

The Role of Sustainable Agroecosystems as a Source of Raw Materials for Smart Biopackaging: A Systematic Literature Review

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ABSTRACT

Single use plastic packaging and the underutilization of agricultural residues remain important environmental challenges. This review examines the potential of agroecosystem-derived biomass as a renewable resource for smart biopackaging, with particular attention to material modification strategies and end of life considerations. A Systematic Literature Review (SLR) using a descriptive qualitative approach was conducted based on scientific publications retrieved from Scopus and Web of Science. The selected literature was synthesized into three main themes: biomass potential, technological modification, and end of life or circular economy impacts. The reviewed studies identified cassava starch; cellulose derived from oil palm empty fruit bunches, rice straw, and corn residues; fruit peels; and plant proteins as promising structural materials for sustainable packaging. Anthocyanins obtained from red cabbage, butterfly pea flowers, purple sweet potatoes, and roselle were among the most frequently reported natural pH responsive indicators. The incorporation of antimicrobial, antioxidant, and colorimetric functions into biopolymer based materials may help extend food shelf life, reduce food waste, and provide visual information on product freshness. However, wider application remains constrained by variability in raw-material properties, insufficient mechanical and barrier performance, instability of active compounds, production costs, and regulatory requirements. Further development therefore requires improved biomass standardization, scalable processing technologies, pilot-scale validation, and clearly defined food contact regulations.

KEYWORDS: Agroecosystem, Smart biopackaging, Agricultural waste, Circular economy

1. INTRODUCTION

Plastic pollution has become a major environmental concern, particularly because packaging accounts for a substantial proportion of short lived plastic consumption. In 2023, global plastic production reached approximately 414 million metric tons, with 36% used by the packaging sector, mainly for single-use products (de Sousa, 2024). This increase has contributed to the accumulation of plastic waste and environmental degradation (Pottinger et al., 2024; Cottom et al., 2024). As a result, packaging is shifting from a passive material that only contains and protects products into a functional material with biodegradable, active, and intelligent properties. At the same time, agro-industrial activities generate large amounts of waste rich in biopolymers and bioactive compounds, but much of it remains poorly managed. These two problems create an opportunity to develop sustainable biopackaging from renewable agricultural resources.

Agricultural and agro-industrial wastes, such as oil palm empty fruit bunches, fruit peels, rice straw, and corn residues, are potential sources of structural biopolymers for sustainable packaging (Carnaval et al., 2024; Kossalbayev et al., 2025; Selvam et al., 2025). Meanwhile, anthocyanins from red cabbage, butterfly pea flowers, purple sweet potatoes, and roselle can function as natural pH-sensitive indicators in intelligent packaging (Halonen et al., 2020; Remedio & Parada Quinayá, 2024). However, an integrated review of agricultural resources as sources of both structural biopolymers and natural indicators remains limited. This study addresses this gap by identifying promising materials, technological advances, current limitations, and future research directions for sustainable smart biopackaging. Although previous studies have discussed agricultural biomass and smart packaging, these aspects are often reviewed separately. An integrated review linking agroecosystem-derived biomass, material modification, smart packaging functions, and end-of-life considerations remains limited. Therefore, this study addresses this gap through a comprehensive systematic review within a circular economy framework.

In this context, sustainable agroecosystem based biopackaging is a strategic alternative with significant potential for development. A sustainable agroecosystem can be understood as an agricultural production system

managed with ecological principles in mind, namely, by regulating the relationships between biotic components, such as plants, microorganisms, and animals, and abiotic components, such as soil, water, and climate, which interact dynamically (Adams et al., 2025; Chaudhary et al., 2025).

Biomass waste from agroecosystems, such as cellulose from straw, bagasse, and banana peels, can be used as a valuable biopolymer resource that can be processed into biodegradable packaging materials (Sharma et al., 2025). Biopolymer materials extracted from agroecosystem waste include cellulose, hemicellulose, lignin, starch, pectin, chitin, chitosan, and vegetable proteins. These materials have great potential for processing into films, composites, and biomaterials, which can serve as alternatives to conventional plastics and support the development of more sustainable food packaging (Carnaval et al., 2024; Dirpan et al., 2023; Westlake et al., 2023; Selvam et al., 2025).

In this context, packaging refers to food packaging that functions as a product protector while supporting quality, safety, shelf life, distribution, and consumer acceptance. Appropriate packaging plays an important role in maintaining product quality and extending the shelf life of food products (Suryaningsih et al., 2025). Studies on food packaging research developments over the past few years have shown a shift from conventional passive packaging to sustainable biopolymer-based packaging that not only protects the product but also has additional functions in maintaining food quality and safety. The packaging in question is smart biopackaging, a biomaterial-based packaging concept that not only functions as a passive barrier but also possesses active and/or intelligent capabilities. Active packaging works by releasing or absorbing specific compounds to extend shelf life, whereas smart packaging provides information about food conditions, such as changes in pH, volatile gases, temperature, or product freshness. The integration of biopolymers, antimicrobial compounds, antioxidants, natural color indicators, and nanofillers makes smart biopackaging one of the main directions of modern food packaging innovation (Abdullah et al., 2022; Halonen et al., 2020; Remedio & Parada Quinayá, 2024).

Sustainable agroecosystems hold a strategic position in the development of smart biopackaging because they can provide renewable raw material sources, both from primary agricultural products and agro-industrial residues. Biomasses such as rice straw, sugarcane bagasse, corncobs, husks, fruit peels, cassava peels, banana stems, vegetable waste, and horticultural residues contain starch, cellulose, hemicellulose, lignin, pectin, proteins, pigments, and bioactive compounds that can be converted into packaging materials. Using a circular economy approach, low-value residues can be transformed into films, coatings, composites, nanomaterials, or smart packaging indicators (Padhi et al., 2023; Fatima et al., 2024; Mehdizadeh et al., 2026).

Based on the dynamics of these problems, a comprehensive study that integrates agroecosystem waste management with environmentally friendly technologies is required. Therefore, this study aimed to analyze the potential of agroecosystem byproducts as a biomass source, evaluate various technological modification strategies to improve the mechanical and functional performance of packaging materials, and map the environmental impacts of the packaging's end of life cycle.

2. MATERIALS AND METHODS

This study was conducted using a descriptive qualitative approach. A structured extraction form was used to record the biomass source, biopolymer composition, modification method, reported packaging performance, and end-of-life information for each study. Rather than pooling results statistically, the extracted information was organized into three analytical themes: biomass potential, technological modification, and end of-life or circular economy implications. Findings were then compared across the selected studies to trace recurring patterns, technological progress, limitations, and research opportunities in sustainable smart biopackaging.

2.1. Study Area Information Sources and Search Strategy.

This study, based on a Systematic Literature Review (SLR), was conducted digitally, collecting data through academic databases, institutional websites, study selection, data extraction, synthesis of findings, and reporting of limitations in scientific journals. This multi-source SLR approach resulted in a structured analysis of the relationship between agroecosystem waste and biomass and the development of smart and environmentally friendly packaging.

Scopus and Web of Science (WoS) were searched for publications issued from 2020 to 2026. Eligible records were peer-reviewed research articles or review articles written in English and addressing agroecosystem or agroindustrial waste, biopolymers, biodegradable packaging, active packaging, intelligent packaging, or smart biopackaging. Articles were excluded when they were outside the food-packaging context, lacked relevant information on biomass sources or packaging applications, duplicated another record, or did not provide sufficient full-text information. Screening was performed in sequence: potentially relevant records

were identified, duplicates were removed, titles and abstracts were screened, full texts were assessed for eligibility, and studies meeting the criteria were retained for data extraction and synthesis.

3. RESULTS AND DISCUSSION

3.1. Agroecosystem Waste as a Source for Smart Biopackaging

Review of the selected literature grouped agroecosystem derived feedstocks into five broad categories: starch-rich materials, lignocellulosic biomass, fruit and vegetable residues, plant proteins, and plant-derived bioactive compounds (Table 1). Starch-rich materials, such as cassava, corn, potato, sago, rice, and tuber waste, are a primary source of biodegradable films owing to their abundant availability, relatively low production costs, and ability to form films after processing with plasticizers. However, starch-based films generally suffer from disadvantages such as high sensitivity to moisture and limited mechanical properties. Therefore, improving the performance of starch-based films can be achieved through polymer blending, crosslinking, and the addition of nanofillers to improve the mechanical strength, thermal stability, and water vapor barrier properties (Fatima et al., 2024); Chaudhary et al., 2025). Lignocellulosic biomass derived from rice straw, bagasse, corncobs, banana stalks, rice husks, pineapple fiber, and wood residues contains cellulose, hemicellulose, and lignin as the main components. Cellulose can be converted into nanocellulose, such as cellulose nanofibers (CNF) and cellulose nanocrystals (CNC), which act as reinforcements in biopolymer composites (Paudel et al. 2026). The addition of nanocellulose has been reported to increase the tensile strength, improve the barrier properties, and enhance the thermal stability of packaging materials. Furthermore, lignin can act as a natural antioxidant and absorb ultraviolet light, thus supporting the protective function of food packaging (Padhi et al., 2023); Kossalbayev et al., 2025).

Fruit and vegetable waste, such as banana peels, orange peels, apple peels, pomegranate peels, grape skins, purple cabbage, tomato, and mango waste, are sources of pectin, anthocyanins, and polyphenols. Pectin can be used as a biodegradable film matrix, whereas anthocyanins have a unique role as pH indicators because their color changes can represent changes in food conditions in real time. The combination of pectin, natural pigments, and bioactive compounds makes horticultural waste an important ingredient in the development of smart colorimetric packaging or color-indicator-based smart packaging capable of providing visual signals of food freshness or spoilage (Remedio & Parada Quinayá, 2024; Said & Lee, 2025).

Plant proteins from wheat, wheat gluten, and soy protein have good oxygen barrier properties but low water resistance; therefore, they need to be combined with polysaccharides or lipids (Abdullah et al., 2022; Asrafali et al., 2026). Bioactive plant compounds, such as essential oils, curcumin, and polyphenols, provide antimicrobial, antioxidant, and color indicator functions that are incorporated into biopolymer matrices for active and smart packaging (Halonen et al., 2020); Abdullah et al., 2022).

Overall, the use of agroecosystem waste as a source of smart biopackaging shows great potential in supporting the development of sustainable food packaging. However, each biomass type has distinct characteristics, advantages, and limitations. Material selection therefore needs to be followed by formulation and modification suited to the specific feedstock, together with evaluation of mechanical and barrier performance, food-contact safety, and biodegradability. An environmentally friendly origin is important, but the final material must also perform reliably as food packaging.

3.2. Smart Biopackaging Development: Agroecosystem-Based Active and Intelligent Packaging

The two main pillars in the development of agroecosystem based smart biopackaging are active and intelligent packaging. Although both utilize the same biopolymer matrix from agro industrial waste, they have opposing yet complementary functional directions and interaction mechanisms. Active packaging is intended to act on the food or its surrounding environment to slow quality deterioration, whereas intelligent packaging communicates information about product condition. Combining these functions increases the usefulness of the package while creating an additional route for valorizing agro-industrial residues.

3.2.1. Active Functions in Agro-Ecosystem-Based Smart Biopackaging

The development of active functions in smart biopackaging aims to maintain and sustain the quality of food products dynamically through antimicrobial, antioxidant, oxygen scavenger, moisture regulator, and inhibition of undesirable volatile compound formation. This agroecosystem-based active packaging system utilizes natural polymers, such as starch, chitosan, alginate, or carrageenan, as a carrier matrix for natural antimicrobial and antioxidant agents. The functional mechanism of this system relies on the biological activity of phytochemical compounds, including polyphenols, flavonoids, essential oils, and antimicrobial peptides (Said & Lee, 2025). When these active components are integrated into the biopolymer matrix, packaging can

interact in a controlled manner with the food microenvironment to slow the rate of microbiological deterioration and oxidative damage (Halonen et al., 2020; Abdullah et al., 2022).

Table 1. Sources of Biopolymer Raw Materials From Agroecosystem Waste

Raw Material Sources	Agricultural Waste Source	Bioactive Constituents	Role in Smart Biopackaging
starch (Fatima et al., 2024)	Cassava, corn, potato, sago, rice, tuber waste	starch	Starch Forms a biodegradable film; thermoplastic properties after processing with plasticizer; abundantly available and low cost
Lignocellulosic biomass (Padhi et al., 2023) (Mehdizadeh et al., 2026)	Rice straw, bagasse, corn cobs, banana stalks, husks, pineapple fiber, wood residue	Cellulose, hemicellulose, lignin; can be converted into cellulose nanofiber (CNF) and cellulose nanocrystal (CNC)	Nanocellulose functions as a composite reinforcement; increases mechanical strength, barrier properties, and thermal stability; lignin acts as a natural antioxidant and UV absorber.
Fruit and vegetable waste (Remedio & Parada Quinayá, 2024)	Banana peel, orange peel, mango peel, apple peel, pomegranate peel, grape peel, purple cabbage, tomato waste	. Pectin, fiber, flavonoids, anthocyanins, polyphenols, organic acids	Pectin as a biodegradable film matrix; anthocyanin as a pH and color indicator, a combination of pectin, natural pigments and bioactive compounds
Vegetable protein (Abdullah et al., 2022),(Asrafali et al., 2026)	corn, wheat, soybeans, nuts and seeds	Plant protein with film-forming ability	Good oxygen barrier properties; can be combined with polysaccharides, lipids, nanofillers, or active compounds to improve packaging stability and function; composite films produce better mechanical, optical, and barrier characteristics
Bioactive compounds of plants (Halonen et al., 2020), (Abdullah et al., 2022)	Essential oil, leaf extract, spice extract, tannin, catechin, curcumin, anthocyanin, chlorophyll, polyphenol	Antimicrobial compounds, antioxidants, and natural pigments	Incorporated into biopolymer matrices for active packaging (antimicrobial/antioxidant) and smart packaging (color indicators); extends shelf life and monitors food quality; strengthens sustainability value

Antimicrobial activity in active packaging can be achieved through the integration of bioactive compounds, such as essential oils, spice extracts, leaf extracts, chitosan, or specific phenolic compounds. The mechanism of antimicrobial inhibition is closely related to the induction of damage to the target microbial cell membrane, disruption of intracellular permeability, inhibition of essential enzyme activity, and increased oxidative stress in pathogenic cells. In biopolymer-based materials, antimicrobial effectiveness is greatly influenced by the concentration of the active ingredient used, compatibility between the components and matrix, controlled release rate of the active compound, and intrinsic characteristics of the packaged food product (Hanan et al., 2024; Abdullah et al., 2022 ;Asrafali et al., 2026).

On the other hand, the antioxidant function in smart biopackaging can be obtained from polyphenols, flavonoids, tannins, lignin, curcumin, anthocyanins, and extracts from fruits and spices. The application of these antioxidant properties is crucial for inhibiting lipid oxidation, color degradation, off-flavor deterioration, and nutritional value reduction. This is particularly useful for food products containing high levels of fat, such as meat, fish, cooking oil, and similarly processed foods (Figure 1). Furthermore, the use of natural antioxidants sourced from agricultural waste not only provides functional protection to food but also supports waste valorization programs towards realizing the concept of developing environmentally friendly, sustainable food packaging (Halonen et al., 2020 ; Abdullah et al., 2022; Mehdizadeh et al., 2026).

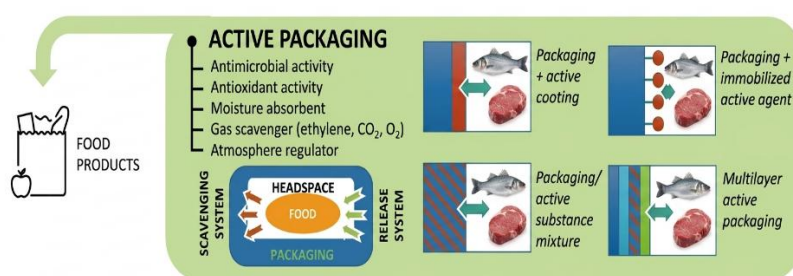


Figure 1. Active Packaging Mechanism (Versino et al., 2023)

3.2.2. Smart Functions in Agroecosystem-Based Smart Biopackaging

Smart functions in biopolymer-based packaging systems (smart biopackaging) are shifting from the use of synthetic indicators to agroecosystem-based functional materials (Halonen et al., 2020). The integration of active compound components as sensory agents into the packaging matrix offers advantages such as non-destructive properties, high biocompatibility, and safety in direct contact with food products (food-grade material). The use of agricultural waste from local commodities as raw material for smart indicators not only increases the economic value of agroecosystem products but also serves as a crucial pillar in realizing the concept of sustainable food logistics (Ligarda-Samanez et al., 2025; Tabassum et al., 2023).

Smart functions provide information on food conditions and storage environments (Figure 2). One of the most widely developed approaches involves pH-based color indicators using natural pigments, particularly anthocyanins. Anthocyanins from purple cabbage, purple sweet potato, roselle, grape skin, blueberries, and black rice can change color under acidic, neutral, and alkaline conditions, making them potentially useful for monitoring the freshness of fish, meat, shrimp, and other perishable foods (Halonen et al., 2020; Remedio & Parada Quinayá, 2024).

Furthermore, anthocyanin-based pH indicators function because the spoilage of high-protein foods often produces volatile base compounds such as biogenic amines and total volatile basic nitrogen, which alter the pH of the packaging microenvironment. This pH change triggers changes in the chemical structure of anthocyanins, resulting in a visually observable color change. The advantages of these indicators are their non-destructive nature, ease of reading, and ability to be developed from natural pigments derived from agroecosystems (Remedio & Parada Quinayá, 2024; Tabassum et al., 2023). In addition to anthocyanins, curcumin, betalains, chlorophyll, and other phenolic pigments can be used as smart indicators. However, the stability of natural pigments remains a challenge because they can be affected by light, oxygen, temperature, humidity, pH extremes, and interactions with polymer matrices. Strategies such as encapsulation, immobilization, multilayer films, the use of nanofillers, and the selection of appropriate biopolymer matrices are required to maintain the sensitivity and stability of indicators during storage (Halonen et al., 2020; Remedio & Parada Quinayá, 2024 ; Said & Lee, 2025).



Figure 2. Intelligent Packaging Mechanism (Versino et al., 2023)

3.3. Contribution to Sustainability

Sustainable agroecosystems play a crucial role in accelerating the transition from a linear to a bio based circular economy. This is achieved by utilizing crop waste as the primary raw material to create environmentally friendly smart packaging (smart biopackaging). Through integrated natural waste processing technology, agricultural waste that is typically discarded or incinerated can now be recycled into high-value natural polymers, such as cellulose, starch, pectin, lignin, chitosan, alginate, and PHA. The process of converting waste from worthless materials into valuable products can increase the added value of agricultural produce and help boost local farmers' income. This waste utilization has also successfully built a close and mutually supportive chain of work between the upstream agricultural sector and the downstream smart packaging industry (Guillard et al., 2018).

Smart biopackaging can also reduce food loss and waste by extending shelf life and directly monitoring product freshness. On the one hand, active packaging components work to slow bacterial growth and the rancidity (oxidation) process. However, smart packaging features can provide visual signals such as color changes when food quality begins to decline. In this way, bio-based packaging not only successfully reduces dependence on fossil fuel-based plastics but also effectively increases the efficiency of the food system as a whole (Halonen et al., 2020; Abdullah et al., 2022).

3.4. Technical and Implementation Challenges

One of the primary challenges in developing agroecosystem-based smart biopackaging is the inherent variability of agricultural raw materials. The composition and functional properties of biomass-derived materials are strongly influenced by plant species, cultivar, growing season, geographical origin, cultivation practices, maturity at harvest, postharvest handling, and storage conditions. Variations in starch, cellulose, hemicellulose, lignin, pectin, protein, and bioactive compound contents can consequently produce inconsistent film-forming ability, mechanical strength, barrier performance, optical properties, and indicator sensitivity (Padhi et al., 2023; Fatima et al., 2024; Mehdizadeh et al., 2026).

Seasonal variability affects different agricultural raw materials in distinct ways because changes in rainfall, temperature, solar exposure, maturity, and postharvest conditions can alter their chemical composition and functional properties (Kossalbayev et al., 2025; Selvam et al., 2025).

In starch rich residues such as cassava and other tuber processing byproducts, variation may occur in starch yield, the amylose to amylopectin ratio, granule morphology, moisture content, and gelatinization characteristics. These differences can translate into changes in film formation, flexibility, tensile strength, thermal behavior, and sensitivity to water and humidity (Fatima et al., 2024; Dirpan et al., 2023).

Lignocellulosic residues show a different pattern. In oil palm empty fruit bunches, rice straw, corn residues, and related crop by-products, growing season and plant maturity may influence cellulose crystallinity, fiber dimensions, lignin content, surface impurities, and reinforcement efficiency (Padhi et al., 2023; Sharma et al., 2025; Mehdizadeh et al., 2026). Consequently, fiber-matrix compatibility, mechanical strength, film opacity, dimensional stability, and barrier performance may differ between feedstock batches (Tabassum et al., 2023; Kossalbayev et al., 2025).

Horticultural residues are particularly sensitive to raw-material variability because their pectin, phenolic compounds, organic acids, and natural pigments change with cultivar, ripening stage, environmental conditions, and storage history (Carnaval et al., 2024; Said & Lee, 2025). A film prepared from fruit residues may therefore show different antioxidant capacity, film-forming behavior, color intensity, pH response, or freshness-indicating performance even when the same general type of biomass is used (Remedio & Parada

Quinayá, 2024; Said & Lee, 2025; Asrafali et al., 2026). The comparison across feedstock groups is useful: starch-rich materials tend to vary most in film formation and moisture response, lignocellulosic residues in structural reinforcement, and pectin- or pigment-rich fruit wastes in active and intelligent packaging functions.

Performance relative to conventional synthetic plastics remains another practical limitation. Films based on starch, pectin, and proteins are generally hydrophilic, so they often show high water-vapor permeability and reduced stability under humid conditions. To compensate for these weaknesses, studies have used polymer blending, composite formation, multilayer structures, emulsion incorporation, molecular crosslinking, and nanoscale fillers such as nanocellulose and lignin nanoparticles (Abdullah et al., 2022; Padhi et al., 2023; Remedio & Parada Quinayá, 2024). The effectiveness of these modifications still depends on the composition and purity of the starting biomass. This makes pretreatment, raw-material specifications, and quality control important parts of any scale-up strategy.

The functional ingredients themselves also create stability problems. Essential oils can be lost through volatilization, polyphenols are prone to oxidation, and anthocyanins can fade or degrade during exposure to light, elevated temperature, oxygen, or extreme pH. For this reason, smart biopackaging formulation has to account for the way an active compound interacts with the polymer matrix. Encapsulation, controlled-release design, and careful adjustment of indicator sensitivity may be needed, together with migration assessment to ensure that incorporated substances do not compromise the packaged food (Halonen et al., 2020; Said & Lee, 2025).

Moving from laboratory experiments to commercial use introduces a different set of constraints. Production cost, process reproducibility, industrial scalability, and regulatory compliance remain unresolved in many studies, which are still based on small-scale preparation. Pilot production, manufacturing trials, real-food applications, and storage studies are therefore needed before broader implementation. Packaging systems that contain active compounds or indicators must also meet food-contact requirements through migration and toxicity assessment, stability testing, biodegradability verification, and consumer acceptance (Abdullah et al., 2022; Mehdizadeh et al., 2026). Addressing these challenges will require standardized biomass grading, seasonal raw material monitoring, adaptable processing conditions, and closer collaboration among researchers, biomass suppliers, packaging manufacturers, food industries, and regulatory authorities.

4. CONCLUSIONS

The literature reviewed here indicates that agroecosystem residues can help address two linked problems: dependence on conventional plastic packaging and the low-value disposal of agricultural by-products. Starch rich residues, lignocellulosic biomass, plant proteins, and horticultural wastes can be converted into packaging matrices or functional components, while active and intelligent elements add preservation and freshness-monitoring functions. The evidence also shows that technical feasibility at laboratory scale does not automatically translate into commercial readiness. Wider use will require consistent biomass specifications, clear food-contact regulations, appropriate financial support, and stronger investment in scalable production and integrated supply chains. Future work should prioritize material performance and validation with real foods under realistic storage conditions so that agroecosystem-based smart biopackaging can move from experimental formulations toward dependable commercial packaging.

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