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Influence of Carbon Nanotube on Physical and Mechanical Properties of Vetiver Root Fiber-Reinforced Bioplastic Composites

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Abstract

Development of sustainable bio-based materials from agricultural by-products represents a critical direction for addressing environmental challenges while supporting circular economy initiatives. This research investigates the influence of carbon nanotubes (CNTs) on the physical and mechanical properties of vetiver root fiber-reinforced polylactic acid (PLA) bio composites. A composite formulation with a 90:10 ratio of PLA to vetiver root fibers was prepared with varying concentrations of CNTs (2, 4, 6, 8, and 10% by weight). Control samples of pure PLA, PLA with vetiver fibers only, and PLA with CNTs only were also fabricated for comparative analysis. The samples were characterized by tensile strength, flexural strength, density, water absorption, thickness swelling, and thermal stability. Results revealed that pure PLA exhibited the highest tensile strength (10.37±0.88 MPa), which decreased with increasing CNT content, reaching a minimum at 6% CNTs before slightly recovering at higher concentrations. This behavior was attributed to CNT agglomeration and interfacial incompatibility between hydrophobic CNTs and hydrophilic natural fibers. Similarly, flexural properties followed comparable trends, with lowest values at 6% CNTs. Physical properties showed that density increased with CNT content, while water absorption and thickness swelling peaked at 6% CNTs before decreasing at higher concentrations. Thermogravimetric analysis demonstrated enhanced thermal stability at higher CNT loadings due to the barrier effect and improved heat distribution. This research demonstrates the potential of CNT-reinforced vetiver root fiber bio composites as environmentally friendly materials with tailorable properties for various applications.

Keywords : Composites; Carbon Nanotubes; Vetiver Root Fibers; Mechanical Properties; Thermal Stability

Introduction

Vetiver grass has a deep, strong root system that grows vertically and branches into a dense network, effectively anchoring soil, preventing erosion, and maintaining soil moisture [1, 2]. Studies on the mechanical properties of vetiver roots have shown they are strong, resistant to tensile forces and bending, highly flexible, and can withstand curvature stress well [3, 4]. These properties give vetiver roots high potential for use as reinforcement material in various composite materials, especially in the development of bio-hybrid composites that integrate natural materials with biopolymers to enhance impact resistance, reduce brittleness, and improve biodegradability while maintaining adequate mechanical strength.

Polylactic Acid (PLA) is a widely popular biopolymer used in bioplastic production, as it is made from renewable resources such as plant starch or sugar from corn, cassava, or sugarcane [5, 6]. PLA has good mechanical properties, such as high stiffness and tensile strength [7, 8]. However, PLA has significant limitations, including high brittleness, low impact resistance, and insufficient moisture resistance for use in harsh environments [9] such as temperature fluctuations [10], moisture resistance is limited [11] and UV radiation [12]. These exceptional properties make CNTs ideal reinforcement agents for addressing the inherent limitations of PLA when combined with natural fibers.

Carbon Nanotubes (CNTs) are nanomaterials with outstanding mechanical and electrical properties, extremely high strength, excellent flexibility, light weight, and good thermal and electrical conductivity [13]. Adding even a small amount of CNTs (0.1-5% by weight) to polymer composite systems can significantly improve the mechanical properties of materials [14]. CNTs function as a network for distributing forces within composite materials, reducing crack formation and propagation, and increasing the ability to withstand various forces such as tensile, compressive, and bending forces [15, 16].

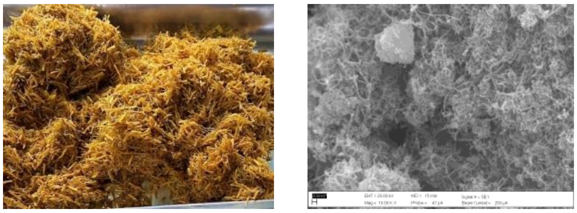
The combination of natural fibers from vetiver roots with CNTs in a PLA matrix represents an innovative approach to developing eco-friendly high-performance bio composites. Literature reviews have shown that reinforcement with appropriate amounts of CNTs can increase tensile strength by up to 30-45% and elastic modulus by 15-60% compared to neat polymers [15, 17], while natural fibers help increase toughness and impact resistance of the materials [18].

This research specifically aims to develop environmentally friendly bio-hybrid composite materials. This focused application directs our research parameters and analytical approaches, allowing for more targeted investigation of the material properties required for flooring applications. By developing a composite specifically for flooring, we can establish clear performance benchmarks for mechanical strength, water resistance, and microstructure that directly inform our experimental design and manufacturing processes.

For environmentally friendly bio-hybrid composite flooring, the material must demonstrate excellent flexural properties to withstand foot traffic, low water absorption to maintain dimensional stability in varying humidity conditions, and adequate thermal stability for diverse installation environments including areas with underfloor heating systems. This application-specific development model guides our selection of CNT concentrations (2-10% by weight) and testing methodologies to optimize performance for flooring applications while maintaining environmental sustainability. This focused approach aligns with Thailand's Bio-Circular-Green Economy (BCG Model) initiative [19] and provides a clear pathway from laboratory research to commercial application in the sustainable building materials sector, promoting the utilization of local resources according to the royal initiative while offering an eco-friendly alternative to conventional flooring materials that often contain harmful chemicals and non-renewable resources.

Materials and Methods

Raw materials



(a) (b)

Figure 1 Raw materials (a) vetiver root fibers (b) SEM micrograph of CNTs

The raw materials prepared for this research included upland vetiver grass (*Vetiveria Nemoralis A. Camus*), Roi-Et variety, collected from Ban Pla Bu village, Nong Saeng sub-district, Wapi Pathum district, Maha Sarakham province, Thailand. These vetiver grasses are selected from mature plants that are approximately 3 years old, with the most suitable strength and flexibility of the fibers. The root section of the vetiver grass was used in this study as shown in Figure 1(a). The first step involved preparing and separating the vetiver root fibers by washing them with distilled water to remove soil and impurities, followed by sun-drying for 8 hours. Subsequently, the dried roots were cut using a precision cutting machine to obtain fibers with diameters ranging between 200-300 µm, widths of approximately 1-2 mm, and lengths of about 20-40 mm. The cutting process was carefully controlled to ensure consistent fiber dimensions, as larger fibers can significantly impair mechanical properties, processing efficiency, and final product quality. This precise size control is critical for achieving optimal dispersion of fibers within the polymer matrix and maintaining consistent performance in the application. In the next step, the fiber surface was modified by soaking in 0.5% by volume concentration of sodium hydroxide solution for 2 h at room temperature. The fibers were then washed with distilled water, and the water condition was verified to have a neutral pH using a pH meter. Afterward, the fibers were dried in a hot air oven at 60°C for 24 h to achieve an average moisture content of 4-13%. Meanwhile, the matrix was prepared from Polylactic Acid (PLA) supplied by GLOBAL BIOPOLYMERS, Bangkok, Thailand. The multi-walled carbon nanotubes (MWCNTs) utilized in this experimental study were of high purity (>95 wt%) with inner diameters ranging from 3-5 nm and outer diameters of 8-15 nm as shown in Figure 1(b). These nanotubes were synthesized using the Chemical Vapor Deposition (CVD) method, which is recognized for producing high-quality carbon nanostructures with controlled dimensions and properties. The MWCNTs were commercially procured from AliExpress, China, and were selected based on their dimensional consistency and high purity to ensure reliable experimental outcomes.

Preparation of Bioplastic Composite Materials

For this research, a base formulation with a ratio of 90:10 %wt between PLA and dry vetiver root fibers (moisture content 4-13%) was established. Carbon nanotubes (CNTs) were subsequently incorporated into this base mixture at varying concentrations of 2, 4, 6, 8, and 10 %wt according to the experimental conditions. Additionally, control samples were prepared for comparative analysis, consisting of pure PLA (100 %wt), PLA reinforced only with vetiver root fibers, and PLA reinforced only with CNTs, to serve as standards for comparing various properties of the composite materials. The composite materials were processed using a closed-system mixer at a temperature of 200°C for 6 min. These temperature and time parameters were optimized to ensure uniform distribution of the constituent materials, particularly the dispersion of carbon nanotubes within the polymer matrix. The selected temperature was appropriate for the melting of PLA while preventing thermal degradation of the natural fibers and carbon nanotubes. Following the mixing process, all samples were finely ground using a material grinder to produce uniform, small plastic granules suitable for subsequent injection molding.

Specimen Fabrication and Testing

The finely ground composite granules were then injection molded using an injection molding machine at 180°C to produce test specimens according to ASTM standard dimensions. The injection molding temperature was optimized to ensure proper melting and flow of the composite material without causing degradation of the components. The fabricated specimens were subjected to mechanical property testing, including tensile strength tests according to ASTM D638 standard and flexural strength tests according to ASTM D790 standard, using a universal testing machine. For physical property testing, evaluate density (ASTM D792), thickness swelling (ASTM D570), and water absorption (ASTM D1037), which are key parameters indicating dimensional stability and moisture resistance critical for flooring materials that may be exposed to varying environmental conditions. To ensure statistical reliability, five replicate specimens were tested for each experimental condition in all mechanical and physical property tests. Thermal property testing to determine the decomposition temperature of the composite materials was conducted using Thermogravimetric Analysis (TGA), with testing temperatures ranging from 30 to 850°C to encompass the thermal decomposition range of all components in the composite materials.

Microstructural Analysis

The microstructural study of the composite materials was performed using Scanning Electron Microscopy (SEM) to analyze the adhesion characteristics between the polymer matrix and reinforcing materials, the distribution of vetiver root fibers, and the quality of carbon nanotube dispersion within the composite structure. This morphological analysis provided important information regarding the relationship between microstructural features and the observed mechanical and physical properties.

Statistical Analysis

All test data were presented as mean values with standard deviations and analyzed for statistical differences using one-way Analysis of Variance (ANOVA) at a 95 percent confidence level ($\alpha = 0.05$). One-way ANOVA was selected because our design compared multiple CNT concentration groups on single dependent variables. Data normality and variance homogeneity were verified before analysis to ensure ANOVA assumptions were met to assess the statistical significance of differences observed between experimental groups. The significance criterion was established at $p < 0.05$, which enables accurate and reliable interpretation of the influence of carbon nanotube concentration on various properties of the vetiver root fiber-reinforced bioplastic composites. Additionally, Pearson correlation analysis was performed to quantify relationships between different mechanical and physical properties.

Table 1 Physical and mechanical average values of tests performed

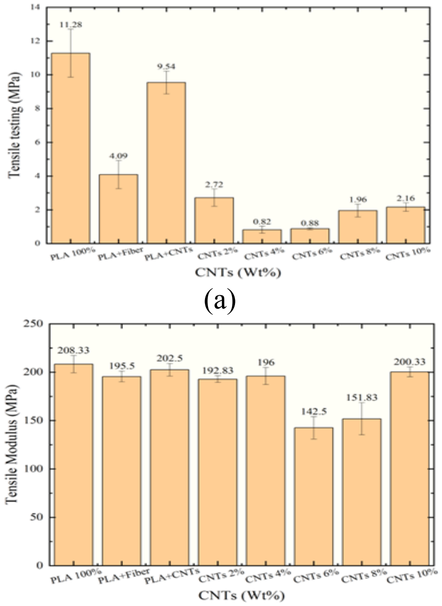
Sample	Density (g/cm^3)	Water absorption (%)	Thickness Swilling (%)	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)
PLA 100%	0.435±0.03	4.31±0.99	4.13±0.91	10.37±0.88	208.33±8.96	0.50±0.010	5.33±0.76
PLA+ Fiber	0.543±0.05	2.06±0.09	5.18±1.05	4.55±0.73	195.50±5.63	0.16±0.046	5.00±1.32
PLA+ CNTs	0.560±0.06	5.92±1.20	7.55±1.35	9.93±0.57	202.50±6.5	0.44±0.04	5.67±0.29
CNTs 2% wt	0.424±0.07	5.00±1.07	3.23±0.63	2.27±0.51	192.83±3.51	0.15±0.02	5.17±0.58
CNTs 4% wt	0.400±0.03	4.32±1.37	5.25±0.37	1.03±0.21	196.00±8.79	0.10±0.07	3.17±1.26
CNTs 6% wt	0.691±0.11	7.3±1.05	6.34±1.69	0.88±0.06	142.50±11.5	0.04±0.00	1.83±0.76
CNTs 8% wt	0.623±0.07	3.43±0.91	3.64±0.75	2.00±0.21	151.83±16.6	0.13±0.06	5.00±0.50
CNTs 10% wt	0.740±0.18	3.74±0.45	3.11±1.28	2.21±0.18	198.33±5.03	0.11±0.01	4.50±0.87
p-value	0.002*	0.000*	0.001*	0.000*	0.000*	0.000*	0.001*

where *is significantly difference at $p<0.05$

Results and Discussion

Mechanical properties

1. Tensile test



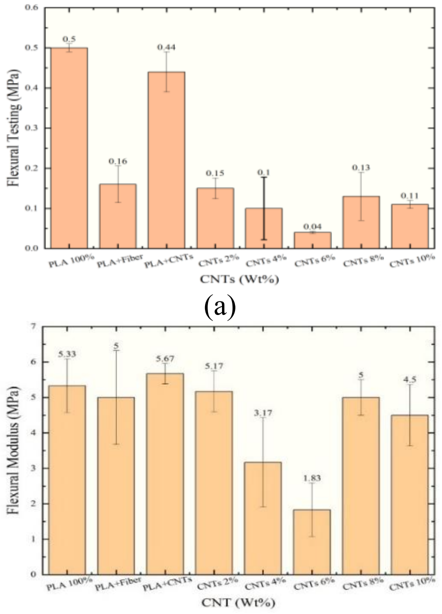
(a)

(b)

Figure 2 Tensile properties of Bioplastic composites (a) Tensile strength (b) Tensile modulus

Figure 2(a) illustrates the relationship between CNT content and tensile strength, showing a significant decreasing trend as carbon nanotube concentration increases in the composite material. Pure PLA (100%) exhibited the highest tensile strength at 11.28 MPa, followed by PLA+CNTs at 9.54 MPa. The vetiver root fiber and carbon nanotube composite (PLA+Fiber+CNTs) demonstrated a continuous decline in tensile strength with increasing carbon nanotube content, reaching its lowest value of 0.58 MPa at 6% wt CNTs. Subsequently, the tensile strength slightly increased to 1.96 MPa and 2.16 MPa at CNT concentrations of 8% wt and 10% wt, respectively. This phenomenon can be explained by the theory of carbon nanotube dispersion in polymer matrices. As described by [20], at lower CNT concentrations, nanotube dispersion in the matrix is more uniform. However, as CNT content increases, agglomeration occurs, creating defect sites within the composite structure that serve as failure initiation points when subjected to tensile forces [21]. Additionally, the reduction in tensile strength may result from the incompatibility between hydrophobic carbon nanotubes and hydrophilic vetiver root fibers, leading to interfacial voids and reduced load transfer efficiency between the matrix and reinforcing materials [22]. Nevertheless, the slight increase in tensile strength at 8% and 10% CNT content may be attributed to the formation of an interconnected network at higher concentrations, enhancing load-bearing capacity, which aligns with findings by [23] that high-concentration CNTs can form continuous networks and increase strength. Figure 2(b) demonstrates the relationship between carbon nanotube content and tensile modulus, revealing a non-linear variation with CNT concentration. Pure PLA exhibited a high tensile modulus of 208.33 MPa, while the composite materials showed relatively stable or slightly decreased modulus values at 2% and 4% CNT content (192.83 MPa and 196 MPa, respectively). However, a significant decrease occurred at 6% and 8% CNT concentrations (142.5 MPa and 151.83 MPa), before increasing again at 10% CNTs (198.33 MPa). This pattern aligns with percolation threshold theory, which explains that at a critical concentration of carbon nanotubes, significant changes in composite material behavior occur [24]. In this case, 6% CNT content may represent the percolation threshold causing structural changes within the composite, possibly due to excessive CNT agglomeration resulting in matrix discontinuity. The increase in modulus at 10% CNTs corresponds with research by [25], which found that at very high CNT concentrations, a percolated network forms throughout the matrix, improving force absorption and distribution, thereby increasing the modulus. Statistical analysis of the data in Table 1 reveals p-values less than 0.05 ($p<0.05$) for all experimental conditions, indicating statistically significant differences between group means at a 95% confidence level. The analysis confirms that pure PLA has the highest tensile strength (10.37±0.88 MPa), significantly different from all composite types. The addition of vetiver root fibers alone significantly reduced tensile strength (4.55±0.73 MPa). Furthermore, incorporating CNTs into the PLA/vetiver root fiber system resulted in significantly lower tensile strength compared to pure PLA, though slight increases were observed at 8% and 10% CNTs concentrations.

2. Flexural test



(a)

(b)

Figure 3 Flexural properties of Bioplastic composites (a) Flexural strength (b) Tensile modulus

Figure 3(a) illustrates the relationship between CNTs content and flexural strength, demonstrating a declining trend as CNTs concentration increases in the composite material. Pure PLA (100%) exhibited the highest flexural strength at 0.50 MPa, followed by PLA+CNTs at 0.44 MPa, while the composite material containing only vetiver root fibers (PLA+Fiber) showed a significantly reduced flexural strength of 0.16 MPa compared to pure PLA. When examining composite materials with various CNTs concentrations, the flexural strength showed a continuous decrease from 0.15 MPa at 2% wt CNTs to 0.10 MPa at 4% wt CNTs, reaching its lowest value of 0.04 MPa at 6% wt CNTs. Subsequently, the flexural strength slightly increased to 0.13 MPa and 0.11 MPa at CNTs concentrations of 8% wt and 10% wt, respectively. This phenomenon can be explained by theories of dispersion and interaction between component materials in composites. As [26] described, the reinforcement efficiency of carbon nanotubes depends on their dispersion and adhesion to the polymer matrix. When CNTs content increases, the likelihood of agglomeration also increases, creating stress concentration points and reducing load transfer efficiency [27].

Figure 3(b) depicts the relationship between CNTs content and flexural modulus, revealing an interesting pattern. The PLA+CNTs composite shows the highest modulus at 5.67 MPa, slightly higher than pure PLA at 5.33 MPa, while PLA+Fiber exhibits a lower modulus of 5.00 MPa compared to pure PLA. When analyzing composite materials with varying CNTs concentrations, the flexural modulus demonstrates a decreasing trend as CNT content increases from 5.17 MPa at 2% wt CNTs to 3.17 MPa at 4% wt CNTs, reaching its lowest value of 1.83 MPa at 6% wt CNTs. Subsequently, the modulus increases significantly to 5.00 MPa and 4.50 MPa at CNTs concentrations of 8% wt and 10% wt, respectively. This non-linear relationship between CNTs content and flexural modulus aligns with critical loading theory, which explains that there is critical filler content that significantly affects the mechanical properties of composite materials [28]. The increase in modulus at CNTs concentrations of 8% and 10% compared to 6% corresponds with research by [25], who found that at the percolation threshold of carbon nanotubes, an interconnected network forms throughout the matrix, enhancing the composite material's resistance to deformation, which is reflected in the increased modulus values. The mean values and standard deviations of flexural strength and flexural modulus, as shown in Table 1, reveal that the p-value for all experimental conditions is less than 0.05 ($p<0.05$), indicating that the differences between the mean values of each group are statistically significant at the 95% confidence level.

For flooring applications, flexural properties directly indicate performance under distributed loads from foot traffic and furniture. At 8-10% wt, the composites showed flexural values suitable for residential flooring applications, with recovery in properties that suggest optimization potential. The mechanical profile at these concentrations' balances strength requirements with other beneficial properties critical for flooring performance.

Physical properties test

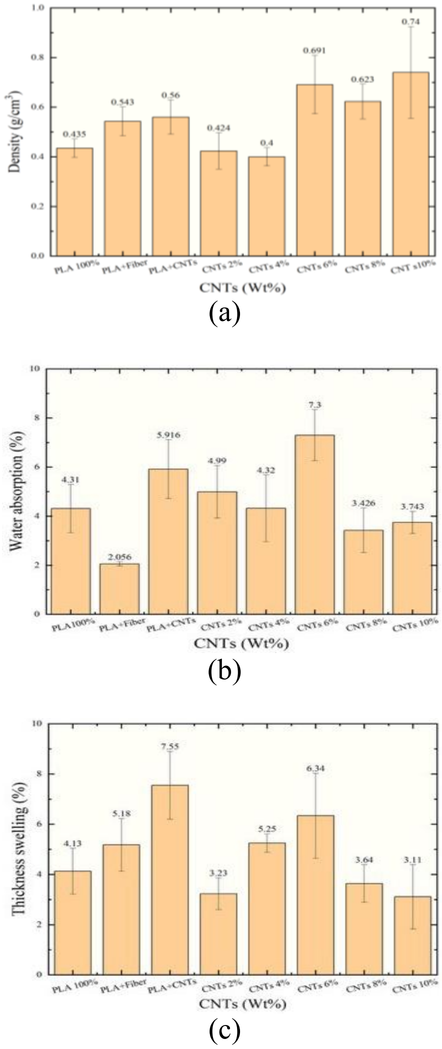


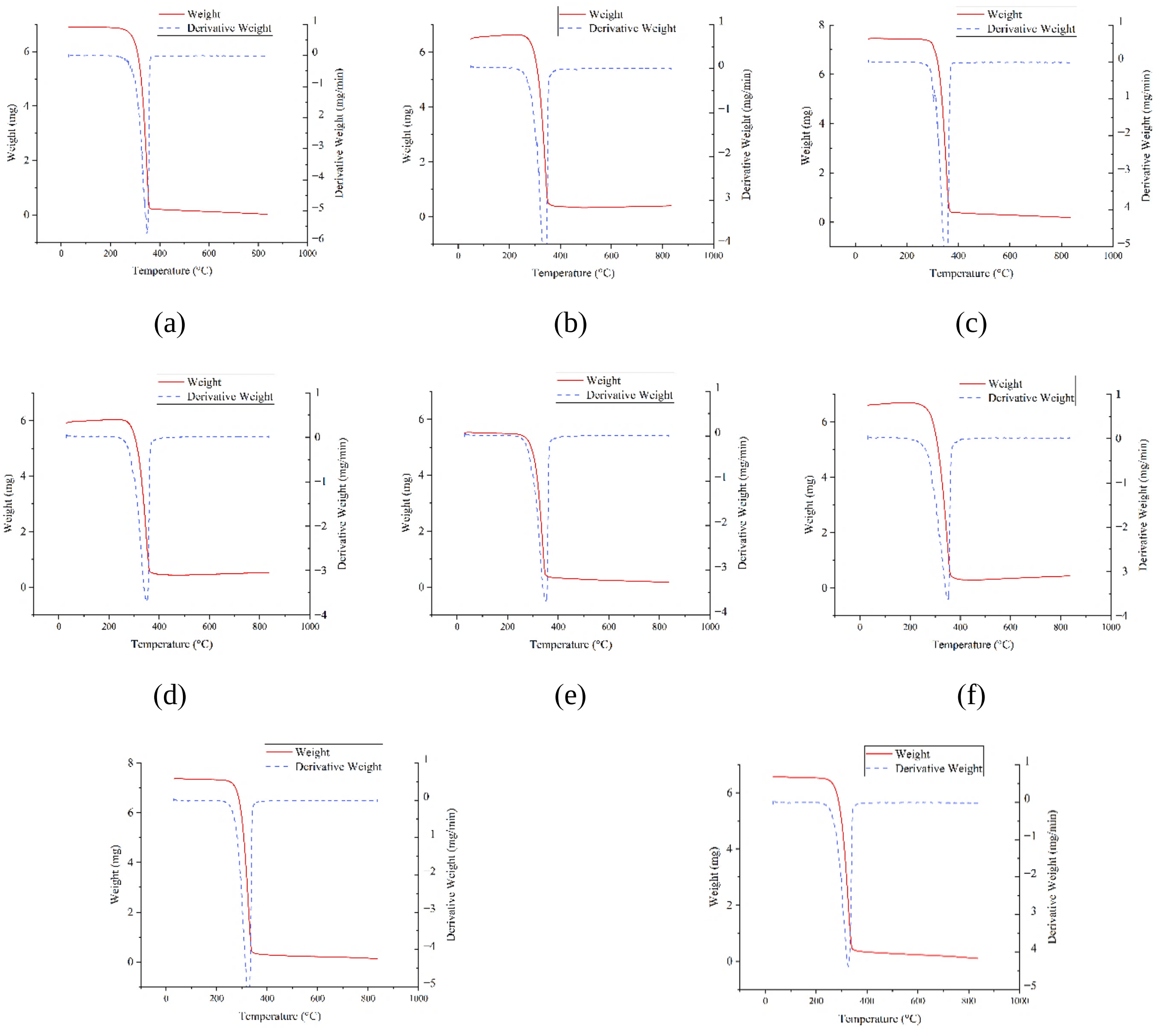
Figure 4 Physical properties of Bioplastic composites (a) Density (b) Water absorption and (c) Thickness swelling

Thermal properties test

Figure 5 presents the thermal decomposition profiles of various bioplastic composites analyzed using Thermogravimetric Analysis (TGA). All samples exhibit similar decomposition patterns, with the primary weight loss occurring in the temperature range of approximately 300-400°C, corresponding to the degradation of the PLA matrix as evidenced by the sharp drops in the weight curves and corresponding peaks in the derivative weight curves. Pure PLA (Figure 5a) shows a single-step decomposition with maximum degradation at approximately 350°C, consistent with the thermal breakdown of PLA. The PLA+Fiber composite (Figure 5b) demonstrates a slightly more complex degradation pattern, with the fiber component likely contributing to a minor secondary decomposition process. The addition of CNTs to PLA (Figure 5c) appears to maintain a thermal profile similar to pure PLA, indicating minimal interference with the polymer's thermal degradation mechanisms. When examining various CNT concentrations (Figures 5d-h), a trend emerges where higher CNT content (particularly at 8 %wt and 10 %wt, Figures 5g-h) results in slightly enhanced thermal stability, as indicated by the shifted decomposition temperatures. This improvement can be attributed to the barrier effect of well-dispersed CNTs, which impede the release of volatile degradation products and retard mass loss during heating [32]. Additionally, the high thermal conductivity of CNTs facilitates more efficient heat distribution throughout the composite, potentially delaying localized thermal degradation [33]. These results demonstrate that carbon nanotube materials can enhance the thermal stability of polymer composites.

Enhanced thermal stability at 8-10% CNT loadings is particularly beneficial for flooring installed over radiant heating systems or in areas receiving direct sunlight. The improved heat distribution properties of these composites may contribute to more comfortable walking surfaces while reducing the risk of thermal deformation. This thermal profile complements the dimensional stability advantages, creating a material well-suited to the variable environmental conditions flooring materials must withstand.

Microstructural analysis of tensile fracture surfaces provides critical insights into these mechanical behavior patterns. Figure 6 presents SEM micrographs of tensile fracture surfaces for (a) PLA+Fiber, (b) 6% CNT, and (c) 10% CNT composites. The PLA+Fiber sample shows relatively good fiber-matrix adhesion with minimal pull-out. In contrast,



(a) (b) (c)

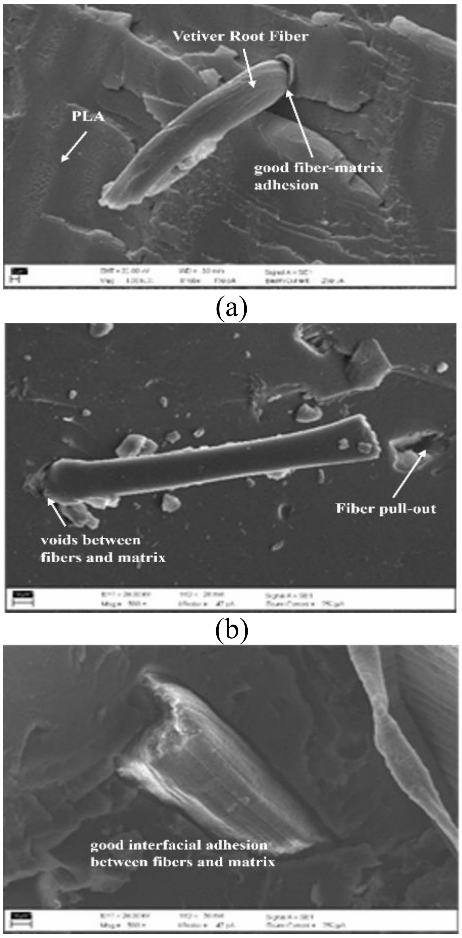
(d) (e) (f)

(g) (h)

Figure 5 Decomposition temperature of Bioplastic composites (a) PLA100% wt (b) PLA+Fiber (c) PLA+CNT (d)CNT 2% wt (e) CNT4% wt (f) CNT6% wt (g) CNT8% wt (h) CNT10% wt

the 6% CNT sample exhibits significant CNT agglomeration and interfacial voids between fibers and matrix, explaining the observed mechanical property minimum. The 10% CNT sample reveals formation of a continuous CNT network bridging between fibers and matrix with improved interfacial adhesion, corresponding to the recovery in tensile properties. Similar structural features are observed in flexural fracture surfaces, confirming that CNT dispersion quality and network formation directly determine mechanical performance in these composites. Based on our comprehensive analysis, 8-10% CNT formulations provide the optimal balance for flooring applications with superior dimensional stability and thermal performance. Pure PLA and 2% CNT formulations, with higher mechanical strength, are better suited for packaging applications, while intermediate concentrations (4-6%) are not recommended for structural uses.

Microstructural analysis



(a)

(b)

(c)

Figure 6 SEM micrographs (a) PLA+fiber at 1000x (b) PLA + fiber with 6 wt% CNT at 500x and (c) PLA + fiber with 10 wt% CNT at 500x

Conclusions

This study demonstrates that CNTs content significantly influences the properties of vetiver root fiber-reinforced PLA bio-composites developed for environmentally friendly flooring applications. The research revealed a non-linear relationship between CNTs concentration and material performance, with 6% wt CNTs representing a critical threshold where properties reached minimum values before improving at higher concentrations. Composites with 8-10% wt CNT content demonstrated the most balanced performance profile for flooring applications. While mechanical strengths were lower than pure PLA, these formulations exhibited superior dimensional stability with reduced water absorption (3.43-3.74%) and thickness swelling (3.64-3.11%), critical factors for flooring durability. The results establish specific formulation guidelines for developing sustainable bio-hybrid composite flooring from vetiver roots and CNTs that align with Thailand's Bio-Circular-Green Economy model.

Future work will expand on these findings to include electrical conductivity characterization, as the conductive nature of CNTs could provide additional functional properties such as antistatic behavior beneficial for specialty flooring applications. Preliminary testing suggests a correlation between the mechanical property threshold and electrical percolation threshold, which warrants comprehensive investigation.

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