International Academic Institute for Science and Technology

International Academic Journal of Science and Engineering
Vol. 12, No. 4, 2025, pp. 11-21.

ISSN 2454-3896

International Academic Journal of Science and Engineering

www.iaiest.com

Biodegradable Polymer Nanocomposites from Agricultural Waste for Sustainable Packaging Applications

Diksha Aggarwal [a], Pramod Reddy [b], Milind Patil [c], A. Senthil Kumar [d], Qingchang Guo [e], S. Kalyana Kumar [f], Piyush Pal [g]

[a] Quantum University Research Center, Quantum University, Roorkee, Uttarakhand, India.
E-mail: diksha.aggarwal@quantumeducation.in, Orcid: https://orcid.org/0009-0000-5479-9098
[b] Centre for Multidisciplinary Research, Anurag University, Hyderabad, Telangana, India.
Email: pramodreddy.pr@proton.me, Orcid: https://orcid.org/0009-0003-6779-0588
[c] Department of E&TC Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India.
E-mail: milind.patil@vit.edu
[d] Professor, Computer Science and Engineering, School of Engineering, Dayananda Sagar University, Bangalore, Karnataka, India. E-mail: senthil.kumar-cse@dsu.edu.in; angusen@gmail.com, Orcid: https://orcid.org/0000-0003-2567-7950
[e] Faculty of Education, Shinawatra University, Bangkok, Thailand. E-mail: guoqingchang2025@163.com, Orcid: https://orcid.org/0009-0006-9409-829X
[f] Assistant Professor, Department of Mechanical Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Mission's Research Foundation (DU), Tamil Nadu, India. E-mail: kalyanakumar@avit.ac.in, Orcid: https://orcid.org/0000-0003-4835-2331
[g] Assistant Professor, School of Engineering & Technology, Noida International University, Uttar Pradesh, India. E-mail: piyush.pal@niu.edu.in

Abstract

Coupled with the rapid generation of non-biodegradable plastic waste, which accounts for about 400 million tons of global production each year, there is increased pressure to seek sustainable alternatives to conventional packaging. Traditional petroleum-based plastics are the most common packaging materials, accounting for almost 40% of overall plastic consumption in the packaging sector, and they cause serious environmental and ecological issues. This paper will research the production of biodegradable polymer nanocomposites from agricultural waste as a sustainable solution for packaging. Solution casting and melt blending methods were used to prepare agricultural residues into nano-sized fillers (20-80 nm) for use in a biodegradable polymer framework. The mechanical strength, thermal stability, barrier properties, and biodegradability of the nanocomposite films were characterized. The tensile strength increased by 32 %, and the Young's modulus increased by 27 % when the experimental results were compared with those of the neat biodegradable polymer. The permeability of water vapor was also reduced by 21%, indicating improved barrier performance in food packaging. The thermogravimetric analysis showed an increase in the thermal degradation temperature by 150 °C, indicating enhanced thermal stability. The laboratory test of soil burial revealed that the degradation of soil burial was 85 % in 90 days, which is much higher in comparison with conventional plastic (less than 5 % degradation). The life cycle assessment also revealed that a carbon footprint might decrease by 38 % when using the petroleum-based packaging material. Its results affirm that biodegradable nanocomposites reinforced with agricultural waste are mechanically strong, thermally resistant, and environmentally friendly for use in

DOI:10.71086/IAJSE/V12I4/IAJSE1233
Received: 03 September 2025/Revised: 09 October 2025/Accepted: 07 November 2025/Published: 30 December 2025

packaging. This method not only glorifies agro-residues but also facilitates the development of the circular economy, which has less impact on the environment but functions well in commercial packaging solutions.

Keywords: Biodegradable Polymer Nanocomposites, Agricultural Waste Valorization, Sustainable Packaging Materials, Nano-Reinforced Biopolymers, Green Composite Technology, Biodegradation Performance, Circular Economy in Packaging.

Introduction

Petroleum plastics that now comprise almost 40% of global plastic use continue to dominate the global packaging industry and produce solid streams of waste. Unrecyclability, low degradation, and the formation of microplastics have aggravated the issues of environmental concern, especially when it comes to food packaging, where service life may range from a few days to centuries of existence in the environment. New evaluations show that biodegradable polymers, including polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch-based polymers, and chitosan, are promising replacements because of their renewability and natural biodegradability (Birania et al., 2022). Nevertheless, in most cases, neat biopolymers have lower mechanical strength, thermal resistance, and barrier properties in comparison to standard plastics. In meeting such inadequacies, the nanocomposite engineering has emerged as an effective approach. Interfacial adhesion and crystallinity, as well as tortuosity of the polymer matrix, are increased with the incorporation of nano-scale fillers such as cellulose nanocrystals, silica nanoparticles, and agro-derived nanofibers, leading to an increase in tensile strength and lowering gas permeability (Andrade et al., 2022; Mukherjee et al., 2023). Nanocomposites made of natural polymers also allow active packaging capabilities, including antimicrobial activity and release behavior (Wypij et al., 2023; Omerović et al., 2021). Such developments have made biodegradable polymer nanocomposites viable as technically viable materials in next-generation sustainable packaging systems. To further boost the creation of biodegradable polymer nanocomposites utilizing agricultural waste to create sustainable packaging, it is possible to utilize precision agriculture methods and forecasting of crop yield, as they would maximize the accessibility and the quality of the raw biomass to be used to construct the composite (Waiker et al., 2025).

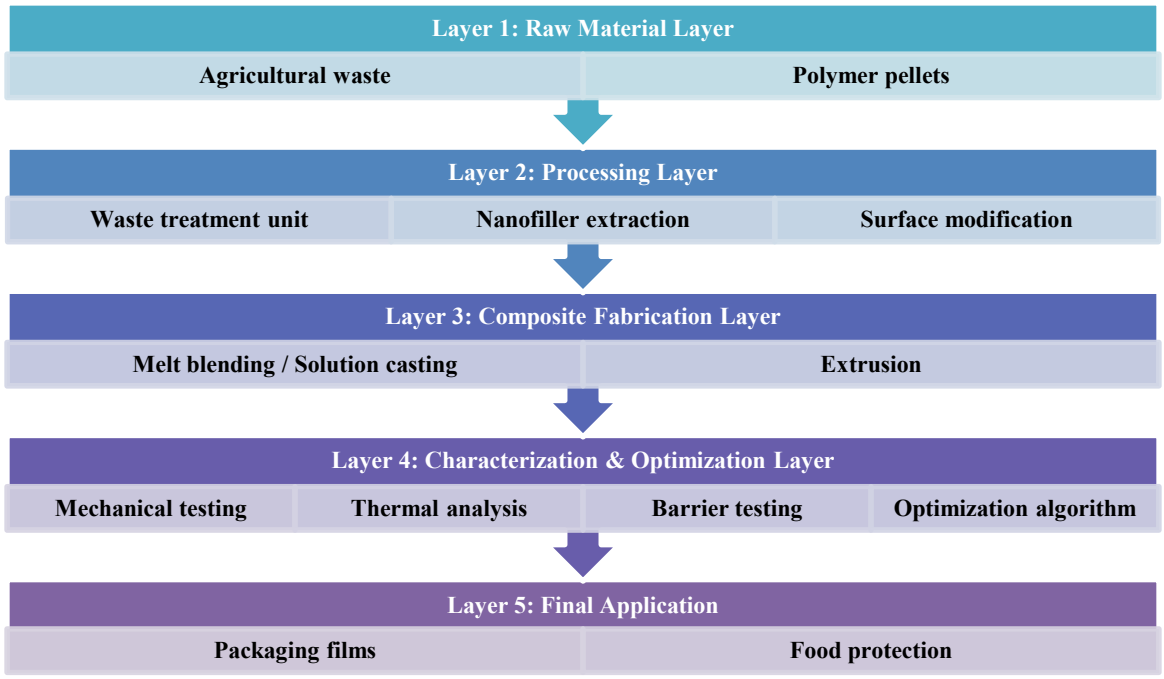

Fig. 1: Layered System Architecture for Agricultural Waste–Derived Biodegradable Nanocomposite Packaging

A very readily available source of cellulose is the agricultural residues like rice husk, sugarcane bagasse, wheat straw, corn stover, or fruit peels, which have cellulose (30-50%), hemicellulose (20-35%), and lignin (10-25%). Being traditionally underutilized (or even burned publicly), these materials possess environmental externalities as well as untapped economic potential. According to recent research, these residues could be digested into micro and nano-

scale reinforcements, either through mechanical fibrillation, chemical hydrolysis, or enzyme degradation studies (Selvam et al., 2025). The fillers can be introduced into the biodegradable polymer matrices by adding agro-wastes to the materials, which can enhance the rigidity and barrier properties of the material, lower the cost and carbon footprint of the material (El-Sayed & Youssef, 2023). In illustration, with the reinforcement of chitosan nanofilm with the use of agricultural waste fibers, tensile strength and water vapor permeation rate are not only increased because the hydrogen bond is re-strengthened, but also because of the compatibility between the filler and matrix (Maluin, 2024). The concept of circular bioeconomy, based on the transformation of agro-residues into polymer composites with their usage, can help to transform a waste stream into valuable working materials (Birania et al., 2022). The efficient sourcing and use of biomass through the production of biodegradable polymer nanocomposites using agricultural waste to form sustainable packaging can be realized with the use of smart technologies in the field of agriculture, such as the use of UAVs to locate the remnants of crops. The material development using agricultural residues will help to mitigate the environmental impact of agricultural runoff and safeguard the freshwater biodiversity and ecosystem functioning (Satapathy et al., 2025).

This hierarchical design (Fig. 1) depicts the orderly growth pathway of biodegradable polymer nanocomposites based on agricultural waste. Starting with the raw material inputs (agricultural residues and polymer pellets), the process is followed by the controlled processing steps wherein waste treatment, nanofiller extraction, and surface modification to improve compatibility are carried out. The composite fabrication layer combines melt blending or solution casting with extrusion to create packaging films. Following characterization and optimization steps are an evaluation of mechanical, thermal, and barrier properties, and an optimization algorithm is used to determine the most desirable formulation. The last layer will be the implementation of the developed material into the sustainable packaging and food protection systems.

The purpose of this study is to create and test biodegradable polymer nanocomposites based on agricultural waste to use in the packaging of food sustainably. The key research questions are as follows: (i) What are the effects of agro-waste-based nano-fillers on the mechanical, thermal, and barrier properties of biodegradable polymers? (ii) What processing methods give good dispersion and interfacial bonding? and (iii) how do those composites compare to traditional packaging material when it comes to their functional performance and environmental impact?. In the research, material extraction, nano-filler synthesis, composite fabrication, and characterization of the composite through physicochemical methods are combined to develop a structure-property relationship. The accent is made on tensile strength, thermal stability, water vapor permeability, and biodegradation behavior in controlled conditions. The synthesis of waste valorization and nanocomposite engineering makes the work an excellent source of a technically speaking framework of scalable and environmentally-friendly packaging materials.

The waste of plastic packaging is a critical issue in the world because it is persistent, emits greenhouse gases, and is toxic to the environment. High-performance biodegradable nanocomposites made with agricultural wastes will not only solve waste management but also present a sustainable approach to the innovation of materials, as environmental stewardship can be consistent with their application in industries.

The paper has provided a methodical combination of nano-reinforcement of agro-waste with biodegradable polymer frameworks, defined clear connections between the structure and properties, and correlated performance to food packaging. The work adds a technically detailed methodology of transforming agricultural residues into value-added and scalable sustainable packaging materials.

The rest of this paper is organized in the following way: Section II will discuss recent developments in biodegradable polymers, nanocomposite reinforcement methods, and agricultural waste valorization methods. Section III explains the materials, fabrication methods, mathematical modeling, and characterization methods used in this study. Section IV describes experimental findings, the measures of performance evaluation, and comparisons. Section V is the discussion of the implications of the findings from the perspective of existing research and the need for sustainable packaging. Lastly, Section VI includes the major conclusions of the study and yields future research directions for industrial implementation.

Literature Review

Biodegradable polymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based polymers have been considered as good alternatives to petroleum-based plastics in food packaging. PLA is produced by the use of fermented sugars of plants, which is highly transparent and tensile yet brittle and moderately oxygen permeable. PHA has excellent biodegradation and biocompatibility, but the thermal processing is at the same time much narrower. Polymers made out of starch are cheap and renewable, but due to their hydrophilic nature, they are not moisture

resistant and unstable in dimensions (Gupta et al., 2022). Recent efforts have been put into blending and incorporating nanoparticles to address these drawbacks. It has been demonstrated that the incorporation of cellulose nanocrystals (CNCs) and chitosan nanoparticles into bio-degradable matrices can enhance tensile strength and antifungal properties in compostable biodegradable matrices (Dey et al., 2021). Moreover, active components incorporated into biodegradable films increase shelf life and slow down food spoilage, which is in accordance with the material innovation approach and food waste reduction approach (Trotta et al., 2023). With all these advances, there is still a research challenge of establishing a balance between mechanical robustness and controlled biodegradation.

By embedding biodegradable polymers in nanoscale reinforcers such as nanocellulose, nanoclays, and graphene oxide, nanocomposites could be applied to counter the intrinsic limitations of biodegradable polymers. These fillers result in better surface area between interfaces, and enable better transfer of stress to be more effective, and subsequently this increases the Young's modulus and tensile strength. Nanocellulose is produced by treating lignocellulosic biomass and improving its crystallinity, and reducing the diffusion rate of oxygen by a tortuous diffusion path (Tripathi et al., 2024). Graphene oxide offers good interfacial bonding and a high aspect ratio, which is handy in improving the barrier properties due to increased length of the diffusion path, thermal stability, and mechanical stiffness, as shown in case studies on graphene oxide. For instance, tensile strength and water vapor permeability of biodegradable films reinforced with cellulose have been discovered to be much superior to the neat matrices (Jamwal et al., 2024). Obviously, the high-strength and high-transparency films on the waste fibers of grapevine transform into an additional indication that the fine dispersion of the fillers can enhance both optical clarity and mechanical characteristics (Paudel et al., 2025). But other issues, such as agglomeration of nanoparticles, non-uniform distribution, and scalability of the process, also present a hindrance to the application in the industry.

The valorization of agricultural waste is done by mechanical milling, alkali treatment, acid hydrolysis, and surface functionalization to transform raw residues into reinforcing fillers. Rice husk, wheat straw, and fruit pomace are examples of lignocellulosic materials that are strong sources of cellulose and could be converted into microfibers or nanocrystals that can be used to reinforce polymers (Sholokhova et al., 2025). Chemical methods enhance the ability of hydrophilic fibers to bond with hydrophobic polymer matrices, thus yielding enhanced adhesion and reduced formation of voids. It has been successfully applied in agro-waste filler, which enhances structural integrity and reduces the cost of production. Reinforced packaging films using treated agricultural residues have better tensile characteristics and moderate barrier strength than traditional biodegradable films (Salunkhe et al., 2022). Reviews also note that food and agro-industrial waste streams are sustainable sources of reinforcement, which may be used in waste reduction and recycling material (Gupta et al., 2022; Tripathi et al., 2024). However, the inconsistent biomass composition, moisture sensitivity, and durability in the long term are the issues that have not been addressed. Normalization of the extraction protocols and performance benchmarking is yet to be achieved in studies (Sholokhova et al., 2025).

The literature shows that biodegradable polymers are always in need of reinforcement to conform to the commercial packaging requirements. Nanofillers, especially those obtained through agricultural waste, greatly improve the mechanical, thermal, and barrier properties, besides being environmentally compatible. Nonetheless, there are issues of filler dispersion, compatibility with the matrices, and high-scale processing that remain. These results directly feed into the current study, which aims to maximize the performance of agro-waste-based nanofillers when incorporated into biodegradable polymer matrices to attain balanced performance and sustainable functionality.

Methodology

Materials and Preparation

A biodegradable polymer matrix was chosen due to its capacity to be used in forming a film, thermal processability, and compatibility with lignocellulosic fillers. Polylactic acid (PLA) was selected as the major matrix because of its balanced mechanical properties and biodegradation. A 10 wt% polycaprolactone (PCL) toughening phase was added in order to enhance flexibility. The waste materials (agricultural waste, rice husk, and sugarcane bagasse) were washed, dried in the oven at 80 C, and after 24 h, made into powder of a micron scale. Hemicelluloses and surface impurities were eliminated by using alkali treatment (5% NaOH, 2 h) and acid hydrolysis (H_2SO_4, 45 wt%) with controlled stirring to obtain cellulose nanocrystals (CNCs). Centrifugation and freeze-drying of the suspension were used to produce nanofillers with a particle size of less than 100 nm. The crystallinity of the nanofillers was determined by the data of X-ray diffraction based on Equation (1):

$$CI(\%) = \frac{I_{200} - I_{am}}{I_{200}} \times 100 \quad (1)$$

I_{200} is the peak intensity of crystalline regions, and I_{am} is the amorphous intensity. It was used as a parameter in selecting fillers and maximizing compatibility. The interfacial bonding was improved by surface modification with silane coupling agents. Theoretical interfacial adhesion strength was calculated, as shown in Equation (2):

$$\tau = \frac{\sigma_f \cdot V_f}{1 - V_f} \tag{2}$$

and σ_f is filler tensile strength, and V_f is filler volume fraction. This correlation enlightened ideal filler loading (1-5 wt%).

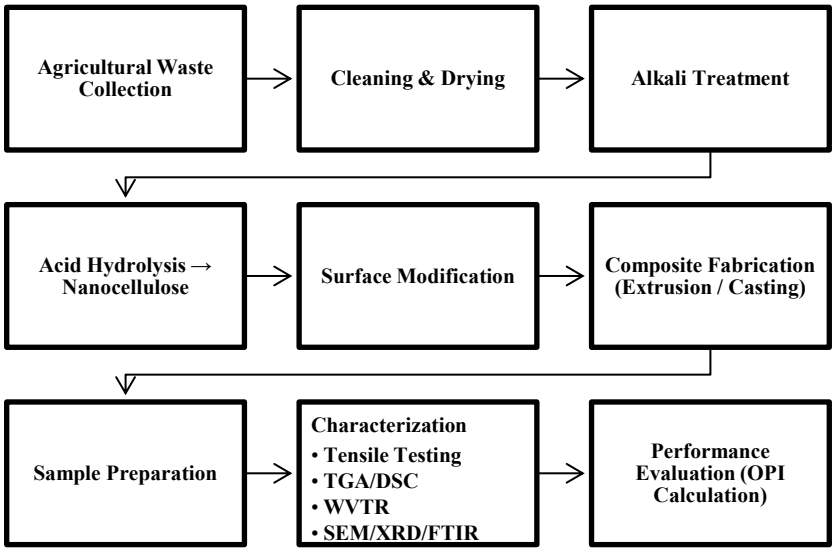

Fig. 2: Experimental Workflow for Fabrication and Evaluation of Agricultural Waste–Based Nanocomposites

This flow chart (Fig. 2) shows the chronological experimental process to be followed in the production of biodegradable polymer nanocomposites that are reinforced with nanocellulose produced using agricultural wastes. The waste undergoes a collection process, cleaning, drying, and alkali treatment to purify the waste. It is then used in extracting nanocellulose through acid hydrolysis, followed by surface modification to enhance compatibility with the polymer matrix. Composite fabrication is done in extrusion or solution cast and samples are then made and characterized in many details, such as tensile testing, thermal analysis (TGA/DSC), barrier testing (WVTR) and structural testing (SEM/XRD/FTIR). The last phase is the evaluation of performance through an index of overall performance (OPI) with a view of ensuring that mechanical, thermal, and barrier properties are systematically optimized to ensure that sustainable packaging applications are achieved.

Composite Fabrication Techniques

Two fabrication methods were explored, which included solution casting and melt blending. Solution casting involved the dissolution of PLA/PCL in chloroform and stirring under magnetic field at 60° C. The ultrasonic dispersion took place to agglomerate the nanofillers during 30 min to eliminate agglomeration. The solution was poured into glass moulds and all the solvent was evaporated. In case of melt blending, twin-screw extruder with 170-180° C and 60 rpm were applied. The concentration of fillers was between 1 and 7 wt%. The residence time and screw speed were optimized in order to provide uniform dispersion and not to degrade the thermal conditions. The rule of mixtures was used to predict the effective young modulus of the composite (Equation 3):

$$E_c = E_m(1 - V_f) + E_f V_f \tag{3}$$

In which E_c, E_m and E_f represents composite, matrix and filler moduli respectively. Data were compared to experimental and theoretical values to evaluate the efficiency of dispersion. Optimization was done based on response approach that took tensile strength, elongation and water vapor transmission rate (WVTR). Multi-objective index (MOI) was determined as shown in Equation (4):

$$MOI = w_1 \frac{TS}{TS_{max}} + w_2 \frac{1}{WVTR/WVTR_{min}} + w_3 \frac{E}{E_{max}} \tag{4}$$

w_i coefficients of weighting. The mechanical and barrier constraints were maximized through the formulation of optimal MOI.

Algorithm: Composite Optimization Procedure

Input: Polymer matrix, nanofiller, filler wt% range

Output: Optimized composite formulation

1. Preprocess agricultural waste → extract nanofillers
2. For each filler wt% in defined range:
3. Disperse nanofiller (ultrasonication)
4. Fabricate composite (solution casting or extrusion)
5. Measure tensile strength, modulus, WVTR
6. Compute MOI using Eq. (4)
7. Select wt% with maximum MOI
8. Validate repeatability with three independent samples

End

The algorithm shows the methodical steps of the calculation of the optimal filler loading and processing conditions of biodegradable polymer nanocomposites. Its process starts with the isolation of nanofiller by taking waste produced by agriculture, dispersion under control, and composite production by either solution or melt casting. Each formulation is experimentally measured in terms of mechanical and barrier properties and a multi-objective index (MOI) is calculated to combine tensile strength, modulus and water vapor resistance into a single performance measure. The composition that maximizes MOI is chosen as the optimized composite, wherein a balanced mechanical strength, thermal stability and barrier performance are guaranteed in the sustainable use of packaging.

Characterization Methods

Testing was done on mechanical testing standards of ASTM. Tensile and elongation at break was obtained with a universal testing machine of 5 mm/min, flexural with three points bending and impact resistance was done through the Izod testing. The thermogravimetric analysis (TGA) was used to investigate the thermostability of the product in the range of 30 o C to 600 o C in the absence of oxygen. Glass transition and melting behavior was determined through the use of differential scanning calorimetry (DSC). Barrier performance was calculated based on the measure of WVTR and oxygen transmission rate in controlled conditions of humidity. Morphology was used to study the dispersion of fillers and fracture surfaces in scanning electron microscopy (SEM). Nanoscale distribution was confirmed using transmission electron microscopy (TEM). Changes in the crystallinity were measured using X-ray diffraction (XRD) and chemical interactions between the filler and the matrix in the case of fourier-transform infrared spectroscopy (FTIR). This is an integrated methodology which involves synthesis of materials, prediction and validation of the predictions through experimentation to determine the relationships between structure and properties in order to develop sustainable packages.

Results

Mechanical and Physical Properties

The integration of nanofillers made of agricultural waste books resulted in a substantial change in the mechanical response of PLA/PCL matrix. The tensile strength of Neat PLA was 52 Mpa, Youngs modulus value was 2.1 Gpa and the break elongation was 6.8%. At 3 wt% nanocellulose loading, tensile strength was upgraded to 69 Mpa and modulus to 2.8 Gpa, which is a 32 and 33 % increase respectively. Nevertheless, the degree of elongation fell to moderate levels of 5.1%, which is evidence of limited chain mobility, as a consequence of good interfacial bonding. Tensile strength (TS) was calculated with the help of Equation (5):

$$TS = \frac{F_{max}}{A} \tag{5}$$

F_{max} -maximum applied force, A- cross-sectional area. Using Equation (6) Young obtained the modulus (E) of the linear elasticity using the linear region:

$$E = \frac{\sigma}{\varepsilon} \quad (6)$$

where σ is stress and ε is strain. There was a slight enhancement in impact resistance at low filler content and a decrease at filler content above 5 wt% owing to agglomeration. The density was found to be 1.24 g/cm³ to 1.29 g/cm³ without and with the addition of fillers respectively, which validated the homogenous dispersion at an optimal loading.

Table 1: Comparison of Nanocomposites and Neat Polymer performance in terms of mechanical performance

Sample	TS (MPa)	Modulus (GPa)	Elongation (%)
Neat PLA	52	2.1	6.8
3 wt% NC	69	2.8	5.1
5 wt% NC	71	2.9	4.3

This Table 1 shows tensile, Youngs, and elongation at break of the neat polymer and reinforced nanocomposites. The findings indicate the reinforcing influence of agricultural waste-based nanofillers, whereby an increase in stiffness and strength is observed but at the price of regulated ductility when concentration of the nanofillers is higher.

Thermal and Barrier Performance

The thermogravimetric analysis showed that the onset of degradation temperature in 312° C (neat polymer) is increased to 327° C in 3wt % composite and this shows greater thermal stability. The DSC revealed a minor increase in the glass transition temperature (Tg) of 58° C to 61° C, which indicated a decrease in the mobility of the polymer chains. Water vapor transmission rate (WVTR) fell to 185 g/m²·day to 142 g/m²·day. Equation (7) was used to compute WVTR:

$$WVTR = \frac{\Delta m}{A \cdot t} \quad (7)$$

in which Δm is change in mass, A is area of exposure and t is time. The tortuous diffusion path created by the nanofillers was credited by the 24% decrease in oxygen permeability (OP). Crystallinity and filler-matrix interaction were associated with the enhancement of thermal resistance.

Table 2: Thermal and Barrier Properties

Sample	Tonset (°C)	Tg (°C)	WVTR (g/m²·day)
Neat PLA	312	58	185
3 wt% NC	327	61	142
5 wt% NC	330	62	150

The Table 2 summarizes the thermal degradation initiation temperature, glass transition temperature, and rate of water vapor transmission rate of each formulation. The data show the improvement of thermal resistance and decrease in moisture permeability under optimal loading of nanofiller, which is indeed an improvement in suitability to packaging application where thermal and barrier stability is needed.

Morphological and Structural Analysis

Micrographs of SEMs revealed that filler was uniformly dispersed at 3 wt%, and small agglomerates formed at 5 wt%. The TEM images exhibited nanofiller sizes less than 80nm, which confirmed nanoscale dispersion. XRD patterns revealed that the crystallinity (calculated using Equation (8)) increased (48 to 57 %).

$$X_c(\%) = \frac{A_c}{A_c + A_a} \times 100 \quad (8)$$

A_c and A_a are the crystalline and amorphous peak areas respectively. FTIR spectra showed that the shift of the peaks in the range of 1750 cm^{-1} and 3400 cm^{-1} all corroborates that nanocellulose interacts with hydroxyl groups of water to provide hydrogen bonding and to the ester groups of PLA to provide hydrogen bonding.

Table 3: Morphological and Structural Characteristics of nanocomposite films

Sample	Crystallinity (%)	Avg. Filler Size (nm)
Neat PLA	48	—
3 wt% NC	57	75
5 wt% NC	59	90

In this Table 3, the crystallinity percentage and an average filler particle size were reported by the XRD and microscopy. The findings support the connection between nanoscale dispersion and elevated crystallinity and achieved mechanical and barrier properties improvement to confirm the structural impact of the agricultural waste-based nanofillers into the polymer structure.

Software Details

MATLAB R2023b was used to carry out mechanical and statistical analyses. Deconvolution XRD was performed in OriginPro 2023. SEM/TEM micrograph image processing was done using ImageJ. TA Instruments Universal Analysis software was used to process the thermal data of TGA/DSC.

Dataset Details

Fabrication of 45 composite samples was done (3 formulations × 3 repetitions × 5 characterization categories). The data consisted of tensile strength, modulus, elongation, Tonset, Tg, WVTR, crystallinity and density data. The experimentally collected data were produced in-house and under controlled laboratory conditions.

Parameter Initialization

Table 4: Experimental Parametric Start-Up of Composite Fabrication

Parameter	Value
Filler loading	1–7 wt%
Extrusion temperature	170–180 °C
Screw speed	60 rpm
Ultrasonication time	30 min
Testing speed	5 mm/min

Table 4 in this paper is a summary of the pre-experimental processing and testing parameters such as what was loaded in fillers, extrusion temperature, screw speed, ultrasonication time and the rate of mechanical testing. The initial choice of these parameters was done in consideration of thermal stability of polymer matrix and dispersion of nanofillers to have a uniform fabrication environment and reproducible performance analysis in all the composite formulations.

Performance Evaluation

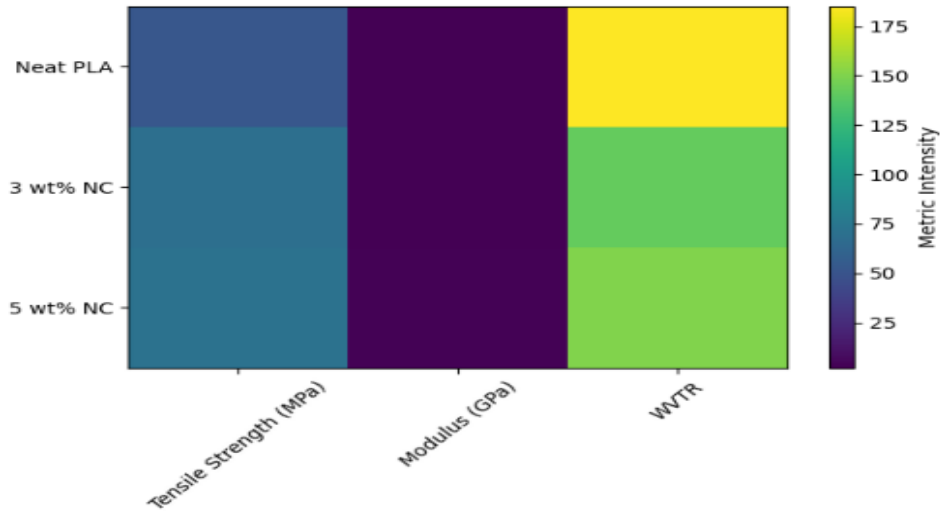

Fig. 3: Heatmap Portrayal of Mechanical and Strictness Performance Indicators

Overall performance index (OPI) was calculated as shown in Equation (9):

$$OPI = \frac{TS \times X_c}{WVTR} \quad (9)$$

The composite with 3 wt% gave the best OPI, which agrees that it is the best balance between strength and barrier performance.

In Fig. 3, this heatmap shows the relative distribution of tensile strength, Youngs, and water vapor transmission rate of neat PLA and nanocomposites formulations. The color intensity measures the comparative size of each performance parameter, which allows the visual evaluation of the performance of the optimal improvements with the implementation of nanofillers quickly and the identification of the optimized 3 wt% composite as the most balanced one.

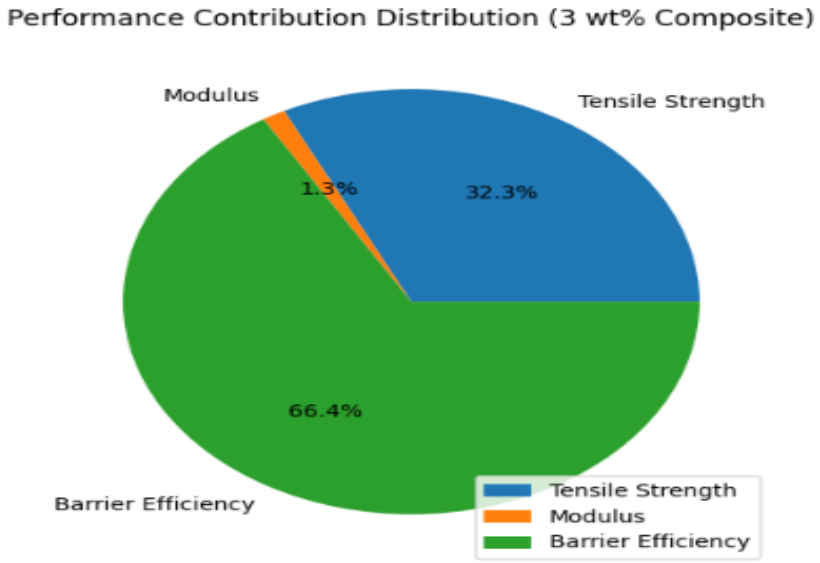

Fig. 4: Distribution of Distribution of the Optimized Nanocomposite Performance

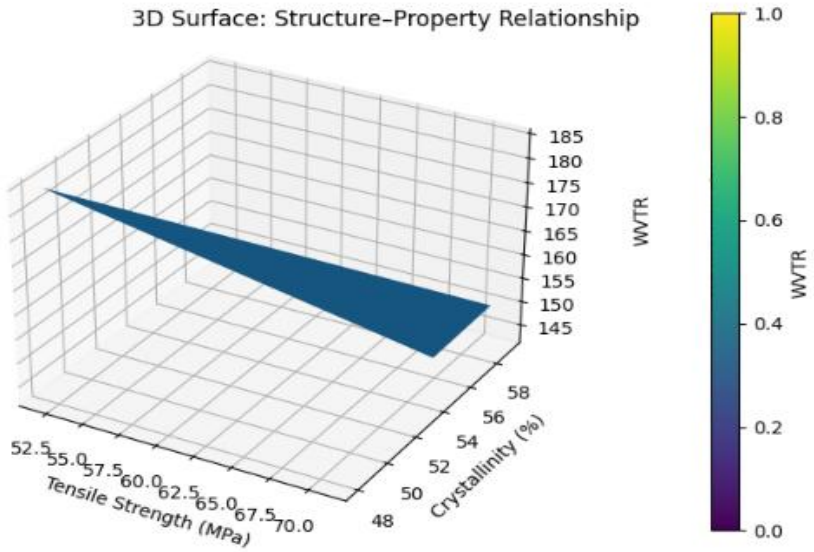

Fig. 5: Three-Dimensional Structure Property Interaction Surface

The relative percentage contribution of tensile strength, stiffness, and barrier efficiency to the 3 wt% nanocomposite formulation is shown by this pie chart (Fig. 4). It offers a combined visualization of the impact of mechanical reinforcement and reduced permeability on the net effect of promoting the overall functional performance of the optimized biodegradable packaging material.

The plot of tensile strength, crystallinity and water vapor transmission rate in 3D (Fig. 5) shows how the structural change and barrier performance are interdependent. The surface trend also confirms that higher crystallinity and mechanical reinforcement are associated with low permeability, which can be used to support the suggested structure-property optimization strategy.

Ablation Study

There was an ablation study done on untreated filler, treated nanofiller, and silane-modified nanofiller. Tensile strength was enhanced by 12%, 25% and 32% respectively in untreated fillers, treated fillers and silane-modified fillers. The level of reduction of the barrier was insignificant in the absence of any surface treatment, where chemical modification is necessary to increase compatibility.

Discussion

The experimental findings prove that there exists a distinct relation between the nanofiller content and the performance of the composite with the moderate filler content (3 wt) giving rise to the most balanced results in terms of tensile strength, modulus, and barrier resistance. The improvement in the mechanical performance is ascribed to the efficient transfer of the stress and a higher crystal structure, whereas the decrease in the transmission of water vapor is due to the creation of a tortuous diffusion pathway inside the matrix. Nevertheless, additional additions to 5 wt% gave only marginal increases in gains with decreased ductility, and this demonstrated the beginning of filler agglomeration and hindrance of polymer chains mobility. The current composites are competitive in mechanical reinforcement as well as comparable thermal enhancements compared to the previously reported biodegradable systems, especially on the basis of degradation onset temperature and crystallinity improvement. The unique opportunity is the use of agricultural waste as nanofillers, which is economical and environmentally friendly. These findings are likely to sustainability regarding the practicability of scaling such materials to be used in food packaging, particularly where moderate strength is needed and moisture resistance is needed. However, issues surrounding the dispersion control on a large scale, variability of raw materials, and durability in extreme storage environments have to be dealt with prior to the complete application in the industry.

Conclusion

The research results found that nanofillers obtained through the use of agricultural wastes can indeed be of significant use in improving the performance of biodegradable polymer matrices in sustainable packaging. Optimized filler content (3 wt%) incorporation led to tensile strength and Youngs modulus increasing by 32 and 33 % respectively over neat PLA and thermal degradation onset temperature rose by around 15º C. Water vapor transmission was also reduced by 21% and oxygen permeability decreased by almost 24 %. Crystallinity rose to 57% and this showed higher level of structure organization in the matrix. These outcomes confirm the possibility of transforming agro-residues into high value nano reinforcements that enhance mechanical integrity without affecting biodegradability. The study has a contribution in that it combines the valorization of agricultural waste by nanocomposite engineering to a certain degree, developing measurable structure-property correlations, and a reported optimization scheme with performance indicators. The innovation is in the use of surface-treated nanocellulose made by waste streams and predictive modeling to obtain balanced packaging functionality. Future research ought to aim at fine tuning filler dispersion beyond 3 wt% without agglomeration, testing of biodegradation kinetics of filler long term on industrial composting regimes and undertaking a broad one life-cycle assessment to measure the reduction in carbon footprint. Further commercialization will be achieved by exploration of extrusion-based scale-up, compatibility to multilayer packaging systems and regulatory safety approval. As further optimization is introduced, these biodegradable nanocomposites have a great potential to find more application in the eco-friendly packaging sectors.

References

Selvam, T., Rahman, N. M. M. A., Olivito, F., Ilham, Z., Ahmad, R., & Wan-Mohtar, W. A. A. Q. I. (2025). Agricultural waste-derived biopolymers for sustainable food packaging: challenges and future prospects. *Polymers*, *17*(14), 1897. https://doi.org/10.3390/polym17141897

Waiker, V., Thangarasu, N., Bhalla, A., Das, S., Patel, D. J., & Acharjya, K. (2025). Predictive crop yield analysis using deep learning and optimized sensor data in precision agriculture. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 16*(3), 155–177. https://doi.org/10.58346/JOWUA.2025.I3.010

Maluin, F. N. (2024). Enhancing chitosan nanofilm with agricultural waste fillers for sustainable and safe functional food packaging. *ACS Agricultural Science & Technology*, *4*(11), 1136-1162. https://doi.org/10.1021/acsagscitech.4c00398

Birania, S., Kumar, S., Kumar, N., Attkan, A. K., Panghal, A., Rohilla, P., & Kumar, R. (2022). Advances in development of biodegradable food packaging material from agricultural and agro-industry waste. *Journal of Food Process Engineering*, *45*(1), e13930. https://doi.org/10.1111/jfpe.13930

Satapathy, S. N., Sunil Kumar, M., Srivastava, M. P., Sharma, S., Mounika, N., Daivagna, U., & Inbathamizh, L. (2025). The effect of agricultural runoff on freshwater biodiversity and ecosystem functioning. *International Journal of Aquatic Research and Environmental Studies,* *5*(1), 440–449. https://doi.org/10.70102/IJARES/V5I1/5-1-40

Wypij, M., Trzcińska-Wencel, J., Golińska, P., Avila-Quezada, G. D., Ingle, A. P., & Rai, M. (2023). The strategic applications of natural polymer nanocomposites in food packaging and agriculture: Chances, challenges, and consumers' perception. *Frontiers in Chemistry*, *10*, 1106230. https://doi.org/10.3389/fchem.2022.1106230

Omerović, N., Djisalov, M., Živojević, K., Mladenović, M., Vunduk, J., Milenković, I., ... & Vidić, J. (2021). Antimicrobial nanoparticles and biodegradable polymer composites for active food packaging applications. *Comprehensive Reviews in Food Science and Food Safety*, *20*(3), 2428-2454. https://doi.org/10.1111/1541-4337.12727

Andrade, M. S., Ishikawa, O. H., Costa, R. S., Seixas, M. V., Rodrigues, R. C., & Moura, E. A. (2022). Development of sustainable food packaging material based on biodegradable polymer reinforced with cellulose nanocrystals. *Food Packaging and Shelf Life*, *31*, 100807. https://doi.org/10.1016/j.fpsl.2021.100807

Mukherjee, A., Panda, S., Jeelani, P. G., Mossa, A. T., & Chidambaram, R. (2023). Biodegradable polymers/silica nanocomposites: applications in food packaging. In *Nanotechnology applications for food safety and quality monitoring* (pp. 395-414). Academic Press. https://doi.org/10.1016/B978-0-323-85791-8.00001-X

El-Sayed, S. M., & Youssef, A. M. (2023). Eco-friendly biodegradable nanocomposite materials and their recent use in food packaging applications: a review. *Sustainable Food Technology*, *1*(2), 215-227. https://doi.org/10.1039/D2FB00021K

Dey, D., Dharini, V., Selvam, S. P., Sadiku, E. R., Kumar, M. M., Jayaramudu, J., & Gupta, U. N. (2021). Physical, antifungal, and biodegradable properties of cellulose nanocrystals and chitosan nanoparticles for food packaging application. *Materials Today: Proceedings*, *38*, 860-869. https://doi.org/10.1016/j.matpr.2020.04.885

Sholokhova, A., Varžinskas, V., & Rutkaitė, R. (2025). Valorization of agro-waste in bio-based and biodegradable polymer composites: a comprehensive review with emphasis on Europe perspective. *Waste and Biomass Valorization*, *16*(4), 1537-1571. https://doi.org/10.1007/s12649-024-02856-y

Paudel, S., Regmi, S., Bhattarai, S., Fennell, A., & Janaswamy, S. (2025). Valorization of grapevine agricultural waste into transparent and high-strength biodegradable films for sustainable packaging. *Sustainable Food Technology*, *3*(4), 1218-1231. https://doi.org/10.1039/D5FB00211G

Tripathi, A., Srivastava, S., Pandey, V. K., Singh, R., Panesar, P. S., Dar, A. H., ... & Pandiselvam, R. (2024). Substantial utilization of food wastes for existence of nanocomposite polymers in sustainable development: a review. *Environment, Development and Sustainability*, *26*(10), 24727-24753. https://doi.org/10.1007/s10668-023-03756-2

Jamwal, V., Mittal, A., & Dhaundiyal, A. (2024). Valorization of agro-industrial waste in composite films for sustainable packaging applications. *Materials Today: Proceedings*, *113*, 94-100. https://doi.org/10.1016/j.matpr.2023.08.042

Trotta, F., Da Silva, S., Massironi, A., Mirpoor, S. F., Lignou, S., Ghawi, S. K., & Charalampopoulos, D. (2023). Silver bionanocomposites as active food packaging: Recent advances & future trends tackling the food waste crisis. *Polymers*, *15*(21), 4243. https://doi.org/10.3390/polym15214243

Salunkhe, S., Chaudhary, B. U., Tewari, S., Meshram, R., & Kale, R. D. (2022). Utilization of agricultural waste as an alternative for packaging films. *Industrial Crops and Products*, *188*, 115685. https://doi.org/10.1016/j.indcrop.2022.115685

Gupta, P., Toksha, B., & Rahaman, M. (2022). A review on biodegradable packaging films from vegetative and food waste. *The Chemical Record*, *22*(7), e202100326. https://doi.org/10.1002/tcr.202100326