

APPLICATION OF BAMBOO POWDER COMPOSITES IN FRUIT PACKAGING

การประยุกต์ใช้วัสดุเชิงประกอบจากผงไม้ไผ่ในบรรจุภัณฑ์ผลไม้

Yumei Fu^{1*}, Miyoung Seo², Kriangsak Khiaomang³ยูเหมย ฟู่^{1*}, มียอง โซ², เกียงศักดิ์ เขียวมั่ง³¹Student, Master of the Fine Arts Program in Visual Arts, Design, and Cultural Management, Faculty of Fine and Applied Arts Burapha University²Assistant Professor, Department of Product design, Faculty of Fine and Applied Arts, Burapha University³Associate Professor, Department of Product design, Faculty of Fine and Applied Arts, Burapha University

*Corresponding Author, E-mail: 158015280@qq.com

Article submission date: March 25, 2026; Article review date: April 11, 2026; Article acceptance date: April 15, 2026;

Online publication date: April 29, 2026

Abstract: Amid global efforts to mitigate carbon emissions and plastic pollution, the fruit packaging industry urgently seeks renewable and biodegradable alternatives to conventional petroleum-based materials. Although low-density polyethylene (LDPE) films and polypropylene (PP) trays possess excellent moisture resistance and structural stability, they lack biodegradability. Conversely, while corrugated cardboard and molded pulp are biodegradable, their structural integrity significantly degrades under high-humidity conditions, limiting their utility in cold-chain logistics. This study prepared and evaluated bamboo powder/PBAT/PLA composites for fruit packaging applications. Four bamboo powder particle sizes (60, 200, 400, and 800 mesh) were investigated under identical formulation conditions. The results revealed that particle size exerts a significant influence on the mechanical properties of the composites. Among the experimental groups, the 400-mesh bamboo powder-reinforced composite exhibited the optimal overall performance, characterized by a tensile strength of 26.30 ± 1.30 MPa, elongation at break of $16.20 \pm 2.00\%$, flexural strength of 40.10 ± 3.10 MPa, flexural modulus of 3.00 ± 0.20 GPa, and impact strength of 13.80 ± 1.30 kJ/m². Compared to the 60-mesh group, the 400-mesh composite showed markedly improved tensile and flexural properties, indicating superior filler dispersion and interfacial compatibility within the polymer matrix. Based on the material performance data and the structural requirements for fruit packaging in China and Thailand, a “material parameters–structural functions–application pathways” framework was established. The analysis indicates that the composite has significant potential for tray supports and cushioning liners, whereas its application in external packaging structures necessitates further validation through compression and moisture-resistance testing. This study provides both experimental and application-oriented support for the development of low-carbon and biodegradable fruit packaging materials.

Keywords: Bamboo powder composites, Fruit packaging materials, Low-carbon alternatives, Biodegradable polymers

บทคัดย่อ: ท่ามกลางความพยายามในระดับโลกเพื่อลดการปล่อยคาร์บอนและมลพิษจากพลาสติก อุตสาหกรรมบรรจุภัณฑ์ผลไม้มีความต้องการวัสดุทางเลือกที่สามารถหมุนเวียนและย่อยสลายได้ทางชีวภาพเพื่อทดแทนวัสดุฐานปิโตรเลียมแบบดั้งเดิมอย่างเร่งด่วน แม้ว่าฟิล์มพอลิเอทิลีนความหนาแน่นต่ำ (Low-Density Polyethylene: LDPE) และกรดพอลิโพรพิลีน (Polypropylene: PP) จะมีคุณสมบัติในการต้านทานความชื้นและความเสถียรเชิงโครงสร้างที่ดีเยี่ยม แต่เป็นวัสดุที่ไม่สามารถย่อยสลายได้ทางชีวภาพ ในทางตรงกันข้าม กระดาษลูกฟูกและเยื่อกระดาษขึ้นรูปสามารถย่อยสลายได้ทางชีวภาพแต่กลับแสดงความเสถียรเชิงโครงสร้างที่ต่ำภายใต้สภาวะที่มีความชื้นสูง ซึ่งเป็นข้อจำกัดในการนำไปประยุกต์ใช้ในบรรจุภัณฑ์ผลไม้สำหรับระบบโลจิสติกส์โซ่ความเย็น การศึกษานี้ได้ดำเนินการเตรียมและประเมินวัสดุเชิงประกอบจากผงไม้ไผ่ร่วมกับพอลิเมอร์ PBAT และ PLA สำหรับการใช้งานในบรรจุภัณฑ์ผลไม้ โดยวิเคราะห์ขนาดอนุภาคของผงไม้ไผ่ 4 ระดับ ได้แก่ 60, 200, 400 และ 800 เมช (Mesh) ภายใต้เงื่อนไขสัดส่วนผสมเดียวกัน ผลการทดสอบแสดงให้เห็นว่าขนาดอนุภาคส่งผลอย่างมีนัยสำคัญต่อสมบัติเชิงกลของวัสดุเชิงประกอบ โดยกลุ่มที่ใช้ผงไม้ไผ่ขนาด 400 เมช ให้สมรรถนะโดยรวมดีที่สุด ซึ่งมีค่าความต้านทานแรงดึงเท่ากับ 26.30 ± 1.30 เมกะพาสกัล (MPa) ค่าความยืดหยุ่น ณ จุดขาดร้อยละ 16.20 ± 2.00 ค่าความต้านทานแรงดัด 40.10 ± 3.10 เมกะพาสกัล (MPa) ค่ามอดูลัสการดัด 3.00 ± 0.20 กิกะพาสกัล (GPa) และค่าความต้านทานแรงกระแทก 13.80 ± 1.30 กิโลจูลต่อตารางเมตร (kJ/m²) เมื่อเปรียบเทียบกับกลุ่ม 60 เมช พบว่ากลุ่ม 400 เมช มีสมบัติแรงดึงและแรงดัดที่เพิ่มขึ้นอย่างชัดเจน ซึ่งชี้ให้เห็นถึงการกระจายตัวของสารเติมแต่งและความเข้ากันได้กับบริเวณพื้นผิวสัมผัสภายในเมทริกซ์พอลิเมอร์ที่ดีกว่าจากผลสมรรถนะของวัสดุและข้อกำหนดเชิงโครงสร้างของบรรจุภัณฑ์ผลไม้ในกรณีศึกษาตัวแทนตลาดจากประเทศจีนและประเทศไทย การวิจัยนี้จึงได้กำหนดกรอบการวิเคราะห์แบบ “พารามิเตอร์วัสดุ-หน้าที่เชิงโครงสร้าง-แนวทางการประยุกต์ใช้” ผลการวิเคราะห์ระบุว่าวัสดุเชิงประกอบนี้มีศักยภาพในการนำไปใช้สำหรับถาดรองรับและแผ่นรองกันกระแทก ในขณะที่การนำไปใช้ในโครงสร้างบรรจุภัณฑ์ภายนอกยังจำเป็นต้องมีการตรวจสอบเพิ่มเติมผ่านการทดสอบแรงกดและการต้านทานความชื้น งานวิจัยนี้ให้ข้อมูลสนับสนุนเชิงทดลองและเชิงประยุกต์สำหรับการพัฒนาวัสดุบรรจุภัณฑ์ผลไม้คาร์บอนต่ำที่ย่อยสลายได้ทางชีวภาพ

คำสำคัญ: วัสดุเชิงประกอบจากผงไม้ไผ่, วัสดุบรรจุภัณฑ์ผลไม้, ทางเลือกคาร์บอนต่ำ, พอลิเมอร์ย่อยสลายได้ทางชีวภาพ

1. Introduction

Driven by the global transition toward low-carbon development and the urgent need to reduce plastic pollution, the ecological transformation of packaging materials has become an important direction in sustainable industrial innovation [1], [3]. Fruit packaging is a high-consumption and fast-turnover packaging category, and it must provide sufficient load-bearing capacity, cushioning protection, and environmental adaptability during transportation, stacking, retail

display, and cold-chain storage [2]. At the same time, packaging systems are increasingly expected to reduce environmental impact through recyclability, biodegradability, and the use of renewable biomass resources [3].

At present, petroleum-based plastics such as low-density polyethylene (LDPE) films and polypropylene (PP) trays are widely used in fruit packaging because of their excellent moisture resistance, structural stability, and preservation performance [1], [2]. However, these

materials are non-biodegradable and create long-term environmental burdens after disposal [1]. In contrast, fiber-based materials such as corrugated cardboard and molded pulp have clear environmental advantages because they are recyclable or biodegradable [4], [11]. Nevertheless, these materials are sensitive to moisture and may lose structural integrity under high-humidity or cold-chain conditions [2], [11]. Therefore, a major challenge in fruit packaging is to develop materials that can balance mechanical protection, moisture resistance, and environmental sustainability [2], [3].

Among renewable biomass resources, bamboo has attracted increasing attention because of its rapid growth, wide availability, and high renewability [3], [14]. Bamboo powder can be used as a natural filler in biodegradable polymer matrices to improve stiffness and structural performance while reducing dependence on petroleum-based materials [5], [6], [7], [8], [12]. Recent studies on bamboo-based or natural fiber-reinforced composites have mainly focused on material composition, interfacial compatibility, and basic mechanical properties [5], [6], [7], [8], while studies on sustainable packaging have emphasized biodegradability, environmental trends, and material substitution [3], [4], [12]. In parallel, research on fruit packaging has highlighted the need for structural protection, cushioning performance, and compatibility with cold-chain logistics [2], [9]. However, existing studies still show three limitations. First, there is a lack of systematic comparison of bamboo powder particle size effects on the overall mechanical performance of biodegradable composites [5], [6], [7], [8]. Second, limited research has linked composite test results directly with the structural requirements of

specific fruit packaging systems [2], [9]. Third, few studies have integrated material performance, packaging structure, and application pathways into a unified analysis for practical packaging design [2], [12].

To address these gaps, this study investigates the performance and application of bamboo powder/PBAT/PLA composites in fruit packaging. Bamboo powder with particle sizes of 60, 200, 400, and 800 mesh was incorporated into the same formulation system, and the effects of particle size on particle characteristics and mechanical properties were analyzed. On this basis, representative fruit packaging cases from China and Thailand were examined to identify the functional requirements of different packaging structures, including tray supports, cushioning liners, and outer packaging components. A “material parameters–structural functions–application pathways” framework was then established to connect composite performance with packaging application needs.

The main contributions of this study are as follows. First, it systematically compares the effects of bamboo powder particle size on the mechanical performance of biodegradable composites. Second, it relates material test results to the functional requirements of fruit packaging structures. Third, it proposes application pathways and optimization directions for using bamboo powder composites in fruit packaging. Through this combination of material testing and application analysis, the study provides experimental and design-oriented support for the development of low-carbon and biodegradable fruit packaging materials.

2. Research Objectives

The primary objectives of this study were to evaluate the performance of bamboo powder/PBAT/PLA composites with diverse bamboo powder particle sizes and to examine their applicability in fruit packaging systems. The specific research objectives were as follows:

2.1 To compare the effects of varying bamboo powder particle sizes on the physical and mechanical properties of bamboo powder/PBAT/PLA composites. 2.2 To analyze the correlation between the material performance of the composites and the functional requirements of fruit packaging, encompassing load-bearing capacity, cushioning protection, and environmental adaptability. 2.3 To evaluate the application feasibility and structural compatibility of bamboo powder composites within representative fruit packaging components, such as tray supports, cushioning liners, and outer packaging structures. 2.4 To propose application pathways and optimization strategies for the implementation of bamboo powder composites in low-carbon and biodegradable fruit packaging.

3. Scope of Research

3.1 Content Scope

3.1.1 Packaging Application and Market Scope This study investigates the contemporary utilization of fruit packaging materials and structures to identify practical application requirements for bamboo powder-based composites. The scope encompasses:

1) Analysis of commonly utilized fruit packaging materials in contemporary markets;

2) Evaluation of representative packaging structures and their respective performance characteristics;

3) Investigation of representative fruit packaging cases to identify the functional limitations of conventional materials;

4) Analysis of the application potential of bamboo powder composites within fruit packaging systems.

3.1.2 Material and Performance Scope This study focuses on the material characteristics and performance of bamboo powder/PBAT/PLA composites concerning fruit packaging applications. The scope includes:

1) Review of existing research on bamboo powder composites and environmentally responsible packaging materials;

2) Preparation and formulation of bamboo powder/PBAT/PLA composite materials with varying bamboo powder particle sizes;

3) Characterization of particle size distribution and the specific surface area of bamboo powder;

4) Evaluation of the mechanical properties of the composites following processing and film formation.

This scope delineates the research boundaries from both material and application perspectives. The study concentrates on the effects of bamboo powder particle size on composite performance and the correlation between material properties and fruit packaging requirements. Primary emphasis is placed on performance testing, structural matching, and application analysis, rather than on

large-scale industrial production or long-term commercial validation.

3.2 Research Approach This study examines the performance and application of bamboo powder/PBAT/PLA composites in fruit packaging using a “material parameters–structural functions–application pathways” framework. Initially, bamboo powder of varying particle sizes was incorporated into a standardized formulation system to evaluate the influence of particle size on particle characteristics, interfacial interactions, and mechanical performance. This step served to identify the particle size range yielding the most favorable reinforcement effect.

Subsequently, the structural requirements for fruit packaging were analyzed, encompassing load-bearing capacity, cushioning performance, compression resistance, and environmental adaptability during transportation, stacking, and cold-chain conditions. Representative fruit packaging cases from China and Thailand were examined to identify the primary limitations of conventional packaging materials, specifically the poor moisture resistance of fiber-based materials and the environmental impact of petroleum-based plastics. Finally, the material test results were aligned with the structural requirements of diverse fruit packaging components, such as tray supports, cushioning liners, and outer packaging structures, to evaluate application feasibility and propose practical pathways for bamboo powder composites. This comprehensive approach integrates material performance evaluation with packaging application analysis, providing a technical foundation for developing low-carbon and biodegradable fruit packaging materials

4. Research Methods

4.1 Research Type and Approach This study employs a combination of material performance testing and application-oriented analysis to evaluate the potential of bamboo powder/PBAT/PLA composites for fruit packaging. The research synthesizes material characterization, mechanical property evaluation, literature review, and market case analysis. Utilizing the “material parameters–structural functions–application pathways” framework, the study examines the effects of bamboo powder particle size on composite performance and further correlates the test results with the functional requirements of fruit packaging, emphasizing structural protection, cushioning behavior, and environmental adaptability. This approach provides both experimental support and application-oriented interpretation for the development of low-carbon and biodegradable fruit packaging materials.

4.2 Research Steps

4.2.1 Literature Collection and Theoretical Analysis Relevant international and domestic literature on bamboo powder composites, biodegradable polymers, environmentally responsible packaging materials, and fruit packaging systems was reviewed. This step was conducted to identify the key material properties required for packaging applications and to establish the theoretical foundation for subsequent material evaluation and application analysis.

4.2.2 Material Preparation and Performance Parameter Collection Bamboo powder/PBAT/PLA composites with varying bamboo powder particle sizes were prepared under identical formulation conditions. The particle size distribution,

specific surface area, and mechanical properties of the composites were then collected and organized for comparative analysis. Concurrently, the renewable and biodegradable characteristics of the composite system were considered to support the environmental evaluation of the material.

4.2.3 Analysis of Structural Requirements for Fruit Packaging The functional requirements of fruit packaging were analyzed from the perspectives of transportation, stacking, retail display, and cold-chain storage. Significant emphasis was placed on load-bearing capacity, compression resistance, cushioning performance, and environmental adaptability to ensure that the technical demands of various packaging components could be clearly identified.

4.2.4 Matching Analysis between Material Properties and Packaging Requirements The physical and mechanical properties of the composites were compared with the structural requirements of fruit packaging. This matching analysis was conducted to evaluate the suitability of bamboo powder-based composites for various packaging components, including tray supports, cushioning liners, and outer packaging structures.

4.2.5 Application Feasibility Analysis Utilizing the material performance results and the structural matching analysis, the application potential of bamboo powder composites in fruit packaging was evaluated. This stage focused on mechanical performance, processing adaptability, environmental attributes, and practical application limitations to propose suitable application pathways for the material.

4.3 Data Sources and Analytical Methodology

4.3.1 Data Sources The data utilized in this study were derived from three primary sources. First, experimental data were obtained from bamboo powder/PBAT/PLA composites, encompassing formulation composition, particle size distribution, specific surface area, and mechanical properties. These data served to evaluate the influence of bamboo powder particle size on composite performance. Four particle-size groups were investigated under identical formulation conditions; the detailed formulation design is presented in Table 2. Second, the data comprised representative fruit packaging cases observed in wholesale and retail markets in China and Thailand. These cases were utilized to identify common packaging structures, material limitations, and practical functional requirements for fruit packaging applications. Typical cases included apple, persimmon, mango, and blueberry packaging systems, reflecting variations in load-bearing, cushioning, retail display, and environmental responsibility requirements. Third, the data included published academic literature and industry reports concerning biodegradable materials, fruit packaging, molded fiber packaging, and bamboo-based alternatives. These references supported the interpretation of material performance, environmental advantages, and application trends in environmentally responsible packaging.

4.3.2 Analytical Methods This study employs comparative analysis, structural-functional matching, and application-oriented evaluation. Initially, the effects of bamboo powder particle size on particle characteristics and mechanical properties were compared across the four experimental groups.

Subsequently, the test results were aligned with the functional requirements of fruit packaging structures. Finally, the feasibility of applying bamboo powder composites to diverse packaging components was evaluated by considering structural performance, processing characteristics, and environmental attributes within the proposed “material parameters–structural functions–application pathways” framework. This analytical process was designed to connect material testing with practical packaging application analysis.

4.4 Experimental Methods

4.4.1 Chemical Properties of Matrix Materials and Additives To facilitate formulation design and the selection of processing parameters, the

chemical and thermal properties of the matrix materials and additives were evaluated. In this composite system, poly (butylene adipate-co-terephthalate) (PBAT) and polylactic acid (PLA) were utilized as the biodegradable polymer matrix, while KH570 and ethylene bis-stearamide (EBS) served as the silane coupling agent and processing additive, respectively. PBAT primarily contributed flexibility, whereas PLA provided rigidity and dimensional stability. KH570 improved interfacial adhesion between the bamboo powder and the polymer matrix, and EBS enhanced melt flowability during processing. The chemical formulas, molecular weights, glass transition temperatures, and melting points of these materials are summarized in Table 1.

Table.1: Chemical Properties of Base Materials and Additives

Material	Chemical Formula	Molecular Weight (g/mol)	Glass Transition Temperature (°C)	Melting Point (°C)
PBAT	$(C_{12}H_{20}O)_n$	25,000–35,000	-30 ~ -20	110–120
PLA	$(C_3H_4O_2)_n$	50,000–200,000	55–65	150–180
KH570 (Silane)	$C_9H_{20}O_5Si$	236.34	—	217
EBS (stearamide)	$C_{36}H_{70}N_2O_2$	593.0	—	140–145

4.4.2 Formulation Composition of Experimental Groups with Varying Particle Sizes

To investigate the influence of bamboo powder particle size on composite performance, four experimental groups were established using bamboo

powder with particle sizes of 60, 200, 400, and 800 mesh. Across all groups, particle size served as the solitary variable, while the formulation composition was maintained constant. The detailed formulation for each experimental group is presented in Table 2.

Table.2: Formulation Composition of Experimental Groups with Different Bamboo Powder Particle Sizes

Group	Bamboo Powder Particle Size (Mesh)	Bamboo Powder (%)	PBAT (%)	PLA (%)	KH570 (%)	EBS (%)	Total mass(kg)
1	60	15.0	25.0	58.0	1.0	1.0	1.50
2	200	15.0	25.0	58.0	1.0	1.0	1.50
3	400	15.0	25.0	58.0	1.0	1.0	1.50
4	800	15.0	25.0	58.0	1.0	1.0	1.50

5. Research Findings and Analysis

5.1 Market Analysis of Fruit Packaging Materials

5.1.1 Common Fruit Packaging Material Types and Performance Characteristics Common fruit packaging materials in contemporary markets primarily consist of petroleum-based plastics and fiber-based materials. Among these, low-density polyethylene (LDPE) and polypropylene (PP) are widely utilized due to their superior toughness, rigidity, and moisture resistance, rendering them suitable for plastic bags, fresh-keeping films, and rigid trays. However, these materials are non-biodegradable and are associated with a significant environmental burden

following disposal. Conversely, corrugated cardboard and molded pulp offer distinct environmental advantages as they are recyclable or biodegradable. Corrugated cardboard is frequently utilized for outer packaging due to its compressive strength, whereas molded pulp is commonly used for fruit trays due to its cushioning performance. Nevertheless, molded pulp exhibits poor moisture resistance and tends to soften under humid conditions, which restricts its reliability in cold-chain logistics and storage. The primary characteristics of these common materials are summarized in Table 3.

Table.3: Comparison of Common Fruit Packaging Materials and Their Performance Characteristics

Material Type	Main Composition	Key Structural Performance Characteristics	Moisture Resistance	Environmental Attributes	Typical Application Forms
Low-Density Polyethylene (LDPE)	Petroleum-based plastic	Good impact resistance and high toughness	Excellent moisture resistance	Non-biodegradable; high carbon emissions	Plastic bags; fresh-keeping films
Polypropylene (PP)	Petroleum-based plastic	Relatively high rigidity and impact resistance	Excellent moisture resistance	Non-biodegradable	Plastic trays
Corrugated Cardboard	Pulp fiber	Good compressive strength	Moderate moisture resistance	Recyclable	Outer packaging boxes
Molded Pulp	Plant fiber	Good cushioning performance	Easily absorbs moisture	Biodegradable	Fruit trays

Overall, existing fruit packaging materials continue to exhibit a distinct trade-off between structural performance and long-term environmental responsibility. Petroleum-based plastics demonstrate superior moisture protection and structural stability, whereas fiber-based materials offer enhanced environmental profiles but remain susceptible to

moisture and varied operating conditions. This limitation underscores the difficulty in identifying a singular packaging material that concurrently meets requirements for protection, moisture resistance, and environmental responsibility. Figure 1 illustrates representative examples of these common fruit packaging materials observed in contemporary market.



(a) LDPE flexible packaging



(b) PP rigid plastic tray



(c) Corrugated transport carton



(d) Molded pulp tray

Figure1: Representative fruit packaging materials observed in current markets

Source: Field survey conducted by the author.

5.1.2 Analysis of Common Fruit Packaging Structures and Functional Issues Representative fruit packaging structures in contemporary markets exhibit distinct differences based on fruit characteristics, transport conditions, and retail requirements Apples are commonly packaged in corrugated cartons combined with polyethylene (PE) or polypropylene (PP) mesh sleeves and partition boards This structure is cost-effective and facilitates stacking; however, it possesses limited moisture resistance and is susceptible to deformation under compression during transportation

Persimmons are frequently packed in polyethylene terephthalate (PET) clamshell containers, which provide superior product visibility and display performance, yet their environmental impact remains relatively high due to their non-biodegradable nature Mangoes are often transported in expanded polystyrene (EPS) foam boxes, which offer substantial cushioning protection but are difficult to recycle and occupy a relatively large volume Blueberries are typically sold in transparent plastic cups or hinged containers, which are suitable for retail display but have

limited structural strength and involve high plastic consumption. The primary characteristics and functional issues of these common packaging structures are summarized in Table 4.

Table.4: Comparison of Common Fruit Packaging Structures and Functional Issues

Fruit Type	Packaging Material	Structural Form	Functional Advantages	Existing Problems
Apple	Corrugated cardboard + PE/PP mesh sleeve	Box body + mesh sleeve + partition board	Low cost; easy stacking	Insufficient moisture resistance; easily deformed under compression
Persimmon	PET plastic box	Clamshell tray/box	Good product visibility and display performance	Non-biodegradable; relatively high environmental burden
Mango	EPS foam box	Integral cushioned box structure	Strong cushioning performance	Difficult to recycle; bulky volume
Blueberry	Transparent plastic cup	Clamshell cup-type container	Convenient for retail display	Limited structural strength; high plastic consumption

These cases indicate that contemporary fruit packaging systems continue to encounter a common challenge: packaging structures that exhibit superior performance in cushioning, display, or stacking frequently depend on petroleum-based or non-recyclable materials, whereas environmentally responsible alternatives are often constrained by moisture sensitivity or insufficient structural stability.

Consequently, the development of alternative materials necessitates not only environmental benefits but also compatibility with the specific structural and functional requirements of fruit packaging. Figure 2 illustrates representative fruit packaging structures observed in wholesale and retail markets in China and Thailand.



(a) Apple – Corrugated carton with PE/PP foam net



(b) Persimmon – PET clamshell container



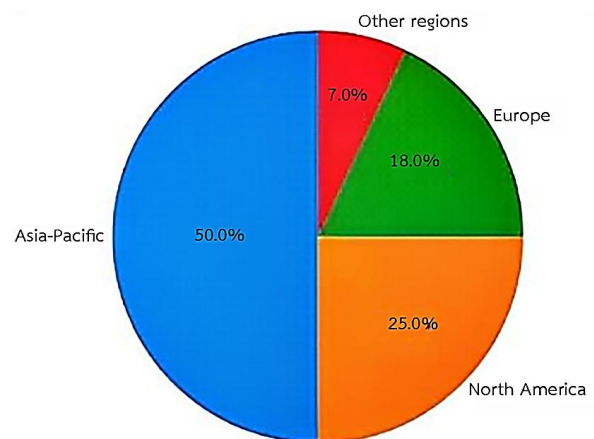
(c) Mango in EPS cushioning box



(d) Blueberry in transparent hinged plastic cup

Figure 2: Representative fruit packaging structures observed in wholesale and retail markets**Source:** Field survey conducted by the author

5.2 Regional Development Trends of Bamboo-Based Packaging Materials Figure 3 illustrates that molded fiber packaging activity is primarily concentrated in the Asia-Pacific region, followed by North America and Europe [13]. Although these data do not directly represent the exact market size of bamboo powder composites, they provide a valuable reference for understanding regional development trends in biomass-based packaging materials. Recent studies also indicate that food packaging materials are gradually shifting from conventional wood pulp to non-wood biomass fibers, such as bagasse, wheat straw, and bamboo. Alongside improvements in pulping and thermoforming technologies, this trend underscores the growing application potential of bamboo-based materials in fruit packaging. However, their actual suitability necessitates further evaluation in conjunction with material performance, processing behavior, and packaging functional requirements.

**Figure 3:** Regional market share distribution of molded fiber packaging

5.3 Fabrication and Performance Analysis of Bamboo Powder Composites

5.3.1 Bamboo Powder Particle Size Distribution and Specific Surface Area The particle size distribution and specific surface area of bamboo powder are important factors affecting filler dispersion, interfacial contact, and the mechanical performance of the composites. As shown in Table 5, the particle size decreased progressively with increasing mesh number, while the specific surface area increased accordingly. For example, the D50 value decreased from 250.0 μm at 60 mesh to 38.0 μm at 400 mesh and 18.0 μm at

800 mesh, while the specific surface area increased from 2.10 m²/g to 18.20 m²/g and 35.70 m²/g, respectively. These results indicate that finer bamboo powder provides a larger contact area with the polymer matrix, which is beneficial for interfacial interaction. However, the Span value also increased from 0.68 to 1.50 as the particle size became finer, suggesting a

broader particle size distribution and a higher possibility of agglomeration and processing instability. Therefore, particle refinement can improve the reinforcement potential of bamboo powder, but excessively fine particles may also create dispersion and processing challenges. The detailed particle size distribution and specific surface area data are summarized in Table 5.

Table 5: Statistics on Bamboo Powder Particle Size Distribution and Specific Surface Area

Bamboo powder particle size (mesh)	D10(μm)	D50(μm)	D90(μm)	Span	Specific surface area(m ² /g)
60	180.0	250.0	350.0	0.68	2.10
200	45.0	75.0	120.0	1.00	8.50
400	20.0	38.0	65.0	1.18	18.20
800	8.0	18.0	35.0	1.50	35.70

5.3.2 Mechanical Properties Analysis Figure 4 illustrates that bamboo powder particle size exerted a significant influence on the mechanical properties of the composites. The overall performance demonstrated an upward trend from 60 mesh to 400 mesh, followed by a decline at 800 mesh. Among the evaluated experimental groups, the 400-mesh composite exhibited the optimal overall performance, characterized by a tensile strength of 26.30 ± 1.30 MPa, a flexural strength of 40.10 ± 3.10 MPa,

and an impact strength of 13.80 ± 1.30 kJ/m². Conversely, both the 60-mesh and 800-mesh groups displayed inferior mechanical performance. This result indicates that the 400-mesh bamboo powder provided a superior balance between filler dispersion and interfacial reinforcement, whereas excessively coarse or excessively fine particles proved less effective. These findings provide a technical foundation for the subsequent evaluation of the material for fruit packaging applications.

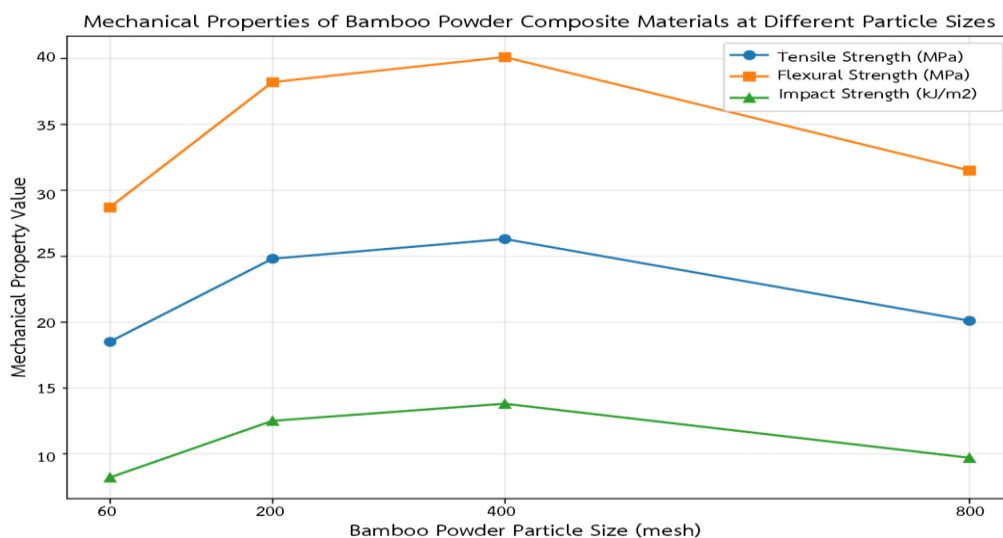


Figure 4: Mechanical Properties of Bamboo Powder Composite Materials at Different Particle Sizes

5.3.3 Images Related to the Experimental Process Figure 5 illustrates representative images depicting the preparation and processing stages of the bamboo powder composites, encompassing material handling, masterbatch preparation, and hot-melt film formation. These images provide visual documentation

of the fabrication procedure, demonstrating the processability of the composite materials under the designated experimental conditions. Nevertheless, these visuals primarily serve as procedural documentation and do not inherently constitute a comprehensive validation of packaging performance.

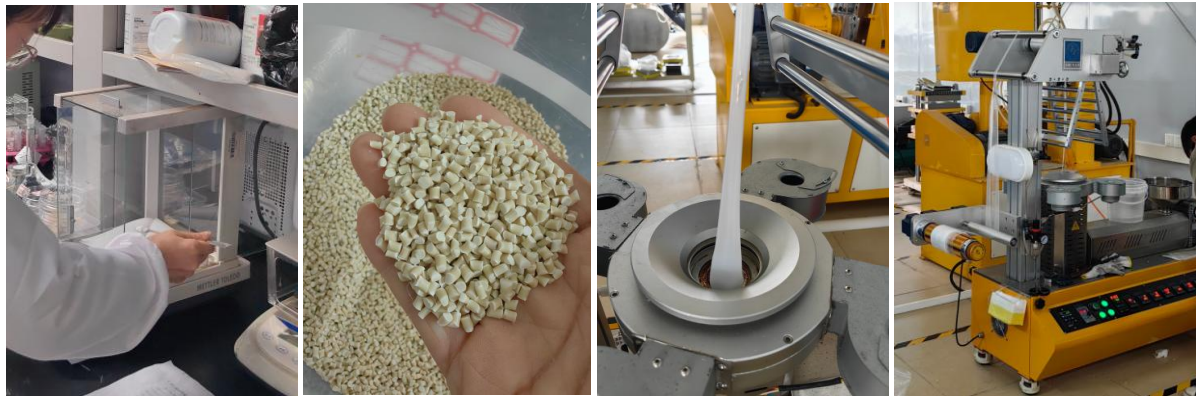


Figure 5: Representative images of bamboo powder composite masterbatch preparation and hot-melt film formation.

Source: Experimental photographs taken by the author.

6. Conclusions and Discussion

This study examined the performance and application potential of bamboo powder/PBAT/PLA composites for fruit packaging and established a “material parameters–structural functions–application pathways” framework to align material test results with packaging requirements. The findings revealed that bamboo powder particle size exerted a significant influence on composite performance. Among the evaluated groups, the 400-mesh bamboo powder demonstrated the optimal overall mechanical performance, indicating a more favorable balance between filler dispersion, interfacial interaction, and reinforcement efficiency. Based on the material test results and the structural requirements of representative fruit packaging systems, the composites exhibit potential for utilization in tray supports and

cushioning liners. These outcomes provide experimental and application-oriented support for the development of low-carbon and biodegradable fruit packaging materials. From an application perspective, the study suggests that bamboo powder composites may offer both structural and environmental advantages over conventional petroleum-based materials in specific packaging components.

Utilizing bamboo powder as a renewable biomass filler can reduce reliance on fossil-based resources, while the PBAT/PLA matrix provides a biodegradable foundation. However, the current results should be interpreted within the scope of this investigation. Although the material demonstrated favorable mechanical performance and fundamental processing feasibility, the present work did not encompass prototype compression testing, high-humidity moisture-

resistance testing, or long-term service validation under actual logistics and cold-chain conditions. Consequently, the current conclusions support preliminary application feasibility rather than comprehensive industrial validation.

Claims regarding large-scale commercial implementation should be pursued with caution until further engineering verification is finalized. In summary, this study contributes to the field in three primary ways. First, it compares the influence of bamboo powder particle size on the performance of biodegradable composites under a controlled formulation system. Second, it correlates material test results with the structural and functional requirements of fruit packaging in representative market cases from China and Thailand. Third, it proposes application pathways for utilizing bamboo powder composites in fruit packaging while acknowledging the current boundaries of validation. These outcomes provide a foundation for future prototype design, performance testing, and environmentally responsible packaging development.

7. Recommendations

7.1 Technical Application Recommendations For practical packaging design, the utilization of bamboo powder composites should initially focus on applications with relatively controllable structural requirements, such as tray supports and cushioning liners. In these applications, the material formulation, bamboo powder content, and structural geometry should be adjusted in accordance with fruit characteristics, packaging forms, and transportation conditions. Significant emphasis should be placed on the relationship between mechanical support, cushioning performance, and processability.

Furthermore, the interfacial compatibility between bamboo powder and the PBAT/PLA matrix should be continuously optimized to enhance the overall stability and efficiency of the composite structure. Prior to broader implementation, prototype development and fundamental engineering validation are recommended.

7.2 Recommendations for Industrialization and Engineering Implementation

Prior to large-scale commercial utilization, small-batch pilot trials should be conducted to assess the material under realistic transportation, stacking, and cold-chain conditions. Specifically, future engineering evaluations should encompass prototype compression testing, moisture-resistance testing under high-humidity conditions, and processing consistency assessments [15]. Concurrently, a preliminary economic comparison with conventional petroleum-based plastics and fiber-based packaging materials should be considered to clarify the practical advantages and current limitations of the composite system. Life Cycle Assessment (LCA) is also recommended to quantify carbon reduction potential, resource utilization, and environmental impacts [16]. These procedures are essential for transitioning from laboratory-scale material evaluation to industrial decision-making.

7.3 Recommendations for Future Research

Future investigations should further optimize processing parameters and examine the influence of bamboo powder content, particle size distribution, and matrix ratios on composite behavior. More importantly, future work should involve replicated experiments and statistical validation to clarify the quantitative relationship between particle size and mechanical performance. Additional studies should also examine long-term durability, degradation behavior, and

functional stability within actual packaging environments To better meet the requirements of fresh-fruit supply chains, subsequent research may further investigate moisture-barrier enhancement, structural prototype design, and the potential incorporation of active or intelligent packaging functions for fresh-fruit preservation [10], [17], [18].

8. Acknowledgments

The authors extend sincere gratitude to their advisor for the professional guidance and valuable suggestions provided throughout the research and revision of this thesis.

9. References

- [1] Geyer, R., Jambeck, J. R. and Law, K. L. 2017. "Production, use, and fate of all plastics ever made," *Science Advances*, 3(7): p. e1700782. [Online]. Available: <https://doi.org/10.1126/sciadv.1700782>
- [2] Defraeye, T. and et al. 2015. "Towards integrated performance evaluation of future packaging for fresh produce in the cold chain," *Trends in Food Science & Technology*, 44(2): pp. 201-225. [Online]. Available: <https://doi.org/10.1016/j.tifs.2015.04.008>
- [3] Mohanty, A. K. and et al. 2018. "Composites from renewable and sustainable resources: Challenges and innovations," *Science*, 362: pp. 536-542. [Online]. Available: <https://doi.org/10.1126/science.aat9072>
- [4] Amara, C. and et al. 2021. "Nanocellulose-based composites for packaging applications," *Current Opinion in Green and Sustainable Chemistry*, 31: p. 100512. [Online]. Available: <https://doi.org/10.1016/j.cogsc.2021.100512>
- [5] Bari, E. and et al. 2019. "Assessment of physical and mechanical properties of bamboo-plastic composites," *Polymer Composites*, 40(7): pp. 2834-2839. [Online]. Available: <https://doi.org/10.1002/pc.25097>
- [6] Hu, F. and et al. 2022. "Surface characteristics of thermally modified bamboo fibers and its utilization potential for bamboo plastic composites," *Materials*, 15(13): p. 4481. [Online]. Available: <https://doi.org/10.3390/ma15134481>
- [7] Ochi, S. 2022. "Mechanical properties of bamboo fiber bundle-reinforced bamboo powder composite materials," *European Journal of Wood and Wood Products*, 80: pp. 263-275. [Online]. Available: <https://doi.org/10.1007/s00107-021-01757-4>
- [8] Nukala, S. G. and et al. 2022. "Development of biodegradable composites using polycaprolactone and bamboo powder," *Polymers*, 14(19): p. 4169. [Online]. Available: <https://doi.org/10.3390/polym14194169>
- [9] Zheng, D. and et al. 2022. "Packaging design to protect Hongmeiren orange fruit from mechanical damage during simulated and road transportation," *Horticulturae*, 8(3): p. 258. [Online]. Available: <https://doi.org/10.3390/horticulturae8030258>
- [10] Sani, M. A. and et al. 2021. "Recent advances in the development of smart and active biodegradable packaging materials," *Nanomaterials*, 11(5): p. 1331. [Online]. Available: <https://doi.org/10.3390/nano11051331>

- [11] Semple, K. E. and et al. 2022. "Moulded pulp fibers for disposable food packaging: A state-of-the-art review," *Food Packaging and Shelf Life*, 34: p. 100908. [Online]. Available: <https://doi.org/10.1016/j.fpsl.2022.100908>
- [12] Bangar, S. P. and et al. 2023. "Plant-based natural fibers for food packaging: A green approach to the reinforcement of biopolymers," *Journal of Polymers and the Environment*, 31(12): pp. 5029-5049. [Online]. Available: <https://doi.org/10.1007/s10924-023-02849-3>
- [13] DI Research. 2024. *Global molded fiber pulp packaging competitive landscape professional research report 2024*. [Online]. Available: <https://www.marketresearch.com/Deep-Insights-Research-Co-DIR-v4285/Global-Molded-Fiber-Pulp-Packaging-37313502/>
- [14] Li, Y., Wang, N. and Abdul Latiff, A. R. 2025. "Development of the bamboo forest economy: Reviewing China's 'bamboo as a substitute for plastic' initiative and its development," *Advances in Bamboo Science*, 11: p. 100130. [Online]. Available: <https://doi.org/10.1016/j.bamboo.2025.100130>
- [15] Jalali, A. and et al. 2019. "Application of humidity absorbing trays to fresh produce packaging: Mathematical modeling and experimental validation," *Journal of Food Engineering*, 244: pp. 115-125. [Online]. Available: <https://doi.org/10.1016/j.jfoodeng.2018.09.006>
- [16] Ponnusamy, P. G. and Mani, S. 2022. "Life cycle assessment of manufacturing cellulose nanofibril-reinforced chitosan composite films for packaging applications," *The International Journal of Life Cycle Assessment*, 27: pp. 380-394. [Online]. Available: <https://doi.org/10.1007/s11367-022-02035-y>
- [17] Rodriguez, O. T. and et al. 2024. "Performance of biodegradable active packaging in the preservation of fresh-cut fruits: A systematic review," *Polymers*, 16(24): p. 3518. [Online]. Available: <https://doi.org/10.3390/polym16243518>
- [18] Jahangiri, F., Mohanty, A. K. and Misra, M. 2024. "Sustainable biodegradable coatings for food packaging: Challenges and opportunities," *Green Chemistry*, 26: pp. 4934-4974. [Online]. Available: <https://doi.org/10.1039/D3GC02647G>