Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.36491

A Comprehensive Review on Development, Biodegradable Properties and Environmental Impacts of Packaging Materials

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Abstract. With the continuous expansion of food processing and biomedical industries, the consumption of disposable packaging rises every year. Petroleum, plastic and laminated paper packaging cause microplastic pollution, resource waste and other ecological risks. Driven by global carbon neutrality and plastic restriction policies, biodegradable eco-packaging has become a key research field. This paper adopts two ways, literature review and life cycle assessment (LCA), as research methods, which sort out the evolution of packaging types, for instance, traditional plastic, plain paper, polylactic-acid (PLA) and polyhydroxyalkanoates (PHA) biopolymers, rice straw composite substrates and curcumin-zein active films, comparing their biodegradation mechanisms, physical performance, merits and drawbacks. With LCA experimental data of blueberry containers, environmental burdens under four waste treatments, including recycling, industrial composting, landfill and incineration, are quantified. Relevant experimental results prove that rice straw-reinforced polylactic acid (RPLA) composite packaging generates the lowest carbon emission in all scenarios. Curcumin-zein composite films integrate antibacterial, UV-blocking and fully biodegradable functions, yet the cost of mass commercial production remains high. Multi-layer coated paper boxes bring far higher marine ecotoxicity than other materials. According to special research on pharmaceutical packaging, fresh food and medical products require completely different packaging standards. Thus, optimization strategies can be proposed in terms of waste classification, modification of materials and policy support, providing reliable theoretical guidance for green packaging application and development of circular systems in the food and medical industries.

Keywords: packaging materials, life cycle assessment, green packaging, pharmaceutical packaging, biodegradability

1. Introduction

Modern commodity circulation heavily relies on all kinds of packaging materials. Fresh fruits, medicines and daily goods need packages for storage and long-distance transportation. Traditional polypropylene (PP) and polyethylene terephthalate (PET) plastic are cheap and stable against water, so they have dominated the market for decades. However, their stable molecular structure requires hundreds of years to decompose fully in nature. Broken microplastics penetrate soil, rivers and oceans, accumulate along food chains and harm human and wildlife health [1]. Paper packaging uses renewable wood resources, which seems eco-friendly. Nevertheless, paper manufacturing consumes massive amounts of water and electricity. Most commercial food cartons are covered with plastic films. The mixed paper-plastic structure is hard to separate during waste sorting. Discarded coated paper flows into oceans and releases plastic fragments for a long time, worsening water pollution. To reduce white pollution, governments worldwide have launched plastic-limiting policies. Researchers develop multiple biodegradable materials, divided into synthetic biopolymers (PLA, and PHA), agricultural waste composites and plant protein active films. Lin et al. [2] pointed out that pharmaceutical packaging has stricter safety standards than food packages. Materials must release few chemicals and avoid chemical reactions with active drugs. Traditional plastic may denature protein medicines, so biodegradable substrates fit medical logistics better. For soft fruits such as blueberries, Mannheim et al. [3] designed four commercial packages and completed a full LCA evaluation, calculating carbon emission, resource depletion and ecotoxicity under four waste disposal routes, which supplies quantitative evidence for sustainable fruit packaging. Liu's group [4] and Li et al. [5] conducted a series of experiments on curcumin-zein films, proving the composite film can keep food fresh, inhibit bacteria and degrade completely. However, complex purification and casting processes raise large-scale production costs. Most existing papers merely test one single material, without a horizontal comparison covering both food and medical fields. Few studies combine LCA data to evaluate the overall environmental burdens of different packages. Accordingly, this paper systematically compares the degradation performance, merits and drawbacks of five packaging categories, analyses key barriers to the popularization of green packaging, and puts practical development suggestions, which would help manufacturers cut packaging-related environmental costs and provides theoretical support for the formulation of industrial environmental standards.

2. Development history and classification of packing materials

2.1. Conventional non-biodegradable packing

2.1.1. Petroleum-based plastics (PP & PET)

PP and PET are the most common raw materials for disposable packaging. They have a mature forming craft, low cost and stable waterproof tensile strength, widely applied in fruit punnets, food bags and simple medicine boxes. According to Gao's [1] industry summary, early double-degradable plastic only splits into fragments instead of complete decomposition, and its photosensitive additives lead to carcinogenic risks, which have been phased out gradually. Pure petroleum plastic is still massively used now. Its most serious drawback is the extremely long degradation cycle. Random waste creates constant microplastic pollution and damages soil and marine ecosystems. Besides, plastic production depends heavily on non-renewable fossil oil, accelerating resource depletion.

2.1.2. Laminated cardboard packaging

Pure paper can be recycled and generates less carbon when incinerated. However, single-layer paper cannot resist water, so manufacturers add plastic film to produce Cast-Coated-Board (CBC) laminated carton [3]. The composite structure solves water leakage but brings two main drawbacks. First, paper and plastic layers cannot be separated easily, which largely increases waste sorting costs.

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Second, LCA data indicates coated paper creates far higher marine ecotoxicity than PP and RPLA throughout its life cycle. Discarded coated paper threatens marine creatures for a long time. Uncoated CB-flute (CB) cardboard is easier to recycle, yet it balances air permeability and water resistance poorly, leading to higher loss during transportation.

2.2. Three generations of biodegradable packaging

2.2.1. First generation—simple degradable plastic

Early light and double-degradable plastic mixes starch with photosensitizer to split into small pieces, but they cannot be fully digested by microbes, leaving tiny plastic residues. Gao stated that photosensitive additives inside these materials are toxic. Long-term accumulation in soil releases harmful substances continuously, so factories basically stop producing them as qualified eco-packaging [1].

2.2.2. Second generation—pure biopolymers

PLA and PHA are made from fermented cornstarch and microbes, belonging to full bio-based substrates [2]. They can only degrade completely in industrial compost over 55℃. It takes 1 to 3 years to break down under normal outdoor or landfill conditions. If cities lack compost equipment, their environmental merits disappear. Pure PLA is brittle with poor shock and water resistance, and is easy to break when used alone. PHA has better mechanical performance, but its complicated fermentation process raises basic material costs.

2.2.3. Third generation—active composite films

This category includes rice straw-reinforced PLA and curcumin-zein composite films. RPLA uses waste crop straw as filler. Blueberry packaging LCA tests prove it has the lowest carbon footprint. Curcumin-zein films are made of corn protein mixed with natural curcumin, gaining antibacterial and UV-shielding capacity. They fully degrade within 15 days buried in soil without toxic residues [4, 5]. Apart from zein-based packaging membranes, konjac glucomannan is another promising natural polysaccharide substrate. Researchers fabricated cinnamaldehyde-loaded konjac glucomannan antibacterial films with humidity-triggered release characteristics, which can dynamically adjust the release rate of antibacterial ingredients according to ambient humidity and realize targeted fresh preservation for fruits and vegetables, offering a new idea for intelligent biodegradable packaging development [6]. These materials, which are mainstream research targets, are suitable for mass fresh produce and high-end fresh-keeping and medical packaging.

2.3. Different demands for food and pharmaceutical packaging

Soft berries such as blueberries are easy to rot during transportation, so packages need lightweight, ventilated holes and mild buffering. RPLA straw punnets have standard air holes, are made of farm waste and leave no residue after composting, perfect for berry fruits [3]. Pure PLA and coated paper lack proper ventilation design and cause higher fruit loss.

Lin's [2] review on pharmaceutical packaging clarifies that core standards include low migration and chemical inertness. Protein drugs and vaccines are sensitive to dissolved substances. Traditional PP plastic leads to protein aggregation and reduces drug efficacy. PLA and zein films have stronger chemical stability and do not react with medicines, becoming ideal medical green packaging.

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Besides, curcumin composite films pass cell and plant toxicity tests and meet medical safety requirements.

3. Comparison of biodegradation mechanism and performance

3.1. Degradation defects of plastic and coated paper

Plastic macromolecules own stable chemical bonds. Microbes in nature cannot break long carbon chains, only weather plastics into microplastic particles that stay in water and soil for decades. Coated cardboard degrades asynchronously: paper pulp rots fast while plastic film remains intact for a long time. Separation during recycling is difficult. Plenty of discarded CBC boxes flow into oceans and raise marine ecotoxic values [3].

3.2. Degradation restrictions of pure PLA and PHA

These two biopolymers decompose fast only in humid industrial compost over 55 ℃ . Normal outdoor and landfill sites have low temperatures and slow down degradation, which takes 1 to 3 years. Without compost factories in cities, waste PLA and PHA still create microplastic pollution and lose environmental benefits. PHA molecular chains are easier to break down by soil bacteria at room temperature, while its fermentation cost is high for mass production.

3.3. Degradation advantages and disadvantages of rice straw - PLA

Rice straw is agricultural waste. Mixing into the PLA matrix accelerates overall decomposition and cuts carbon emissions during composting. However, weak binding between straw fibre and PLA leads to cracks under damp storage. The material softens above 60°C, is unsuitable for hot food, and only fits for room-temperature fruits and general medicine packages.

3.4. Degradation performances of curcumin-zein composite film

Zein is a natural polymer fully digested by soil microbes, and curcumin leaves no chemical residue. The film disappears after 15 days buried in soil, and its decomposed matter is non-toxic to mung bean seedlings and L929 cells [4]. Adjusting ethanol concentration changes binding force between curcumin and zein. 80% ethanol creates the highest binding affinity and stable film functions [5].

3.5. Special degradation requirements for medical packaging

Medical degradable films must not release irritant toxic small molecules during decomposition to prevent drug deterioration. Degraded zein produces natural organic matter without heavy metals or chemical additives, suitable for vaccines and biological drugs. PLA only breaks into CO_2 and water, also meets medical environmental standards [2].

4. Analysis of merits and drawbacks of main packaging types

4.1. Petroleum plastic

Mature production craft, low raw material cost, balanced water barrier and tensile strength. Widely used for mass daily goods and cheap fruits with common processing equipment and stable energy

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consumption. Relying on non-renewable oil cannot fully degrade naturally with lasting microplastic risks. Some plastic additives migrate and poison drugs after long contact [2].

4.2. Laminated cardboard

Paper-based materials are renewable and can be separately recycled after disposal. Uncoated CB creates less carbon when incinerated. But coated CBC is hard to separate. LCA data prove it has the highest marine ecotoxicity among four packages. Paper manufacturing wastes huge volumes of water [3].

4.3. Rice straw - PLA

Utilizing agricultural straw waste for resource recovery significantly reduces fossil raw material consumption and the full treatment model achieves the lowest carbon footprint. The ventilated design fits soft berries and degrades safely in compost. The heat resistance is insufficient, and it is prone to cracking in humid environments; the impact strength is lower than that of pure PP plastic and not fit for hot food.

4.4. Curcumin-zein composite film

Wide antibacterial effect and full UV shielding, reducing fruit weight loss and rot within 12 days. Fully biodegradable with high biosafety verified by cell and plant tests [4]. Complicated zein purification and casting processes make mass cost two or three times higher than PP plastic, limiting large-scale application.

4.5. Bio-based medical packaging

Stable chemical property without harmful migration, no reaction with vaccines and protein drugs, and the degradation products are safe and pollution-free. Strict modification standards raise research costs compared to common fruit packages.

5. LAC environmental load evaluation based on blueberry data

This LCA takes one single blueberry punnet as a functional unit and adopts the CML-2016 standard to calculate global warming potential, aquatic/marine ecotoxicity and fossil depletion. Four end-of-life modes, recycling, compost, landfill, incineration, cover raw material extraction, production, usage and waste disposal [3].

Carbon emission ranking: coated CBC > PP > pure PLA > RPLA. Marine toxicity of coated paper accounts for over 70% of its total environmental burden. More than 80% of pollution comes from raw material and production, less than 20% from waste treatment. A recycling rate over 60% sharply cuts carbon output; below 60%, eco-materials lose most advantages.

Medical packages need extra modification steps to reduce chemical migration, consuming more energy and creating slightly higher carbon than fruit RPLA. However, they avoid long-term microplastic pollution and bring better long-term environmental benefits [2].

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6. Barriers restricting wide applications of green packaging

Several prominent constraints hinder the large-scale application of biodegradable eco-packaging. In terms of material-related technology, RPLA and zein films are inferior to PP in tensile property and waterproof capability, which brings about a higher rate of fruit damage in long-distance transportation. Besides, the complicated manufacturing process of curcumin films pushes up production costs and prevents manufacturers from adopting alternative raw material solutions. As for the waste disposal system, waste sorting awareness has not been well established among residents, who often mix conventional plastics with biodegradable waste and thereby increase sorting expenses. Most cities also lack standardized composting plants. As a direct consequence of this situation, discarded PLA and straw-derived materials are sent to landfills or incinerators rather than undergoing complete biodegradation. Different regional environmental standards force factories to change packages and raise costs. Eco-friendly packaging commands a higher selling price, making retailers worry about reduced sales volume, and there remains an absence of unified inspection specifications for biodegradable materials applied to food and medical scenarios [1, 2].

7. Optimized development paths

Multiple practical approaches can be adopted to tackle the existing drawbacks of biodegradable eco-packaging. When dealing with material-related limitations, researchers can carry out the modification of PLA with low-cost agricultural waste, including rice and wheat straw, to greatly cut the consumption of precious grain-based raw materials. Production staff may also simplify the complicated purification process of zein and adjust ethanol ratios carefully so that the high manufacturing cost of curcumin films can be effectively lowered [5]. Higher-level heat resistance and strong-shocking resistance properties can be achieved to suit a wider range of daily and industrial usage environments.

Turning to waste management, exclusive recycling containers ought to be arranged in public zones for composite packaging waste. Standard running composting sites can be constructed nationwide, while straightforward and easy-to-understand waste classification knowledge gets widely spread among ordinary citizens. This useful practice keeps ordinary plastic items separate from biodegradable rubbish and makes certain straw—PLA and protein-based films—go through full composting breakdown.

In regard to market-related and administrative matters, unified inspection criteria for food-grade and medical-use biodegradable packaging should be officially issued. Local authorities are able to introduce favorable regulations, for instance, decreasing in tax and manufacturing subsidies for environmentally friendly packages, restricting the circulation of disposable petroleum-derived plastic and giving financial support to businesses that develop straw-reinforced and zein films [1]. For targeted usage improvement, lightweight and breathable RPLA trays are fit for fresh-commodity transportation. Meanwhile, low-migration curcumin-zein films are applied within biomedicine, combining a good balance between long-term preservation, chemical safety and complete biodegradation [3, 4].

8. Conclusion

This paper systematically sorts out the development of five typical packaging types: traditional petroleum-based plastic, laminated paperboard, PLA and PHA biopolymers, rice straw reinforced composites and curcumin-zein composite films. It comprehensively compares their degradation

DOI: 10.54254/2755-2721/2026.36491

mechanisms, fundamental physical properties, inherent merits and practical drawbacks, and further quantifies full-life-cycle environmental burdens under four typical waste treatment routes by adopting blueberry packaging LCA experimental data. The experimental results demonstrate that rice straw reinforced PLA generates the lowest carbon footprint across all disposal scenarios, making it the optimal low-carbon packaging candidate for fresh agricultural produce. Curcumin-zein composite films integrate outstanding antibacterial capacity, ultraviolet shielding performance and complete biodegradability. Nevertheless, the excessive cost of large-scale manufacturing greatly restricts its extensive commercial application. By contrast, multi-layer coated paper imposes severe marine ecological pollution risks and results in persistent long-term environmental losses. In particular, pharmaceutical packaging follows independent low-migration safety specifications. Accordingly, zein and PLA bio-based substrates possess obvious advantages over conventional petroleum plastics for drug storage. At present, the popularization of green packaging is hindered by three primary obstacles: inadequate comprehensive material performance, imperfect waste treatment infrastructure and inconsistent industrial testing standards. One notable limitation is that the adopted LCA parameters originate from European production systems, which have certain deviations when applied to domestic manufacturing and waste management contexts.

Thus, future research can concentrate on low-cost modification technologies for agricultural residues and establish regionalized LCA models adapted to every country's practical conditions. When coordinated with tax policies, the construction of industrial composting facilities and systematic public environmental education, the industrialization of eco-friendly packaging for food and pharmaceuticals can be effectively accelerated, therefore promoting low-carbon, circular and sustainable development across the whole packaging industry.

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