STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Issue 2, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

High-Performance Carbon Nanotube-Reinforced Biodegradable Polymer Composites for Packaging

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Abstract

The growing issues concerning the properties of petroleum-based plastics on the environment increased the demand for biodegradable alternatives and polylactic acid (PLA) is one of the most promising options available. However, its poor toughness, thermal resistance, and barrier properties limit broader applications in sustainable packaging. This study reports the fabrication and characterization of PLA-based nanocomposites reinforced with carbon nanotubes (CNTs) at varying loadings (0.1-2 wt.%). Structural analysis (FTIR, XRD) confirmed strong interfacial interactions and increased crystallinity, while FESEM revealed homogeneous dispersion up to 1 wt.% CNTs. Mechanical testing demonstrated a tensile strength enhancement of over 40% at 1 wt.% CNTs, with corresponding improvements in modulus and impact strength. Thermal analysis (DSC, TGA) indicated higher glass transition and degradation temperatures, confirming improved stability. The barrier property test demonstrated this trend dramatically by providing substantial decreases in oxygen and water vapor transmission rates, reflecting CNTs' ability to provide torturous diffusion paths. The tests in composting confirmed that the composites were biodegradable, although they exhibited slightly reduced degradation kinetics compared to neat PLA. All in all, CNTs reinforcement improved the mechanical, thermal, and barrier properties of PLA without compromising compostability, making them competitive candidates for future eco-friendly packaging.

Keywords: Biodegradable polymers, Polylactic acid (PLA), Carbon nanotubes (CNTs), Nanocomposites, Mechanical properties

INTRODUCTION

The increasing environmental concerns associated with the traditional petroleum based plastics has exponentially elevated the interest to develop and commercialize a new category of plastic products which can be biodegraded especially towards packaging applications that are sustainable and environmentally sound. Conventional plastics like polyethylene (PE) and polypropylene (PP) continue to dominate the packaging sector because of their durability, cost-effectiveness, and versatile functionality. However, their persistence in the environment and contribution to greenhouse gas emissions during both production and disposal have raised serious concerns regarding plastic waste accumulation and long-term ecological damage. In response, researchers and industries worldwide have increasingly focused on biodegradable polymer systems as potential substitutes. Biodegradable polymers including polylactic acid (PLA), polyhydroxyalkanoates (PHAs), starch-based polymers, and poly(butylene succinate)

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Received Date: January 31, 2026
Accepted Date: February 10, 2026
Published Date: April 14, 2026

Citation: Chandra Shekhar Verma, Renu Dhetarwal, Mohammed Tajammul Hussain, Mohammed Faisal Ahmed, Naresh Kumar Sharma. High-Performance Carbon Nanotube-Reinforced Biodegradable Polymer Composites for Packaging. Journal of Polymer & Composites. 2026; 14(2):183–194p.

(PBS) have been widely recognized for their end-of-life compostability, renewability, and comparatively reduced carbon footprint when benchmarked against petroleum-based plastics [1-3].

Among these, PLA is one of the most characterized and commercially available biodegradable plastics. Renewably sourced as a byproduct of agricultural commodities (such as corn starch or sugarcane), PLA has the advantages of being easy to process using existing thermoplastic techniques and having a clear appearance, but also the disadvantages that PLA can be cost-competitive at high production volumes, although the raw material cost (from corn syrup) remains relatively high [4]. These features have led to PLA being adopted in food packaging, disposable tableware, and biomedical applications. Nevertheless, despite these advantages, PLA and similar biodegradable polymers suffer from inherent drawbacks that limit their competitiveness with mainstream synthetic plastics. Key deficiencies include low impact toughness, limited thermal resistance which restricts usage under elevated temperatures, and poor barrier properties against gases such as oxygen and water vapor. These shortcomings are particularly problematic in high-performance packaging applications where extended shelf life, mechanical stability, and durability are critical [5-7]. Consequently, despite their potential, biodegradable polymers have not yet achieved widespread substitution for PE and PP in demanding sectors of the packaging market.

These challenges have triggered researchers to look into ways of mitigating these limitations by copolymerizing, blending and/or integrating the use of reinforcing additives. Nanocomposites reinforcement is one of the ways found to be most effective and promising in enhancing the physical, thermal and barrier related properties of biodegradable polymers. By adding nanoscale fillers, one can take advantage of their very large surface area and aspect ratio to dramatically enhance the properties of the host polymer, and as a result one can produce commercially useful end products with improvement of properties up to 1000-fold in some instances [8]. CNTs in particular have drawn considerable attention in recent years. With a tensile strength of nearly ~100 GPa and an exceptionally high Young's modulus of ~1 TPa, CNTs exhibit outstanding mechanical reinforcement potential. Additionally, their inherent electrical and thermal conductivity allows them to introduce multifunctionality into otherwise insulating and thermally limited polymers. A further advantage is their ability to form continuous percolation networks even at very low filler concentrations, which amplifies reinforcement efficiency [9].

When CNTs are embedded into biodegradable biomaterials, such as PLA, they have repeatedly been reported to increase tensile strength, elastic modulus, gas barrier performance, and, in one case, thermal stability [10-12]. As an example Kumar et al. [13] demonstrated that a small amount of CNTs added to PLA just brought about an impressive 71% increase in tensile strength, a remarkable illustration of the strong reinforcing potential of CNTs even with low loadings. In the same manner, Gorrasi et al. [14] pointed out the benefit of CNT addition in enhancing the water vapor transmission resistance, which is an important parameter in food packaging applications. Moreover, Adu et al. [15] showed that improved oxygen barriers were evident in CNT-reinforced nanocomposites of PLA, and this aspect has shown relevance to promoting shelf-life in packaged foods systems. As indicated in these studies, CNTs are not only beneficial as a mechanical reinforcement material but can also be used as a significant barrier enhancer due to the tortuous diffusion pathways that they create through the polymeric plastic that impedes the migration of gases and vapors through the polymeric, therefore, giving a dual purpose benefit to packaging applications. Despite these substantial advancements, several technical challenges continue to hinder the full-scale industrial application of CNT-biodegradable polymer nanocomposites. The primary obstacle is the homogeneous and consistent dispersion of CNTs in the rather hydrophilic biodegradable matrices. CNTs tend to form agglomerates (bundles), which dramatically lowers the anticipated reinforcement efficiency as a result of the high surface energy and strong van der Waals forces between tubes [15]. The potential to apply surfactants, compatibilizers, or chemical functionalization of CNTs is under study as a potential way out, but so far cost-effectiveness and scalability is a deterrent. Also, the impact of CNTs on the biodegrading characteristic of host polymers, under composting and natural conditions, is not fully established yet. At higher loadings, CNTs may

suppress microbial growth and alter degradation processes; therefore, their long-term environmental sustainability and safety remain unclear [16].

Another underexplored dimension is the performance of CNT-biodegradable polymer nanocomposites under realistic service conditions. While laboratory studies have predominantly focused on static measurements of tensile strength, barrier properties, and thermal resistance, fewer investigations have examined performance under cyclic thermal stress, fluctuating humidity, or prolonged storage conditions. These factors are especially important for packaging materials that must withstand diverse transport and storage environments [17]. Therefore, while CNT-reinforced biodegradable nanocomposites represent an exciting frontier in sustainable material development, continued research into dispersion strategies, degradation pathways, and long-term functionality is essential before their widespread adoption in commercial packaging systems can be realized.

Given these gaps, the present study is based on the development and systematic evaluation of high-performance CNT-reinforced biodegradable polymer composites tailored for packaging applications. The objectives are to: (i) achieve effective CNT dispersion using melt-compounding and solution processing with compatibilizers; (ii) characterize structure-property relationships via field emission scanning electron microscopy (FESEM), tensile and impact testing, and thermal analysis (DSC/TGA); (iii) assess barrier performance through oxygen transmission rate (OTR) and water vapor transmission rate (WVTR) tests; and (iv) evaluate biodegradability in controlled composting conditions. By taking together these experimental analyses, the study seeks to establish a clear understanding of the trade-offs between reinforcement and environmental performance, thereby contributing to the design of next-generation sustainable packaging materials.

EXPERIMENTAL PROCEDURE

Materials

The biodegradable polymer matrix selected for this study was Polylactic acid (PLA) (Ingeo™ 4032D, NatureWorks, supplied through Matrix Polymers India Pvt. Ltd., Mumbai, India). This polymer was chosen owing to its commercial availability and proven biodegradability.

Carbon nanotubes (CNTs) were obtained with a purity of 95-100% and average diameter and length of 10-20 nm and 5-15 μm, respectively, from Ad-Nano Technologies Pvt. Ltd., Shivamogga, Karnataka, India. To enhance dispersion, a compatibilizer, Polyethylene glycol (PEG-4000) (SRL Chemicals, Mumbai, India.), was added. Analytical grade solvents including chloroform and acetone were purchased locally (Merck India, Mumbai, India.) and used without further purification.

Composite Preparation

The composites were fabricated through melt compounding in a twin-screw extruder (PTW 16, Thermo Electron Corporation, Dreieich, Germany) available in the in-house laboratory. Prior to compounding, CNTs at different loadings (0.1, 0.5, 1, and 2 wt.%) were ultrasonically dispersed in chloroform using a Vibra-Cell VCX 750 sonicator (Sonics & Materials Inc., Newtown, CT, USA) for 30 minutes. The polymer–CNT mixture was then extruded at 190-200°C with a screw rotation speed of 60 rpm. The extrudates were pelletized and compression-molded into sheets (2-3 mm thick) using a hot-press molding unit (Hot-press molding unit, Remi Instruments, Mumbai, India). For barrier property evaluation, thin films (~100 μm) were prepared by solution casting in chloroform followed by solvent evaporation under vacuum at 40°C.

Characterization Techniques

Structural Characterization

X-ray diffraction (D8 Advance, Bruker AXS GmbH, Karlsruhe, Germany (XRD, 2θ range 5-60°) was performed to analyze crystallinity changes due to CNT reinforcement. Fourier transform infrared spectroscopy (Spectrum Two, PerkinElmer Inc., Waltham, MA, USA (FTIR, 4000-500 cm^{-1}) was

performed to study functional group interactions. FTIR and XRD analyses were conducted on representative specimens for each composite composition.

Morphological Analysis

FESEM (Sigma 300, ZEISS, Oberkochen, Germany) was used to examine CNT dispersion and fracture morphology. FESEM images were taken from multiple fractured regions to ensure reproducibility of observed features.

Thermal Properties

Glass transition (Tg), crystallization, and melting behaviors were analyzed using differential scanning calorimetry (DSC 3+, Mettler-Toledo AG, Greifensee, Switzerland). The samples were heated from 25 to 300°C at a uniform rate of 10 °C/min under a nitrogen atmosphere. Thermogravimetric analysis (TGA Q500, TA Instruments, New Castle, DE, USA) was performed between 30 and 700°C with a heating rate of 10 °C/min, also under nitrogen flow. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) were repeated on three samples per composition to ensure reproducibility, and representative thermograms are shown in results and discussion section.

Mechanical Properties

Tensile properties were evaluated using a Universal Testing Machine (UTM3382, Instron, Norwood, MA, USA) in accordance with ASTM D638 for plastics at a crosshead speed of 5 mm/min. For each composition, five specimens (n = 5) were tested. All experimental data are presented as mean ± standard deviation (SD). Statistical significance was determined using one-way ANOVA followed by Tukey's post-hoc test to compare CNT-reinforced samples with neat PLA. The impact resistance was determined with an Izod pendulum impact tester (Tinius Olsen, Horsham, PA, USA) as per ASTM D256. Dynamic mechanical analysis (DMA, Q800, TA Instruments, New Castle, DE, USA) was performed in tensile mode within the temperature range of –50 to 150°C at a frequency of 1 Hz to determine the storage modulus, loss modulus, and damping factor (tan δ). Dynamic mechanical analysis (DMA) was performed on two samples per composition.

Barrier Properties

The oxygen transmission rate (OTR) was measured by a OX-TRAN 2/21 system (MOCON Inc., Minneapolis, MN, USA) in accordance with ASTM D3985. The water vapor transmission rate (WVTR) was tested by use of a PERMATRAN-W 3/33 (MOCON Inc., Minneapolis, MN, USA) in accordance with ASTM F1249. Oxygen transmission rate (OTR) and water vapor transmission rate (WVTR) tests were conducted in triplicate (n = 3), and mean values with standard deviations are presented in results and discussion section.

Biodegradability Assessment

Biodegradation tests were conducted under controlled composting conditions following ASTM D5338. Film samples were buried in a compost medium (maintained at 58 ± 2°C and 55% relative humidity). Biodegradation tests were performed in triplicate (n = 3) under controlled composting conditions, and the average percentage weight loss was calculated after 90 days.

RESULTS AND DISCUSSION

Structural Characterization

Fourier transform infrared (FTIR) spectroscopy was used to analyze and identify the characteristic functional groups present in PLA and its CNT-reinforced nanocomposites. The neat PLA spectrum showed strong and well-defined absorption bands at 1755 cm^{-1}, corresponding to the C=O stretching of ester groups, which is the most prominent peak of aliphatic polyesters. Additional absorption bands appeared at 1180-1080 cm^{-1}, attributable to C-O-C stretching vibrations of ester linkages, while weaker but distinct C-H stretching bands were located at 2995-2940 cm^{-1} (Figure 1). The PLA blend exhibited similar features, confirming its semi-crystalline aliphatic polyester structure. After the incorporation of CNTs, additional signals appeared around 1580 cm^{-1}, which are associated with C=C stretching

vibrations of the graphitic structure of CNTs. Interestingly, the introduction of 2 wt.% CNTs induced a noticeable redshift of the carbonyl stretching band from 1755 to 1749 cm^{-1}.

The redshift of the carbonyl band from 1755 to 1749 cm^{-1} indicates interfacial interactions between CNTs and PLA matrix. This variation means that there are non-covalent bonds between the CNTs and both the ester functional groups of PLA. These interfacial interactions, typically associated with π-π stacking and dipole-dipole interactions between CNT surfaces and esters, are widely observed to enhance stress transfer across the filler-matrix interface and have long been noted in PLA/CNT systems [18-20]. This provides strong evidence that CNTs do not remain inert fillers but actively interact with the polymeric chains, enhancing compatibility at the molecular level.

X-ray diffraction (XRD) patterns further substantiated the changes in structural order. As seen in Figure 2, Neat PLA exhibited a broad diffraction halo at $2\theta \approx 16.7°$, characteristic of its semi-crystalline morphology. Upon CNT incorporation, sharp reflections emerged near $2\theta \approx 25.8°$, which correspond to the (002) plane of graphitic carbon, confirming the successful integration of CNTs into the polymer matrix [21-23]. Moreover, the calculated degree of crystallinity increased notably from 24.5% for the neat blend to 32.1% at 2 wt.% CNT loading.

The emergence of sharp reflection at $2\theta \approx 25.8°$ corresponds to the (002) plane of graphitic carbon, and the increase in crystallinity from 24.5% to 32.1% demonstrates the nucleating effect of CNTs. This is an improvement on the nucleating power of CNTs, which enhances more efficient chain packing and rapid crystallization. The nucleation effects of CNTs in PLA based nanocomposites have been well studied with the addition mending a heterogeneous nucleation, an increase in crystallization rates and a stabilisation of the crystalline phases [24]. Thus, in terms of structural analysis, CNT addition has a dual effect on strengthening filler-matrix interaction and promoting favorable polymer chain ordering, and both contribute to the functional property improvement in subsequently obtained results.

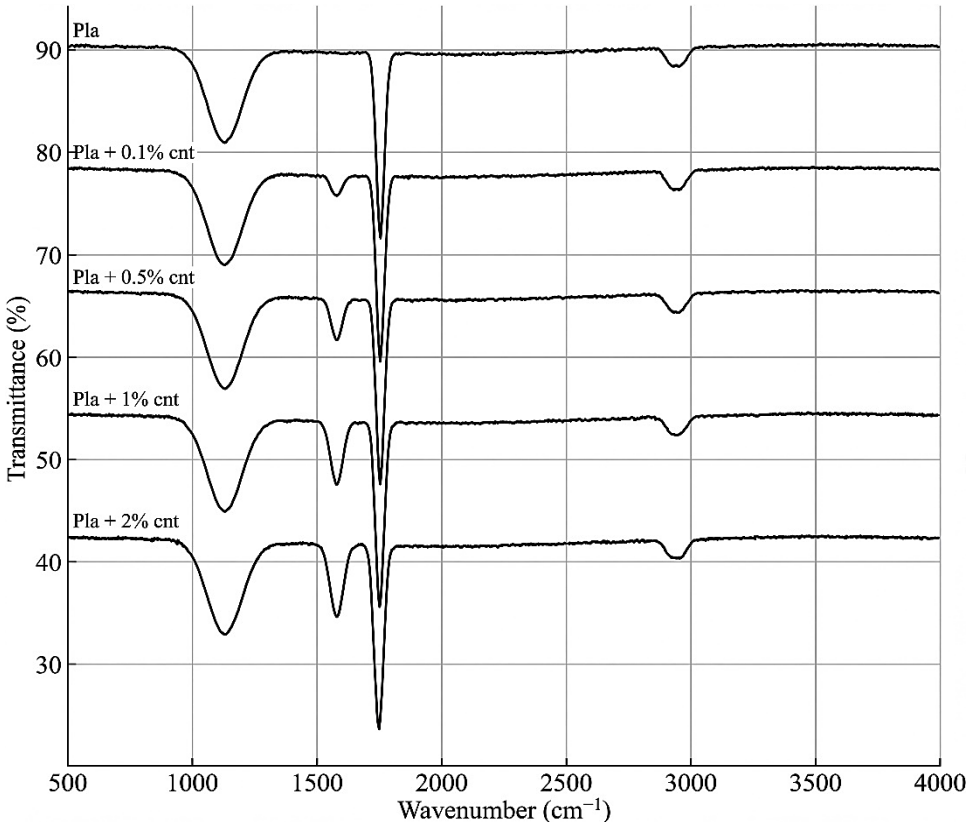

Figure 1. FTIR spectra of neat PLA and PLA-CNT (2 wt%) nanocomposites showing characteristic absorption bands of ester groups and graphitic carbon.

Morphological Analysis

The morphology of the PLA-CNT nanocomposites was examined using field emission scanning electron microscopy (FESEM). Analysis of the cryo-fractured surfaces (Figure 3a) showed that at CNT loadings up to 1 wt.%, the nanotubes were well dispersed within the polymer matrix, with only minor indications of agglomeration.

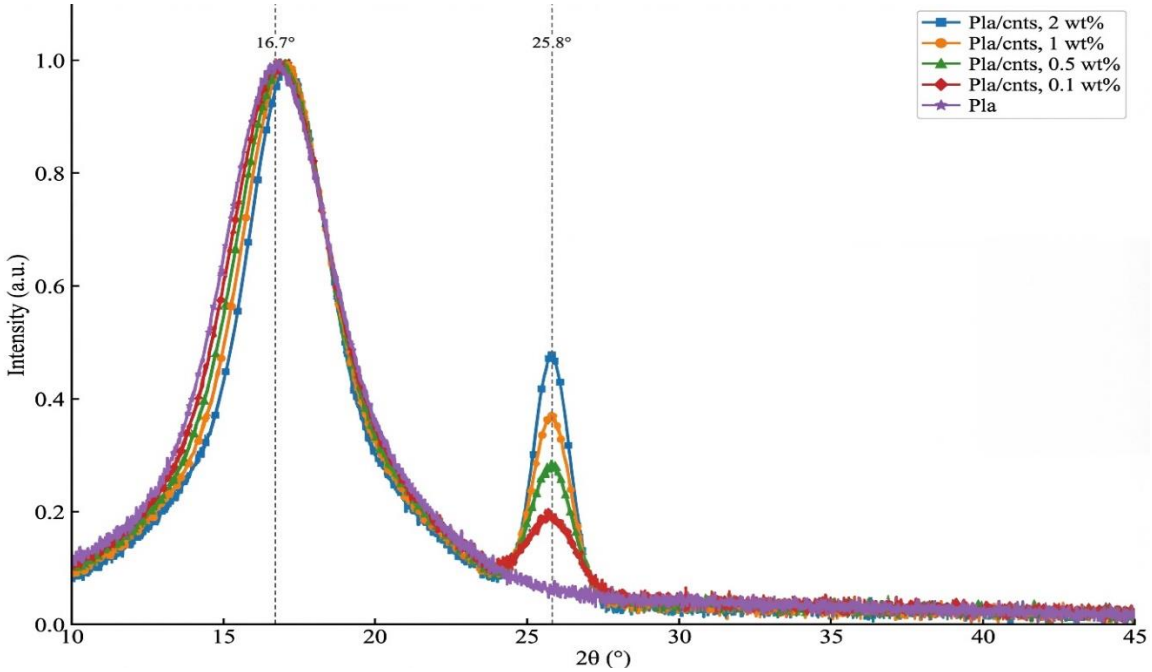

Figure 2. X-ray diffraction (XRD) patterns of neat PLA and PLA-CNT (2 wt%) nanocomposites

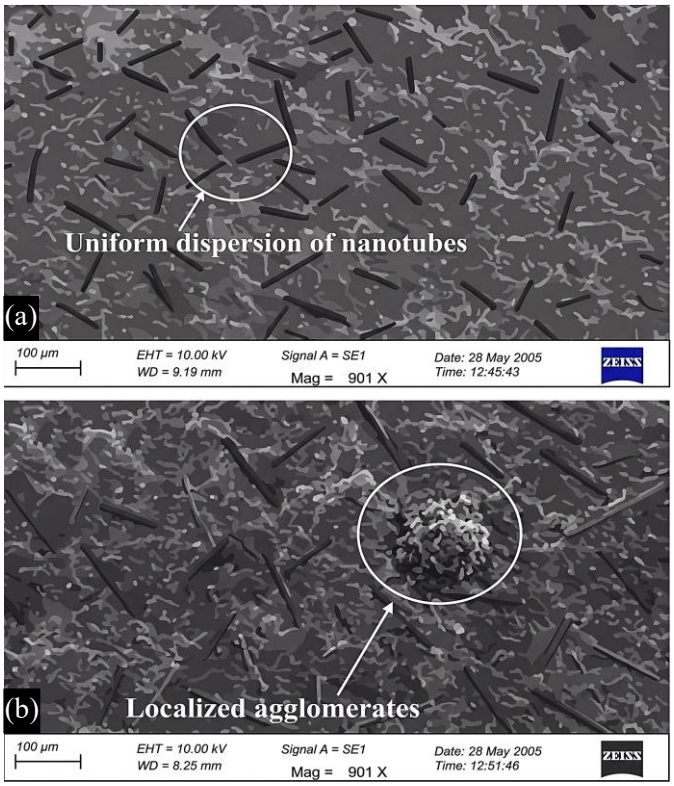

Figure 3. FESEM images of (a) PLA/CNT 1 wt% sample showing homogeneous CNT dispersion with good interfacial adhesion and minimal agglomeration, (b) PLA/CNT 2 wt% sample

Figure 3. showing localized CNT agglomeration due to increased filler loading and van der Waals attractions between nanotubes. This homogeneous distribution facilitated good interfacial contact, which is essential for efficient load transfer. At 2 wt.% CNT loading (Figure 3b), however, localized agglomerates became visible, likely due to the intrinsic van der Waals attractions between nanotubes. Interestingly, even these agglomerates contributed positively by introducing mechanisms such as crack deflection, crack pinning, and localized energy dissipation, thereby contributing to toughness enhancement.

Thermal Properties

The effects of CNT incorporation on glass transition temperature (Tg), melting profile, and crystallization of the PLA matrix were studied using Differential scanning calorimetry (DSC). The neat PLA showed a Tg of 58.3°C, which gradually increased with CNT loading up to 62.1°C at 2 wt.% loadings. The adjunct of Tg is explained by limited chain mobility due to the interactions between CNTs and polymer chains that act to suppress segmental relaxation.

The systematic increase in Tg from 58.3°C to 62.1°C and Tc from 113.2°C to 118.9°C demonstrates the nucleating effect and chain mobility restriction induced by CNT addition. Meanwhile as seen in Figure 4, the melting temperature (Tm) remained nearly unchanged at ~171°C across all compositions, indicating that CNTs primarily affect crystallization kinetics rather than crystalline phase stability. The crystallization temperature (Tc), however, displayed a distinct upward shift from 113.2°C for the neat blend to 118.9°C at 2 wt.% CNT loading, further confirming the nucleating role of CNTs [25].

Figure 5 showing improved thermal stability with CNT incorporation. The onset degradation temperature (Tonset) increased from 320.4°C for neat PLA to 348.7°C with 2 wt.% CNTs, while the maximum degradation temperature (Tmax) shifted from 363.5°C to 388.2°C, demonstrating the barrier effect of CNTs against thermal degradation. Thermogravimetric analysis (Figure 5) revealed significant improvements in thermal stability upon CNT addition. The onset degradation temperature (Tonset) increased from 320.4°C for neat PLA to 348.7°C with 2 wt.% CNT incorporation. Similarly, the maximum degradation temperature (Tmax) shifted from 363.5°C to 388.2 °C. This stabilization effect can be attributed to the barrier action exhibited by CNTs being obstacles to the diffusion of volatile degradation products and as physical shields to heat transfer processes. The results reported by the previous studies comparable to the ones obtained in this paper are the demonstration of CNTs reducing

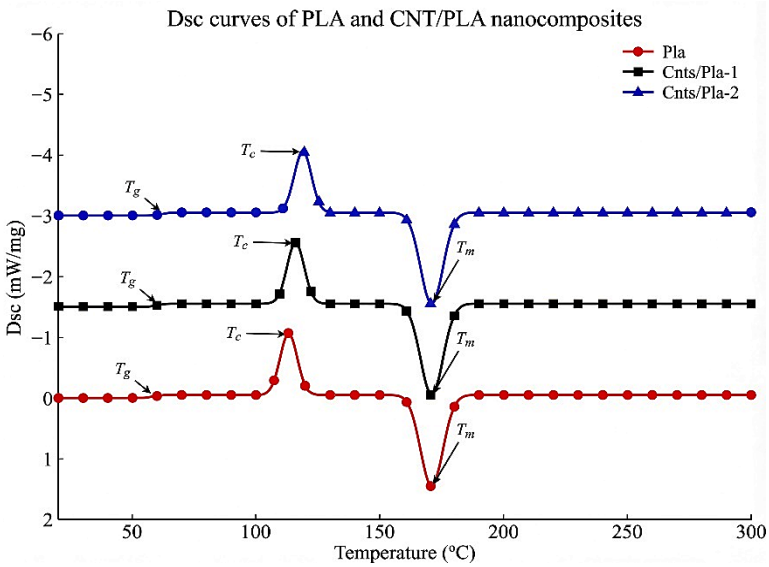

Figure 4. Differential scanning calorimetry (DSC) thermograms of neat PLA and CNT/PLA nanocomposites with different CNT loadings (0.1, 0.5, 1.0, and 2.0 wt.%), showing the glass transition temperature (Tg), crystallization temperature (Tc), and melting temperature (Tm).

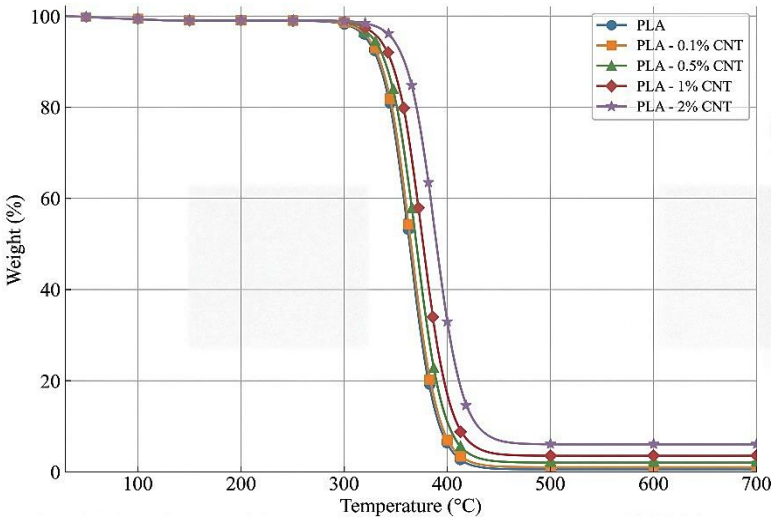

Figure 5. Thermogravimetric analysis (TGA) curves of neat PLA and PLA/CNT nanocomposites at different CNT loadings.

Table 1. Effect of CNT loading on tensile strength, elastic modulus, elongation at break, and impact strength of PLA/CNT nanocomposites

CNT loading (wt.%)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Impact strength (kJ/m²)
0 (neat)	42.6 ± 1.2	1.85 ± 0.06	7.2 ± 0.3	2.1 ± 0.1
0.1	48.3 ± 1.5*	1.98 ± 0.05*	6.9 ± 0.4 (ns)	2.6 ± 0.1*
0.5	55.2 ± 1.7**	2.18 ± 0.07**	6.4 ± 0.3 (ns)	3.1 ± 0.2**
1.0	61.4 ± 1.6***	2.37 ± 0.08***	6.0 ± 0.2*	3.5 ± 0.2***
2.0	63.2 ± 1.8***	2.45 ± 0.09***	5.8 ± 0.3*	3.3 ± 0.2**

decomposing rates by hindering the polymer chain scission and delaying its mass loss [19,26]. These results lead to the conclusion that CNTs not only increase crystallinity but also provide better resistance of thermal degradation, and expand potential application range of PLA composites.

Mechanical Properties

Mechanical testing revealed a clear reinforcing effect of CNTs on the PLA blend (Table 1). The tensile strength of the neat matrix (42.6 MPa) increased significantly to 61.4 MPa at 1 wt.% CNTs, marking an improvement of over 40%. The tensile strength plateaued at 63.2 MPa for 2 wt.% CNTs, suggesting diminishing returns due to filler agglomeration. The tensile modulus showed a consistent rise from 1.85 GPa (neat) to 2.45 GPa at 2 wt.% CNTs, confirming increased stiffness of the material. However, elongation at break decreased slightly from 7.2% to 5.8%, reflecting the reduced ductility typical of reinforced nanocomposites where chain flexibility is restricted. The average test result values along with standard deviations are reported in Table 1.

Values represent mean ± standard deviation (n = 5). Statistical significance compared to neat PLA determined by one-way ANOVA followed by Tukey's post-hoc test: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; ns = not significant compared to neat PLA Impact strength also improved with CNT incorporation, rising from 2.1 kJ/m² for neat PLA to a maximum of 3.5 kJ/m² at 1 wt.% CNTs. At 2 wt.% CNTs, the value slightly decreased to 3.3 kJ/m², likely due to stress concentration effects caused by CNT clusters. This behavior mirrors prior studies, which consistently report optimum reinforcement at low loadings (~0.5-1 wt.%), while excessive filler content introduces defects and limits property enhancement [9]. Collectively, these results highlight the dual role of CNTs as mechanical reinforcements and crack deflectors, though careful optimization of loading is required to maximize the balance of strength, stiffness, and toughness.

Dynamic Mechanical Properties

Dynamic mechanical analysis (DMA) provided insights into the viscoelastic behavior of the composites. As shown in Figure 6, the storage modulus (E′) at room temperature increased from 2.3 GPa for neat PLA to 3.0 GPa at 2 wt.% CNTs, reflecting substantial reinforcement of the elastic response. The tan δ peak, which corresponds to the glass transition temperature (Tg), shifted from 59.5°C to 62.8°C with CNT addition.

The storage modulus at room temperature increased from 2.3 GPa for neat PLA to 3.0 GPa at 2 wt.% CNTs, and the tan δ peak shifted from 59.5°C to 62.8°C, confirming improved thermal-mechanical stability. This elevated shift is congruent with DSC data and indicates that CNTs successfully constrain chain relaxation to provide an improved thermal-mechanical stability. A similar effect has also been reported in CNT based nanocomposites, where the enhanced interfacial adhesion and limited polymer dynamics lead to the strong filler-matrix bonding [27]. The reinforcing effect of CNTs during dynamic loading performance was confirmed by the combination of increased stiffness and Tg even when the ratio of carbon nanotube-to-polymeric material was increased, which indicates superior potential performance under cyclic stress environments likely to occur in packaging applications.

Barrier Properties

Barrier performance against oxygen and water vapor was significantly improved through CNT reinforcement (Table 2). The oxygen transmission rate (OTR) of neat PLA was 68.4 $cc \cdot m^{-2} \cdot day^{-1}$, which decreased to 35.6 $cc \cdot m^{-2} \cdot day^{-1}$ at 2 wt.% CNT loading. Similarly, the water vapor transmission rate (WVTR) dropped from 22.7 $g \cdot m^{-2} \cdot day^{-1}$ to 11.2 $g \cdot m^{-2} \cdot day^{-1}$. These reductions can be explained by the tortuous diffusion pathway mechanism, wherein CNTs act as impermeable obstacles that force gas and vapor molecules to take longer, more convoluted paths through the polymer matrix. This mechanism has been well established in CNT-reinforced polymer membranes and aligns with the observed improvements [28]. Such barrier property enhancements are especially important for food packaging applications, where oxygen and moisture ingress are primary contributors to spoilage.

Values represent mean ± standard deviation (n = 3). The substantial reduction in both OTR and WVTR demonstrates the effectiveness of CNTs in creating tortuous diffusion pathways that impede gas and vapor permeation.

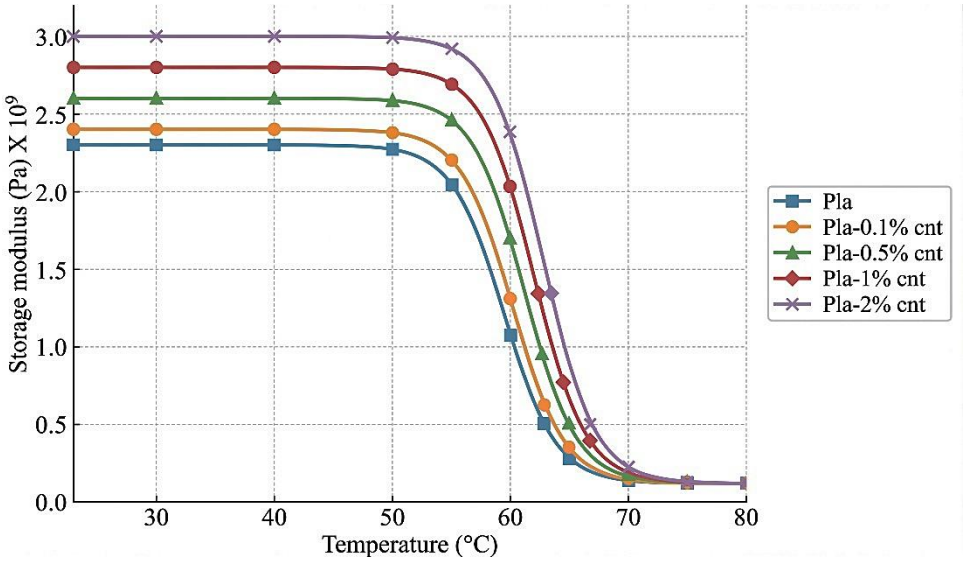

Figure 6. Variation of storage modulus of neat PLA and CNT-reinforced PLA nanocomposites (0.1, 0.5, 1, and 2 wt.% CNT) as a function of temperature, showing enhanced stiffness and thermal resistance with increasing CNT loading.

Table 2. Effect of CNT loading on oxygen transmission rate (OTR) and water vapor transmission rate (WVTR) of PLA/CNT nanocomposites.

CNT loading (wt.%)	OTR (cc·m^{-2}·day^{-1})	WVTR (g·m^{-2}·day^{-1})
0 (neat)	68.4 ± 2.1	22.7 ± 1.0
0.1	60.3 ± 1.8	20.6 ± 0.9
0.5	50.2 ± 1.7	16.4 ± 0.8
1.0	41.7 ± 1.5	13.8 ± 0.7
2.0	35.6 ± 1.4	11.2 ± 0.6

Biodegradability

Biodegradation tests conducted under controlled composting conditions (ASTM D5338) confirmed that PLA/CNT composites remain biodegradable. Neat PLA films exhibited a weight loss of 43.5% after 90 days of composting. With CNT addition, the degradation rate declined slightly, with 2 wt.% CNT composites showing 35.2% weight loss over the same period. The reduced biodegradability is attributed to increased crystallinity and reduced permeability, which limit water absorption and microbial penetration into the matrix. These effects are consistent with previous reports on nanocomposite systems, where higher crystallinity often delays degradation kinetics [29]. Nevertheless, the composites retained compostability under thermophilic conditions, demonstrating that the incorporation of CNTs does not eliminate their eco-friendly nature. Instead, it slightly modulates degradation behavior, striking a balance between extended functional lifespan during use and eventual breakdown in composting environments.

CONCLUSION

This study successfully demonstrated the potential of carbon nanotube (CNT) reinforcement to overcome the intrinsic limitations of polylactic acid (PLA) for sustainable packaging applications. The incorporation of CNTs, even at low loadings, induced strong interfacial interactions with PLA chains, promoted heterogeneous nucleation, and significantly enhanced crystallinity. As a result, the nanocomposites exhibited marked improvements in thermal stability, as evidenced by higher glass transition and degradation temperatures, and superior mechanical performance, with tensile strength rising by over 40% at 1 wt.% CNTs. Dynamic mechanical analysis further validated the reinforcing role of CNTs under cyclic stresses. In addition to mechanical and thermal enhancements, barrier properties against oxygen and water vapor were substantially improved, with OTR and WVTR reduced by nearly 50% at 2 wt.% CNTs, highlighting their effectiveness in extending product shelf life. Importantly, biodegradation studies confirmed that CNT incorporation did not compromise compostability, although a slight reduction in degradation rate was observed due to increased crystallinity and reduced permeability. Overall, the results indicate that PLA/CNT nanocomposites offer an attractive trade-off between enhanced performance and environmental friendliness. Through a more optimized method of CNT loading and dispersion, these materials appear to be the most promising eco-friendly packaging materials to use in future since they would meet paradoxically the two contradictory demands of high performance and biodegradabilty.

Acknowledgments

The authors acknowledge the Central Instrumentation Facility at Indian Institute of Technology Mumbai and National Institute of Technology Karnataka for providing access to characterization equipment. We are grateful to Matrix Polymers India Pvt. Ltd., Mumbai for supplying the PLA material, and Ad-Nano Technologies Pvt. Ltd., Shivamogga for providing carbon nanotubes. The authors also thank the technical staff of the Department of Chemical Engineering for their assistance during experimental work.

REFERENCES

1. Kumar K, Khatri A, Thakur IS. Existing Scenario and Environmental Significance of Biodegradable Plastics: A Review for a Sustainable Future. J Green Energy Environ Technol. 2025 July.

2. Samir A, Ashour FH, Abdel Hakim AA, Bassyouni M. Recent advances in biodegradable polymers for sustainable applications. npj Mater Degrad. 2022;6:68.
3. Naser AZ, Deiab I, Darras BM. Poly(lactic acid) (PLA) and polyhydroxyalkanoates (PHAs), green alternatives to petroleum-based plastics: a review. RSC Adv. 2021;11(28):17151-–17196.
4. Mosomi EK, Olanrewaju OA, Adeosun SO. Pivotal role of polylactide in carbon emission reduction: A comprehensive review. Eng Rep. 2024;6(8):e12909.
5. Zheng L, Kim MS, Xu S, Urgun-Demirtas M, Huber GW, Klier J. Biodegradable High-Molecular-Weight Poly(pentylene adipate-co-terephthalate): Synthesis, Thermo-Mechanical Properties, Microstructures, and Biodegradation. ACS Sustain Chem Eng. 2023;11(38):13885-–13895.
6. Dharai R, Chakraborty Y, Murmu R, Senapati P, Sutar H, Roy D. Polymer-Filler Interactions in Graphite-Infused Polypropylene: Experimental Design, a Fundamental and Applied Study. Compos Sci. 2025;9:351.
7. Yue S, Zhang T, Wang S, Han D, Huang S, Xiao M, Meng Y. Recent Progress of Biodegradable Polymer Package Materials: Nanotechnology Improving Both Oxygen and Water Vapor Barrier Performance. Nanomater. 2024;14:338.
8. Rouf T, Kokini J. Biodegradable biopolymer-graphene nanocomposites. Mater Sci. 2016;51.
9. Yaqoob S, Ali Z, D'Amore A, Lo Schiavo A, Petraglia A, Rubino M. Enhanced Mechanical and Electrical Performance of Epoxy Nanocomposites Through Hybrid Reinforcement of Carbon Nanotubes and Graphene Nanoplatelets: A Synergistic Route to Balanced Strength, Stiffness, and Dispersion. Compos Sci. 2025;9:374.
10. Hussain M, Khan SM, Shafiq M, Al-Dossari M, Alqsair UF, Khan SU, Khan MI. Comparative study of PLA composites reinforced with graphene nanoplatelets, graphene oxides, and carbon nanotubes: Mechanical and degradation evaluation. Energy. 2024;308:132917.
11. Ali H, Ali S, Ali K, Ullah S, Ismail PM, Humayun M, Zeng C. Impact of the nanoparticle incorporation in enhancing mechanical properties of polymers. Results Eng. 2025;27:106151.
12. Bardot M, Schulz MD. Biodegradable Poly(Lactic Acid) Nanocomposites for Fused Deposition Modeling 3D Printing. Nanomater. 2020;10:2567.
13. Kumar GSP, Keshavamurthy R, Panigrahi SP, Thomas S, Thejaraju R, Hebbar GS, Prasad CD, Aden AA. Enhanced mechanical properties of CNT/Graphene reinforced PLA-based composites fabricated via fused deposition modelling. Results Eng. 2025;25:104472.
14. Gorrasi G, Pantani R, Murariu M, Dubois P. PLA/Halloysite Nanocomposite Films: Water Vapor Barrier Properties and Specific Key Characteristics. Macromol Mater Eng. 2014;299.
15. Adu PCO, Aakyiir M, Su X, Alam J, Tran LC, Dai J, Meng Q, Kuan HC, Ma J. Challenges and advancements in Elastomer/CNT nanocomposites with mechanochemical treatment, reinforcement mechanisms and applications. Smart Mater Manuf. 2024;2:100053.
16. Phan D, Jr D, Frank B, Bouwer E, Fairbrother D. Biodegradability of carbon nanotube/polymer nanocomposites under aerobic mixed culture conditions. Sci Total Environ. 2018;639:804–814.
17. Mujtaba M, Lipponen J, Ojanen M, Puttonen S, Vaittinen H. Trends and challenges in the development of bio-based barrier coating materials for paper/cardboard food packaging; a review. Sci Total Environ. 2022;851(2).
18. Di Crescenzo A, Ettorre V, Fontana A. Non-covalent and Reversible Functionalization of Carbon Nanotubes. Beilstein J Nanotechnol. 2014;5:1675-–1690.
19. Li H, Wang G, Wu Y, Jiang N, Niu K. Functionalization of Carbon Nanotubes in Polystyrene and Properties of Their Composites: A Review. Polymers. 2024;16(6):770.
20. Chou D, Rehman A, Inc M, et al. Examination of Heat Transfer in Carbon Nanotube Nanofluids under Thermal Radiation, Magnetic Field, and Viscosity Distribution. Multiscale Multidiscip Model Exp Des. 2025;8:237.
21. Wu TM, Lin YW. Doped Polyaniline/Multi-Walled Carbon Nanotube Composites: Preparation, Characterization and Properties. Polymer. 2006;47:3576–3582.
22. Wang H, Biswas SK, Zhu S, Lu Y, Yue Y, Han J, Xu X, Wu Q, Xiao H. Self-Healable Electro-Conductive Hydrogels Based on Core-Shell Structured Nanocellulose/Carbon Nanotubes Hybrids for Use as Flexible Supercapacitors. Nanomaterials. 2020;10(1):112.

23. Liu M, Du Y, Miao YE, Ding Q, He S, Tjiu W, Pan J, Liu T. Anisotropic Conductive Films Based on Highly Aligned Polyimide Fibers Containing Hybrid Materials of Graphene Nanoribbons and Carbon Nanotubes. Nanoscale. 2014;7.
24. Bikiaris D. Microstructure and Properties of Polypropylene/Carbon Nanotube Nanocomposites. Materials. 2010;3(4):2884–2946.
25. Cerrada ML, Arranz-Andrés J, Caballero-González A, Blázquez-Blázquez E, Pérez E. The β Form in PVDF Nanocomposites with Carbon Nanotubes: Structural Features and Properties. Polymers. 2023;15(6):1491.
26. Su SP, Xu YH, Wilkie C. Thermal Degradation of Polymer-Carbon Nanotube Composites. In: Polymer-Carbon Nanotube Composites: Preparation, Properties and Applications; 2011. p. 482–510.
27. Gkikas G, Barkoula NM, Paipetis A. Effect of Dispersion Conditions on the Thermo-Mechanical and Toughness Properties of Multi-Walled Carbon Nanotubes-Reinforced Epoxy. Compos Part B Eng. 2012;43:2697-–2705.
28. Nurazzi NM, Sabaruddin FA, Harussani MM, Kamarudin SH, Rayung M, Asyraf MRM, Aisyah HA, Norrrahim MNF, Ilyas RA, Abdullah N, Zainudin ES, Sapuan SM, Khalina A. Mechanical Performance and Applications of CNTs Reinforced Polymer Composites—A Review. Nanomater. 2021;11(9):2186.
29. Glaskova-Kuzmina T, Starkova O, Gaidukovs S, Platnieks O, Gaidukova G. Durability of Biodegradable Polymer Nanocomposites. Polymers. 2021;13(19):3375.

