

Hybrid Agro-Waste Reinforced PLA Smart Composites with Embedded NFC for Sustainable Lifecycle Monitoring

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Abstract

The growing demand for sustainable engineering materials has accelerated the development of biodegradable polymer composites capable of combining structural performance with intelligent lifecycle management. In this study, a smart biodegradable agro-waste polymer composite reinforced with rice husk and sugarcane bagasse fibers were developed using a polylactic acid (PLA) matrix integrated with an embedded passive Near Field Communication (NFC) tag for digital traceability and circular economy applications. The composite containing 80 wt.% PLA, 15 wt.% hybrid agro-waste reinforcement and 5 wt.% PLA-g-MA compatibilizer was fabricated through twin-screw extrusion followed by compression molding. SEM analysis confirmed uniform fiber dispersion and strong fiber–matrix bonding. Tensile strength increased from 58 MPa to 74 MPa, while flexural strength improved from 82 MPa to 106 MPa, representing enhancements of 27.6% and 29.3%, respectively. Thermogravimetric analysis demonstrated improved thermal stability through delayed degradation and higher residual char formation. Controlled

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composting showed progressive biodegradation, with the hybrid NFC-integrated composite achieving approximately 47.5% weight loss after 56 days compared with 19% for neat PLA. The embedded passive NFC tag maintained reliable functionality without affecting structural integrity or biodegradation behavior. The developed smart biodegradable composite successfully combines enhanced mechanical performance, thermal stability, controlled biodegradability and digital lifecycle tracking, demonstrating strong potential for sustainable packaging, agricultural products, consumer goods and other environmentally responsible circular economy applications while supporting efficient product identification, recycling, resource recovery initiatives globally.

Keywords: Agro waste, polymer composite, polylactic acid, bagasse fibers, biodegradation

INTRODUCTION

The growing concern over environmental pollution, depletion of fossil resources, and increasing accumulation of plastic waste has accelerated research into sustainable polymeric materials capable of replacing conventional petroleum-based

plastics. Biodegradable polymer composites reinforced with renewable agro-waste fibers have emerged as promising alternatives because they combine environmental compatibility with satisfactory mechanical performance. These materials utilize agricultural residues that would otherwise be discarded or openly burned, thereby reducing environmental pollution while promoting efficient biomass utilization [1]. Consequently, agro-waste-reinforced biodegradable composites have attracted considerable attention for lightweight engineering applications, packaging, automotive interiors, and consumer products owing to their low density, biodegradability, and renewable origin.

Agricultural residues – such as rice husk, sugarcane bagasse, wheat straw, coconut coir, banana fibers, and corn stalks – are rich in cellulose and possess favorable specific strength and stiffness, making them suitable as reinforcement materials for biodegradable polymers. Among the available biodegradable matrices, polylactic acid (PLA) has gained widespread acceptance because of its excellent processability, good mechanical strength, biodegradability, and commercial availability. Incorporating chemically treated agro-waste fibers into PLA not only enhances stiffness and strength but also reduces raw material cost while supporting sustainable waste valorization. Surface modification techniques including alkali and silane treatment further improve fiber–matrix compatibility, leading to enhanced stress transfer, improved dimensional stability, and reduced moisture absorption [2, 3].

Recent developments in polymer composite engineering have demonstrated that hybrid agro-waste reinforcements can significantly improve the mechanical, thermal, and environmental performance of biodegradable composites. The combination of particulate and fibrous natural reinforcements provides a balanced microstructure that enhances tensile and flexural properties while maintaining lightweight characteristics. Advances in processing techniques – such as twin-screw extrusion, compression molding, and injection molding – have enabled the fabrication of homogeneous biodegradable composites with improved reinforcement dispersion and interfacial bonding. These developments have expanded the potential applications of biodegradable polymer composites into packaging, transportation, agricultural equipment, and structural consumer products [4].

Despite these advantages, one of the major limitations of biodegradable polymer composites is the lack of effective product identification and lifecycle monitoring after fabrication. Conventional biodegradable materials generally provide structural functionality but offer limited capability for tracking manufacturing history, maintenance records, usage conditions, recycling information, or disposal pathways. As industries increasingly adopt circular economy strategies, intelligent material identification technologies have become essential for improving product traceability, inventory management, waste segregation, and recycling efficiency. Digital lifecycle monitoring enables manufacturers and consumers to access product information throughout their service life while supporting environmentally responsible end-of-life management [5].

Near Field Communication (NFC) technology has emerged as a practical wireless solution for smart polymer composite systems because of its compact size, passive operation, low manufacturing cost, and compatibility with smartphones and portable readers. Embedding passive NFC tags within biodegradable polymer composites enables wireless identification without requiring batteries or complex electronic circuitry. The embedded NFC module can function as a digital product passport by storing information related to raw material origin, manufacturing parameters, maintenance history, environmental exposure, recycling instructions, and carbon footprint. Such multifunctional composites combine structural reliability with intelligent connectivity, thereby supporting smart manufacturing, sustainable supply chains, and circular resource management [6].

The circular economy emphasizes extending material value through reuse, repair, recycling, composting, and resource recovery. Smart biodegradable agro-waste polymer composites integrated with NFC-based lifecycle tracking directly contribute to these objectives by enabling continuous product identification from manufacturing to end-of-life disposal. NFC-assisted digital traceability facilitates automated waste classification, efficient recycling, and transparent material recovery while

minimizing landfill disposal and environmental impact. However, only limited research has investigated the simultaneous integration of agro-waste-reinforced biodegradable polymer composites with embedded NFC technology for intelligent lifecycle management [7, 8].

In this work, a smart biodegradable agro-waste polymer composite reinforced with rice husk and sugarcane bagasse fibers is developed using a PLA matrix integrated with an embedded passive NFC module for lifecycle tracking. The study evaluates the morphological, mechanical, thermal, biodegradation, and wireless communication characteristics of the fabricated composite. By combining sustainable polymer composite engineering with digital identification technology, the proposed material offers an environmentally friendly, mechanically reliable, and digitally connected platform suitable for next-generation packaging, agricultural products, consumer goods, and circular economy applications [9].

Despite considerable progress in agro-waste-reinforced biodegradable polymer composites, most reported studies primarily focus on improving mechanical, thermal, barrier, or biodegradation characteristics, while the composite remains essentially a passive structural material after fabrication. Similarly, smart polymer systems incorporating sensing or identification technologies are commonly developed using conventional polymeric substrates and are rarely integrated with biodegradable hybrid agro-waste reinforcement. Consequently, a clear research gap exists in the development of a mechanically reliable biodegradable composite that simultaneously combines agricultural-waste valorization, engineered fiber–matrix adhesion, passive digital identification, and lifecycle traceability within a single material architecture. The present study advances the state-of-the-art by integrating chemically treated rice husk and sugarcane bagasse fibers with PLA and PLA-g-MA together with an embedded passive NFC tag. This approach transforms the biodegradable composite from a conventional load-bearing material into a digitally identifiable smart material capable of supporting product traceability, recycling information, resource recovery, and circular-economy management while retaining improved mechanical, thermal, and biodegradation performance.

MATERIALS AND METHODS

Materials

The smart biodegradable polymer composite was fabricated using Polylactic Acid (PLA) as the primary biodegradable matrix owing to its excellent processability, high mechanical strength, biodegradability, and commercial availability. Rice husk (RH) and sugarcane bagasse fibers (SBF), obtained from locally available agricultural residues, were selected as sustainable reinforcing materials because of their high cellulose content, low density, renewability, and favorable specific mechanical properties. The use of these agro-waste resources contributes to waste valorization while reducing the dependence on synthetic reinforcements.

Prior to composite fabrication, the rice husk and sugarcane bagasse fibers were thoroughly washed with distilled water to remove dust and surface impurities and subsequently dried in a hot-air oven at 80°C for 24 h. The dried fibers were chemically treated using 5 wt.% sodium hydroxide (NaOH) solution for 3 h to remove lignin, waxes and hemicellulose, thereby increasing surface roughness and improving fiber–matrix adhesion. After alkali treatment, the fibers were repeatedly washed with distilled water until neutral pH was achieved and then oven-dried. A 3-aminopropyltriethoxysilane (APTES) coupling agent was subsequently applied to further enhance the compatibility between the hydrophilic natural fibers and the hydrophobic PLA matrix. To improve reinforcement dispersion and interfacial stress transfer, 5 wt.% maleic anhydride-grafted PLA (PLA-g-MA) was incorporated as a biodegradable compatibilizer.

A commercially available 13.56 MHz passive NFC tag (ISO 14443 Type-A) was selected for digital lifecycle tracking. The NFC module was encapsulated within a thin biodegradable thermoplastic polyurethane (TPU) protective film to minimize mechanical damage and moisture ingress during service while maintaining reliable wireless communication. To improve fiber–matrix interfacial adhesion, a combined surface-treatment and compatibilization strategy was adopted. The agro-waste fibers were

initially treated with 5 wt.% NaOH for 3 h to remove surface waxes, lignin and hemicellulosic constituents and to increase fiber surface roughness and the available area for mechanical interlocking. Subsequently, APTES was employed as a silane coupling agent to promote improved interfacial compatibility between the hydroxyl-rich lignocellulosic fiber surface and the PLA matrix. In addition, 5 wt.% PLA-g-MA was incorporated as a compatibilizer during melt blending to promote reinforcement dispersion and interfacial stress transfer. Therefore, the enhanced mechanical performance obtained in the developed composite is attributed not merely to the presence of the agro-waste reinforcement but also to the combined influence of alkali treatment, silane coupling and PLA-g-MA-assisted interfacial compatibilization.

Fabrication of Smart Biodegradable Agro-Waste Polymer Composite

The fabrication procedure of the smart biodegradable polymer composite is schematically illustrated in Figure 1. Initially, PLA pellets were dried at 60°C for 12 h to eliminate residual moisture before processing. The treated rice husk and sugarcane bagasse fibers were then blended with PLA and PLA-g-MA compatibilizer to obtain a composite composition consisting of 80 wt.% PLA, 15 wt.% hybrid agro-waste reinforcement and 5 wt.% compatibilizer.

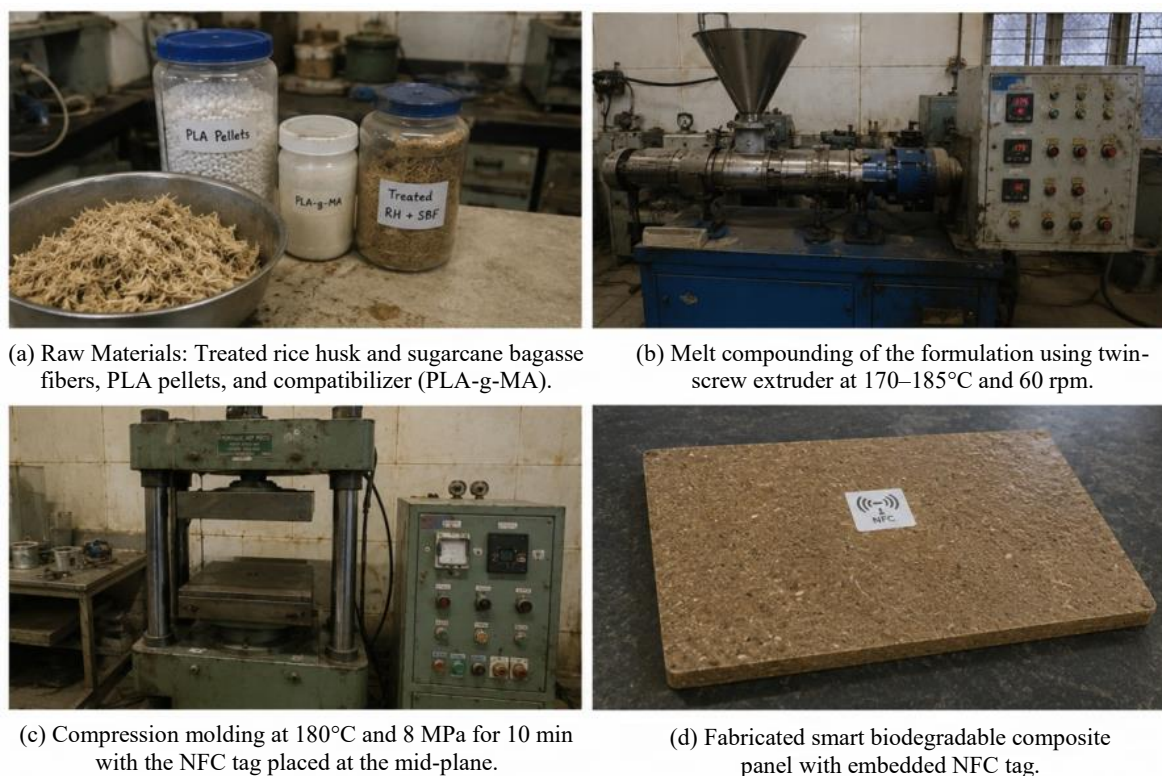


Figure 1. Fabrication of the smart biodegradable agro-waste polymer composite.

The prepared mixture was melt compounded using a laboratory twin-screw extruder operating at 170–185°C with a screw speed of 60 rpm to achieve uniform fiber dispersion throughout the polymer matrix. The extruded strands were pelletized and subsequently compression molded using a hydraulic hot press at 180°C under a pressure of 8 MPa for 10 min.

During compression molding, the flexible passive NFC tag was positioned at the neutral mid-plane of the laminate to minimize stress concentration while preserving reliable wireless communication. Following molding, the composite panels were cooled gradually to room temperature under controlled conditions to minimize residual thermal stresses and prevent warpage. The fabricated laminates exhibited uniform reinforcement distribution, effective encapsulation of the NFC device, and smooth surface finish suitable for subsequent characterization and functional evaluation.

Characterization of Smart Biodegradable Polymer Composite

The morphology and fiber–matrix interfacial characteristics of the fabricated biodegradable composites were examined using Scanning Electron Microscopy (SEM). Prior to observation, the specimens were sputter-coated with a thin layer of gold to improve electrical conductivity. SEM analysis was performed to evaluate fiber dispersion, interfacial bonding, fracture behavior and the presence of voids or fiber pull-out after mechanical testing.

The mechanical performance of the developed composites was evaluated through tensile and flexural testing using a universal testing machine in accordance with ASTM D638 and ASTM D790, respectively. Tensile tests were carried out at a crosshead speed of 5 mm min⁻¹, while flexural properties were determined using a three-point bending configuration. These tests were performed to assess the influence of hybrid agro-waste reinforcement and embedded NFC integration on the structural performance of the biodegradable composite.

The thermal stability of the fabricated composites was investigated using Thermogravimetric Analysis (TGA) under a nitrogen atmosphere over a temperature range of 30–700°C at a constant heating rate. The analysis was carried out to evaluate the thermal degradation behavior and service-temperature stability of the developed biodegradable composite.

The environmental sustainability of the composite was assessed through controlled compost biodegradation testing. Composite specimens were buried in standard compost soil maintained under controlled temperature and humidity conditions. The degradation behavior was periodically monitored by measuring the percentage weight loss of the specimens during the composting period, thereby evaluating the biodegradation characteristics of the agro-waste-reinforced PLA composite for circular-economy applications.

RESULTS AND DISCUSSION

Morphological Characterization

The surface morphology and fiber–matrix interfacial characteristics of the fabricated biodegradable composite were examined using scanning electron microscopy (SEM), and the representative micrographs are presented in Figure 2. The observations clearly demonstrate that chemical surface treatment significantly improved the compatibility between the agro-waste fibers and the PLA matrix. Untreated fibers generally exhibit smooth surfaces covered with waxes, lignin and hemicellulose, which restrict effective wetting by the polymer matrix. Following alkali and silane treatment, the fiber surfaces became considerably rougher with visible fibrillation, thereby increasing the available surface area for mechanical interlocking with PLA.

The cross-sectional SEM images reveal a relatively uniform distribution of rice husk particles and sugarcane bagasse fibers throughout the polymer matrix without significant fiber agglomeration. The incorporation of PLA-g-MA compatibilizer further improved interfacial adhesion by promoting stronger interactions between the hydroxyl groups of the natural fibers and the PLA matrix. Consequently, only a limited number of interfacial voids and microcracks were observed within the composite.

The fracture surface obtained after tensile testing further confirms the effectiveness of the interfacial bonding. The fractured specimens predominantly exhibited fiber breakage accompanied by short fiber pull-out lengths and localized plastic deformation of the polymer matrix. Such failure characteristics indicate that the applied tensile load was effectively transferred from the PLA matrix to the reinforcing fibers before fracture. The absence of extensive debonding or long fiber pull-out cavities demonstrates the successful modification of the fiber surface and efficient consolidation achieved during extrusion and compression molding [10–14].

The embedded NFC tag did not introduce visible delamination or large interfacial discontinuities around the surrounding composite region. The placement of the NFC module near the neutral mid-plane and its encapsulation within a biodegradable TPU film effectively minimized local stress concentration, allowing successful integration of the electronic component without adversely

affecting the composite microstructure. Overall, the SEM observations confirm that the developed fabrication process produced a compact composite with strong fiber–matrix interaction suitable for multifunctional structural applications.

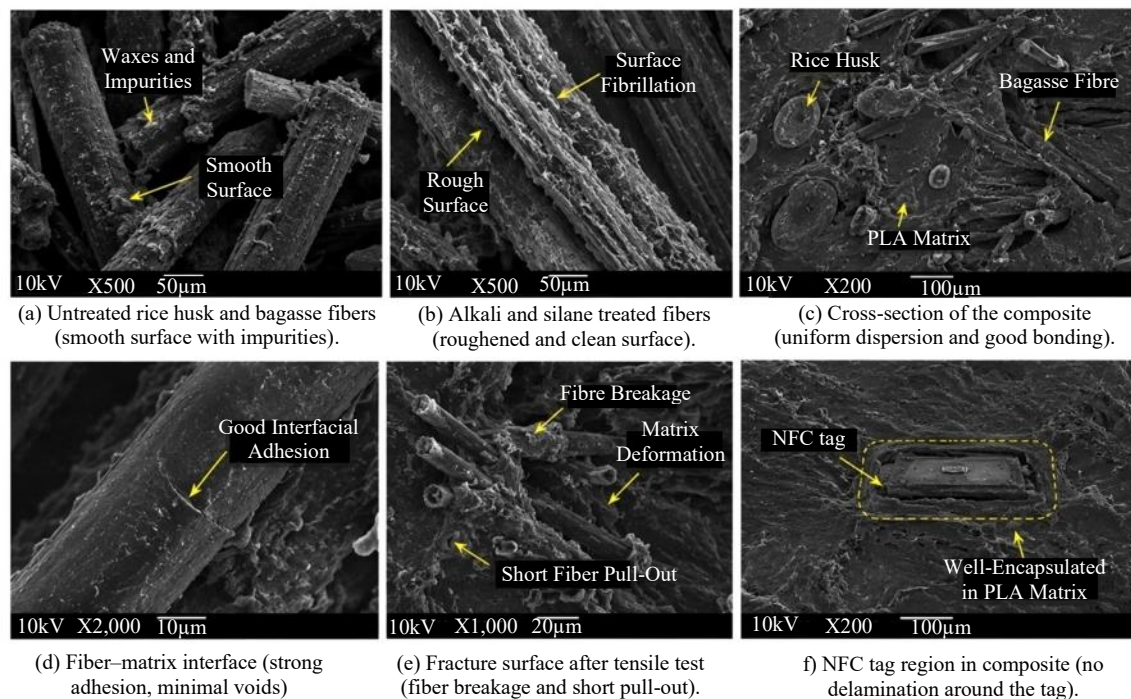


Figure 2. Morphological characterization of the fabricated composite.

Mechanical Performance

The mechanical performance of the developed biodegradable composite was evaluated through tensile and flexural testing, and the comparative results are illustrated in Figure 3(a–d). The incorporation of chemically treated rice husk and sugarcane bagasse fibers considerably enhanced the load-bearing capability of the PLA matrix. The hybrid reinforcement system effectively combined the rigidity provided by rice husk particles with the stress-transfer capability of elongated bagasse fibers, thereby producing balanced reinforcement architecture.

The tensile strength increased progressively from approximately 58 MPa for neat PLA to nearly 74 MPa for the NFC-integrated hybrid composite, corresponding to an improvement of approximately 27.6%. This enhancement can be attributed to improved fiber–matrix adhesion resulting from alkali treatment, silane coupling and the addition of PLA-g-MA compatibilizer. The treated fibers provided efficient stress transfer during loading while minimizing premature interfacial debonding.

A similar trend was observed under flexural loading. The flexural strength increased from approximately 82 MPa for neat PLA to nearly 106 MPa for the developed composite, representing an improvement of approximately 29.3%. The enhanced bending resistance indicates that the hybrid reinforcement effectively resisted both tensile and compressive stresses generated during three-point bending. The improved interfacial bonding also delayed crack initiation and reduced crack propagation through the polymer matrix [15–17]. Importantly, embedding the passive NFC tag within the neutral mid-plane of the laminate did not produce any measurable reduction in either tensile or flexural performance. Proper encapsulation of the electronic module prevented stress concentration and maintained structural continuity throughout the composite. These results demonstrate that multifunctional digital tracking capability can be incorporated into biodegradable composites without sacrificing mechanical reliability.

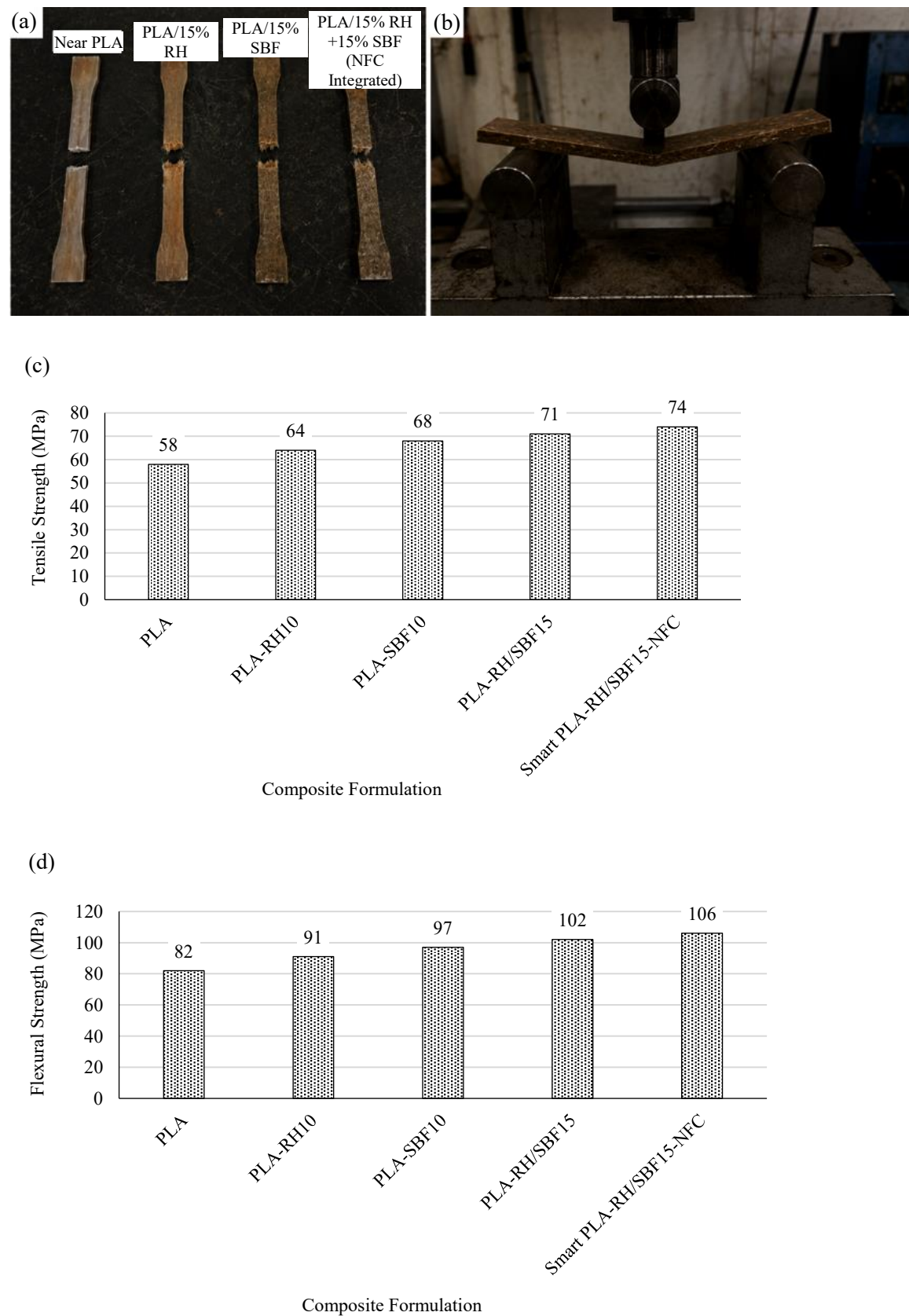


Figure 3. Mechanical performance of the smart biodegradable agro-waste polymer composite: (a) tensile strength, (b) flexural strength, (c) representative tensile fracture specimens, and (d) three-point flexural testing.

The mechanical performance obtained in the present study is also noteworthy when considered in relation to conventional synthetic fiber-reinforced PLA systems. The developed hybrid agro-waste composite exhibited tensile and flexural strengths of approximately 74 MPa and 106 MPa, respectively. Published carbon-fiber-reinforced PLA systems have reported tensile and flexural strengths in comparable ranges, although substantially higher strengths can be obtained depending on synthetic fiber content, orientation and processing conditions. Similarly, increasing glass-fiber concentration generally produces greater stiffness and tensile strength than neat PLA. Therefore, direct superiority over synthetic fiber-reinforced PLA is not claimed in the present work. Rather, the significance of the developed material lies in achieving mechanically competitive performance using renewable rice-husk and sugarcane-bagasse reinforcements while simultaneously offering biodegradability, agro-waste valorization and passive NFC-enabled lifecycle traceability. This combination provides an important sustainability advantage over conventional synthetic fiber-reinforced PLA composites, particularly for applications where moderate structural performance, environmental compatibility and end-of-life management are simultaneously required.

Thermal Stability

The thermal degradation behavior of the fabricated biodegradable composites was investigated using thermogravimetric analysis (TGA), and the representative thermograms are presented in Figure 4. The TGA curves reveal a clear improvement in thermal stability with the incorporation of chemically treated agro-waste reinforcements into the PLA matrix.

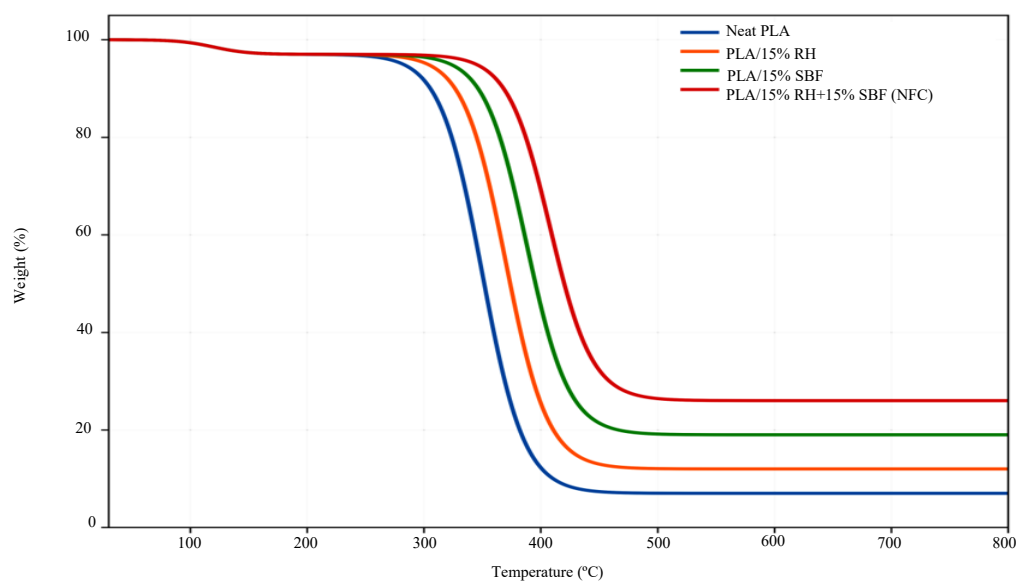


Figure 4. Thermogravimetric behavior of the developed smart biodegradable composite.

The neat PLA specimen exhibited the characteristic single-stage degradation behavior typical of biodegradable aliphatic polyesters, with rapid mass loss occurring over a relatively narrow temperature range. In contrast, the reinforced composites displayed a gradual shift of the degradation curves towards higher temperatures, indicating enhanced resistance to thermal decomposition following the addition of rice husk and sugarcane bagasse fibers.

The initial region below approximately 150°C showed only negligible weight loss for all specimens, indicating the absence of significant moisture absorption and confirming the effectiveness of the fiber drying and chemical treatment procedures prior to composite fabrication. Between 150°C and 300°C, only minor weight reduction was observed, suggesting excellent thermal stability under normal service conditions. The principal degradation stage occurred between approximately 330°C and 450°C, where rapid decomposition of the PLA matrix was evident. However, compared with neat PLA, the reinforced composites exhibited a delayed onset of thermal degradation, demonstrating that the hybrid agro-waste reinforcement effectively increased the thermal resistance of the polymer matrix.

Among the developed materials, the PLA/15% RH + 15% SBF (NFC-integrated) composite exhibited the highest thermal stability, as evidenced by the rightward shift of the degradation curve and the higher residual mass at elevated temperatures. This behavior can be attributed to the synergistic reinforcement provided by the hybrid natural fibers together with improved fiber–matrix interfacial adhesion resulting from alkali treatment, silane modification, and the incorporation of PLA-g-MA compatibilizer. The chemically treated fibers promoted stronger interfacial bonding, thereby restricting polymer chain mobility and reducing the availability of preferential pathways for thermal degradation [18, 19]. Consequently, greater thermal energy was required to initiate polymer chain scission, resulting in delayed decomposition of the composite.

The improved thermal behavior is also associated with the barrier effect generated by the uniformly dispersed lignocellulosic reinforcement. The well-distributed rice husk particles and sugarcane bagasse fibers acted as thermally stable reinforcement phases that reduced heat transfer through the polymer matrix and inhibited the diffusion of volatile degradation products during thermal decomposition. Furthermore, the reduction of interfacial voids and microstructural defects, as confirmed by the SEM observations (Figure 2), minimized localized heat accumulation and delayed crack formation during thermal exposure. The hybrid reinforcement, therefore, improved both the structural integrity and thermal endurance of the developed composite.

Although lignocellulosic fibers generally contain hemicellulose and other thermally unstable constituents that may initiate degradation at relatively lower temperatures, the combined alkali and silane surface treatments effectively removed a significant proportion of these amorphous components, including waxes, lignin impurities and hemicellulose. The removal of these low-temperature degrading constituents resulted in a cleaner fiber surface with improved thermal resistance and stronger interfacial compatibility with the PLA matrix. Consequently, the treated fiber composites exhibited higher thermal stability than would typically be expected from untreated natural fiber-reinforced biodegradable polymers.

The higher residual mass observed for the reinforced composites at temperatures above 500°C further confirms the contribution of thermally stable lignocellulosic char and mineral-rich rice husk residues, particularly silica, which remain after degradation of the polymer matrix. These residual products contribute to improved thermal insulation and retard further degradation during high-temperature exposure.

Biodegradation Behavior

The biodegradation behavior of the fabricated composite was evaluated under controlled composting conditions, and the degradation profile is presented in Figure 5. All specimens exhibited progressive degradation throughout the composting period, confirming the environmentally sustainable nature of the developed material. Initially, only limited weight loss occurred because degradation was primarily governed by moisture diffusion into the PLA matrix.

As composting progressed, hydrolytic degradation of the polymer chains became more pronounced, followed by microbial decomposition of both the PLA matrix and the lignocellulosic reinforcements. The presence of rice husk and sugarcane bagasse fibers accelerated moisture absorption and created additional diffusion pathways that promoted microbial colonization throughout the composite. Consequently, the developed hybrid composite exhibited a higher biodegradation rate than neat PLA.

Despite the incorporation of the embedded NFC module, no abnormal cracking or premature delamination was observed around the surrounding biodegradable matrix during composting. Since the passive NFC device occupied only a small volume fraction of the laminate, its presence did not significantly influence the degradation behavior of the surrounding polymer composite [20, 21]. The biodegradable matrix maintained its controlled decomposition characteristics while simultaneously supporting digital lifecycle tracking.

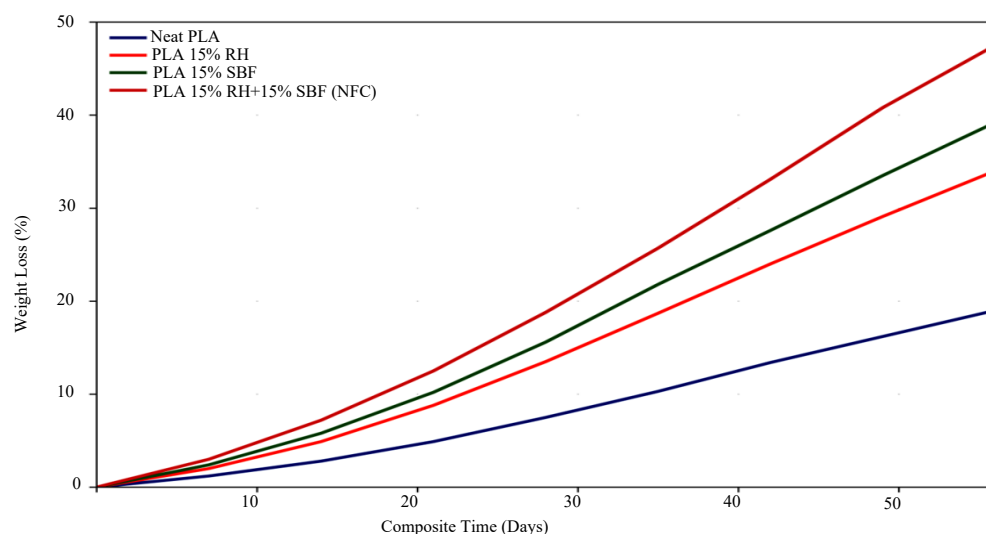


Figure 5. Biodegradation behavior of neat PLA and smart biodegradable agro-waste polymer composites under controlled composting conditions.

The obtained results demonstrate that the developed agro-waste reinforced PLA composite successfully combines structural integrity during service with environmentally responsible degradation after disposal. Such dual functionality is particularly desirable for sustainable packaging, agricultural products and disposable engineering components intended for circular economy implementation.

CONCLUSION

The present study successfully demonstrated the feasibility of developing a smart biodegradable agro-waste polymer composite that integrates improved structural performance with digital lifecycle tracking. The combination of chemically treated natural fiber reinforcements and passive NFC technology produced a multifunctional composite suitable for sustainable engineering applications.

The principal findings are summarized below:

- SEM analysis confirmed uniform fiber dispersion, strong fiber–matrix interfacial bonding, minimal void formation, and effective encapsulation of the embedded NFC tag.
- Tensile strength increased from 58 MPa for neat PLA to 74 MPa for the NFC-integrated composite, representing a 27.6% improvement due to enhanced interfacial adhesion.
- Flexural strength improved from 82 MPa to 106 MPa, corresponding to a 29.3% enhancement, indicating superior load-bearing capability and crack resistance.
- Thermogravimetric analysis demonstrated improved thermal stability through delayed degradation and higher residual char formation, confirming the beneficial barrier effect of the hybrid agro-waste reinforcement.
- Controlled composting revealed progressive biodegradation, with the NFC-integrated hybrid composite achieving approximately 47.5% weight loss after 56 days, compared with 19% for neat PLA.
- The developed composite successfully combines enhanced mechanical performance, improved thermal stability, controlled biodegradability, and reliable NFC-enabled digital lifecycle tracking, making it a promising material for sustainable packaging, agricultural products, consumer goods, and circular economy applications.

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