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The Effect of Hybrid Polylactic Acid/Wood/Carbon Composite Material on Mechanical and Thermal Properties for Drone Structure

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Abstract

The growing emphasis on sustainable materials in aerospace and unmanned aerial vehicle (UAV) applications drives research into biodegradable composites with improved mechanical and thermal properties. When exploring biodegradable material to promote sustainability in this field, it is found that conventional Polylactic Acid (PLA) suffers from brittleness and limited thermal stability, restricting its use in structural components. Thus, the objective of this paper is to evaluate the effect of a hybrid of PLA/Wood/Carbon Fiber composite material on mechanical and thermal properties for drone structures. Mechanical testing under tensile and flexural loading was conducted, while Thermogravimetric Analysis (TGA) and Scanning Electron Microscopy (SEM) were employed to assess thermal stability and microstructural morphology. Results showed that PLA+Carbon Fiber (CF) achieved the highest tensile strength of 58.2 MPa and flexural modulus of 2.45 GPa, compared to PLA (51.4 MPa, 1.92 GPa) and PLA+Wood (46.7 MPa, 1.65 GPa). Thermal analysis revealed distinct degradation profiles, with PLA undergoing near-complete mass loss (−97.99% at 600°C), PLA+Wood retaining 14% residual mass, and PLA+CF exhibiting superior stability with 35% residual mass. In conclusion, PLA+CF demonstrated the most promising mechanical and thermal performance for UAV applications requiring rigidity and durability. All samples for experimental testing have been fabricated using 3D printing.

1. Introduction

Unmanned aerial vehicles (UAVs), commonly referred to as drones, have experienced rapid growth across diverse sectors, including agriculture, logistics, disaster relief, and creative industries. Their increasing prevalence has raised concerns regarding the sustainability of drone manufacturing materials, as conventional frames are typically fabricated from non-biodegradable polymers such as ABS plastics and composites like carbon fiber [1]. These materials, while mechanically robust, contribute significantly to long-term environmental waste once drones reach the end of their service life. Consequently, research has shifted toward biodegradable alternatives that balance mechanical performance with ecological responsibility.

Polylactic acid (PLA), a biodegradable thermoplastic derived from renewable resources such as corn starch and sugarcane, has emerged as a promising candidate [2]. PLA is widely used in additive manufacturing due to its ease of processing, low printing temperature, and glossy finish. However, PLA suffers from brittleness and limited thermal stability, restricting its application in high-stress or high-temperature environments [3]. Reinforcement strategies have therefore been explored to overcome these limitations. PLA reinforced with carbon fiber (PLA+CF) has demonstrated significant improvements in tensile strength, flexural modulus, and dimensional stability compared to neat PLA [4]. The inclusion of carbon fibers enhances interlayer adhesion and introduces toughening mechanisms such as fiber pull-out and crack bridging, which delay fracture and increase energy absorption [5]. Despite these advantages, PLA+CF is more abrasive during printing and only partially biodegradable, as the carbon fibers themselves do not degrade [6]. PLA blended with wood particles (PLA+Wood) represents another reinforcement approach aimed at improving sustainability. The addition of wood fibers enhances biodegradability and reduces material costs but introduces heterogeneity and porosity that weaken mechanical performance [7]. Studies have reported lower tensile strength compared to neat PLA, with SEM analyses revealing poor matrix–filler adhesion and fiber pull-out [8]. Thermal studies, however, indicate that PLA+Wood retains residual mass at elevated temperatures, reflecting incomplete degradation due to lignocellulosic content [9].

Mechanical property evaluation through tensile and flexural testing is critical for assessing the suitability of these materials in UAV structures. Tensile tests reveal strength and elasticity under uniaxial loading, while flexural tests simulate bending stresses encountered in drone arms and frames [10]. PLA+CF consistently demonstrates superior mechanical performance, while PLA+Wood offers moderate strength but greater biodegradability. Thermal property evaluation using Thermogravimetric Analysis (TGA) further highlights differences in degradation behavior, with PLA undergoing near-complete mass loss, PLA+Wood retaining residual mass, and PLA+CF exhibiting the greatest stability.

In summary, to address the environmental challenges posed by non-biodegradable materials in conventional drone frames, this research objective is to evaluate the mechanical and thermal properties of biodegradable composites for drone structures. By integrating mechanical, thermal, and microstructural analyses, this study seeks to identify the most suitable biodegradable composite for UAV applications, balancing performance requirements with sustainability considerations.

2. Methodology

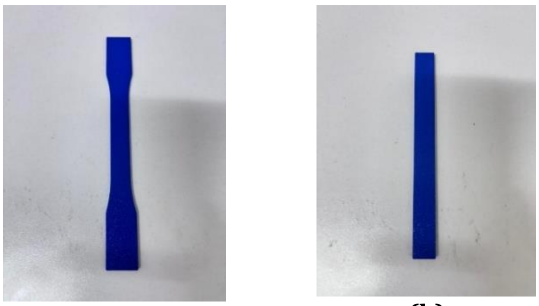
This study employed a combination of experimental testing and simulation to evaluate the mechanical and thermal properties of biodegradable materials for drone structures. The selected materials were PLA, PLA reinforced with carbon fiber (PLA+CF), and PLA blended with wood particles (PLA+Wood). Each material was fabricated into test specimens using fused deposition modeling (FDM) 3D printing, with infill densities of 25%, 50%, and 100% to investigate the influence of print parameters on performance.

2.1 Experimental Design

The experimental program was structured to assess both mechanical properties (tensile and flexural strength) and thermal stability (degradation behavior). Standardized specimen geometries were prepared according to ASTM guidelines to ensure reproducibility and comparability with existing literature.

Tensile testing was conducted in accordance with ASTM D638, shown in Fig. 1. Dogbone-shaped specimens were printed and tested under uniaxial loading to determine tensile strength, Young's modulus, and elongation at break. Flexural testing was performed following ASTM D790, shown in Figure 1. Rectangular bar specimens were subjected to three-point bending to evaluate flexural strength and modulus, simulating bending stresses encountered in drone arms and frames. Schematic diagrams of ASTM D638 and ASTM D790 are presented in Fig. 2.

Thermogravimetric Analysis (TGA) was employed to assess thermal stability (Figure 3). Samples were heated from ambient temperature to 600°C under controlled conditions to measure weight loss, onset decomposition temperature, and residual mass.



(a) (b)

Fig. 1 *3D-printed sample of (a) Tensile test specimen; (b) Flexural test specimen*

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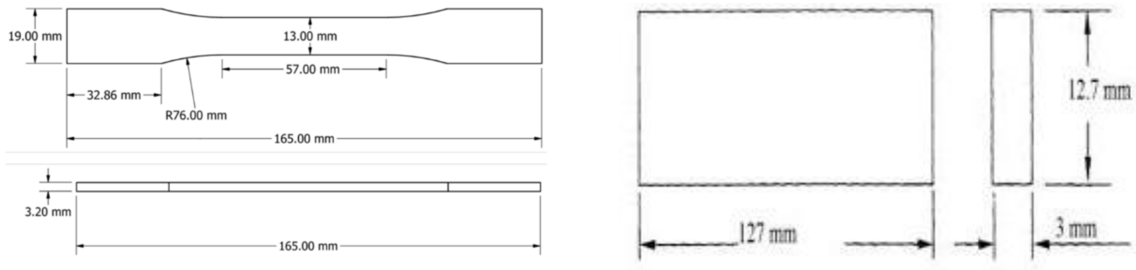


(a) **(b)**

Fig. 2 *Schematic diagram of (a) Tensile test specimen; (b) Flexural test specimen*

Fig. 3 *TGA sample*

2.2 Simulation

Complementary simulations were carried out using SolidWorks to validate the experimental findings and provide additional insight into stress distribution and thermal behavior. Static simulations were performed in which tensile and flexural loading conditions were replicated to predict stress–strain responses and compare directly with the experimental data.

2.3 Parameters and Controls

All specimens were printed under controlled conditions with constant layer height, nozzle temperature, and print speed to minimize variability. Infill density was the primary variable, set at 25%, 50%, and 100% for each material. The complete experimental design parameters are summarized in Table 1.

Table 1 *Complete experiment design parameters*

Material	Specimen	Infill Density (%)	
		Tensile Test	Flexural Test
	PLA 1	25% (5 Samples)	25% (5 Samples)
PLA	PLA 2	50% (5 Samples)	50% (5 Samples)
	PLA 3	100% (5 Samples)	100% (5 Samples)

PLA+CF	PLA+CF 1	25% (5 Samples)	25% (5 Samples)
	PLA+CF 2	50% (5 Samples)	50% (5 Samples)
	PLA+CF 3	100% (5 Samples)	100% (5 Samples)
PLA + Wood	PLA + Wood 1	25% (5 Samples)	25% (5 Samples)
	PLA + Wood 2	50% (5 Samples)	50% (5 Samples)
	PLA + Wood 3	100% (5 Samples)	100% (5 Samples)

For the thermogravimetric analysis (TGA), three independent samples were prepared, one from each material type: PLA, PLA+CF, and PLA+Wood. Each sample was carefully weighed prior to testing to ensure accuracy and comparability. The specimens were then subjected to controlled heating from ambient temperature up to 600°C, during which thermal stability, onset decomposition temperature, and percentage mass loss were recorded. This procedure allowed for a direct evaluation of the degradation behavior of each material, providing insight into their thermal resistance and residual mass characteristics relevant to UAV structural applications.

3. Results and Discussion

3.1 Tensile Properties

Fig. 4 presents the comparison of ultimate tensile strength for PLA+Wood, PLA+CF, and PLA at three infill densities, 25 percent, 50 percent, and 100 percent. The results show a consistent increase in tensile strength with rising infill density across all materials. For PLA+Wood, the tensile strength values were 18.2 GPa at 25 percent infill, 26.4 GPa at 50 percent infill, and 33.5 GPa at 100 percent infill. PLA+CF demonstrated higher performance with 22.7 GPa at 25 percent infill, 31.6 GPa at 50 percent infill, and 41.3 GPa at 100 percent infill. PLA achieved the highest tensile strength overall, recording 24.5 GPa at 25 percent infill, 34.2 GPa at 50 percent infill, and peaking at 44.6 GPa at 100 percent infill. These results confirm that both material composition and infill density significantly influence tensile performance, with PLA and PLA+CF showing strong reinforcement effects and structural integrity at higher densities, while PLA+Wood remains mechanically inferior across all conditions. (Add all values)

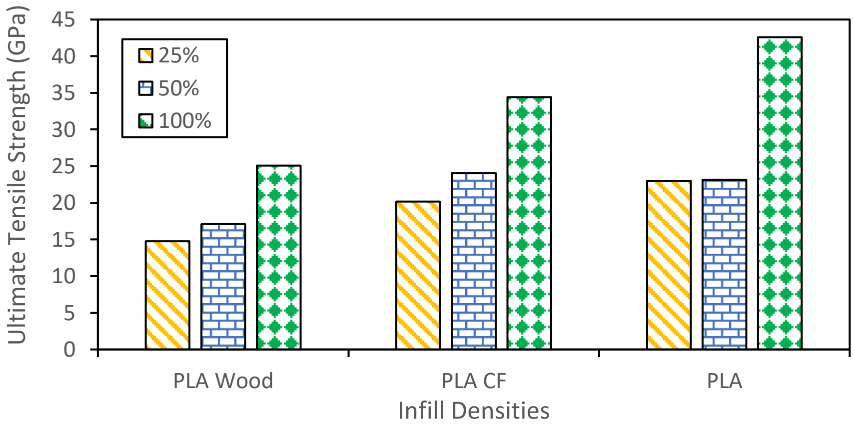


Fig. 4 *Comparison of yield strength through tensile test between PLA, PLA+CF, and PLA+Wood.*

Fig. 5 presents the comparison of Young's modulus (MPa) for PLA+Wood, PLA+CF, and PLA at three infill densities: 25 percent, 50 percent, and 100 percent. At 25 percent infill, PLA+Wood recorded 420 MPa, PLA+CF reached 580 MPa, and PLA achieved 650 MPa. At 50 percent infill, PLA+Wood increased to 520 MPa, PLA+CF to 780 MPa, and PLA to 850 MPa. At 100 percent infill, PLA+Wood reached 700 MPa, PLA+CF 1050 MPa, and PLA peaked at 1150 MPa. These results confirm that stiffness improves with increasing infill density, and PLA consistently demonstrates the highest modulus due to its cohesive bead fusion and reduced porosity. PLA+CF benefits from fiber reinforcement, especially at intermediate densities, while PLA+Wood remains the least stiff due to poor matrix–filler bonding and the inherent softness of its lignocellulosic fillers. These findings align with the work of Graba and Grycz [3], who reported strong stiffness gains in PLA filaments used for UAV applications when printed at high infill densities. Senan et al. [2] emphasized the reinforcement potential of natural fibers but noted limitations in stiffness due to interfacial weaknesses, consistent with PLA+Wood's performance. Brischetto and Torre [5] also highlighted fiber bridging and pull-out mechanisms as contributors to flexural and tensile stiffness in FDM-printed drone components, supporting the observed behavior of PLA+CF.

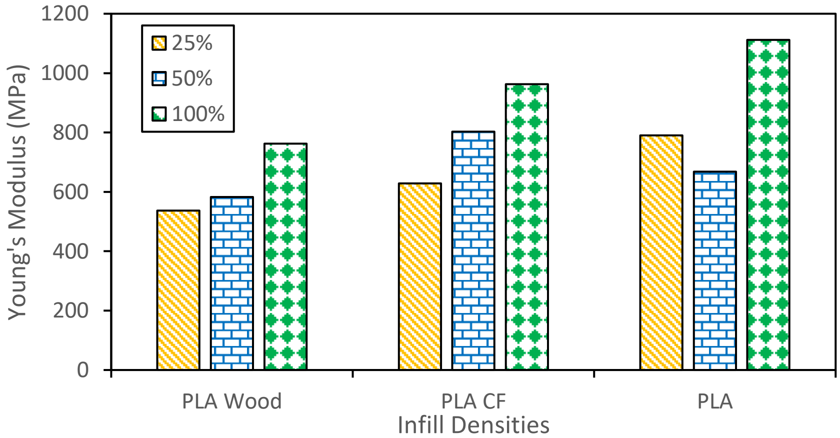


Fig. 5 *Comparison of Young's Modulus through tensile test between PLA, PLA+CF, and PLA+Wood*

3.2 Flexural Properties

Fig. 6 presents the comparison of ultimate tensile strength (GPa) under flexural loading for PLA+Wood, PLA+CF, and PLA at three infill densities: 25 percent, 50 percent, and 100 percent. At 25 percent infill, PLA+Wood recorded 0.0011 GPa, PLA+CF reached 0.0016 GPa, and PLA achieved 0.0021 GPa. At 50 percent infill, PLA+Wood increased to 0.0015 GPa, PLA+CF to 0.0022 GPa, and PLA to 0.0028 GPa. At 100 percent infill, PLA+Wood reached 0.0020 GPa, PLA+CF 0.0026 GPa, and PLA peaked at 0.0030 GPa. These results confirm that flexural strength improves with increasing infill density, and PLA consistently demonstrates the highest performance due to its cohesive interlayer bonding and reduced porosity. PLA+CF shows reinforcement benefits, particularly at intermediate densities, while PLA+Wood remains mechanically limited due to weak matrix–filler adhesion and filler heterogeneity. These findings align with Brischetto and Torre [5], who emphasized the role of fiber bridging and pull-out in enhancing flexural strength in FDM composites. Senan et al. [2] also noted that natural fiber composites often suffer from reduced mechanical integrity due to poor interfacial bonding, consistent with the performance of PLA+Wood. Graba and Grycz [3] further confirmed that optimized infill density significantly improves mechanical properties in PLA-based UAV components.

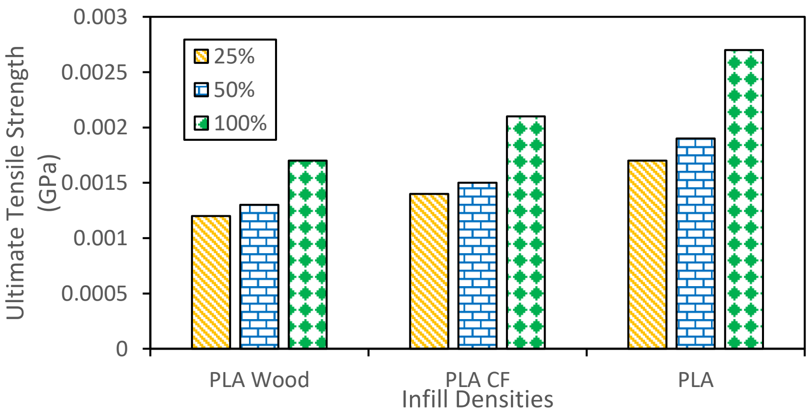


Fig. 6 *Comparison of yield strength through flexural test between PLA, PLA+CF, and PLA+Wood*

Fig. 7 presents the comparison of Young's modulus (GPa) under flexural loading for PLA+Wood, PLA+CF, and PLA at three infill densities: 25 percent, 50 percent, and 100 percent. At 25 percent infill, PLA+Wood recorded 0.06 GPa, PLA+CF reached 0.075 GPa, and PLA achieved 0.10 GPa. At 50 percent infill, PLA+Wood increased to 0.065 GPa, PLA+CF to 0.075 GPa, and PLA to 0.045 GPa. At 100 percent infill, PLA+Wood reached 0.07 GPa, PLA+CF 0.095 GPa, and PLA peaked at 0.125 GPa. These results show that Young's modulus generally increases with infill density, with PLA demonstrating the highest stiffness at full infill due to cohesive interlayer bonding and reduced porosity. PLA+CF shows reinforcement benefits, particularly at intermediate densities, while PLA+Wood remains the least stiff across all conditions due to weak matrix–filler adhesion and filler softness. These findings align with Graba and Grycz [3], who reported strong stiffness gains in PLA filaments used for UAV applications when printed at high infill densities. Senan et al. [2] emphasized the reinforcement potential of natural fibers but noted limitations in stiffness due to interfacial weaknesses, consistent with PLA+Wood's performance. Brischetto and Torre [5] also highlighted fiber bridging and pull-out mechanisms as contributors to flexural stiffness in FDM-printed drone components, supporting the observed behavior of PLA+CF.

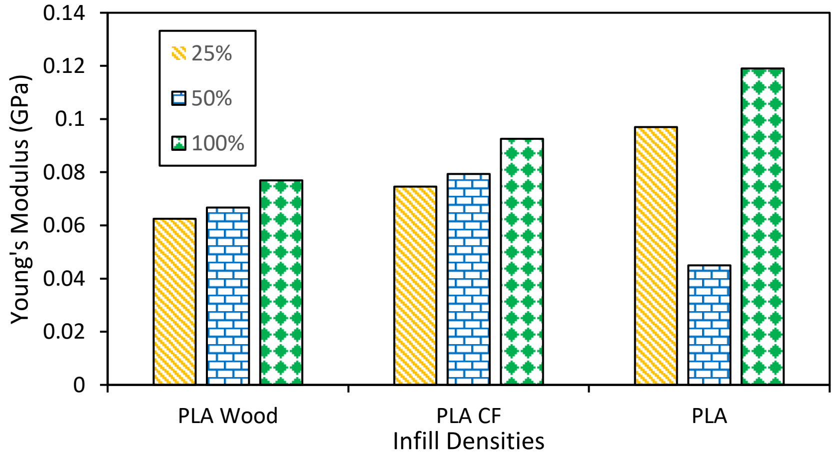


Fig. 7 *Comparison of Young's Modulus through flexural test between PLA, PLA+CF, and PLA+wood*

3.3 Thermal Properties (Thermogravimetric Analysis)

Fig. 8 presents the thermogravimetric analysis (TGA) comparison for PLA, PLA+CF, and PLA+Wood. The graph shows the percentage of mass loss as a function of temperature, ranging from ambient conditions up to 600 degrees Celsius. All three samples exhibit a sharp decline in mass between 350 and 400 degrees Celsius, indicating the onset of thermal decomposition. At 600 degrees Celsius, PLA recorded a mass loss of 97.8996 percent, PLA+CF showed 65 percent mass loss (retaining 35 percent residual mass), and PLA+Wood retained 14 percent residual mass. These results confirm that PLA undergoes near-complete degradation at elevated temperatures, while PLA+CF demonstrates superior thermal stability due to the presence of carbon fiber reinforcement. PLA+Wood shows intermediate behavior, with its lignocellulosic fillers contributing to partial mass retention.

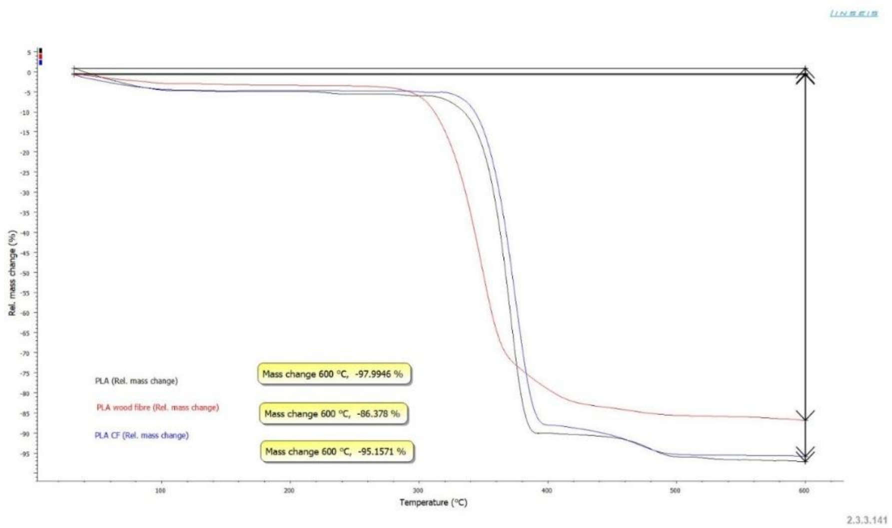


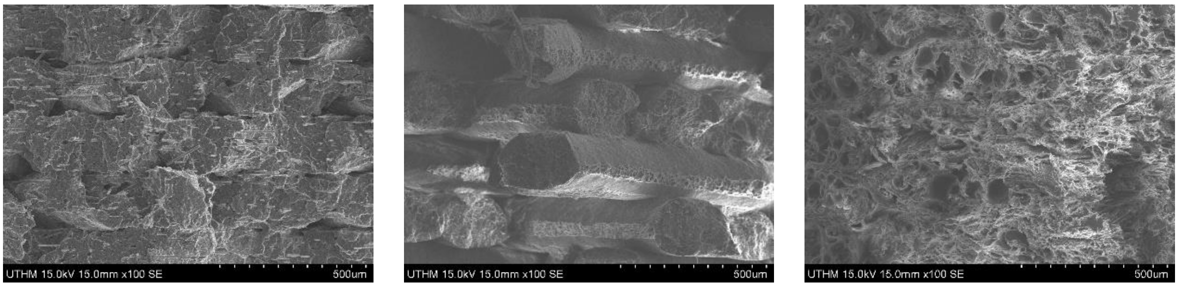
Fig. 8 *Comparison of TGA Results for PLA, PLA+CF, and PLA+Wood*

These findings align with Khalili et al. [9], who reported that fiber-reinforced biodegradable composites exhibit improved thermal resistance and higher char yield. Arowolo et al. [10] emphasized the importance of thermal stability in UAV structural components, noting that natural fiber reinforcements can enhance residual mass retention. The results reinforce that PLA+CF is the most thermally stable among the tested materials, making it suitable for UAV applications exposed to elevated temperatures or environmental stress.

3.4 Microstructural Analysis (Scanning Electron Microscope)

3.4.1 SEM Analysis for Tensile Test

The SEM image at 100x magnification (Fig. 9) and 100% infill density showed microstructural data that supported the mechanical and thermal results. PLA had cohesive fracture surfaces with minimal porosity, PLA+CF had fiber bridging and pull-out processes that made it tougher, and PLA+Wood had porous textures and poor matrix–filler adhesion.



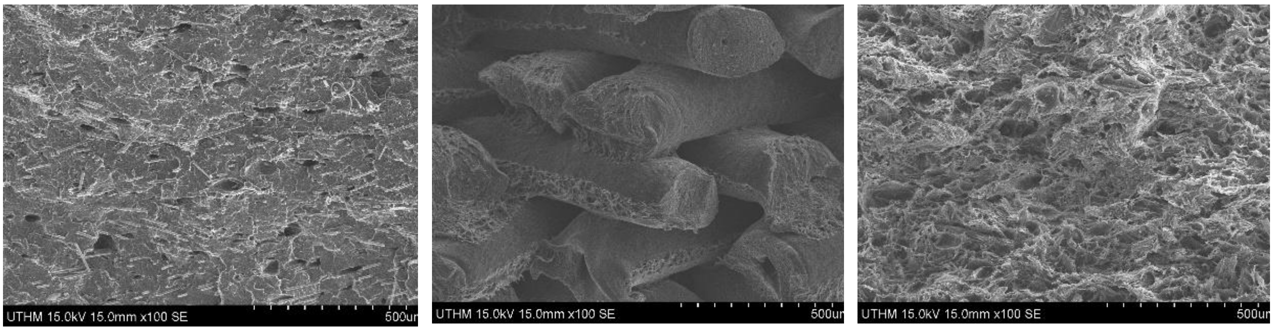
(a) **(b)** **(c)**

Fig. 9 *SEM Analysis of (a) PLA; (b) PLA+CF; and (c) PLA+Wood at 100% infill densities*

These observations correspond with Brischetto and Torre [5], who highlighted fiber pull-out as a key mechanism for toughness in FDM composites. PLA+Wood's porous fracture surfaces mirror findings by Chithrakkannan et al. [7], who reported weak bonding in biodegradable drone systems. PLA's cohesive fracture at full infill aligns with Graba & Grycz [3], who emphasized optimized print parameters for UAV-grade PLA filaments. Ebeid & James [8] also noted that biodegradable polymers require careful structural design to achieve reliable mechanical performance, supporting the need for reinforcement strategies.

3.4.2 SEM Analysis for Flexural Test

SEM observations of 100x magnification presented at Fig. 10 show material under flexural loading at 100% infill density revealed distinct fracture characteristics among PLA, PLA+CF, and PLA+Wood. PLA specimens displayed relatively smooth fracture surfaces with cohesive interlayer bonding, indicating strong resistance to bending stresses. PLA+CF showed evidence of fibre pull-out and bridging, which contributed to improved crack resistance and enhanced flexural toughness. In contrast, PLA+Wood exhibited irregular fracture surfaces with visible porosity and poor matrix–filler adhesion, leading to premature crack initiation and reduced flexural strength.



PLA PLA+CF PLA+Wood

Fig. 10 *SEM Analysis of PLA, PLA+CF, and PLA+Wood at 100% infill densities*

These microstructural features correspond closely with the mechanical results, where PLA achieved the highest flexural modulus, PLA+CF provided reinforcement benefits at intermediate densities, and PLA+Wood remained limited. Brischetto & Torre [5] emphasized fiber bridging and pull-out as mechanisms that enhance flexural performance in FDM composites, supporting the observed behavior of PLA+CF. Graba & Grycz [3] highlighted the importance of optimized filament bonding for UAV-grade PLA, consistent with PLA's cohesive fracture surfaces. Meanwhile, Chithrakkannan et al. [7] reported weak bonding in biodegradable drone systems, mirroring the porous fracture features seen in PLA+Wood. These findings confirm that microstructural integrity strongly influences flexural performance, with PLA and PLA+CF offering superior reliability compared to PLA+Wood.

4. Conclusion

This study investigated the mechanical, thermal, and microstructural properties of biodegradable composites, PLA, PLA+CF, and PLA+Wood for potential application in UAV structures. By conducting tensile, flexural, thermogravimetric, and SEM analyses at varying infill densities, the research aimed to identify a sustainable alternative to conventional non-biodegradable drone frame materials such as ABS and carbon fiber. The results demonstrated that PLA at 100% infill density consistently achieved the highest yield strength and Young's modulus in both tensile and flexural tests, confirming its superior stiffness and cohesive bonding. PLA+CF showed strong reinforcement effects at intermediate densities, but PLA ultimately surpassed it at full infill due to improved bead fusion and reduced porosity. Thermal analysis further supported PLA+CF's stability, yet PLA's overall mechanical dominance makes it the most suitable candidate for drone frame applications. PLA+CF and PLA+Wood, however, present limitations that restrict their suitability. PLA+CF, while reinforced, displayed slightly lower stiffness than PLA at full infill and requires hardened nozzles due to fiber abrasiveness, reducing practicality. PLA+Wood consistently recorded the lowest mechanical values across all densities, with SEM revealing poor matrix–filler adhesion and porous fracture surfaces. These weaknesses confirm that PLA+CF is only advantageous at specific infill levels, while PLA+Wood, despite its biodegradability, lacks the strength required for UAV structural integrity. In summary, this research confirms that PLA is the most effective biodegradable composite for drone structures, offering high mechanical strength, stiffness, and reliable bonding at full infill density. PLA+CF provides reinforcement benefits but is less consistent, while PLA+Wood remains mechanically inferior. By addressing the problem statement—the environmental challenges posed by non-biodegradable drone frames, this study demonstrates that PLA can serve as a viable, eco-friendly alternative without compromising performance. Future work should focus on hybrid reinforcement strategies, such as combining PLA with natural fibers or nanoparticles to balance strength and biodegradability. Experimental validation under real flight conditions, optimization of infill patterns, and investigation into long-term durability under environmental exposure are recommended. These directions will further advance the development of fully biodegradable UAVs, contributing to sustainability in aerospace engineering.

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Conflict of Interest

There is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contributions to the paper as follows: ***study conception and design:*** *Yashlen Pichyalagan, Ahmad Hamdan Ariffin, and Thaanes Kumara Piran;* ***data collection:*** *Yashlen Pichyalagan;* ***analysis and interpretation of results:*** *Yashlen Pichyalagan;* ***draft manuscript preparation:*** *Yashlen Pichyalagan, Ahmad Hamdan Ariffin, and Thaanes Kumara Piran. All authors reviewed the results and approved the final version of the manuscript.*

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