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Bio-waste Alchemy: Turning Agricultural Residue into Green Gold for Food Packaging, A Systematic Review

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Abstract. *The increasing environmental concerns associated with conventional plastic packaging have accelerated the global pursuit of sustainable alternatives. This review explored the innovative transformation of agricultural waste into eco-friendly food packaging materials, highlighting its potential to address both ecological and economic challenges. Agricultural residues—such as cereal by-products, sugar and starch crop wastes, fruit processing leftovers, and leaf waste—were rich in biopolymers like cellulose, starch, and pectin, making them suitable candidates for biodegradable packaging. Through advancements in green chemistry, biotechnology, and materials science, these wastes are now being repurposed into high-performance, compostable packaging solutions. Relevant literature was selected through a systematic search of peer-reviewed journal articles from databases such as Scopus, ScienceDirect, and Google Scholar, focusing on publications from the last five years that addressed agricultural waste utilization in ecofriendly food packaging. The review synthesizes recent research and technological breakthroughs in this field, showcasing applications ranging from rice husk-based films to cassava starch bioplastics. Furthermore, it examines the environmental benefits of reduced plastic pollution and landfill burden, alongside the economic advantages of waste valorization, rural job creation, and market competitiveness. By turning agricultural residues into valuable resources, this approach supports circular economy principles, enhances food system sustainability, and paves the way for a greener packaging industry.*

Keywords: *Agricultural waste, biodegradable packaging, bioplastics, sustainable food packaging, eco-friendly materials.*

1. Introduction

The world is moving toward sustainable alternative due to the growing concern over environmental degradation and the over-reliance on fossil-based plastics. Conventional plastic packaging has been widely used in several industries including food industry because of its properties such as durability, lightweight nature, and low cost and environmentally friendly (Maurizzi *et al.*, 2022). On the other hand, plastic packaging also brings a serious threat to the environmental as a result of its non-biodegradable nature which means that it can accumulate the

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environment for years that lead to land, water and marine pollution (Abimbola *et al*., 2024; Pilapitiya & Ratnayake, 2024). Moreover, the production of conventional plastics that relies majorly on finite, non-renewable fossil fuels also causes issues related to overconsumption of resource and greenhouse gas emissions (Tilsted *et al*., 2023). As a result of growing public awareness toward the environmental consequences of non-biodegradable plastics packaging, numerous studies have been conducted to seek out sustainable packaging alternatives (Altenburger *et al*., 2024). The development and adoption of materials that are both biodegradable and derived from abundant sources offer an environmentally responsible solution without compromising functionality or safety (Jha *et al*., 2024).

One of the most potential strategies in the quest for sustainable materials is the application of agricultural waste as a raw material for eco-friendly packaging because it can be degraded naturally (Varžinskas & Markevičiūtė, 2020). Globally, millions of tons of agricultural waste are produced every years leads to significant environmental and economic challenges (Riseh *et al*., 2024). However, this waste is not merely a major issue due to it represents a valuable resource that can be harnessed through innovative processing technologies. Agricultural waste is rich in valuable compounds such as starches, proteins, pectin, cellulose, and fibers that can be utilized as source of raw materials that can be transformed into biodegradable and sustainable packaging alternatives (Carvalho *et al*., 2025; Hossain *et al*., 2024). Agro-waste can be converted into high performance materials through the application of innovative processing technologies that are not only reducing our reliance on petroleum-based plastics but also contribute to a circular economy (Rosenboom *et al*., 2022). This approach not only addresses the urgent need for sustainable packaging but also promotes the responsible management of food systems and resources. Current advancements in green chemistry, biotechnology, and materials science have significantly accelerated the development of sustainable packaging solutions generated from agricultural waste (Oboturova *et al*., 2024). These innovations have created new opportunities for transforming several kinds of organic residues such as fruit peels, vegetable scraps, shellfishes waste into biodegradable, compostable, and functional packaging materials (Carnaval *et al*., 2024).

This review aims to comprehensively examine cutting-edge development and emerging technologies in the processing and conversion of agricultural waste for packaging applications. It examines how different scientific approaches are being applied for extraction of valuable biopolymers from waste and reapply them into high-performance packaging alternatives. In addition, in order to highlighting the latest trends in research and development, the review also addresses the technological, environment, and economic benefits adoption of these materials.

2. Materials and Methods

This review was based on a comprehensive literature search through several scientific databases such as Springer, Science Direct, Google Scholar, MDPI, and Web of Science. While ResearchGate was also used as a supplementary platform to access full-text version of already identified articles. Keywords including "agricultural waste," "biodegradable materials from agricultural waste," "eco-friendly packaging," and "sustainable packaging innovation", “food packaging technologies,” “circular economy biodegradable packing,” “environment effect of bio packings” were used. Relevant studies from the past five years (2020–2025) of 83 articles were selected in order to ensure updated insight, with data extracted and synthesized thematically to highlight key findings and research gaps. The literature selection was guided by the PRISMA approach, including stages of identification, screening, eligibility, and inclusion. The selected studies were then thematically analyzed to explore current applications of residues, material development methods, performance characteristics, environmental advantages, and remaining research challenges.

3. Results and Discussion

3.1 Trends in Agricultural Waste-Based Materials for Food Packaging

Over the past few years, a notable rise occurred in scientific interest and research efforts focused on the utilization of agricultural waste into sustainable packaging materials. The availability of raw materials for these environmentally friendly packing is wide and diverse. Mostly, agricultural waste (as shown in Figure 1) can be found in the nature are fruit peels, cereal and grain by products, sugar and starch crops residues, leaves, nuts and shells waste. These agricultural waste materials are generally rich in valuable biopolymers such as starch, pectin, cellulose, and proteins, which are valuable for preparation sustainable packaging materials.

3.1.1 Cereal and Grain By-products

Cereal and grain by-products are majorly generated in large quantities from the processing of crops such as rice, wheat, and corn. Rice (*Oryza sativa*) was an essential staple crop grown globally for feeding more than half of the world’s population, especially in Asia and parts of Africa and Latin America (Mohidem *et al*., 2022). It is mainly cultivated in waterlogged rice fields, and it produces a range of agricultural residues during corps collection and processing, such as rice husk, bran, straw, and broken grains (Bajsic *et al*., 2021). These by-products, often discarded or used for low-value purposes, are increasingly recognized for their potential as raw materials in sustainable packaging due to their high cellulose, lignin, and silica content (Sutama *et al*., 2025).

Various studies have been conducted regarding the utilization Rice crop by-products, Bajsic (2021) has investigated the application of rice husk (RH) enhanced with low-density polyethylene (LDPE) in order to generate biocomposite films, the study revealed moderate flexibility of films with tensile strength of 10.56 MPa and elongation at break of 35.48% at low relative humidity. While water vapor permeability increased from 4.65 to 20.45 g/m²·day at higher RH due to filler clumping, the films showed partial biodegradability properties in which it took 21 days to degrade. Moreover, these films effectively kept fruit freshness and offer a promising solution for short-term food packaging applications with lower plastic dependency. Similarly, Nwanna (2024) has also examined the potential of cellulose nano-crystals (CNC) rice husk combined with gelatin/carboxyl methyl cellulose (CMC) as edible food wrappings. The composite film showed good flexibility showed stretch capacity of 68.68% and mechanical strength up to 7.70 MPa, along with enhanced water resistance with total dissolved solids from 72% to 65%. Even though the material remains hydrophilic, its uniform structure and promising biodegradability reinforce its strong potential as a natural and compostable food packaging.

Figure 1. Types of Agricultural Waste (Riseh, 2024)

In line with this, nanocellulose from rice husk reinforced polyvinyl alcohol (PVA) also exhibited potential for biodegradable films for food packaging (Cholant *et al*., 2025). This study successfully developed PVA-based films reinforced with nanocellulose extracted from rice husk with potential mechanical properties (tensile strength 295.45%), while the films stayed as flexible as regular PVA. These materials also exhibited low water vapor permeability and solubility, indicating improved resistance to water penetration. Additionally, the films showed extended degradation resistance, remaining stable for over 45 days in biodegradability testing, confirming their strong potential as durable, eco-friendly packaging alternatives. Moreover, rice husk extract can also integrated with other waste such potato peels to synthesize food packaging bioplastics as investigated by (Azmin *et al*., 2024) demonstrating promising flexibility with an elongation at break of 24.3% influenced by the optimized ratio of glycerol and silica. The films also showed moderate water resistance with a moisture content of 31.22% and a thickness of 1.87 mm. Although further refinement is needed to improve uniformity, the biodegradable nature of the materials and their renewable origin underscore their potential as eco-friendly packaging solutions derived from agricultural waste.

Wheat (*Triticum aestivum* L.), a member of the Poaceae family, stood as one of the world's most essential cereal crops, particularly cultivated across temperate regions. As a staple for roughly 35% of the global population, wheat plays a central role in food security, with the majority of its production—over two-thirds—dedicated to human consumption and a smaller portion utilized for animal feed. Its nutritional profile, dominated by 75–80% carbohydrates and 9–18% protein, also includes dietary fiber, B vitamins, and key minerals such as calcium and iron, making it a significant source of energy and nutrition. In the global market, wheat is a major traded commodity, with an estimated 150 million of tones exchanged annually, underscoring its economic and agricultural importance worldwide (Ammar *et al.*, 2023; Deepthi & Ranjith, 2023; Khalid *et al.*, 2023). The processing of wheat for flour and other products produce significant agricultural residues such as wheat bran, husk, straw, and germ, which categorize as valuable material for sustainable and eco-friendly food packaging materials (Danciu *et al.*, 2023).

Several researches focused on the utilization of wheat-based residues. According Sharma *et al.* (2025), wheat strew showed potential as ecofriendly alternative for paper based packaging materials coffee pods processed using a disc refiner and further enzymatically treated through surface esterification. Prepared packaging materials revealed tensile index of 15.8 N·m/g and sheet density of 363 kg/m³, while enzymatic modification reduced water spread by up to 51%, indicating good moisture resistance. Wheat bran is also capable for production bio films such an investigation conducted by Deepthi and Ranjith (2023), synthesized from wheat straw using acid-alkali bleaching and sorbitol-gelatin blending via controlled heating demonstrated good mechanical integrity and biodegradability. These films achieved promising tensile strength (25.6 Pa), flexible elongation at break (18.3%), as well as solubility and swelling index values of 20% and 25%, respectively. Degradation study showed that these films losing 85% of their weight within two weeks of burial conditions. Furthermore, Yilmaz-Turan *et al.* (2020) has also investigated the application of wheat based waste as packaging materials that revealed bio film based wheat bran developed from wheat straw demonstrated good flexibility and mechanical strength, which were further enhanced by the incorporation of sorbitol and gelatin as natural plasticizers has high tensile strength and elongation break. Other application of wheat straw residues was also done by Hagel and Schütt (2024) through study waste paper based packaging enhancing with sodium carbonate. The films showed tensile strength up to 30%, making them suitable for packaging.

Table 1. Summary of Studies on Cereal and Grain Based Waste as Packaging Materials

Study	Raw Materials	Method	Flexibility	Water Resistance	Mechanical Properties	Limitations / Challenges	Industrial Application Potential
Sharma *et al.* (2025)	Wheat straw	Disc refining, Enzymatic esterification	Moderate	Good (reduced water spread 51%)	Tensile index 15.8 N.m/g; density 363 kg/m³	Coarse material affects sheet quality	Suitable for paper-based packaging (e.g., coffee pods)
Deepthi and Ranjith (2023)	Wheat straw	Acid alkali bleaching, casting	High (EB 18.3%)	Moderate (Swelling 25%)	Tensile strength 25.6 Pa	Limited thickness control	Biodegradable biofilms for packaging
Yilmaz-Turan *et al.* (2020)	Wheat bran, Sorbitol and gelatin	Film formation using plasticizer	Good	Not specified	Improved TS and EB	Needs optimization for shelf-life stability	Bio-based flexible packaging
Hagel and Schütt (2024)	Wheat straw, Recycled paper	Sodium carbonate pulping	Moderate	Moderate	Tensile strength increased up to 30%	High treatment may reduce paper strength	Reinforced paper packaging
Singh *et al.* (2025)	Corn husk, Starch, Neem, Glycerol	Surface coating via fluidized bed drying	High (EB 26%)	Good (54% lower absorption)	TS ≈ 4.9 MPa	Requires coating uniformity	Flexible antimicrobial packaging
Torres-Vargas *et al.* (2025)	Corn starch, Alginate, CCNC (from husks)	Casting, Controlled drying	Moderate (EB ~19.8%)	Excellent (WVP reduced 30%)	TS up to 8.25 MPa	Extraction process complexity	High barrier food packaging
Iheanacho *et al.* (2024)	Corn starch, Glycerol	Casting, Gelatinization, Drying	Moderate (EB 24%)	Low absorption	TS ≈ 2.58 MPa; thickness ~1.4 mm	Biodegradability affected by formulation	Low cost flexible packaging
Kowser *et al.* (2025)	Corn starch, Silver	Blending, Heating, Molding	Good	Decreased water absorbency	Moderate tensile strength good antimicrobial	Requires safe silver levels	Antimicrobial food contact packaging
Duan *et al.* (2024)	Corn stover, Gelatin, Beeswax	Casting method	Good	Moderate; waterproof if beeswax <9%	TS up to 9.2%; smooth surface	Manual process affects consistency	Agricultural product packaging
Bajsic (2021)	Rice husk, LDPE	Melt blending	Moderate (EB 35.48%)	Moderate (WVP ↑ with RH)	TS ≈ 10.56 MPa	Filler clumping at high RH	Short-term fruit packaging
Nwanna (2024)	Rice husk CNC, Gelatin/CMC	Casting	High (EB 68.68%)	Improved (TDS from 72% to 65%)	TS ≈ 7.70 MPa	Remains hydrophilic	Edible compostable food wraps
Cholant *et al.* (2025)	Rice husk nanocellulose, PVA	Film casting	Similar to PVA	Low WVP and solubility	TS ↑ 295.45% compared to base PVA	Extended degradation time	Durable ecofriendly food packaging
Azmin *et al.* (2024)	Rice husk, Potato peel, Glycerol/silica	Casting	Good (EB 24.3%)	Moderate (moisture 31.22%)	Thickness ≈ 1.87 mm	Requires better uniformity	Agricultural waste based packaging

Table 2. Summary of Studies on Sugarcane and Strach Based Waste as Raw Materials for Packaging

Study	Raw Materials	Method	Flexibility	Water Resistance	Mechanical Properties	Limitations / Challenges	Industrial Application Potential
Indarti *et al.* (2021)	Sugarcane bagasse	Fermentation, molded, incubated, dried	Good lightweight and flexible	Not tested	Not reported	Structural durability and moisture resistance need validation	Suitable for low-load single-use applications
Junior *et al.* (2024)	Sugarcane bagasse (SCB), Bacterial cellulose (BC)	High-speed shredding, screen casting, natural drying	Foldable 100× without tearing	Water retention >97%	Strong tear resistance, Good durability	Uniformity and processing optimization required for mass production	Suitable for scalable, durable eco packaging
Azmin *et al.* (2020)	Sugarcane bagasse, Cocoa pod husk	Heating and casting, controlled drying	Optimal at 75:25 ratio	Water absorption: 38.7%	Not detailed	Mechanical strength and long-term water stability not fully established	Good for dry food packaging
Alirach *et al.* (2024)	Sugarcane bagasse, starch	Pulping, calendaring, pressing, drying	Rigid and formable sheets	Absorption: 156%, Wetting resistance: ISO 2	Strip: 25.3 kgf; Tear: 0.34 kgf; Burst: 2.39 kg/cm²; Stiffness: 11 kgf	High moisture uptake may limit use in high-humidity environments	Potential for reusable shopping or retail bags
Pensahan *et al.* (2025)	Cassava peel starch, Sugarcane bagasse cellulose	Gelatinization, homogenization, oven drying	Elongation at break: 22.69%	Not tested	Tensile strength: 1.4 MPa; Peak force: 17.27 N	Water vapor permeability and biodegradability need further evaluation	Promising for food packaging applications
Mamiru *et al.* (2024)	Cassava starch	Casting method, glycerol plasticizer, controlled drying	High flexibility (EAB 62%)	Lower solubility (17.4%)	Tensile strength 1.67 MPa	Variation in variety performance; balance of properties needed	Suitable for moisture- and dry-sensitive foods
Raj *et al.* (2024)	Cassava starch, Fish gelatin, CEON	Casting technique, nano emulsion incorporation	Elongation at break 270.5%	Moisture controlled	Tensile strength: 20.15 MPa; thickness: 0.19 mm	Complex preparation and optimization of ingredient ratios	Good for perishable foods with bioactivity needs
Arias *et al.* (2024)	Cassava, Potato starch	Casting method with sorbitol plasticizer	Strong structurally sound sheets	Low WVP: 4–6 g.mm/m²	Tensile strength up to 32.6 MPa, moderate solubility: 10–15%	Thermal degradation resistance needs improvement	Suitable for film wraps and lids

Corn (*Zea mays*), otherwise known as maize, was a versatile cereal crop widely cultivated for food, animal feed, as well as industrial purposes, particularly in the Americas, Asia, and Africa (Akpan *et al.*, 2024; Bolatova & Engindeniz, 2023). Its processing leads various by-products such as corn husks, cobs, stalks, and bran, which are often neglected despite their high lignocellulosic and starch content (Heppner & Livney, 2025; Purnomo & Setyaningrum, 2025; Wang *et al*., 2024). These residues have been identified a promising potential for biodegradable packaging materials, as numerous studies have explored the utilization of corn wastes for eco-friendly packaging.

Corn husk waste can be treated with other materials to enhance its properties as investigated by Singh *et al*. (2025), who synthesis antimicrobial and flexible biodegradable films for food packaging through surface coating using a starch-based solution enriched with neem flower extract and glycerol via fluidized bed drying. The mechanicals properties test revelaed that such materials possess elongation break at 26%, tensile strength of ~4.9 MPa, and reduced water absorption around 54%. Similarly, the production of biodegradable films from corn starch-based biocomposite reinforce with cellulosic nanocrystals isolated from corn husk (CCNC) is also studied by Torres-Vargas *et al*. (2025). Biocomposite films were designed with the help of casting method followed by controlled drying demonstrated tensile strength up to 8.25 Mpa, elongation break at 19.81%, as well as vapor permeability by up to 30%, confirming their improved barrier performance and biodegradability, making them a promising and sustainable option for food packaging applications. Furthermore, the potential of corn waste as biodegradable plastic packaging has also explored by Iheanacho *et al*. (2024) fabricating packaging materials using the casting method, where a mixture of starch powder, water, and glycerol was heated until gelatinization and then oven-dried to form films. The resulting material demonstrated a good balance of tensile strength at around 2.58 MPa, flexibility with elongation at break of 24%, and film thickness of approximately 1.4 mm, indicating its potential for flexible and durable packaging, low moisture absorption and complete biodegradability within several weeks.

Another investigation by Kowser *et al*. (2025) revealed that silver combined with corn starch based bioplastics offer opportunities as an effective, eco-friendly to petroleum-based plastic for food packaging. Bioplastic films that were formulated through blending, controlled heating, and molding, conveying materials with favorable flexibility, biodegradability, antimicrobial activities especially *E. coli* and *S. aureus*, along with decreased water absorbency and improved soil degradation, indicating nice resistance to moisture while maintaining environmental safety. Other type of corn residues, corn stover is also valuable raw material for bioplastics generated using a simple casting method. The obtained films showed promising flexibility and moderate tensile strength (up to 9.2%), maintaining surface uniformity at levels below 9%. Despite slight inconsistencies in tensile testing due to manual methods, the biofilm's performance in packaging trials demonstrated good durability, biodegradability, and surface appearance, confirming its potential for eco-friendly agricultural product packaging (Duan *et al*., 2024). The utilization of cereal and grain by-products (as shown in Table 1) not only play crucial roles in manufacturing renewable, biodegradable, and often available at low-cost food packaging materials, but also shows contribution to sustainability goals by minimizing reliance on petroleum-based plastics and enhancing the life cycle of agricultural production.

3.1.2 Sugar and Starch Crop Residues

Sugar and starch-rich crop wastes are highly potential for the development of eco-friendly packaging materials. Residues from crops such as sugarcane and cassava are abundant in starches, cellulose, and lignin which are key components that can be employed in the formation of eco-friendly packaging such as biodegradable films and bioplastics. Sugarcane (*Saccharum officinarum*) is a tropical grass cultivated primarily for its high sucrose content, which is widely used in the production of white sugar (Greeshma *et al*., 2024; Mudassar *et al*., 2024). However, its fibrous by-products such as bagasse, generated during juice extraction, pose a significant agro-industrial residue (Brown *et al*., 2025; Indrawati *et al*., 2024). Bagasse, rich in cellulose, hemicellulose, and lignin, has emerged as a valuable raw material for the development of biodegradable food packaging due to its film-forming ability and mechanical strength (Melesse *et al*., 2022; Wang *et al*., 2024). These components allow for the creation of eco-friendly packaging alternatives that can reduce reliance on petroleum-based plastics (Stroescu *et al*., 2024).

As a sustainable packaging material, sugarcane-derived bioplastics and paper-like films are increasingly used in the food industry for containers, trays, biofoam, and wraps, offering both functional performance and environmental benefits (Palanisamy *et al*., 2024; Zafeer *et al*., 2023). Indarti *et al*. (2021) has conducted study the application of sugarcane bagasse combined with coconut fiber combined with commercial mold to manufacture bio foam cup as solution for using plastic or Styrofoam trough fermentation method facilitated by *Rhizopus sp.* as a natural binder. The mycelium-based process produced a lightweight, flexible, and compostable material, offering an eco-friendly alternative to packaging although further testing is needed to investigate structural durability and moisture resistance. Similarly, sugarcane bagasse also capable for producing biodegradable polymers as investigated by Junior *et al*. (2024), these residues is reinforced with bacterial cellulose (BC) using a sustainable method involving high-speed shredding of BC, uniform blending with SCB, and reconstitution via screen-casting followed by natural drying. This process generated a flexible, durable composite with excellent tear resistance (can be fold 100 times without tearing) and water retention capacity which is higher than 97% make these materials suitable for environmentally friendly packaging.

Biodegradable plastic film can also produce by sugarcane waste enhancing with other type of agro waste, cocoa pod husk as investigation done by Azmin *et al*. (2020) that showed such material suitable for food packaging. Bioplastic films developed from cocoa pod husk (CPH) cellulose and sugarcane bagasse fiber were synthesized using a simple heating and casting method, followed by controlled drying. The optimal 75:25 cellulose: fiber blend demonstrated good flexibility, reduced water absorption (38.7%), and improved barrier properties, making it has good potential for food packaging applications. Furthermore, another application of sugarcane waste as bio bags has explored by Alirach *et al.* (2024) which developed from sugarcane bagasse produced through a controlled pulping and calendaring process, with starch and resin used to increase strength and moisture performance. The prepared packaging materials revealed strong mechanical performance with a strip strength of 25.3 kgf, tear strength of 0.34 kgf, bursting strength of 2.39 kg/cm², and stiffness of 11 kgf, as well as demonstrated moderate water absorption (156%) and wetting resistance rated ISO 2, indicating good moisture barrier properties.

Cassava (*Manihot esculenta*) is an essential food crop cultivated majorly in tropical and subtropical regions valued for its high adaptability and carbohydrate-rich tubers (Tran *et al*., 2024). Currently, Global interest in cassava cultivation is affected by its versatility in food, feed, and industrial applications as well as bioethanol products (Budu *et al*., 2025). In spite of its functional qualities, mass cassava production discharges significant agricultural residues such as peels, pulp, and fibrous waste (Minaboon *et al*., 2024; Vieira *et al*., 2022). If not managed properly, these by-products which are often discarded or underutilized, can contribute to the environmental challenges.

Latest finding highlights the promising potential of cassava wastes as raw materials for sustainable food packaging. Valuable materials of cassava such as starch and cellulose are capable of being modified into biodegradable films and bioplastics which also plays role as eco-friendly alternative to conventional plastic packaging. Cassava peels starch combined with sugarcane bagasse cellulose can be generated to become bioplastics using gelatinization, homogenization, and oven-drying techniques, with the 50:50 starch-to-cellulose as optimal ratio. This formulation achieved a peak force of 17.27 N, tensile strength of 1.4 MPa, and elongation at break of 22.69%. Although water vapor permeability and biodegradability have not been evaluated yet, the promising strength and flexibility properties and application of agricultural waste highlight this material's strong potential as a sustainable and eco-friendly alternative to conventional plastics (Pensahan *et al*., 2025). Furthermore, the application of cassava starch as edible films has studied by Mamiru *et al.* (2024) through the application two different types of cassava starches using a casting method, incorporating glycerol for flexibility and drying under controlled heat exhibited greater flexibility with elongation at break of 62% and higher water absorption, higher tensile strength at 1.67 MPa , making it more suitable for dry food packaging. Similarly, Raj *et al.* (2024)

has explored the effectiveness of eco-friendly edible films made from cassava starch enhanced with fish gelatin, and cinnamon essential oil nano emulsion (CEON) in extending fish fillet shelf life that is synthesized via a casting technique with optimized formulation at a 1:3 starch-to-gelatin ratio and 10% CEON. These materials exhibited excellent mechanical strength (20.15 MPa), high flexibility (elongation at break 270.5%), and moderate thickness (0.19 mm), as well as strong antioxidant and antimicrobial activity suitable for perishable food packaging.

Starch based films can also generated from the combination off potato and cassava as done by Arias *et al*. (2024) using a simple casting method with sorbitol as plasticizer in order to yield smooth, bubble-free sheets. These films revealed high tensile strength, up to 32.6 MPa, low water vapor permeability, from 4 to 6 g·mm/m^2), and moderate solubility (10–15 g/100 g) which showed their suitability for food packaging lids or wraps. Meanwhile, biodegradability and thermal stability revealed to be Tg above 100°C, potential for packaging. Moreover, Carvalho *et al*. (2025) has conducted a study that highlights the potential of application cassava bagasse, an agro-industrial waste, to develop starch-based biodegradable films with optimized mechanical and water barrier properties, where cassava bagasse content significantly influenced film performance. Apart from their material properties, the utilization of sugar and starch crop residues supports a circular approach to agriculture by converting what would otherwise be waste into valuable packaging solutions. These materials are renewable, compostable, and environmentally friendly. Moreover, their application helps reduce the dependency on fossil-fuel-based plastics, aligning with global sustainability and waste reduction goals. The summary of application sugarcane and starch-based waste is displayed in Table 2.

3.1.3 Fruit Processing Waste

Fruit processing residues such as peels and seeds generated during juice extraction or canning, presents a valuable source of biodegradable materials for sustainable packaging (Gupta *et al*., 2024). These waste materials are rich in natural polymers such as cellulose, pectin, starch, and fibers, which are essential components in the production of bioplastics and edible films (Mayuri & Balaji, 2024; Yaradoddi *et al*., 2022). Application of fruit processing residues for packaging contributes to reducing agricultural waste since it transforms low-value waste into valuable products (Aït-Kaddour *et al*., 2024). This approach in line with global efforts to decrease plastic reliance on plastic as well as promoting the integration of food and packaging industries in developing green, low-cost, and renewable packaging solutions (Pilapitiya & Ratnayake, 2024). With ongoing research and technological improvements, the future of fruit-waste-derived packaging looks promising for both environmental and economic benefits.

Different types of fruit residues have been explored for their potential in packaging innovation. Banana peels could be used as bioplastics which is low-cost and eco-friendly alternative to petroleum plastics as investigated by Hasan *et al*. (2024), bioplastic films developed from banana peel was prepared via hydrolysis and oven-drying demonstrated tensile strength of 0.4086 N/mm² and no visible decay after two months. The use of glycerol as a plasticizer also raised elasticity and processability. Meanwhile, study of water resistance and structural stability is needed to confirm for long-term application. Moreover, mandarin peels had also shown potentialeaf l for food packaging as explored by Yun and Liu (2024), mandarin peel-based sodium alginate films synthesized through casting technique is revealed to be effective active food packaging materials with elongation at break values ranging from 13.37% to 24.62%**,** and tensile strength between 4.87 MPa and 7.90 MPa**,** showing their suitability for lightweight packaging. In terms of water resistance, the films displayed water contact angles between 26.03° and 90.75° and water vapor permeability of 5.38–8.31 × 10^{-11} g/m.s.Pa**,** indicating good moisture barrier properties.

Further investigations on fruit peels, for instance pitahaya (dragon fruit) by Arroyo-Esquivel (2025) and pomegranate by Baniasadi *et al*. (2025), is also revealed potential of these materials for sustainable food packaging applications. Dragon fruit peels-based polymer films were successfully developed using hydrothermal-assisted extraction method followed by the casting technique, with the addition of plasticizers (glycerol, sorbitol, and ethylene glycol). The obtaining films have thicknesses ranging from 0.087 to 0.175 mm, elongation at break between 11.9% and 14.2%, and water vapor permeability measured at 3.938 $\mu g \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$. Thermal analysis showed solid thermal stability, with Tg at 62.4°C and Tm at 131°C. The studied properties highlight the potential of these peels as a promising, eco-friendly raw material for active packaging, particularly in products that benefit from moderate flexibility and moisture control. Moreover, bio-based foam has also established from pomegranate peel via freeze-drying and esterification techniques demonstrating promising structural performance, with high porosity and low thermal conductivity, along with stable thermal regulation properties, including a phase transition around 2 °C and latent heat storage capacity of 65 J/g. This material also revealing antioxidant effectiveness and high antibacterial activity.

Other part of fruit residues such seeds is also hold potential in sustainable packaging. The potential of soursop seed extracts as a sustainable bioplastics source has explored by Gaboto *et al.* (2025), revealing biodegradability, antimicrobial activity, and suitable mechanical properties in which demonstrating the value of agricultural waste in eco-friendly packaging applications. Bioplastic film from soursop seed extract was successfully developed using Soxhlet oil extraction followed by gelatinization with glycerol and controlled drying to form thin, flexible sheets. The resulting material exhibited tensile strength of 3.5 MPa and flexibility of 7.2 mm, with degradation reaching about 75% within 30 days, antimicrobial activities counter to *E. coli* and *S. aureus*. In line with this, mango seed starch-based bioplastics enhanced with CMC, chitosan, and nanochitosan which is synthesized through a method involving gelatinization, casting, and controlled heat drying, with sorbitol used as a plasticizer and citric acid as a cross-linking agent. This packaging exhibited several properties such as good water resistance (water vapor permeability ranged from 2.16×10^{-7} to 6.29×10^{-7} $g\cdot day^{-1}\cdot m^{-1}\cdot Pa^{-1}$), antimicrobial activity toward *P. aeruginosa, E. coli, S. aureus*, making them potential materials for sustainable food packaging applications as done by Joseph *et al.* (2024) in which also aligns with similar finding on the extraction of avocado seed reinforced with nanocahitosan by Suhartini *et al.* (2023) that successfully developed packaging materials via ultrasonic-assisted extraction (UAE), casting method followed by drying at 45°C. The films exhibited several potentials properties such as moderate thickness (0.10–0.15 cm), LC_{50} antioxidant values ranging from 150–250 ppm, promising flexibility**,** biodegradability**,** and moisture resistance that films were able to extend strawberry shelf life for 3–4 days at room temperature.

The valorization of fruit processing waste into sustainable packaging (as displayed in Table 3), supports waste minimization efforts in the agri-food industry while promoting resource efficiency. Utilizing such waste reduces landfill burden and greenhouse gas emissions associated with organic decomposition. Moreover, it provides an added value to fruit processing chains, contributing to a circular economy. As innovations in green chemistry and material science advance, the commercial application of fruit waste-derived packaging is expected to grow, offering eco-friendly alternatives to conventional plastic materials. Although most of these fruit waste-based packaging materials are still in the research stage and made in laboratories, some have already displayed potential in keeping foods like strawberries and fish fillets fresh, which means small businesses could start using them soon. With further research and development, they could be applied more widely in the food industry.

3.1.4 Leaf Waste

Leaf-based agricultural waste should be put into consideration as a promising source for manufacturing sustainable food packaging due to its biodegradable materials. Traditionally, leaf such banana has been commonly used in food wrapping because of their inherent strength, flexibility, and antimicrobial characteristics (Hounsou *et al*., 2022; Mvuma & Alexander, 2023; Rikasa & Mufeez, 2023; Sari *et al*., 2024). These natural materials are not only biodegradable but also compostable, aligning with eco-friendly single-use packaging needs, particularly in food sectors (Juani & Navaranjan, 2024). Rich in lignocellulosic compounds such as cellulose and lignin, leaf plant wastes provide essential raw materials for developing biodegradable packaging products.

Table 3. Summary of Study on Fruit Waste Base Materials as Food Packaging

Study	Raw Materials	Method	Flexibility	Water Resistance	Mechanical Properties	Industrial Application Potential
Hasan *et al.*, (2024)	Banana peel, glycerol	Hydrolysis, oven-drying	Good elasticity with plasticizer	Not yet evaluated	Tensile strength: 0.4086 N/mm²	Potential for disposable packaging
Yun and Liu (2024)	Mandarin peel, Sodium alginate	Casting technique	Elongation: 13.37%–24.62%	Contact angle: 26.03°–90.75°; WVP: 5.38–8.31×10^{-11}	Tensile strength: 4.87–7.90 MPa	Suitable for lightweight food wraps
Arroyo-Esquivel (2025)	Pitahaya peel, plasticizers	Hydrothermal-assisted extraction, casting	Elongation: 11.9%–14.2%	WVP: 3.938 µg/s/m²/Pa	Thickness: 0.087–0.175 mm	Potential for active packaging with moderate flexibility
Baniasadi *et al.* (2025)	Pomegranate peel	Freeze-drying, esterification	Good structural resilience	Low thermal conductivity	Latent heat capacity: 65 J/g	Suitable for cold-chain packaging
Gaboto *et al.* (2025)	Soursop seed	Soxhlet extraction, gelatinization, drying	Flexibility: 7.2 mm	Degradation: ~75% in 30 days	Tensile strength: 3.5 MPa	Good for food contact use
Joseph *et al.* (2024)	Mango seed starch + CMC, CS, NCS	Gelatinization, casting, heat drying	Improved with sorbitol	WVP: 2.16×10^{-7}–6.29×10^{-7} g/day/m/Pa	Antimicrobial; suitable durability	Antimicrobial food packaging
Suhartini *et al.* (2023)	Avocado seed starch + nanochitosan	UAE extraction, casting, drying	Moderate thickness: 0.10–0.15 cm	Extended strawberry shelf life	Antioxidant LC_{50}: 150–250 ppm	Fresh fruit packaging application

Chanthavong *et al.*, (2023) has explored the use of fallen dried leaves as an alternative for plastic packaging, the study conducted by extracting cellulose microfibers (CMFs) from fallen dried leaves using alkaline peroxide treatment, followed by ultrasonic processing and blending with polyvinyl alcohol (PVA) via solution casting to produce biodegradable composite films with potential mechanical properties, up to 80.37 MPa tensile strength and modulus of 2.51 GPa. The composite also showed a biodegradation enhancement of over 21%**,** supporting its environmental sustainability**.** Furthermore, Arumugam *et al.* (2024) has also developed biodegradable food packaging from banana leaves fabricated using the compression molding method under controlled conditions of 2 bar pressure and 105 °C for 20 minutes exhibited potential tensile strength (approximately 38 MPa), thermal stability up to 230 °C, as well as wettability analysis showed a stable water contact angle (WCA) of 65°. The films also showed excellent shelf-life stability, maintaining their structural integrity for up to 150 days without chemical additives which is preferable properties as alternative to conventional plastic and paper packaging. Utilizing leaf waste in this way supports agricultural waste valorization by transforming low-value biomass into functional, sustainable packaging. This approach contributes to reducing environmental pollution while encouraging the integration of agricultural and packaging sectors to promote innovative, renewable, and low-cost alternatives to conventional plastic packaging. With continuous advancements in green technologies, leaf-waste-derived packaging offers significant environmental and commercial potential.

3.2 Environmental and Economic Benefits

The transformation of agricultural waste into food packaging materials played a crucial role in tackling down environmental issues (Carvalho *et al*., 2025). Most common agricultural residues, for instance husks, peels, stalks, and leaves are frequently neglect to decompose or are incinerated, causing environmental pollution as well as greenhouse gas emission (Saxena *et al*., 2025). One of the most common ways to address these issues is by transferring such residues into valuable packaging products which also causes the reducing of pollution. Furthermore, the nature of these materials which is biodegradable also had potential to lowered environmental footprint compared to conventional plastic packaging, which lasts in ecosystems for centuries (Pham *et al*., 2024). This action is believed not only helps in waste handling but also supports greater sustainability goals such reducing the abuse use for fossil resources. For instance, converting dragon fruit peels into biodegradable packaging reduced fossil fuel use and cut CO_2 emissions by up to 25% compared to traditional petroleum-based polystyrene as investigated by Baniasadi *et al*. (2025).

Integrating agricultural waste into packaging solutions also promotes a circular economy by closing the loop between food production and waste recovery. Instead of projecting waste as a disposal issue, it becomes a raw material for new product development (Arias *et al*., 2024). As an example, the recycling of rice husks, banana leaves, or cassava peels in biodegradable film production highlighting the integration of renewable resources into industrial applications. This circularity promotes sustainable agriculture by adding new value and additional purpose to what was once discarded, encouraging resource efficiency across the food supply chain (Azrial *et al*., 2025). From economic perspective, application agricultural residues adding worth to neglected by-products also unveils new revenue opportunities for farmers, processors, and local entrepreneurs (Baruah *et al*., 2024). The cost efficiency and boarder availability of raw materials from agricultural waste significantly reduce production expenses in the packaging industry (Birania *et al*., 2022). Affordable raw materials make biodegradable packaging able to compete in the market, causing its implementation not only by large manufacturers but also by small and medium enterprises (Moshood *et al*., 2022). Even more, innovations in this sector may render new job opportunities in rural areas, especially in waste collection, preprocessing, and packaging manufacturing. Furthermore, this model fits well within the circular economy framework, where waste is treated as a resource to create new value. By keeping materials in use and regenerating natural systems, agro-waste packaging promotes closed-loop production that minimizes resource depletion and environmental harm.

Lastly, supporting the development of agro-waste-based packaging fosters sustainable business models and local economic resilience. As global markets increasingly demand environmentally responsible products, environmentally friendly packaging becomes a market differentiator (Duarte *et al*., 2024). Moreover, this trend also benefits country rich in agricultural resources due to the developing of domestic industries which centered on biodegradable based materials (Ghasemlou *et al*., 2024). With supportive policy frameworks, research funding, and public awareness, agricultural waste packaging can evolve from a niche innovation into a mainstream solution for both environmental protection and inclusive economic growth.

4. Conclusion

The transformation of agricultural residues into sustainable packaging materials represents a pivotal innovation at the intersection of environmental science, material engineering, and the global push toward a circular economy. As this review comprehensively highlighted, the vast array of agro-wastes—from cereal by-products like rice husks and wheat straw to sugar-rich crop residues such as sugarcane bagasse and cassava peels, and even fruit and leaf wastes—holds immense untapped potential as raw materials for biodegradable, functional, and eco-friendly packaging. These materials not only offered a sustainable alternative to conventional plastics, but also contribute to reducing the environmental footprint of the food industry, mitigating greenhouse gas emissions, and valorizing waste that would otherwise contribute to pollution. Technological advancements in biopolymer extraction, nanomaterial integration, and green chemistry are driving the feasibility and commercial viability of these innovations, fostering a new era where waste becomes a resource rather than a burden. Moreover, the economic implications are equally compelling: by converting low-value by-products into marketable packaging solutions, this approach empowers farmers, supports local industries, reduces dependency on fossil fuels, and creates green jobs. However, challenges remain in scaling up these technologies, including issues related to production consistency, water resistance, and material durability under varying environmental conditions. Future research should also explore policy incentives, life-cycle assessment frameworks, and economic feasibility to support wider industrial adoption of agro-waste-based packaging. Additionally, interdisciplinary collaboration is essential to develop standardized processing methods and ensure regulatory compliance for food safety and environmental impact.

Abbreviations

NC	Cellulose Nanocrystals
CMC	Carboxymethyl Cellulose
PVA	Polyvinyl Alcohol
CCNC	Cellulosic Nanocrystals from Corn Husk
BC	Bacterial Cellulose
CMFs	Cellulose Microfibers
TS	Tensile Strength
EB	Elongation at Break
TDS	Total Dissolved Solids
WVP	Water Vapor Permeability
CEON	Cinnamon Essential Oil Nanoemulsion
UAE	Ultrasonic-Assisted Extraction
LC_{50}	Lethal Concentration 50% (Antioxidant activity indicator)
WCA	Water Contact Angle
Tg	Glass Transition Temperature
Tm	Melting Temperature

Data availability statement

Data will be available upon request.

Authors' Contribution

Annisa Ulhusna: conceptualization, preparation, investigation, and initial draft writing. **Reza Mardhiyah Amir**: methodology, supervision, writing, and formatting editor. **Nuridayah Yusmaidi**: data sourcing and language editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest or competing interests.

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