed energy attained 7.21 J. Otherwise, the lowest energy was absorbed by the HG5 composite, where the peak force and maximum deformation reached 2.42 kN and 5.52 mm, respectively. The energy to peak deformation of 10.77 J was the lowest among the graphene-reinforced composites at this 10 J impact energy level. However, this behavior may be attributed to permanent deformation, where a substantial portion of the supplied impact energy was dissipated through irreversible damage.

Table 3: Impact properties of graphene-reinforced composites at 7 and 10 J.

Energy	Sample Code	Peak Force/Load (kN)	Peak Deformation/Displacement (mm)	Absorbed Energy (J)	Energy to Peak Deformation (J)
7 J	HG1	2.52	4.64	7.21	7.36
	HG3	2.17	6.34	5.74	5.74
	HG5	1.91	4.49	6.90	7.12
10 J	HG1	2.06	7.64	10.72	11.34
	HG3	2.34	10.09	10.82	10.82
	HG5	2.42	5.52	10.06	10.77

The energy–time curves at 7 J (Fig. 3a) and 10 J (Fig. 3b) confirmed that increasing graphene content enhanced stiffness but reduced the total deformation, indicating a shift toward a stiffer and more brittle response. The force-displacement curves at 7 J (Fig. 4a) and 10 J (Fig. 4b) further illustrate the impact response of the graphene-reinforced composites. HG1 exhibited a maximum displacement of 4.63 mm, whereas HG3 recorded 4.20 mm, indicating reduced ductility with increasing nanofiller content.

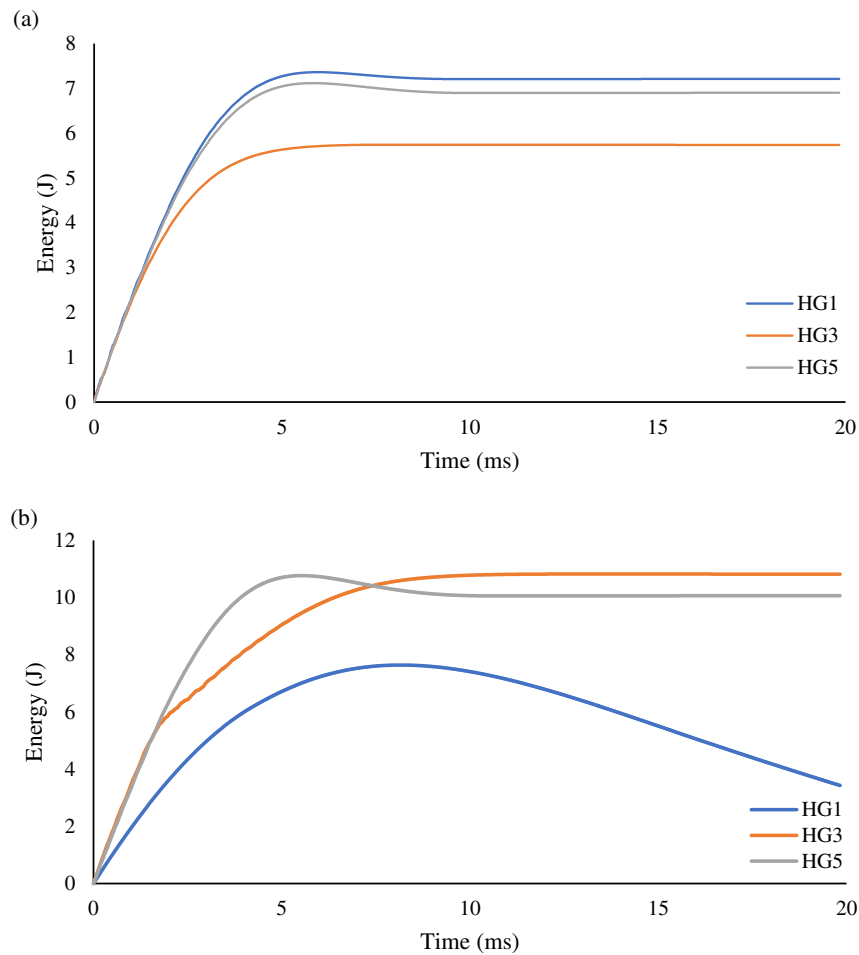


Figure 3: Energy-time curves for HG1, HG3, and HG5 composites with inclusion of graphene during impact energy levels of (a) 7 and (b) 10 J.

In addition, the back face of the G5 composite specimen shows an irregular crack and limited delamination, as shown in Fig. 5. As the composite plate was impacted, the load was spread more evenly over the bottom face sheet, creating high forces that caused delamination and a greater cracking diameter. When there was little support from the composite structure, lower forces were required to shear the face sheet [19]. Therefore, there is not full penetration that occurs during impact at 7 and 10 J. The experimental results in this project demonstrated that failure by impactor penetration occurred on all samples at 7 and 10 J impact energy levels. Both front and back faces of specimens clearly show light cracks, while HG5 had smaller cracks compared to others. Extended delamination appears on the back face of HG5. At this impact energy level, lots of fiber damage occurs on both sides of the impacted area. A combination of cracking and delamination on the face sheet of the impacted area occurs during impact at the high energy level.

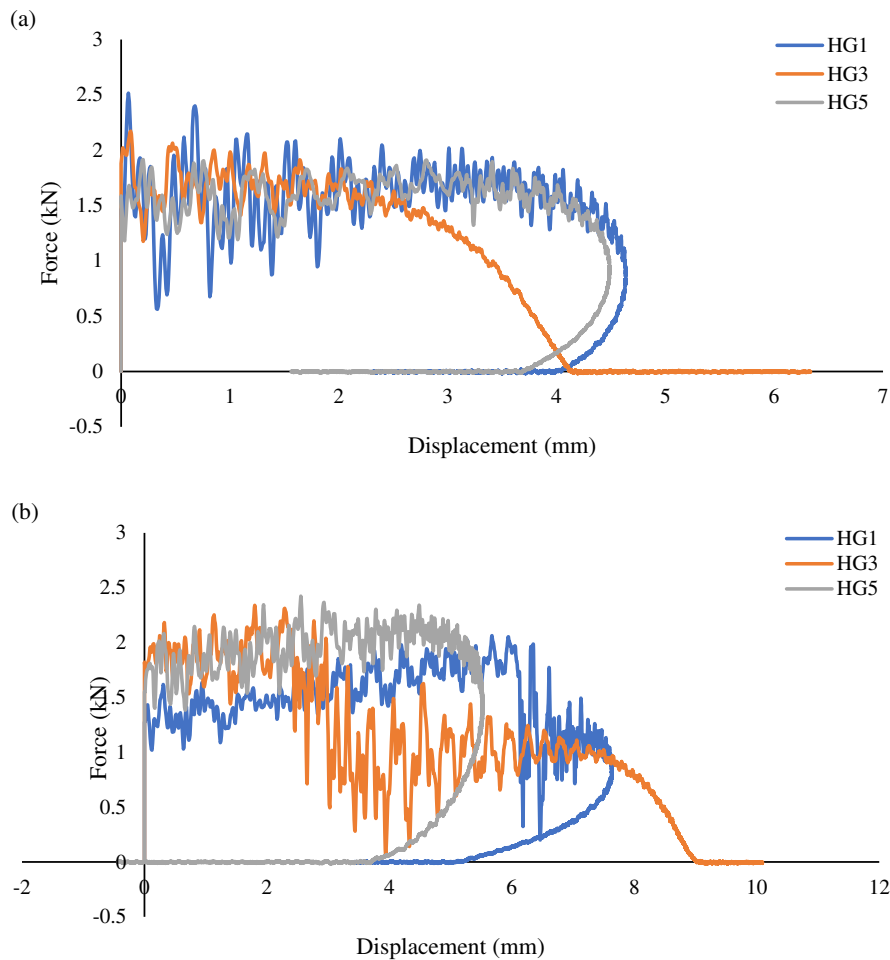


Figure 4: Force-displacement curves for HG1, HG3 and HG5 composites with inclusion of graphene during impact energy levels of (a) 7 and (b) 10 J.

Fig. 5 also shows that the low-velocity impact response of samples has shown a different dependence on the presence of graphene, which was investigated at different impact energy levels to determine the capability of laminates to disperse the impact energy. The test shows that the impact resistance is affected by the graphene content of the composites at different energy levels at 7 and 10 J. It is worth noting that the overall impact energy of 10 J was chosen to be higher than the impact resistance of any prepared composite to measure the absorbed energy of different configurations at the perforation. At an energy level of 7 J, HG1 shows the highest energy dissipation with 7.21 J. In fact, almost all the energy was returned, with residual energy values ranging from 5 to 7 J. This means that the composite only works in the elastic zone, where dissipation phenomena like delamination, interface failure, and matrix cracking are limited [20]. At 7 J, HG1 demonstrated relatively higher absorbed energy compared to HG3 and HG5. A significant portion of the incident energy was elastically recovered at 7 J, as indicated by the rebound portion of the force-displacement response. The response primarily involved elastic deformation with limited damage progression, where damage initiation was largely confined to localized matrix deformation, interfacial debonding, and minor delamination without catastrophic penetration, which is characteristic of sandwich composite structures subjected to low-velocity impact [20,21]. However, HG3 has the lowest energy dissipation with 5.74 J and returns about 5.6 J. Then, HG5 exhibited the highest absorbed energy at an impact energy level of 10 with

10.76 J, whereas HG3 had higher energy dissipation at 10.82 J compared to HG1, which had slightly lower energy dissipation and absorbed energy with 10.72 J. It is important to note that the measured absorbed energies for HG1 and HG5 during the 7 J energy level are almost similar, while HG1 and HG5 during the 10 J energy level are almost different.

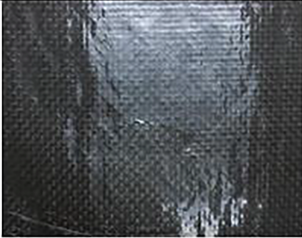
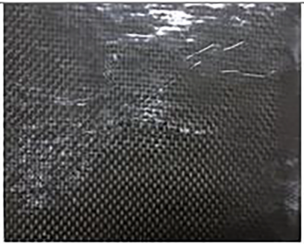
Energy	Plate	HG1	HG3	HG5
7J	Top			
	Bottom			
10J	Top			
	Bottom			

Figure 5: Front and back image of selected sample for HG1, HG3 and HG5 subjected to low velocity impact with 7 and 10 J energy level.

3.2 Impact Response of Nanoclay-Reinforced Composites

Nanoclay-reinforced composites (HN1, HN3, HN5) displayed distinct impact characteristics compared to graphene-reinforced systems (Fig. 6). At 7 J, HN3 exhibited the highest absorbed energy (7.45 J), followed closely by HN1, while HN5 showed a slight decrease in impact resistance. The corresponding peak forces ranged from 1.73 to 1.86 kN. The enhanced performance at moderate nanoclay loading may be associated with improved nanoclay dispersion and filler–matrix interactions within the PLA matrix, which contribute

to improved mechanical response [12,22]. At 10 J, both HN1 and HN3 demonstrated significant increases in absorbed energy (9.77 and 9.53 J, respectively), indicating that the presence of nanoclay facilitated progressive energy dissipation under higher impact loads.

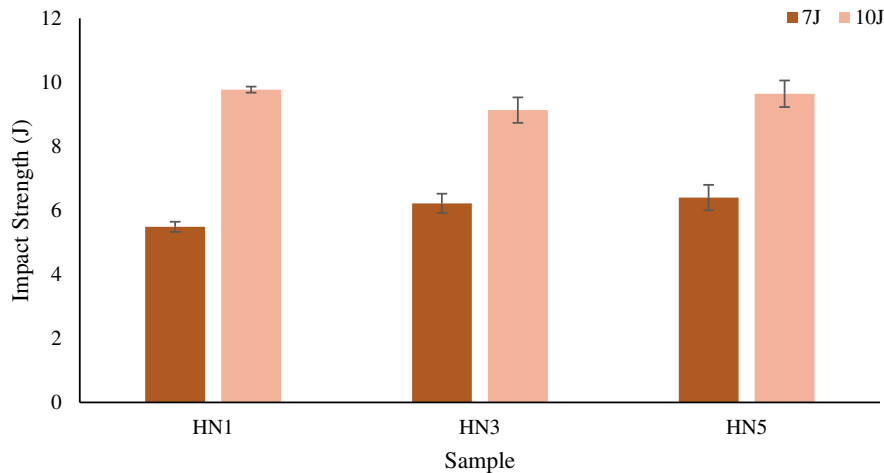


Figure 6: Impact strength of nanoclay-reinforced hybrid PLA/kenaf/carbon fiber sandwich composites at 7 and 10 J.

The nanoclay-reinforced laminates (HN1, HN3, HN5) exhibited distinct deformation characteristics compared to the graphene-modified systems. At 7 J, all samples remained in a sub-penetration regime, with visible surface indentation and limited delamination. Among the tested concentrations, HN1 and HN3 showed slightly higher absorbed energy compared to HN5. The force–displacement responses revealed broader displacement ranges in nanoclay-filled laminates compared to graphene-filled systems, indicating greater deformation capacity under similar loading conditions. The increased displacement observed in nanoclay-filled composites is consistent with previous studies demonstrating that layered silicates promote progressive damage development and improve impact energy dissipation through crack deflection mechanisms [23]. This behavior may be associated with differences in filler–matrix interaction; however, confirmation of dispersion state was beyond the scope of the current work. At 10 J, nanoclay-reinforced laminates demonstrated increased displacement values compared to graphene-reinforced counterparts. Although absorbed energy values varied among concentrations, 1 wt.% nanoclay generally exhibited improved absorption compared to higher filler loading. Damage patterns included front-face indentation and localized rear-face cracking, with no catastrophic perforation. These observations are consistent with previous studies, suggesting that nanoclay promotes progressive damage evolution and improves deformation tolerance under low-velocity impact loading [23]. The observed behavior suggests enhanced deformation tolerance compared with other hybrid laminates in this study under low-energy impact loading. Future studies including fracture surface analysis would be beneficial to clarify crack propagation mechanisms.

The data for this energy level appears to be slightly different from other composites, which show that impact strength is not affected by the addition of nanoclay, as tabulated in Table 4. Alternatively, HN1 showed the highest at an impact energy level of 10 J, where the absorbed energy reached 9.77 J, with a peak force and deformation up to 1.75 kN and 7.94 mm. The peak deformation energy increased up to 7.94 J. Instead, the lowest energy absorbed with 8.91 J for HN3, with the peak force reaching 1.59 kN and deformation of 9.94 mm. The energy of 11.36 J for peak deformation was attained.

Table 4: Impact properties of nanoclay-reinforced composites at 7 and 10 J.

Energy	Sample Code	Peak Force/Load (kN)	Peak Deformation/Displacement (mm)	Absorbed Energy (J)	Energy to Peak Deformation (J)
7 J	HN1	1.86	5.03	7.25	7.31
	HN3	1.62	5.95	7.45	7.88
	HN5	1.52	6.41	7.05	8.01
10 J	HN1	1.75	7.94	9.87	11.42
	HN3	1.59	9.94	8.91	11.36
	HN5	1.37	11.58	10.05	11.49

The energy–time responses (Fig. 7a,b) showed broader peaks and larger rebound zones compared to the graphene-filled composites, suggesting a more ductile and resilient impact response. The force–displacement curves (Fig. 8a,b) demonstrate the deformation behavior of the nanoclay-reinforced composites under impact loading. At 10 J, HN3 achieved a maximum deformation of 9.94 mm, almost double that of the graphene-filled composites, indicating a higher capacity to absorb and dissipate impact energy. The enhanced deformation behavior observed in the nanoclay-reinforced systems may be associated with nanoclay dispersion and filler–matrix interactions within the PLA matrix, which can influence stress transfer and mechanical performance [24]. The enhanced displacement observed in nanoclay-filled systems suggests greater deformation tolerance under impact loading. These observations are also consistent with Ahmed et al. [25], who reported damage-mitigation mechanisms associated with nanoclay reinforcement in polymer-based composites.

As shown in Fig. 9, the impact damage morphology varied significantly among the hybrid nanocomposite samples (HN1, HN3, and HN5). For HN3 and HN5, face sheet cracking propagated from the point of impact across the specimen, oriented perpendicular to the applied compressive load. In contrast, HN1 exhibited a shorter and less pronounced ‘X’-shaped crack pattern. At an impact energy of 7 J, no complete penetration was observed; however, visible surface cracking and delamination occurred on both the front and back faces of the composite specimens. The extent and pattern of the damage differed between samples, indicating variation in energy absorption and failure mechanisms.

The delamination region within the laminates was assessed by monitoring the change in PLA opacity, while internal delamination not associated with the outer faces was excluded from this analysis. From the first impact, delamination spread across the unsupported region of the specimen and progressively increased with repeated impacts, though it did not cover the entire area except in cases of complete perforation. At 10 J impact energy, the delamination on the rear face was relatively small for HN3 and HN5, where the front face damage appeared circular. The HN5 composite displayed an inclined ‘X’-shaped impact mark and partial penetration, evidenced by a small hole at the center of the impacted area.

Fiber damage was initially confined to the contact zone with the impactor tip, with fiber pull-out extending along the fiber direction from the point of impact [26]. At higher impact energies, combined face sheet cracking and delamination were observed, particularly on the bottom face sheet, which also exhibited partial penetration and extensive delamination when subjected to compressive loading, consistent with damage mechanisms commonly reported for sandwich composite structures subjected to low-velocity impact [27–29]. The observed damage progression suggests that the sandwich architecture effectively distributed

impact loads over a larger area, delaying catastrophic failure through progressive core deformation and face-sheet delamination [30]. Overall, HN5 showed improved resistance to penetration compared with HN1 and HN3, indicating enhanced energy absorption and structural integrity.

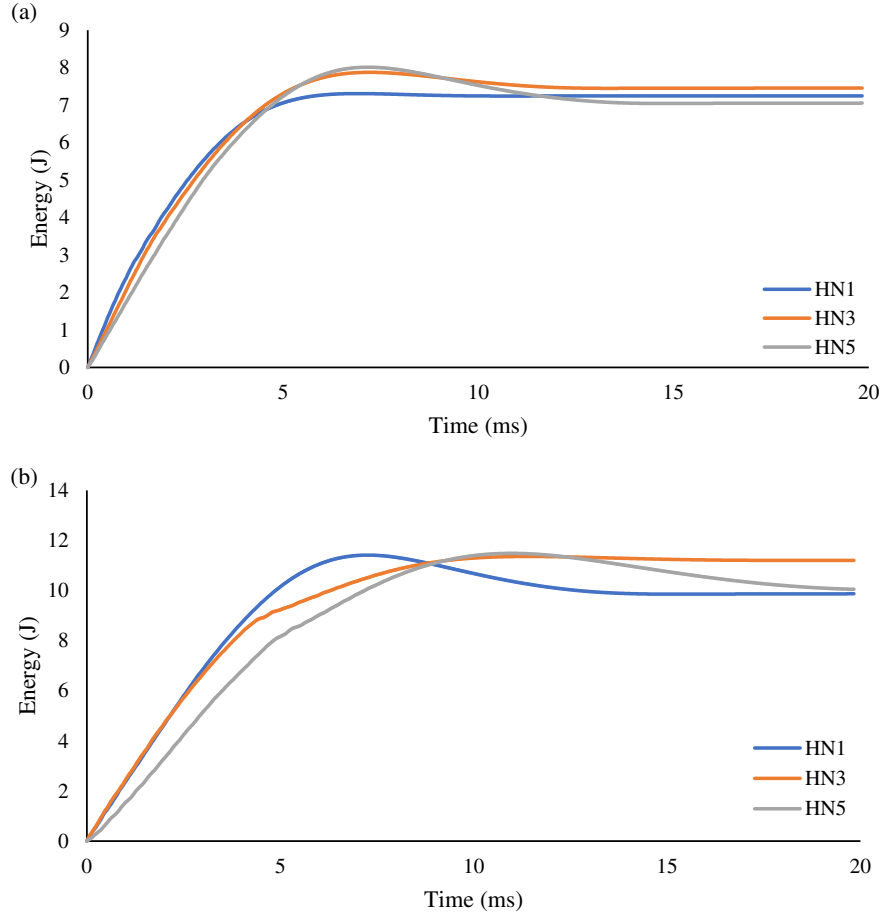


Figure 7: Energy-time curves for HN1, HN3 and HN5 composites with inclusion of nanoclay during impact energy levels of (a) 7 and (b) 10 J.

3.3 Comparative Analysis between Graphene and Nanoclay Composites

Comparing the two nanofiller systems, graphene provided higher stiffness and peak load-bearing capacity, while nanoclay contributed to better energy absorption and deformation capability. Graphene's two-dimensional sheet structure enhances modulus and tensile strength but limits chain mobility, leading to brittle fracture at higher impact energies [9]. Nanoclay, on the other hand, introduces layered silicate structures that facilitate energy dissipation through interlayer shear and interfacial sliding [12,23]. The hybrid fiber configuration, combining kenaf and carbon, also plays a key role by bridging cracks and maintaining structural integrity during impact, as observed by Karsandik et al. [16] and Kueh et al. [30].

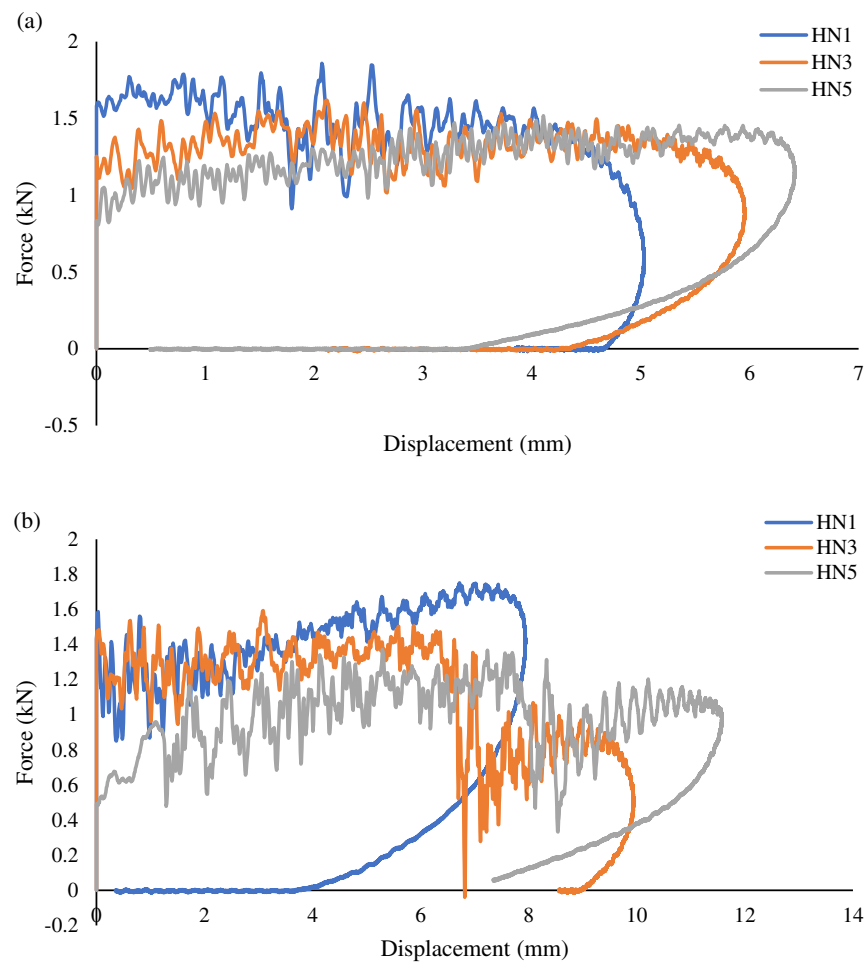


Figure 8: Force-displacement curves for HN1, HN3 and HN5 composites with inclusion of nanoclay during impact energy levels of (a) 7 and (b) 10 J.

The results confirm that the synergy between natural fibers and biosourced rayon-based carbon fibers, together with optimally dispersed nanofillers, plays a critical role in enhancing the impact resistance of biodegradable sandwich composites. The phenolic microsphere core contributed to energy absorption by deforming elastically during the impact event, reducing stress transmission to the skins. Similar energy dissipation mechanisms have been reported for hybrid foam cores in PLA-based sandwich composites by Zhao et al. [31] and Pathipaka et al. [32]. Recent studies have further demonstrated that hybrid sandwich composites incorporating optimized face sheets and lightweight cores achieve an effective balance between impact resistance, structural stiffness, and energy absorption for lightweight engineering applications [24]. The combined reinforcement strategy therefore enhances structural resilience and sustainability, aligning with the requirements of medium-load applications in the automotive and aerospace sectors.

Overall, the low-velocity impact behavior of hybrid PLA/kenaf/carbon fiber sandwich composites was strongly dependent on the type and loading of nanofiller. Graphene reinforcement resulted in peak load capacity, while nanoclay improved energy absorption and deformation resilience. Optimal filler loading between 1 and 3 wt.% resulted in the best balance between strength and toughness. The combination of hybrid fiber reinforcement and nanoscale fillers provided effective energy dissipation, structural stability, and reduced brittle fracture. These results demonstrate the feasibility of using biodegradable hybrid

sandwich composites in medium-load applications where sustainability and mechanical performance are equally critical.

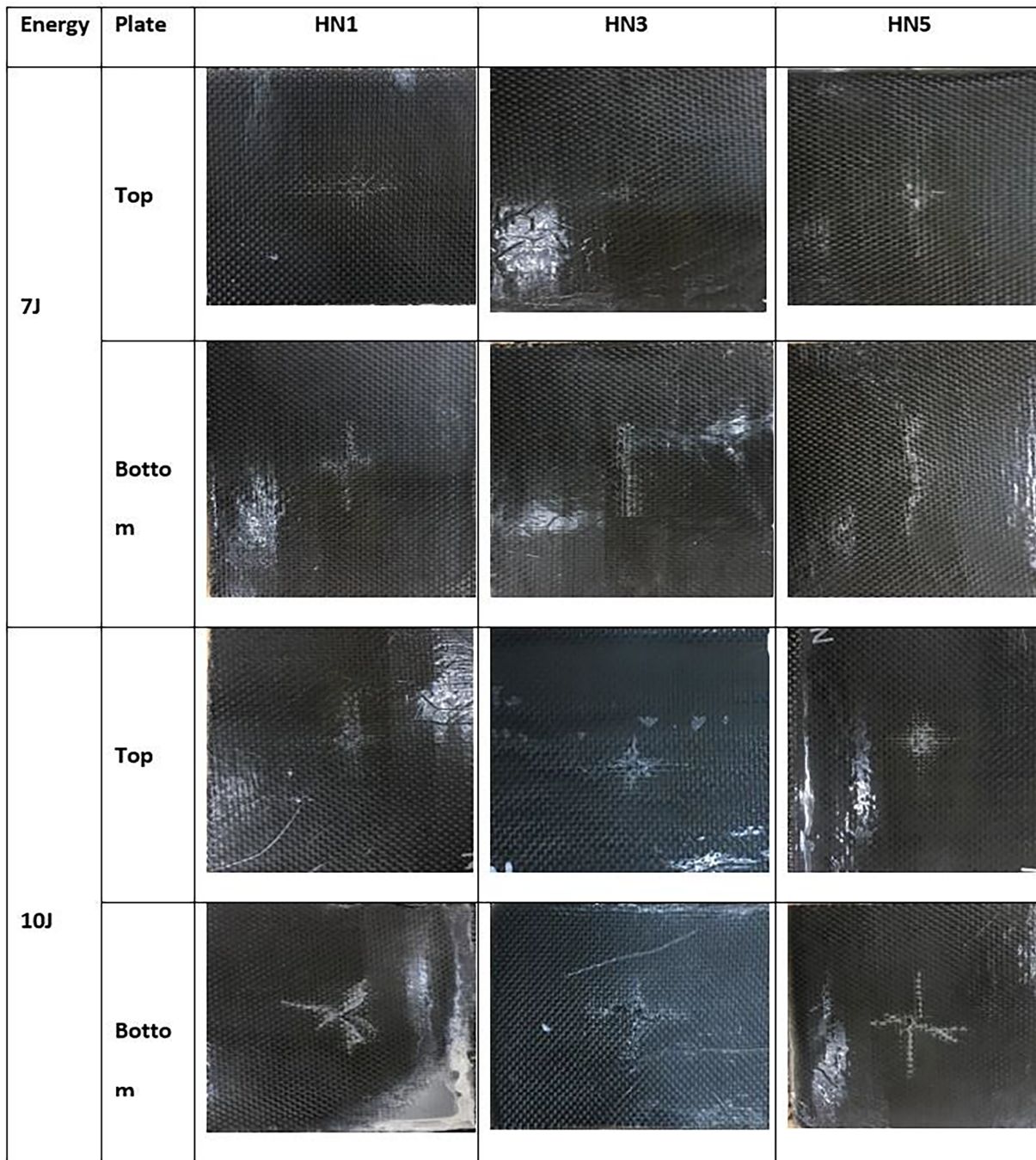


Figure 9: Front and back images of selected samples for HN1, HN3 and HN5 subjected to low-velocity impact with 7 and 10 J energy levels.

The present investigation compares only hybrid sandwich configurations containing different nanofiller types and loadings. Because neat PLA and intermediate control laminates (PLA/KF, PLA/CF, and PLA

containing only phenolic microspheres) were not included, the individual contribution of each reinforcement constituent cannot be quantitatively isolated. Therefore, the observed performance differences should be interpreted as comparative trends among the investigated hybrid systems. Future work incorporating appropriate baseline specimens, together with detailed microstructural characterization, will enable more rigorous structure–property relationships to be established.

4 Conclusion

The present study demonstrated the comparative low-velocity impact performance of graphene- and nanoclay-reinforced hybrid PLA/kenaf/rayon-derived carbon fiber sandwich composites under identical testing conditions. Among the investigated formulations, composites containing 1 wt.% nanofiller generally exhibited superior impact performance compared with higher nanofiller loadings. Graphene reinforcement resulted in higher peak load-bearing capacity, whereas nanoclay enhanced deformation tolerance and energy absorption. No complete penetration was observed at the tested impact energies, indicating that the hybrid sandwich structures possessed adequate damage tolerance under low-velocity impact loading. These findings demonstrate the potential of hybrid PLA-based sandwich composites as sustainable lightweight materials for medium-load applications. The conclusions presented in this work are limited to the comparative performance of the investigated hybrid sandwich composites. Since neat PLA and intermediate control laminates were not included, the individual contribution of each reinforcement constituent could not be quantitatively isolated. Future studies incorporating appropriate baseline specimens together with detailed microstructural characterization will provide a more comprehensive understanding of the structure–property relationships and the individual and synergistic effects of each reinforcement constituent.

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