

**ORGANIC WASTE-BASED BIOPLASTICS FOR SUSTAINABLE FOOD PACKAGING:
ENVIRONMENTAL AND PUBLIC HEALTH IMPLICATIONS****Fika Ardiani^{1*}, Nur Endah Wahyuningsih², Budiyo³, Sulistiyani⁴, Yusniar
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Doi: <https://doi.org/10.33024/mahesa.v6i10.28149>**ABSTRACT**

Petroleum-based plastics remain widely used in food packaging but contribute to persistent environmental pollution and potential human exposure to microplastics, nanoplastics, and plastic-associated chemicals. Organic waste-based bioplastics have emerged as promising alternatives that may support waste valorization, circular economy principles, and more sustainable food packaging development. This systematic review aimed to synthesize current evidence on organic waste-based bioplastics for sustainable food packaging, with emphasis on functional performance, biodegradability, environmental fate, food-contact safety, and environmental and public health implications. The review followed the PRISMA 2020 guideline and was prospectively registered in the Open Science Framework. Literature searches were conducted in Scopus, ScienceDirect, PubMed, and SpringerLink. A total of 181 records were identified, and 34 studies published between 2020 and 2026 were included in the qualitative synthesis. Most studies focused on material performance, particularly mechanical and barrier properties, antioxidant and antimicrobial activity, shelf-life extension, and freshness-monitoring functions. Biodegradation was assessed in 13 studies, while compostability was rarely evaluated. Safety-related assessments were substantially less frequent, with only a limited number of studies examining migration, cytotoxicity or biocompatibility, ecotoxicity, and food-contact safety. None of the included studies conducted a comprehensive life cycle assessment. Organic waste-based bioplastics show considerable potential as functional and more sustainable food packaging materials. However, evidence regarding environmental and public health safety remains limited. Future research should integrate material performance with standardized migration testing, toxicological and ecotoxicological assessment, environmental fate analysis, degradation-product characterization, and life cycle assessment.

Keywords: Bioplastics, Organic Waste, Sustainable Food Packaging, Environmental Health, Public Health.

INTRODUCTION

Petroleum-based plastics remain the dominant materials used in food packaging because they are inexpensive, lightweight, versatile, and suitable for large-scale production. However, their environmental persistence and fragmentation into microplastics and nanoplastics have raised increasing concerns regarding ecosystem contamination and potential human exposure. These particles may enter the human body through food, drinking water, air, and other environmental pathways, while plastic-associated additives and contaminants may further contribute to health risks (Nawab et al., 2024; Rosenboom et al., 2022). Therefore, plastic pollution is not only an environmental issue but also an emerging public health concern that requires safer and more sustainable packaging alternatives.

Organic waste has gained increasing attention as a renewable resource for developing biodegradable food packaging. Agricultural residues, food-processing wastes, and agro-industrial by-products contain valuable components such as cellulose, starch, hemicellulose, pectin, proteins, and other bioactive compounds that can be converted into bioplastic materials. This approach provides a dual environmental benefit by reducing the accumulation of organic waste while decreasing dependence on fossil-derived plastics. Consequently, the development of waste-based bioplastics is closely aligned with waste valorization, resource efficiency, and circular economy principles (Lizundia et al., 2022; Otoni et al., 2021).

Recent developments have extended organic waste-based bioplastics beyond conventional biodegradable films. Natural

extracts, pigments, essential oils, cellulose derivatives, and nanomaterials recovered from organic residues have been incorporated into active and intelligent packaging systems. These materials may improve mechanical and barrier properties, inhibit microbial growth and oxidation, monitor food freshness, and prolong shelf life (Acquavia et al., 2024; Ahmad et al., 2025). Such functions are particularly relevant to public health because maintaining food quality and controlling microbial spoilage may contribute to safer food storage and reduce the risk of food deterioration.

Nevertheless, biodegradability alone does not guarantee environmental sustainability or health safety. The degradation behavior of bioplastics varies according to polymer composition, environmental conditions, microbial activity, and waste-management systems. Materials that degrade under controlled composting conditions may persist in soil, aquatic environments, or landfills and may generate degradation products or residual particles whose environmental effects remain uncertain (Tyagi et al., 2022; Withana et al., 2025). This uncertainty highlights the importance of evaluating the entire life cycle of bioplastic materials rather than relying solely on biodegradability claims.

Food-contact safety represents another important concern. The incorporation of bioactive compounds, pigments, essential oils, and nanoparticles can improve packaging functionality but may also introduce potential risks associated with chemical migration, non-intentionally added substances (NIAS), cytotoxicity, ecotoxicity, nanoparticle release, and long-term

exposure. Therefore, materials intended for food-contact applications should be evaluated not only for their technological performance but also for their potential implications for consumers and the environment (Seref, 2025; Stuparu-cretu et al., 2023).

Although research on organic waste-based bioplastics has expanded rapidly, most studies have concentrated on material formulation, mechanical characteristics, barrier performance, biodegradability, and active packaging functions. Comparatively less attention has been given to migration, toxicological effects, ecotoxicity, environmental fate, and food-contact safety. Existing reviews also tend to discuss material performance or environmental sustainability separately, with limited integration of these aspects into a broader environmental and public health perspective. Consequently, uncertainty remains regarding whether waste-derived bioplastics can simultaneously provide functional, environmental, and health advantages.

Therefore, this systematic review aims to synthesize current evidence on organic waste-based bioplastics for sustainable food packaging, with particular emphasis on waste valorization, functional performance, biodegradability, environmental fate, food-contact safety, migration, toxicity, ecotoxicity, and their broader environmental and public health implications. By integrating these dimensions, this review is expected to identify major research gaps and provide evidence-based directions for the development of bioplastic packaging that is not only functional and biodegradable but also environmentally sustainable and safe for public health.

LITERATURE REVIEW

Organic waste-based bioplastics are developed from renewable biological resources such as agricultural residues, food-processing by-products, and agro-industrial wastes. These materials contain biopolymers including starch, cellulose, hemicellulose, pectin, and proteins that can be processed into biodegradable films and coatings. Their utilization supports waste valorization by converting low-value organic residues into useful packaging materials while reducing dependence on fossil-derived plastics (Lizundia et al., 2022; Otoni et al., 2021).

Recent primary studies demonstrate that organic waste can contribute both structural and functional components to food packaging. Cellulose and hemicellulose recovered from spent coffee grounds, cocoa shell, avocado pruning waste, and other agricultural residues have been incorporated into bioplastic films to improve mechanical strength, water resistance, barrier performance, and structural stability (Ahmad et al., 2025; Freire et al., 2025; Saidi et al., 2025). These findings indicate that waste-derived materials can function not only as alternative raw materials but also as reinforcing components that improve packaging performance.

Organic residues also provide bioactive compounds that enable the development of active and intelligent packaging. Natural pigments, anthocyanins, essential oils, and other bioactive compounds have been incorporated into packaging systems to provide antioxidant, antimicrobial, and freshness-monitoring functions. For example, red cabbage extract has been applied in bacterial cellulose films as a freshness indicator, while

onion- and garlic-derived compounds have been incorporated into intelligent packaging systems for spoilage detection (Abdelkader et al., 2024; Tohamy, 2025b, 2025a, 2026). Other studies have demonstrated antioxidant and antimicrobial functions that may contribute to food preservation and shelf-life extension (Beltrán et al., 2025; Schiavone et al., 2026).

However, improved functionality and biodegradability do not necessarily indicate environmental or health safety. Degradation behavior depends on polymer composition and environmental conditions, while degradation products or residual particles may persist after disposal. In addition, food-contact materials containing natural extracts, pigments, nanoparticles, or other functional additives may release substances through migration and may introduce toxicological or ecotoxicological concerns (Stuparucretu et al., 2023; Tyagi et al., 2022; Withana et al., 2025). Evidence on migration, cytotoxicity, ecotoxicity, degradation products, and long-term environmental fate therefore remains important for determining whether these materials are truly sustainable from an environmental and public health perspective.

The objective of this systematic review is to synthesize current evidence on the functional performance, biodegradability, environmental fate, food-contact safety, and environmental and public health implications of organic waste-based bioplastics for sustainable food packaging.

Accordingly, this review addresses the following research question: To what extent do current studies support the use of organic waste-based bioplastics as food packaging materials that are simultaneously functional,

environmentally sustainable, and safe from a public health perspective?

RESEARCH METHODOLOGY

This study employed a systematic review design conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guideline. The review protocol was prospectively registered in the Open Science Framework (OSF) and is available at <https://doi.org/10.17605/OSF.IO/A R9GZ>. Minor refinements to the eligibility criteria and synthesis focus were made during the review process without altering the main objective of the review.

A systematic literature search was conducted in Scopus, ScienceDirect, PubMed, and SpringerLink, with the final search performed on 7 May 2026. Search terms combined keywords related to organic waste, agricultural waste, food waste, biomass, bioplastics, biodegradable packaging, sustainable food packaging, active packaging, intelligent packaging, migration, toxicity, ecotoxicity, biodegradability, compostability, and environmental health. The search strategy was adapted to the indexing system and search functions of each database.

Eligible studies were original peer-reviewed articles published in English and available in full text. Studies were included if they investigated bioplastics derived from organic waste, agricultural waste, food waste, biomass, or agro-industrial residues intended for food packaging applications and reported at least one relevant outcome related to material performance, biodegradability, compostability, migration, non-intentionally added substances (NIAS), toxicity,

ecotoxicity, environmental fate, life-cycle considerations, or environmental and public health implications. Review articles, conference abstracts, editorials, book chapters, non-peer-reviewed publications, non-English articles, studies unrelated to food packaging, and studies without environmental or health relevance were excluded.

All retrieved records were imported into a reference management system, and duplicate records were removed before title, abstract, and full-text screening. Study selection was conducted by the first author, while articles with uncertain eligibility were discussed with supervisors until consensus was reached. A predefined data extraction form was used to record author, publication year, study title, waste source, polymer matrix, food packaging application, study design, experimental methods, primary outcomes, safety-related assessments, and study conclusions. The study selection process is presented using a PRISMA 2020 flow diagram.

Methodological quality of the included studies was assessed narratively based on predefined criteria, including clarity of study objectives, adequacy of material characterization, relevance to food packaging applications, reporting of functional performance, reporting of safety-related outcomes, and assessment of biodegradability or environmental fate. A formal risk-of-bias tool was not applied because the included studies were predominantly heterogeneous laboratory-based material development studies for which no single validated appraisal tool was considered suitable.

Because substantial heterogeneity existed in waste sources, polymer matrices, fabrication methods, food applications, testing conditions, and reported outcomes, the data were synthesized using a narrative thematic approach. Meta-analysis, publication bias assessment, and certainty-of-evidence grading were not performed because comparable quantitative outcome measures were unavailable.

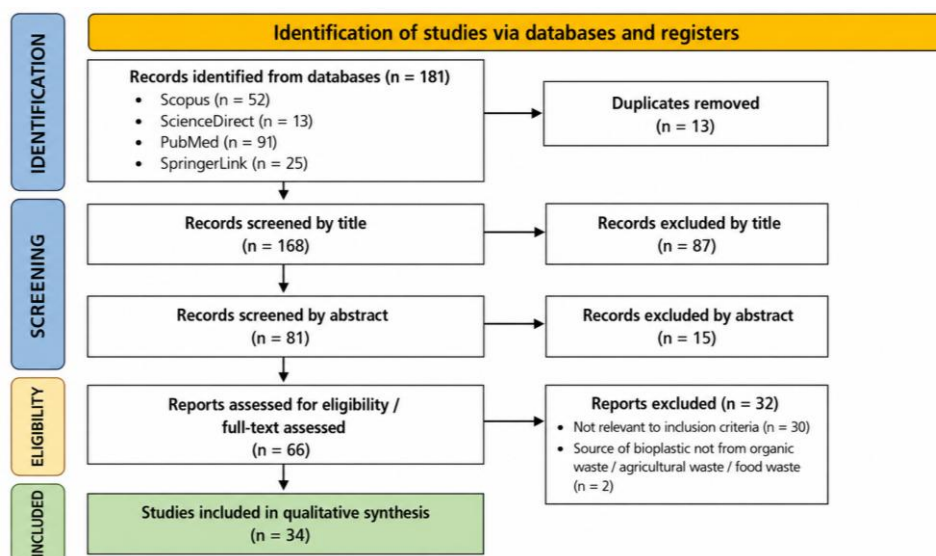


Figure 1. PRISMA 2020 Flow Diagram Of The Study Selection Process

RESEARCH RESULTS

A total of 181 records were identified through searches in Scopus, ScienceDirect, PubMed, and SpringerLink. After duplicate removal and sequential screening of titles, abstracts, and full texts, 34 studies published between 2020 and 2026 met the eligibility criteria and were included in the qualitative synthesis. The study selection process is presented in Figure 1.

The included studies investigated a wide range of organic waste sources, including fruit and vegetable residues, agricultural by-

products, food-processing wastes, cereal residues, and marine biomass. These materials were incorporated into various biopolymer matrices such as starch, cellulose, pectin, chitosan, proteins, and their composites. The resulting materials were developed as biodegradable films, active packaging, intelligent packaging, edible films, coatings, and absorbent pads for food applications. The main characteristics of the 34 included studies are summarized in Table 1.

Table 1. Characteristics of the Included Studies

No	Title and Author (Year)	Waste Source / Material	Function / Applicati on	Key Findings
1	Red cabbage extract immobilized in bacterial cellulose film as an eco - friendly sensor to monitor microbial contamination and gamma irradiation of stored cucumbers. (Abdelkader et al., 2024)	Red cabbage / bacterial cellulose	Intelligent packaging - cucumber	pH-responsive film for microbial contamination, irradiation, and freshness monitoring.
2	A novel anthocyanins hydroxyethyl cellulose film for intelligent chicken meat packaging with mechanical study, DFT calculations and molecular docking study. (Tohamy, 2025a)	Onion peel / hydroxyethyl cellulose	Intelligent packaging - chicken meat	Antimicrobial activity, <i>Salmonella</i> detection, and freshness monitoring.
3	Amylopectin xerogel with onion based sulfur nitrogen doped carbon quantum dots as a chemosensor for chromium and biosensor for microbial spoilage in tomatoes. (Tohamy, 2025b)	Onion peel / amylopectin xerogel	Smart packaging	Cr(VI) detection, microbial spoilage sensing, and pH-responsive monitoring.

No	Title and Author (Year)	Waste Source / Material	Function / Applicati on	Key Findings
4	Enhancing the Water Resistance of Carboxymethyl Cellulose Films with Cellulose Nanofibers from Spent Coffee Grounds and Grapeseed Oil. (Saidi et al., 2025)	Spent coffee grounds / CMC	Biodegradable food packaging	Improved mechanical strength, water resistance, and water-vapor barrier properties.
5	Aggregation-induced emission garlic peel carbon dots infused-carrageenan/whey protein emulsion for apple spoilage biosensing. (Tohamy, 2026)	Garlic peel / carrageenan-whey protein	Intelligent packaging - apple	Fluorescent spoilage detection and antimicrobial activity.
6	Pilot-Scale Development of Biodegradable Packaging Incorporating Pineapple By-product Antioxidants for Sustainable Meat Preservation Through Circular Economy. (Beltrán et al., 2025)	Pineapple by-product / PCL	Active packaging - meat	Improved stability and preserved freshness. oxidative and meat
7	Biodegradable active packaging films reinforced with thyme waste nanoparticles. (Sempere-Torregrosa et al., 2025)	Thyme waste / PLA-PHB	Active food packaging	Improved barrier, antioxidant activity, and compostability. oxygen
8	Fabrication and characterization of waste eggshell microparticles reinforced biodegradable composite packaging films enriched with pectin and orange peel essential oil. (Iffath et al., 2025)	Eggshell waste and orange peel / pectin composite	Active food packaging	Improved strength, thermal stability, barrier, antioxidant, antibacterial, and biodegradation properties.
9	Circular packaging solutions: Active films from food waste pigments and meat	Food-waste pigments / blood plasma-gelatin	Active packaging - beef	Reduced oxidation provided indication. lipid and spoilage

No	Title and Author (Year)	Waste Source / Material	Function / Applicati on	Key Findings
	industry co-products. (Alvarez, 2026)			
10	Hemicellulose / PVA-based bioactive films for food packaging: Effect of the molecular weight of avocado pruning waste-derived hemicellulose on biocomposite properties. (Freire et al., 2025)	Avocado pruning waste / hemicellulose-PVA	Active food packaging	Antioxidant, antimicrobial, UV-blocking, and improved mechanical properties.
11	Novel antioxidant-active food packaging based on olive oil byproducts extracts. (Schiavone et al., 2026)	Olive oil by-products / active packaging matrix	Active packaging - beef	Delayed oxidation through natural antioxidant incorporation.
12	Microfibrillated cellulose films from agri-food wastes and plant residues for food packaging applications - A comparative investigation. (Bellesia et al., 2026)	Agri-food residues / microfibrillated cellulose	Sustainable food packaging	Excellent oxygen barrier, UV shielding, and mechanical performance.
13	Development of innovative antioxidant food packaging systems based on natural extracts from food industry waste and Moringa oleifera leaves. (Barzan et al., 2024)	Food-industry waste / active packaging matrix	Active packaging - beef	Improved antioxidant protection and inhibited lipid oxidation.
14	Development of Antimicrobial Biopolymer Film Incorporated with a Mixture of Sodium Lactate and Diacetate and Studying its Efficacy Against <i>Listeria monocytogenes</i> and Microbiological Spoilage in Deli Meat Over 12 Weeks of	Chicken skin by-product / gelatin-corn starch-nanocellulose	Antimicrobial packaging - ready-to-eat meat	Inhibited <i>Listeria monocytogenes</i> and extended shelf life.

No	Title and Author (Year)	Waste Source / Material	Function / Applicati on	Key Findings
	Storage. (Sierra et al., 2025)			
15	Valorisation of Tomato Waste as a Source of Cutin for Hydrophobic Surface Coatings to Protect Starch- and Gelatine-Blend Bioplastics. (Mroczkowska et al., 2024)	Tomato waste starch-gelatin bioplastic	Biodegradable food packaging	Improved hydrophobicity and water-vapor resistance while maintaining biodegradability.
16	Enhanced extraction of bioactive compounds from tea waste for sustainable polylactide-based bioplastic applications in active food packaging. (Acquavia et al., 2024)	Tea waste / PLA	Active food packaging	Improved antioxidant activity, UV protection, flexibility, and barrier properties.
17	Characteristics Of Edible Film Based On Water Hyacinth (Eichornia Crassipes) As Food Packaging Innovation. (Hapsari et al., 2025)	Water hyacinth / cellulose-carrageenan	Edible food packaging	Improved tensile strength and reduced water absorption.
18	Development and characterization of chitosan-based antimicrobial films: A sustainable alternative to plastic packaging. (Ahmed et al., 2025)	Shrimp shell / chitosan-PVA-gelatin	Antimicrobial food packaging	Biodegradable antimicrobial films with improved mechanical and thermal properties.
19	Development of Sustainable Bioplastic Composite Films from Cocoa Pod Husk Waste Cellulose and Kappa-Carrageenan. (Fadhallah et al., 2025)	Cocoa pod husk / cellulose- κ -carrageenan	Biodegradable food packaging	Improved tensile strength, dimensional stability, and biodegradability.
20	Design and fabrication of smart and biodegradable food packaging film using anthocyanins from eggplant peel based on starch-chitosan	Eggplant peel / starch-chitosan	Smart food packaging	Colorimetric sensing, antioxidant, and antibacterial functions.

No	Title and Author (Year)	Waste Source / Material	Function / Applicati on	Key Findings
	polymer modified with green-synthesized copper nanoparticles. (Piryaei & Khiavi, 2026)			
21	Sustainable Bioplastic Production from Banana Peel Waste: Unveiling Antibacterial Potential and Environmental Impact. (Sree et al., 2025)	Banana peel / banana starch	Biodegradable food packaging	Antibacterial activity and satisfactory mechanical performance.
22	Functional bioplastic films from cocoa shell cellulose and natural waxes: Toward sustainable active packaging. (Ahmad et al., 2025)	Cocoa shell / cellulose-natural wax	Active food packaging	Improved hydrophobicity, antioxidant activity, mechanical properties, and biodegradation.
23	Transparent Bioplastic Derived from CO ₂ -Based Polymer Functionalized with Oregano Waste Extract toward Active Food Packaging. (Tran et al., 2020)	Oregano waste / CO ₂ -derived polycarbonate-cellulose acetate	Active food packaging	Transparent biodegradable films with antioxidant activity, UV protection, and seawater biodegradability.
24	Eco-friendly fabrication of biopolymer films from tannery waste, zinc oxide nanoparticles, and crustacean shells: Advancing sustainable circular bio-economy. (Neela et al., 2025)	Tannery waste and shrimp shell / gelatin-chitosan	Antimicrobial food packaging	Improved mechanical properties, biodegradability, antimicrobial activity, and cytocompatibility.
25	Reinforcement of chitosan / polyvinyl alcohol film by quercetin self-assembled nanocrystals for fresh meat preservation. (Fan, Wang, et al., 2025)	Quercetin / chitosan-PVA	Active packaging - fresh meat	Improved antioxidant activity, barrier properties, and meat shelf life.
26	Characterization of Natural Anthocyanin Indicator Based on Cellulose Bio-Composite Film for	Roselle / HPMC-microcrystalline cellulose	Intelligent packaging	Colorimetric freshness indicator responsive to pH changes.

No	Title and Author (Year)	Waste Source / Material	Function / Applicati on	Key Findings
	Monitoring the Freshness of Chicken Tenderloin. (Boonsiriwit, 2022)		chicken meat	
27	Dialdehyde Cellulose Nanocrystals and Proanthocyanidins Reinforced Soy Protein Isolate Films for Blueberry Preservation. (Wei et al., 2025)	Cellulose nanocrystals / soy protein isolate	Active packaging - blueberries	Improved mechanical strength and antioxidant and antimicrobial activities.
28	A novel active biopolymer coating of pectin, potato starch, and pyrogallol: Impact on postharvest quality of tomato (<i>Solanum lycopersicum</i> L.). (Ramadoss, 2025)	Potato starch and pectin / starch-pectin	Active packaging - tomato	Improved antioxidant, antibacterial, biodegradation, and shelf-life performance.
29	Multifunctional cellulosic aerogels from <i>Posidonia oceanica</i> waste biomass with antioxidant properties for meat preservation. (Amparo et al., 2021)	<i>Posidonia oceanica</i> waste cellulosic aerogel	Active packaging - meat	Reduced oxidation preserved lipid and meat quality.
30	Data on antimicrobial, barrier, and mechanical properties of biocomposites prepared from carrot pomace and wheat gluten with varied eugenol content. (Merino et al., 2024)	Carrot pomace / wheat-gluten biocomposite	Active food packaging	Improved antimicrobial activity, barrier properties, and mechanical performance.
31	Hemp cellulose-based aerogels and cryogels: From waste biomass to sustainable absorbent pads for food preservation. (Cabrera-villamizar & Castanedo, 2025)	Hemp biomass and rice straw / cellulose aerogel	Absorbent pad - meat	High sorption capacity with antioxidant activity.
32	Integrated Zero By-Product Valorization of Orange Peel into	Orange peel / pectocellulosic-ZnO	Active food	Improved mechanical, barrier, antioxidant, antimicrobial, UV-

No	Title and Author (Year)	Waste Source / Material	Function / Applicati on	Key Findings
	Multifunctional Pectocellulosic-ZnO Nanocomposite Films for Sustainable Packaging. (Baraketi et al., 2026)	nanocomposi te	packagin g	protection, and biodegradation properties.
33	Zein / chitosan Janus film incorporated with tannic acid and cinnamon essential oil co-loaded Pickering emulsion for sustained controlled release and pork preservation. (Fan, Yang, et al., 2025)	Cinnamon essential oil / zein-chitosan Janus film	Active packagin g - pork	Controlled release of bioactive compounds and prolonged pork shelf life.
34	Valorization of Blueberry Processing Byproducts for the Development of Intelligent Packaging : A Comparative Study on Biomass versus Extract Use in pH-Sensitive Films. (Arizanova et al., 2026)	Blueberry processing by-products / chitosan	Intellige nt food packagin g	pH-sensitive films with antioxidant release, UV protection, and freshness monitoring.

As shown in Table 1, fruit and vegetable residues, agricultural by-products, and food-processing wastes were among the most frequently utilized sources of raw materials and functional compounds. The resulting packaging systems were predominantly developed as active, intelligent, biodegradable, or edible packaging materials. Active packaging commonly emphasized antioxidant and antimicrobial functions, whereas intelligent packaging focused mainly on freshness or spoilage monitoring. These findings indicate that the reviewed studies addressed not only waste valorization but also the enhancement of food preservation and packaging functionality.

Mechanical properties were the most frequently assessed parameter, reported in 33 of the 34 studies (97.1%), followed by barrier properties in 29 studies (85.3%). Water resistance was evaluated in 17 studies (50.0%), while thermal properties were investigated in nine studies (26.5%). Antioxidant activity was assessed in 23 studies (67.6%), whereas antimicrobial activity and shelf-life evaluation were each reported in 16 studies (47.1%). Intelligent packaging or freshness-monitoring functions were investigated in eight studies (23.5%). Biodegradation was assessed in 13 studies (38.2%), while compostability was explicitly evaluated in only one study (2.9%). Safety-related evaluations remained

limited, including overall migration in two studies (5.9%), cytotoxicity or biocompatibility in three studies (8.8%), ecotoxicity or biotoxicity in one study (2.9%), and food-contact safety evaluation in two studies

(5.9%). None of the included studies conducted a comprehensive life cycle assessment. The distribution of the investigated parameters is presented in Table 2.

Table 2. Distribution of Functional Properties Evaluated in the Included Studies

Evaluation Category	Evaluated Parameter	Number of Studies (n)	Percentage (%)
Material Performance	Mechanical properties	33	97.1
	Barrier properties	29	85.3
	Thermal properties	9	26.5
	Water resistance	17	50.0
Food Preservation Performance	Antioxidant activity	23	67.6
	Antimicrobial activity	16	47.1
	Shelf-life evaluation	16	47.1
	Intelligent packaging / Freshness monitoring	8	23.5
Environmental Sustainability	Biodegradation	13	38.2
	Compostability	1	2.9
	Life cycle assessment (LCA)	0	0.0
Safety-Related Assessment	Overall migration	2	5.9
	Cytotoxicity / Biocompatibility	3	8.8
	Ecotoxicity / Biotoxicity	1	2.9
	Food-contact safety evaluation	2	5.9

DISCUSSION

Organic Waste Valorization and Functional Performance

The findings demonstrate that a wide range of agricultural, food-processing, and agro-industrial residues can be transformed into food packaging materials. Fruit and vegetable residues, cereal and crop wastes, marine biomass, and food-industry by-products provided renewable sources of starch, cellulose, hemicellulose, pectin, chitosan, proteins, and bioactive compounds. Their utilization supports circular economy principles by converting low-value residues

into higher-value packaging materials while reducing dependence on fossil-derived plastics (Tyagi et al., 2022; Withana et al., 2025).

The reviewed studies also show that waste-derived materials can contribute not only to the polymer structure but also to packaging functionality. Natural polyphenols, anthocyanins, essential oils, and other bioactive compounds were incorporated into active and intelligent packaging systems with antioxidant, antimicrobial, and freshness-monitoring properties.

This indicates that waste valorization may provide both environmental and technological benefits rather than functioning solely as a substitute for conventional plastic raw materials (Cheng et al., 2024; Kumar Chandra et al., 2024).

Material performance remained the dominant research focus. Mechanical properties were evaluated in 97.1% of the included studies and barrier properties in 85.3%. Cellulose fibers, starch, pectin, chitosan, proteins, natural waxes, and lignocellulosic reinforcements were frequently associated with improvements in tensile strength, moisture resistance, oxygen barriers, and structural stability (Ahmad et al., 2025; Freire et al., 2025; Saidi et al., 2025). These properties are essential because biodegradable packaging must maintain sufficient integrity during food storage before undergoing degradation after disposal.

Food-preservation functions were also widely investigated. Antioxidant activity was assessed in 67.6% of the studies, while antimicrobial activity and shelf-life evaluation were each reported in 47.1%. Several studies demonstrated reduced lipid oxidation, inhibition of microbial growth, or maintenance of food quality in meat, fruit, and vegetable products (Barzan et al., 2024; Beltrán et al., 2025; Fan, Wang, et al., 2025). Eight studies further investigated intelligent packaging or freshness monitoring using pH-responsive pigments or fluorescent indicators, including anthocyanins and carbon-based materials derived from organic residues (Abdelkader et al., 2024; Arizanova et al., 2026; Tohamy, 2025b, 2025a).

From a public health perspective, these functions may

indirectly contribute to food safety by supporting spoilage detection and maintaining food quality, although they do not replace direct safety assessment of the packaging material itself.

Biodegradability and Environmental Fate

Biodegradability is one of the main environmental advantages associated with organic waste-based bioplastics. However, only 13 of the 34 included studies evaluated biodegradation, and only one explicitly assessed compostability. Most biodegradation studies relied on soil burial, mass loss, or visual changes. Starch-, cellulose-, pectin-, chitosan-, and protein-based materials generally showed progressive degradation, with rates influenced by polymer composition, hydrophilicity, crystallinity, coatings, and reinforcing materials (Fadhallah et al., 2025; Mroczkowska et al., 2024; Sree et al., 2025).

These findings indicate that biodegradability should not automatically be interpreted as complete environmental safety. Several studies demonstrated material degradation without identifying intermediate products, residual particles, or potential ecological effects. Hydrophobic coatings, waxes, and nanomaterials may also improve packaging durability while altering degradation behavior (Ahmad et al., 2025; Iffath et al., 2025; Sempere-Torregrosa et al., 2025). Furthermore, none of the included studies conducted a comprehensive life cycle assessment. Therefore, evidence of mass loss or visual degradation alone is insufficient to establish the long-term environmental sustainability of these materials.

Environmental and Public Health Implications

The most important finding from a public health perspective is the substantial imbalance between functional-performance studies and safety-oriented evaluations. Only two studies evaluated overall migration, three assessed cytotoxicity or biocompatibility, one investigated ecotoxicity or biotoxicity, and two included broader food-contact safety evaluations. This contrasts sharply with the high proportion of studies assessing mechanical, barrier, antioxidant, and antimicrobial performance.

Food-contact safety is particularly relevant because active and intelligent packaging may contain natural extracts, essential oils, pigments, nanoparticles, or other functional additives capable of interacting with food. Although these components may improve antimicrobial or antioxidant performance, their incorporation creates additional considerations regarding migration, non-intentionally added substances, degradation products, and potential consumer exposure. The limited number of migration and toxicological studies identified in this review means that current evidence cannot establish the long-term safety of many waste-derived packaging formulations.

The public health implications therefore extend beyond direct toxicity. Antimicrobial packaging and freshness-monitoring systems may help reduce microbial spoilage and support food preservation (Beltrán et al., 2025; Schiavone et al., 2026). However, these potential benefits should be balanced against possible exposure to migrating compounds or degradation products. A material that improves shelf life or exhibits antimicrobial activity

cannot automatically be considered safe for food contact without appropriate migration and toxicological evaluation.

Environmental exposure is another relevant pathway. Inadequately characterized degradation products or residual particles may enter soil and aquatic environments after disposal, creating potential ecological exposure that may ultimately intersect with human exposure pathways. The very limited ecotoxicological evidence identified in this review therefore represents an important gap in evaluating the broader environmental health implications of biodegradable packaging.

Research Gaps and Future Directions

The reviewed evidence indicates that research on organic waste-based bioplastics remains predominantly focused on material innovation rather than integrated safety assessment. Differences in raw materials, formulations, biodegradation methods, storage conditions, and analytical approaches also make direct comparison between studies difficult. In particular, biodegradation is often demonstrated under laboratory conditions without standardized assessment of compostability, degradation products, or environmental fate (Fadhallah et al., 2025; Mroczkowska et al., 2024).

Regulatory considerations were also rarely incorporated into experimental design. Although these materials are intended for food-contact applications, only a small proportion of studies assessed migration or related safety outcomes. Future studies should therefore integrate functional performance with standardized

migration testing, toxicological and ecotoxicological evaluation, characterization of degradation products, environmental fate assessment, and life cycle analysis. Such assessments are necessary before biodegradable food packaging can be regarded as both environmentally sustainable and safe from a public health perspective.

Based on the synthesized evidence, the authors infer that the main challenge in the development of organic waste-based bioplastics is no longer limited to demonstrating technical feasibility or biodegradability, but to establishing whether these materials remain safe throughout their entire life cycle. Overall, the evidence supports the functional potential of organic waste-based bioplastics and their role in waste valorization and food preservation. However, the current evidence is substantially stronger for material performance and packaging functionality than for environmental and public health safety. Therefore, the sustainability of these materials should be evaluated using an integrated approach that considers performance during use, consumer exposure during food contact, and environmental consequences after disposal.

CONCLUSION

Current evidence supports the potential of organic waste-based bioplastics as functional and more sustainable alternatives for food packaging. Waste-derived materials have been successfully developed into biodegradable, active, and intelligent packaging with improved mechanical and barrier properties, antioxidant and antimicrobial activity, freshness-monitoring functions, and shelf-life extension. Their development also supports

waste valorization and circular economy principles by converting agricultural and food-processing residues into value-added materials.

However, evidence regarding environmental and public health safety remains limited. Migration testing, cytotoxicity, ecotoxicity, environmental fate assessment, and life cycle evaluation were far less frequently investigated than material performance. Therefore, biodegradability and improved packaging functionality alone are not sufficient to establish that these materials are environmentally safe or suitable for long-term food-contact use.

Future researchers are recommended to integrate material performance testing with standardized food-contact migration assessment, toxicological and ecotoxicological testing, characterization of degradation products, environmental fate analysis, and life cycle assessment. Future studies should also evaluate organic waste-based bioplastics under realistic food-contact and end-of-life conditions to provide stronger evidence regarding their long-term safety and environmental sustainability. Such an integrated approach is necessary to ensure that these materials are not only functional and biodegradable but also safe, environmentally sustainable, and suitable for broader food packaging applications.

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