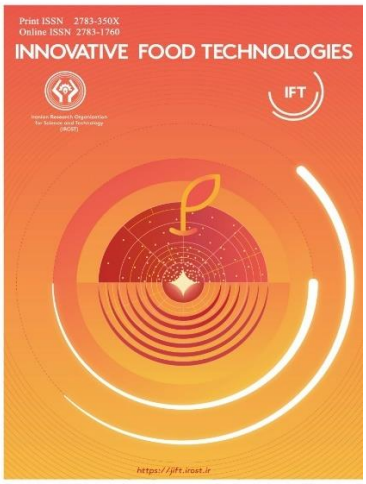
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Antimicrobial PLA/Starch Composites with Plant Biomass Extracts for Food Packaging: A Systematic Review

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Abstract

Petroleum-based plastics are harmful to the environment, and although PLA/starch composites are biodegradable, they are not antimicrobial. This systematic review of 91 studies examines whether plant biomass extracts such as pomegranate peel, olive leaf, betel leaf, grapevine cane, and chicory root can fulfill that role in food packaging. Minimum inhibitory concentrations range from 1.25 to 3.0 mg/mL, while film activity is reported as inhibition zones of approximately 9–16 mm; these two assays are not equivalent. Loadings range from 2 to 10 wt%. In individual studies, tensile strength ranged from 8.6 to 34.5 MPa, below that of neat PLA (50–70 MPa), whereas water vapor permeability (WVP) was reduced by about 55% (olive leaf, grapevine cane) and oxygen permeability by 70% (betel leaf, coated PLA); UV blocking reached 65–66% (tannic acid). These are single-value estimates, not pooled values. PLA-containing systems degraded in 13–60 days, compared with approximately 180 days for neat PLA. The main gaps are: PLA–starch incompatibility, migration testing (less than 15% of studies), pilot-scale validation (less than 5%), and the absence of predictive models. Priority directions are controlled release, synergistic extract combinations, green extraction, and multi-scale computational modelling validated by defined experiments.

Keywords: Polylactic acid; starch; plant extracts; antimicrobial packaging; biodegradable composites; food preservation.

Abbreviations: *PPE (Pomegranate Peel Extract); OLE (Olive Leaf Extract); BETLE (Betel Leaf Extract); GAVCANE (Grapevine Cane Extract); CICR (Chicory Root Extract); WVP (Water Vapor Permeability). MIC (Minimum Inhibitory Concentration); TPC (Total Phenolic Content); TPS (Thermoplastic Starch); PBAT (Poly(butylene adipate-co-terephthalate)); EVOH (Ethylene Vinyl Alcohol); DFT (Density Functional Theory); MD (Molecular Dynamics); QSAR (Quantitative Structure–Activity Relationship).*

1. Introduction

1.1 The Global Plastic Pollution Crisis

Food packaging plays a crucial role in the protection, containment, communication, and convenience of food (Korte et al., 2021). The food packaging industry uses around 40% of the world's total plastic production, and food packaging production exceeds 350 million metric tons per year (X. Li et al., 2023)(Foltynowicz, 2020). Existing petrochemical-based plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) dominate this area because they are inexpensive, have good mechanical properties, and are easily processed. However, these materials last for hundreds, even thousands, of years and degrade in the environment over periods of 100 to 1,000 years, depending on environmental conditions (X. Li et al., 2023) (Foltynowicz, 2020).

The damage to the environment is enormous. Every year, some 8 million metric tons of plastic waste ends up in the ocean, including the Great Pacific Garbage Patch, a stretch of 1.6 million square kilometers (Korte et al., 2021). Microplastics have been found in human blood, placentas, and breast milk, and their potential long-term health effects are a matter of urgent concern (Foltynowicz, 2020). In addition, the traditional plastic manufacturing process uses fossil fuels, which account for around 1.8 billion metric tons of CO_2 equivalent per year in greenhouse gas emissions (X. Li et al., 2023). Such environmental and health issues have led to global policy shifts, such as the European Union's Single-Use Plastics Directive (2019), and more than 100 countries have banned certain plastic products (Korte et al., 2021). The scale of global plastic production and its contribution to packaging waste is illustrated in Figure 1.

Figure 1: Global plastic production and packaging waste trends

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1.2 Food Spoilage and the Need for Antimicrobial Packaging

Microbial contamination results in food spoilage, which causes significant economic losses estimated at US$1 trillion annually worldwide. About 1.3 billion metric tons of food waste are generated annually (Sarkhel et al., 2025). This waste occurs throughout the supply chain: 15–20% at harvest and post-harvest (developing countries), 5–15% at processing and distribution (all countries), and 10–15% at retail and consumer level (developed countries) (Sarkhel et al., 2025). The main pathogens of concern in the food industry include pathogenic bacteria such as Escherichia coli O157:H7, Staphylococcus aureus, Listeria monocytogenes, and Salmonella spp., which cause a total of 600 million foodborne illnesses and 420,000 deaths every year (Novaković et al., 2018) (Sarkhel et al., 2025) (Kamarudin et al., 2022).

The traditional preservation methods are very limited. Refrigeration operates at a low temperature of 4°C, which consumes a large amount of electricity (15% of the world's electricity) and allows the growth of psychrotrophic pathogens. The modified atmosphere packaging (MAP) process lowers oxygen levels to 0–5% and raises CO_2 to 20–80%; it does not work for facultative anaerobes and requires special equipment. Sodium benzoate, potassium sorbate, and sodium nitrite are chemical preservatives that are becoming increasingly unacceptable to consumers due to their health effects (the potential carcinogenic effect of nitrite and the "hypersensitivity" effect of benzoates) Pinto et al., 2023). The clean label trend has raised awareness among consumers of the need for natural alternatives to preservation, with 73% willing to pay higher prices for clean label products (Korte et al., 2021). The major foodborne pathogens responsible for illnesses and deaths worldwide are summarized in Figure 2.

Figure 2: Major foodborne pathogens and associated illnesses

1.3 Biodegradable Polymers as Sustainable Alternatives

Biodegradable polymers are an environmentally friendly alternative to conventional plastics. Of these, polylactic acid (PLA) and starch are the most promising candidates because they are renewable, biodegradable, and possess desirable characteristics (Jayarathna et al., 2022) (Ilyas et al., 2022) (Farah et al., 2016) (Şomoghi et al., 2025). PLA and starch-based materials are expected to contribute about 45% to the global biodegradable plastics market by 2028, and the market is expected to grow to US$22.3 billion by 2028 (Korte et al., 2021).

A specific definition of "biodegradable" must be established. Biodegradable plastics are plastics that must meet the following standards: they should break down by at least 90% in 12 weeks and be biodegradable to at least 90% in 180 days under industrial composting conditions (58°C, 50–60% RH) set by ASTM D6400 and EN 13432 (X. Li et al., 2023). However, the ambient temperature and fluctuating humidity levels of home composting conditions and marine environments pose additional problems, and the degradation rates are usually 2–5 times slower (Şomoghi et al., 2025). Importantly, "biodegradable" does not mean "compostable in home bins," and "biobased" (materials made from renewable resources) does not necessarily mean "biodegradable." Bio-PE and bio-PET are chemically identical to petroleum-based PE and PET, and will not biodegrade (X. Li et al., 2023).

Numerous detailed reviews have summarized current knowledge on PLA- and starch-based antimicrobial packaging. (X. Li et al., 2023) provided a comprehensive review of the synthesis, modification, degradation, and applications of PLA in the construction, medical, packaging, and oil/water separation industries. (Agarwal et al., 2023) reviewed food packaging materials and their properties, with particular focus on biopolymers such as PLA, PHA, starch, chitosan, and cellulose, as well as their applications. (Romaric et al., 2021) critically discussed bio-based packaging polymers that are directly extracted from natural materials, materials synthesized from bio-derived monomers, and packaging produced by microorganisms. In the field of biodegradable food packaging, (Alexe, et al., 2025) provided a comprehensive review of antimicrobial agents, including essential oils, chitosan, bacteriocins, and metal nanoparticles. (Surendren et al., 2022) reviewed sustainable food packaging through agro-waste valorization. (Ilyas et al., n.d.) edited a book on bionanocomposites and hybrid materials based on biopolymers. The chapter by (Uzunlu & Var, n.d.) provided an introduction to active antimicrobial food packaging. (Zhu et al., 2024) summarized modified biomass-reinforced PLA composites (cellulose, lignin, and starch). (Vasile & Baican, 2021) summarized advances in controlled-release antioxidant and

antimicrobial packaging, including mechanisms, kinetics, and testing. (Meena et al., 2023) summarized the key role of microbes in solid waste management, such as the biodegradation of bioplastics. Polymer packaging materials in the circular economy were reviewed by (Foltynowicz, 2020), covering multilayer packaging, nanocomposites, and challenges in recycling. Bio-based polymers for food packaging applications were reviewed by (Şomoghi et al., 2025), with their mechanical, barrier, and antimicrobial properties summarized. The review papers (Vieira et al., 2022) (Apicella et al., 2019) (Chevalia et al., 2016) provide additional supporting information on biopolymer nanocomposites, cold plasma technology, PET functionalization, starch blends, and sustainable biocomposites.

1.4 PLA: Properties, advantages, and disadvantages

PLA is a thermoplastic aliphatic polyester that is produced by fermentation of sugars to lactic acid, followed by ring-opening polymerization of lactide or direct polycondensation of lactic acid using renewable feedstocks such as corn, cassava, and sugarcane (X. Li et al., 2023) (Farah et al., 2016). Commercial PLA grades (such as NatureWorks Ingeo™ or Total Corbion Luminy®) have a tensile strength of 50–70 MPa, a tensile modulus of 3.0–4.0 GPa, and an elongation at break of 1–4%, which are similar to PET and PS in terms of stiffness and strength (Farah et al., 2016) (Şomoghi et al., 2025).

PLA offers several important advantages for food packaging: (1) it is FDA-approved for use as a food contact material (21 CFR 184.1061); (2) it is completely biodegradable under industrial composting conditions (180 days, 58°C); (3) it has good transparency and printability; (4) it is resistant to grease and oil; and (5) it is processable by conventional plastic processing equipment (extrusion, injection molding, and blow molding) (Farah et al., 2016).

However, PLA has some drawbacks: (1) low extensibility (elongation at break <10%); (2) slow degradation at ambient temperatures (12–24 months in soil); (3) lack of inherent antimicrobial properties; (4) poor melt strength for film blowing; (5) relatively high water vapor permeability (around 200–300 g·mm/m²·day); and (6) relatively high cost (US$2.00–2.50/kg compared with US$0.80–1.20/kg for PET) (X. Li et al., 2023) (Ilyas et al., 2022) (Farah et al., 2016). These limitations can be overcome through different modification strategies, such as blending with more flexible polymers, the addition of plasticizers, the use of nanofillers, and, the focus of this review, functionalization with antimicrobial plant extracts.

1.5 Starch: Properties, Advantages, and Disadvantages

Starch is a polysaccharide produced in large quantities. It is inexpensive and renewable, and consists of linear amylose (20–30%) and branched amylopectin (70–80%) (Jayarathna et al., 2022) (Romaric et al., 2021). Starch is obtained from corn (maize being the most common source), potato, tapioca (cassava), wheat, rice, and other cereals and tubers. Starch is one of the most cost-effective biopolymers, with global production of more than 80 million metric tons per year and a price range of US$0.30–0.60/kg.

Under dry conditions, starch-based films have very low oxygen permeability (<0.01–0.1 cm³·mm/m²·day·atm), a property that is achieved through the dense hydrogen-bonded network of amylose and amylopectin (Jayarathna et al., 2022) (Onyeaka et al., 2022). However, starch films have poor tensile strength (usually 2–10 MPa) and water resistance (water solubility up to 20–40%) because of the hydrophilic nature of starch (Jayarathna et al., 2022) (Onyeaka et al., 2022). When heated with a plasticizer such as glycerol, sorbitol, or formamide (usually 20–40 wt% of starch), the hydrogen bonding and crystalline regions of starch are broken, and thermoplastic starch (TPS) is produced (Jayarathna et al., 2022) (Onyeaka et al., 2022). TPS is thermoplastic, so it can be processed with conventional equipment, but it is very humidity sensitive; above 50% RH, its mechanical properties drop sharply (Jayarathna et al., 2022).

1.6 The synergy of the PLA and Starch Composites.

The combination of PLA and starch into composite materials has been mentioned. Although their properties are not as good as those of PLA alone, they are better than those of starch alone, and the composites also remain biodegradable (Jayarathna et al., 2022) (Nazrin et al., 2020) (Şomoghi et al., 2025). PLA has good mechanical properties, water resistance, and processability, and starch promotes biodegradability and reduces cost. The tensile strength of PLA/starch blends is generally in the range of

10–30 MPa, depending on the blend composition. The cost is reduced by 15–30% compared with neat PLA, and the degradation time can be reduced from 180 days in compost to 30–60 days (Jayarathna et al., 2022) (Ilyas et al., 2022).

The main problem, however, is the thermodynamic incompatibility between hydrophobic PLA and hydrophilic starch, which results in phase separation, poor interfacial adhesion, and reduced mechanical properties (Jayarathna et al., 2022) (Ilyas et al., 2022). This challenge has led to intensive studies on compatibilization techniques, which are described in detail in Section 3.2.

1.7 Microbial Polyesters for Packaging

In addition to PLA and starch, microbial polyesters such as polyhydroxyalkanoates (PHAs) and polyhydroxybutyrate (PHB) are other biodegradable materials used for food packaging. (Armentano et al., 2015) prepared bio-based PLA-PHB plasticized blend films that showed improved functional properties for applications in active food packaging. (Gómez-Gast et al., 2022) studied PHA composites using vegetal fibers (cellulose, hemicellulose, lignin) and their mechanical and barrier properties, which could be used as an alternative to conventional packaging materials. (Duangphet, 2012) conducted extrusion foaming of bioplastics based on PHBV for lightweight food packaging; a 61% density reduction was obtained, and 1 kg of prototype thermoformed trays was produced on an industrial scale. (de Eugenio et al., 2023) reported a novel process for PLA production from fungal/lactic acid bacteria consortiums and enzymatic catalysis, which yielded 99% lactic acid from glucose and 65% from starch, followed by the enzymatic synthesis of PLA oligomers and polymers. (Ansari & Fatma, 2007) summarized the use of PHB as a biodegradable plastic, its benefits (renewable, biodegradable, and nontoxic) and limitations (brittleness, high crystallinity, and poor mechanical properties), and PHBV copolymers as a solution. (K. Sharma et al., 2022) also examined PHB as an alternative eco-friendly material to reduce the environmental impact of petroleum-based plastics.

1.8 Plant Biomass Extracts as Natural Antimicrobial Agents

Plant biomass extracts contain bioactive compounds with potent antimicrobial and antioxidant activity, such as phenolic acids, flavonoids, tannins, terpenoids, alkaloids, and essential oils (Sarkhel et al., 2025), (Bose et al., 2023), (Pinto et al., 2023). More than 100 plant species have been studied for their ability to preserve food and to be used as antimicrobial packaging materials, especially extracts from agricultural by-products, such as pomegranate peel, olive leaf, and grapevine cane, which are low-cost, have high valorization potential, and can be used as value-added active compounds (S. Sharma et al., 2022) (Díaz-Galindo et al., 2020) (Soltani et al., 2025).

These natural agents are gaining popularity over synthetic antimicrobials for the following reasons: (1) many plant extracts are generally recognized as safe (GRAS); (2) consumer acceptance is enhanced by the clean-label trend; (3) they are biodegradable and have low environmental impact; (4) they provide additional antioxidant activity useful for food preservation; and (5) they offer potential synergy with biodegradable polymer matrices (Bose et al., 2023) (Pinto et al., 2023). The distribution of plant biomass extract types commonly incorporated into PLA/starch antimicrobial packaging is presented in Figure 3.

Figure 3: Distribution of plant biomass extract types used in PLA/starch antimicrobial packaging

1.9 Scope and Objectives of This Review

This systematic review aims to provide an overview of PLA/starch composites functionalized with plant biomass extracts for antimicrobial food packaging, while allowing for a comprehensive critical analysis. The review is unique in that it appropriately combines both of these areas and critically examines the obstacles to translation from the lab to commercialization. The specific objectives are: analysis of synthesis and processing methods, evaluation of antimicrobial and antioxidant activity, assessment of mechanical, thermal, barrier, and optical properties, evaluation of biodegradation behavior, evaluation of real-food applications, identification of research gaps, and the proposal of a prioritized research agenda from a regulatory and safety perspective. The 91 studies that meet the inclusion criteria (Section 2.1) form the core corpus of this review. Reviews and studies of PLA-only, starch-only, chitosan-coated, or metal-nanoparticle systems are cited for background and mechanistic context.

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2. Methodology of the Review

2.1 Search Strategy and Selection Criteria

The literature search was performed between December 2024 and January 2025 in the Scopus, Web of Science, ScienceDirect, and Google Scholar databases. The following words were used as keywords and Boolean operators: ("PLA" OR "polylactic acid") AND ("starch" OR "thermoplastic starch" OR "TPS") AND ("plant extract" OR "biomass extract" OR "essential oil" OR "phenolic" OR "flavonoid" OR "antimicrobial" OR "antioxidant") AND ("food packaging" OR "active packaging" OR "biodegradable packaging"). The review was conducted according to the PRISMA 2020 reporting guideline. The review protocol was not prospectively registered. The search was updated in December 2025 to capture recent publications; the search period therefore covers December 2024 to December 2025.

The inclusion criteria were: (1) peer-reviewed original research articles or reviews published from 2010 to 2025; (2) English language; (3) composites that contained both PLA and starch (or TPS) as matrix materials (these studies form the core corpus of the review); (4) use of plant-derived antimicrobial/antioxidant agents; (5) reporting of at least one property: antimicrobial activity, mechanical properties, thermal properties, barrier properties, or biodegradation properties; and (6) full-text availability. The following exclusions were applied: (1) studies that used synthetic antimicrobial agents only; (2) composites that did not contain both PLA and starch; (3) conference abstracts, patents, or theses; (4) studies that investigated only non-food applications.

2.2 PRISMA Workflow and Study Selection

The search yielded 847 initial records. After duplicate removal (n = 312), 535 titles and abstracts were screened. Of these, 312 were excluded based on the inclusion/exclusion criteria. Full-text assessment of 223 articles resulted in 91 publications meeting all inclusion criteria. The PRISMA flowchart below summarizes the selection process. The selection arithmetic is as follows: 847 − 312 (duplicates) = 535 records screened; 535 − 312 (excluded at title/abstract) = 223 full-text reports; 223 − 132 (excluded at full text: 48 + 35 + 28 + 12 + 9) = 91 included studies. The number 312 appears twice because the number of duplicates removed and the number of records excluded at screening happen to be equal; however, they are different sets of records.

Figure 4: PRISMA flow diagram

Figure 4, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram, provides a summary of the study selection process. The first database query resulted in 847 hits. A total of 535 records were screened by title/abstract, and 312 were excluded because they did not involve PLA/starch composites, antimicrobial activity, or food packaging applications. A total of 223 remaining full-text reports were assessed for eligibility. Of those, 132 were removed because they lacked both PLA and starch in the composite matrix (48), plant-derived extracts or antimicrobial agents (35), or food packaging applications (28); were conference abstracts or non-peer-reviewed articles (12); or were duplicate publications (9). Thus, 91 studies that fulfilled all the inclusion criteria were included in this systematic review.

2.3 Data Extraction and Synthesis

The following bibliographic information, composite composition and extract details, processing method, antimicrobial activity, mechanical properties, thermal properties, barrier properties, biodegradation, and food application results were recorded on a standardized data extraction form. Data were summarized in tabular form as quantitative data. When a study reported more than one concentration or composition, all reported values were extracted into the extraction sheet, which records the matrix composition, extract type, loading, processing method, and outcomes of each study included in the analysis. Where one value is given in the main-text tables, it is the value at the loading that the original authors chose for their main characterization (the optimum they identified), and it is reported with the loading and, wherever possible, the range tested. This approach avoids subjective selection by the review authors. Because of the heterogeneity of matrices, extracts, loadings, test organisms, and test methods (inoculum, contact time, assay type), the data were synthesized narratively, and the ranges quoted are descriptive ranges from

individual studies. Standard deviations were recorded where reported, and means were used for comparison. The data extracted from each included study are provided in Supplementary File.

2.4 Quality Assessment

The studies included in this review were assessed for methodological quality based on seven criteria: clearly stated objectives, an appropriate experimental design, an adequate number of replicates (≥3), the inclusion of suitable controls, appropriate statistical analysis, satisfactory presentation of results, and a discussion of study limitations. Each criterion was scored as 1 (met) or 0 (not met), yielding a total quality score ranging from 0 to 7 for each study. Studies meeting 6–7 criteria were classified as "high quality," those meeting 4–5 criteria as "medium quality," and those meeting ≤3 criteria as "low quality." For review articles, the replicate and control criteria do not apply; these were marked N/A and the thresholds were adjusted to high = 4–5, medium = 2–3, and low = 0–1. The assessment was conducted by a single assessor. Findings from low-quality studies were not used as the sole basis for drawing conclusions in this review. Of the 91 publications, 47 (51.6%) were rated high quality, 37 (40.7%) medium quality, and 7 (7.7%) low quality. The quality scores of each study are provided in Supplementary File.

3. PLA/Starch Composites: Synthesis, Processing, and Compatibility

3.1 Synthesis of PLA and Starch

PLA can be synthesized by the ring-opening polymerization of lactide or by the direct polycondensation of lactic acid (Farah et al., 2016). Lactic acid is found in two forms: L-lactic acid and D-lactic acid. Poly (DL-lactide) (PDLLA) is amorphous because the L/D ratio is more or less random, and it has a Tg of 50–60°C and no melting peak (Farah et al., 2016). The mechanical properties of PLA are related to its molecular weight (Mn of 50,000–200,000 g/mol), crystallinity, and stereochemistry.

Starch consists of linear amylose (20–30%, Mw 10^5–10^6 g/mol) and highly branched amylopectin (70–80%, Mw 10^7–10^8 g/mol). Amylose is helical and is able to complex lipids and iodine; amylopectin is branched and provides crystallinity. When heated with plasticizers above the glass transition temperature (60–70°C for corn starch), starch gelatinizes (swelling): it absorbs water into the granules, which swell to 5–10× their original size; the crystalline region is disrupted, and amylose is leached out (Jayarathna et al., 2022) (Onyeaka et al., 2022). When cooled, the amylose network creates a continuous matrix (retrogradation), but this recrystallization takes place over time. Retrogradation can be prevented by adding plasticizers, such as glycerol, which form hydrogen bonds with the hydroxyl groups on starch and keep it thermoplastic (20–40 wt%) (Jayarathna et al., 2022). Table 1 provides a concise comparison of PLA and starch properties relevant to composite formulation.

Table 1: Comparison of PLA and starch properties

The use of starch-based biodegradable films for food packaging applications has been the subject of several studies. (Jayarathna et al., 2022) presented a comprehensive review of starch-based blends and composites, their main problems of water sensitivity and poor mechanical properties, and discussed methods such as plasticization, reinforcement, and polymer blending to overcome these problems. In a study on antimicrobial packaging, (López-Pacheco et al., 2022) discussed the use of polysaccharides (starch, cellulose, chitosan) as biodegradable matrices and natural extracts and nanoparticles as antimicrobial agents. (Wang et al., 2024) investigated the use of food waste (brewer's spent grain, spent coffee grounds, sesame cake) as biomass for 3D-printed PLA formulations for controlled drug delivery, which indicates the potential of biomass-PLA composites.

3.2 Compatibility Challenges and Solutions

The incompatibility between hydrophobic PLA ($\delta \approx 20.5$ MPa$^{1/2}$) and hydrophilic starch ($\delta \approx 31.5$ MPa$^{1/2}$) is the major problem in PLA/starch composites (Jayarathna et al., 2022) (Ilyas et al., 2022). This incompatibility results in phase separation, poor adhesion at the interfaces, large starch aggregates (50–200 μm), decreased mechanical properties (tensile strength is often <10 MPa), increased water absorption, and impaired barrier properties (Jayarathna et al., 2022) (Ilyas et al., 2022). Table 2 summarizes the main compatibility enhancement strategies with their mechanisms and outcomes.

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Table 2: Compatibility enhancement strategies for PLA/starch composites

The most effective strategy combines multiple approaches. For example, PLA/starch composites containing 5 wt% maleic anhydride-grafted PLA and 3 wt% nanocellulose achieve a tensile strength of 25–35 MPa, approaching neat PLA values while maintaining accelerated biodegradation (Ilyas et al., 2022) (Nazrin et al., 2020).

Starch modification by chemical, physical, and enzymatic processes has been well studied with respect to the improvement of film properties for packaging applications. (Aaliya et al., 2022) fabricated a biodegradable composite film using talipot starch (Corypha umbraculifera L.) along with CMC and plant extracts (curry tree, neem, tulsi, and Mexican mint) that showed antimicrobial activity against S. aureus and E. coli and also reduced the water vapor permeability and oxygen permeability of the films. (Shi et al., 2022) investigated the effect of biomass (cellulose, hemicellulose, lignin, starch, wood flour, natural fibers) as nucleating agents on the crystallization behavior of PLA, which revealed that these green nucleating agents increase the crystallinity and thermal stability of PLA. A systematic review and meta-analysis of starch-based edible and biodegradable films for food packaging was conducted by (Sadeghizadeh-Yazdi et al., 2019), covering the mechanical properties, water vapor permeability, and biodegradability of the films. (Onyeaka et al., 2022) reviewed recent research on starch-based degradable films for packaging applications, including film formation, mechanical strength, barrier properties, and degradation. Biocomposite films made from PLA and cellulose were developed by (Gowsalya Venkatesan et al., 2024) for antimicrobial packaging applications in the food industry. Medicinal plants as natural antimicrobials have been used by (Ali et al., 2023) to prepare starch-based, environmentally friendly, edible antimicrobial films with a view to edible packaging systems.

Food packaging applications have led to the development of different PLA blends and composites to improve their antimicrobial and mechanical properties. (Natesan et al., 2022) prepared Schiff's base derivatives of phenylenediamine and vanillin and then incorporated them into PLA to enhance its toughness and antimicrobial activity. The PLA-p-SB composite had a lower glass transition temperature, was more hydrophobic, and showed 11–15 mm inhibition against S. aureus and P. aeruginosa. (Belkozhayev et al., 2025) created green coatings for PLA films using matrices based on chitosan and extracts of blackberry leaf and juniper needles, obtaining a reduction of S. aureus of 83–100% and an antioxidant activity of 83–95%. (Contessa et al., 2023) presented a review of agar-agar and chitosan as precursors for functional food films, highlighting their film-forming properties, mechanical strength, and antimicrobial activity. (Srisa et al., 2022) conducted a thorough review of polymeric packaging for antibacterial, antifungal, and antiviral applications in the post-COVID-19 era, with a focus on an active food packaging approach to improve food safety. (Vodnar et al., 2015) summarized the properties of edible film products and their antimicrobial effectiveness in the food industry, including the use of natural antimicrobial agents in biodegradable film matrices. Furthermore, (Jayarathna et al., 2022) and (Agarwal et al., 2023) a basic overview of PLA/starch composites and biopolymer packaging materials, respectively.

3.3 Processing Techniques

There are four main processing methods that are detailed in the literature; each have their own advantages and disadvantages.

The most frequent method used at the laboratory scale is solvent casting (65% of the reviewed studies). In this method, the solution is cast and dried after dissolving PLA in organic solvents (chloroform, dichloromethane, ethyl acetate) and dispersing the starch and extract in the same manner (Zemljič et al., 2022) (S. Sharma et al., 2022) (Díaz-Galindo et al., 2020) (Tagrida et al., 2022) (Soltani et al., 2025). The low processing temperature is a benefit, as is excellent dispersion, because heat-sensitive extracts are not affected by the thermal process. Its drawbacks are the slow processing speed (12–72 h), the use of toxic solvents, the presence of residual solvents in the films (0.5–2 wt%), and poor scalability (Radusin et al., 2019).

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The most common industrial method (used in ~30% of the reviewed studies) is melt blending and extrusion. This typically involves twin-screw extrusion at 150–190°C and 50–200 rpm, with residence times of 1–5 minutes (Farah et al., 2016) (Nazrin et al., 2020). Some benefits include solvent-free processing, scalable production, and compatibility with existing infrastructure. The disadvantages are the thermal degradation sensitivity of heat-sensitive extracts, high shear, and moisture sensitivity (pre-drying is needed) (Farah et al., 2016) (Nazrin et al., 2020).

Electrospinning (about 5% of the reviewed studies) produces nanofibres with diameters between 100 and 1000 nm and a very high surface area (10 to 1000 m^2/g). The benefits are good encapsulation and controlled release properties. The drawbacks are very low throughput (mg/hour), the use of organic solvents, and the poor mechanical properties of the resulting mats (Radusin et al., 2019).

In ~15% of studies, compression molding was used with melt-blended or solvent-cast materials at high temperatures (150–180°C) and pressures (5–15 MPa) for 2–10 minutes (Ilyas et al., 2022) (Farah et al., 2016). The benefits are good mechanical properties and thickness control. However, there are some drawbacks, such as batch processing and the limited production of thin films (<100 μm) (Farah et al., 2016).

For industrial translation, the most viable route is melt extrusion with the direct addition of the extracts, which should be thermally stable under the conditions of the melting process, either by using lower melting temperatures or by encapsulating the extracts to make them thermally stable (Farah et al., 2016) (Nazrin et al., 2020). The method percentages given above (65%, about 30%, about 5%, and about 15%) add up to more than 100%, presumably because some studies combined methods (for example, solvent casting followed by compression molding).

4. Plant Biomass Extracts: Sources, Bioactive Compounds, and Mechanisms

4.1 Major Plant Sources and Their Bioactive Compounds

Plant biomass extracts used in PLA/starch antimicrobial packaging derive from multiple plant parts, including fruit peels (pomegranate), leaves (olive, betel, blackberry), canes (grapevine), needles (juniper), roots (chicory), and rhizomes (turmeric). Table 3 summarizes the most frequently studied sources and their key bioactive compounds.

Table 3: Major plant biomass extracts and their bioactive compounds

TPC = total phenolic content; GAE = gallic acid equivalents; EO = essential oil

F/CNC-reinforced PLA, active packaging, and wound dressings, (Arabacı & Funda Arslanoğlu, n.d.) discussed the suitability of five medicinal-aromatic plants for these applications: Trachyspermum orientalis (hydrogel/wound dressing), Galium aparine (biocomposites), Borago officinalis (active packaging), Arum maculatum (biopolymers), and Crocus species (UV-protective/smart packaging). (Arman Alim et al., 2022) summarized non-biodegradable and biodegradable composites used in food packaging with regard to their mechanical properties, thermal stability, barrier properties, and antimicrobial properties. (Motelica et al., 2020) summarized the current trends in biodegradable antimicrobial food packaging materials such as polysaccharides, PLA, proteins, essential oils, and nanoparticles. (Zemljič et al., 2022) prepared antioxidant (83–100%) and antimicrobial (>95% reduction of S. aureus) chitosan coatings for PLA films using extracts from blackberry and juniper. (Korte et al., 2021) reviewed sustainable packaging made from plant-based polymers (PLA, PHA, starch, cellulose) and additives that can cut food waste. (Llana-Ruíz-Cabello et al., 2017) studied natural additives in PLA, such as oregano oil and Allium extract, which are C3 plant-based ($\delta^{13}C \approx -27‰$), and corn-based PLA ($\delta^{13}C \approx -9$ to $-17‰$). (Shao et al., 2022) summarized the latest developments in the field of antibacterial food packaging using natural antibacterial agents, such as essential oils, plant extracts, chitosan, and bacteriocins. (Varghese et al., 2023) reported the sustainable packaging of agro-waste (crop residues, fruit/vegetable wastes, wastes from farm animals) in the circular economy. (Mori, 2023) provided a

tutorial review on replacing petroleum-based chemical products with natural biomass-based ones, such as biodegradable plastics, coatings, plasticizers, and lubricants.

4.2 Extraction Methods: From Conventional to Green

Several extraction techniques have been employed. Table 4 compares the main methods with their key parameters.

Table 4: Comparison of extraction methods for plant biomass

Green score: 1=worst, 10=best based on solvent, energy, waste, safety

For antimicrobial packaging applications, ultrasound-assisted extraction provides the highest yield, the shortest time, and the greatest adherence to green chemistry principles (Freitas et al., 2023). For heat-sensitive volatile compounds (essential oils), supercritical CO_2 extraction is the most suitable method, but the yields are lower, and the cost is higher than that for polyphenols.

4.3 A Mechanistic Overview of Antimicrobial Mechanisms

The antimicrobial activity of plant biomass occurs through several mechanisms, which may be synergistic (Sarkhel et al., 2025) (Bose et al., 2023) (Pinto et al., 2023). It is essential to be aware of these mechanisms when rationally designing effective packaging materials.

Most phenolic compounds and essential oils work by disrupting cell membranes. Thymol, carvacrol, and eugenol are believed to interact with bacterial cell membranes through hydrogen bonding between their hydroxyl groups and the phospholipids in the membrane (Sarkhel et al., 2025) (Bose et al., 2023). This interaction alters the fluidity and integrity of the membrane, increasing its permeability. Significant leakage of ions and small metabolites takes place at MIC concentrations, and at higher concentrations (4–8× MIC), complete disintegration of the membrane occurs (Sarkhel et al., 2025) (Bose et al., 2023). Gram-negative bacteria are less susceptible (they require 2–4 times higher concentrations) because of an additional layer of lipopolysaccharide (LPS) in the outer membrane, which provides a permeability barrier to hydrophobic compounds (Novaković et al., 2018) (Sarkhel et al., 2025).

The second mechanism of action is enzyme inhibition. Essential bacterial enzymes such as DNA gyrase, dihydrofolate reductase, and ATP synthase are inhibited by polyphenols such as ellagic acid and gallic acid (Bose et al., 2023). This inhibition is caused by hydrogen bonding and hydrophobic interactions with the active sites of the enzymes, frequently at sub-MIC levels, and results in bacteriostatic instead of bactericidal activity (Sarkhel et al., 2025).

Oxidative stress induction: Reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide, and hydroxyl radicals are formed and induce DNA, protein, and lipid oxidative damage (Bose et al., 2023) (Pinto et al., 2023). The generation of ROS upon photoactivation is especially enhanced by curcumin from turmeric (Zende et al., 2025) (Hanafi et al., 2018).

Flavonoids and tannins that intercalate between base pairs of DNA and RNA inhibit DNA/RNA synthesis (Bose et al., 2023). Hydroxychavicol, a compound in betel leaf extract, exhibits strong DNA-binding activity (Tagrida et al., 2022).

Metal ion chelation refers to the binding of polyphenols to metal ions (iron, copper, magnesium) that are essential as cofactors for enzymes in bacteria (Sarkhel et al., 2025). This mechanism is most applicable to extracts that contain a high concentration of catechol and galloyl groups, such as olive leaf extract and pomegranate peel extract (S. Sharma et al., 2022) (Soltani et al., 2025).

Generally, Gram-positive bacteria are more susceptible than Gram-negative bacteria (e.g., S. aureus is more susceptible than E. coli or Salmonella spp.) because they do not have the outer membrane barrier. This disparity has generally been observed across studies; the MIC values of Gram-positive bacteria are generally 2–4× lower than those of Gram-negative bacteria for the same extract (Zemljič et al., 2022) (Tagrida et al., 2022) (Soltani et al., 2025).

The antimicrobial properties and biocompatibility of chitosan and its derivatives have great potential for application in antimicrobial packaging systems. Electrospun films of PLA with the addition of *Allium ursinum* L. were prepared by (Radusin et al., 2019). *Allium ursinum* L. (wild garlic) extract was found to exhibit remarkable antimicrobial activity against foodborne bacteria. (Syafiq et al., 2020) conducted an overview of starch-based biopolymer materials and biocomposites loaded with plant essential oils (clove,

oregano, cinnamon, lemongrass, thyme, peppermint, ginger) for use in food packaging with antimicrobial properties. (Salim et al., 2023) investigated the antimicrobial activity of catechins and nanochitosan on bacterial colonies in PLA/PCL blend packaging films, which showed the effectiveness of the materials in controlling bacteria and enhancing the performance of the packaging films. The comparative antimicrobial activity of plant extracts against Gram-positive and Gram-negative bacteria is illustrated in Figure 5.

Figure 5: Antimicrobial activity comparison (Gram-positive vs. Gram-negative)

4.4 Molecular-Level Mechanisms: From Free Extract to Active Film

The mechanisms in Section 4.3 describe how extract compounds act on microbial cells when the extract is free in solution, which is the situation measured by MIC assays (Bose et al., 2023) (Brobbey et al., n.d.). In a packaging film, activity is the result of three coupled steps (Figure 6): (i) the interaction of the extract with the polymer matrix, which determines how much active compound is retained and how much is available for release; (ii) transport of the compound to the film–food interface and into the food; and (iii) the action of the released compound on the microbial cell.

Membrane interaction. The membrane activity of phenolic compounds depends on their amphiphilicity. Compounds of intermediate lipophilicity, such as the allylphenols (hydroxychavicol and eugenol), partition into the phospholipid bilayer, where the phenolic hydroxyl group lies near the polar head groups and the hydrophobic part lies among the acyl chains. This disorders lipid packing, increases membrane fluidity and permeability, dissipates the proton motive force, and causes leakage of K^+ and ATP, which impairs ATP synthesis (Bose et al., 2023) (Pinto et al., 2023). Large, highly hydroxylated molecules such as punicalagin or tannic acid partition poorly into the bilayer. They act mainly at the cell envelope, by binding and cross-linking surface proteins, and by complexing the divalent cations (Mg^{2+}, Ca^{2+}) that stabilize the lipopolysaccharide (LPS) layer of Gram-negative bacteria. Their size limits passage through porins, which is one reason why they are generally less effective against Gram-negative organisms unless the outer membrane is first destabilized (Novaković et al., 2018) (Sarkhel et al., 2025). Efflux pumps give further protection to Gram-negative bacteria, and inhibition of efflux by some plant phenolics has been proposed as a way of lowering the MIC of other compounds, but this has not been demonstrated in PLA/starch films.

Intracellular targets and redox effects. Polyphenols such as ellagic and gallic acid have been reported to inhibit enzymes including DNA gyrase and dihydrofolate reductase through hydrogen bonding with active-site residues and hydrophobic contacts, which usually gives bacteriostatic rather than bactericidal action (Bose et al., 2023) (Sarkhel et al., 2025). Catechol and pyrogallol groups, which are present in gallic acid, tannins, and oleuropein-derived compounds, can autoxidize in the presence of transition metals to give hydrogen peroxide and semiquinone radicals. The same structural motif can therefore be an antioxidant in the film (radical scavenging) and a pro-oxidant in a culture medium (hydrogen peroxide generation), which is a known artifact of in vitro assays. Chelation of Fe and Cu limits the metal cofactors available to bacterial enzymes. The net effect depends on pH, metal content, and the matrix, which is another reason why MIC data do not transfer directly to food.

Interactions with the polymer matrix. In PLA and TPS films containing phenolic additives, hydrogen bonding between phenolic –OH groups and starch hydroxyl groups is generally inferred from shifts and broadening of the O–H stretching band near 3300 cm^{-1} in FTIR spectra, and bonding to the PLA ester carbonyl is inferred from shifts of the C=O band near 1750 cm^{-1} (Hernández-García et al., 2022) (Ordoñez et al., 2022) (Tawakkal et al., n.d.). Phenolic compounds can also form V-type inclusion complexes with amylose helices. Because PLA is hydrophobic ($\delta \approx 20.5$ MPa^1/2) and starch is hydrophilic ($\delta \approx 31.5$ MPa^1/2), a polyphenol of intermediate polarity with several hydroxyl groups can in principle sit at the interface and act as a weak compatibilizer, while the hydrophobic fraction (terpenes, essential oils) tends to remain in the PLA phase and the polar fraction (glycosides, sugars) in the starch/glycerol phase. The active compound is therefore distributed unevenly between the phases, and its

concentration at the film surface may differ from the nominal loading. These interactions are inferred mainly from spectroscopic data and need to be confirmed by molecular simulation (Section 10.3). Natural additives can also act as nucleating agents for PLA (Shi et al., 2022) (Zhu et al., 2024), which links the matrix interaction in step 1 of Figure 6 to the crystallinity and barrier effects discussed in Section 7.2.

Release and transport. Release from a film into a food or food simulant is controlled by diffusion in the polymer, polymer relaxation and swelling, and partitioning between film and food. In glassy PLA (Tg about 55–65 °C), the diffusion of large polyphenols is slow at refrigeration temperature, whereas in a glycerol-plasticised, moisture-swollen starch phase it is faster, which may explain the burst release (60–80% in 24–48 h) noted in Section 10.3 (Vasile & Baican, 2021). Release is often described by Fick's second law or by the Peppas–Sahlin equation, in which the release exponent separates Fickian diffusion from relaxation-controlled transport. An extract that plasticises PLA and lowers Tg (Section 7.1) may therefore raise the release rate, and hence antimicrobial activity, while lowering strength; this couples the antimicrobial and mechanical results of this review. Contact-dependent or volatile-phase activity (for example thymol, Table 5) should also be distinguished from activity that depends on migration of the compound into the food, because only the latter is subject to migration limits (Section 10.2; (Vieira et al., 2022)).

Implication for reporting. MIC (mg/mL of free extract) and film activity (inhibition zone or log reduction) therefore answer different questions. To allow a film result to be related to an extract result, each study should report the loading (wt%), the release profile in a food simulant, the MIC of the extract against the same strain, and the film assay used (such as ISO 22196 for plastic surfaces, or a challenge test in the food). Figure 6 summarizes this logic: the same extract can give a low MIC (step 3) yet a weak film result if it is strongly retained by the matrix (step 1) or released slowly (step 2), and conversely a plasticising extract can give a strong film result at the cost of mechanical integrity. This framework is used in the remainder of the review to interpret the antimicrobial results in Section 5, the mechanical results in Section 6, and the barrier results in Section 7, and it motivates the modelling workflow in Section 10.3.

Figure 6: Conceptual scheme linking extract–matrix interaction, release and action on the microbial cell

5. Antimicrobial Efficacy of PLA/Starch Composites with Plant Extracts

5.1 Antibacterial Activity

Numerous studies have demonstrated significant antibacterial activity of PLA/starch composites incorporating plant extracts. Table 5 summarizes representative results.

Table 5: Antibacterial activity of PLA/starch composites with plant extracts

The extract-level MIC values reported in the cited studies lie between 1.25 and 3.0 mg/mL (pomegranate peel 2.5–3.0 mg/mL; chicory root 1.25–2.5 mg/mL; Table 5). MIC is a property of the free extract determined in liquid culture, whereas the activity of a film is measured as an inhibition zone, a percentage inhibition, or a log reduction, which also depends on release from the matrix (Section 4.4). The two types of value are not interchangeable, and they are reported separately below. At medium concentrations (5–8 wt%), composites containing pomegranate peel or olive leaf extract generally demonstrate the largest inhibition zones (16 mm or more) (Dai et al., 2022) (Soltani et al., 2025). Betel leaf extract can generate inhibition zones of 9–11 mm against four pathogens at a concentration of 2 wt%, largely owing to its high potency (Tagrida et al., 2022). Grapevine cane extract shows more moderate activity (35% inhibition); however, it has antiadhesive properties, which prevent the attachment of bacteria to food surfaces (Díaz-Galindo et al., 2020).

A non-monotonic dose–response was reported in some of the cited studies: activity improves with increasing concentration until a maximum is reached (usually 5–10 wt%), after which a continued increase results in less activity, or even a decrease in activity, as the extract aggregates and bioavailability decreases (S. Sharma et al., 2022) (Soltani et al., 2025) (Dai et al., 2022). This optimum concentration corresponds to the point of maximum dispersion of the extract without appreciable aggregation in the

polymer matrix. It is a qualitative observation based on a small number of studies with different matrices, extracts, and assays, and not a pooled estimate. A quantitative (meta-analytic) test of the optimum loading is not possible with the data currently available, because most studies tested only two or three loadings. The explanation based on aggregation is plausible, but has rarely been verified by microscopy or particle-size measurements. The antimicrobial readouts of each extract are set alongside their mechanical and barrier effects in Section 7.4, and the mechanisms that link extract concentration to film activity are summarized in Figure 6.

5.2 Antioxidant Activity

The PLA/starch composites also possess considerable antioxidant properties, as shown by the plant extracts. At 8 wt% loading, olive leaf extract is able to scavenge >90% of DPPH and ABTS (Soltani et al., 2025). Betel leaf extract shows values of 93.5 TE (DPPH) and 2817 TE (FRAP) at 2 wt% (Tagrida et al., 2022). Blackberry/juniper mixtures achieve 83–100% scavenging (Zemljič et al., 2022). In particular, lignin nanoparticles (Sun et al., 2023) and ferulic acid (Hernández-García et al., 2022) (Ordoñez et al., 2022) show relatively high antioxidant activity, often above 90% inhibition at moderate concentrations (1–3 wt%).

The antioxidant activity of plant extracts is also similar to their antibacterial activity, and extracts with high total phenolic content (TPC) tend to have high antioxidant activity, but no linear relationship has been found. The TPC values of betel leaf extract and chicory root extract were 150–300 and 60–120 mg GAE/g, respectively, indicating that betel leaf extract exhibited higher antioxidant activity than chicory root extract. This implies that the types and total amount of the phenolics present are both important. The DPPH and ABTS radical scavenging activities of PLA/starch composites incorporating various plant extracts are compared in Figure 7.

Figure 7: Antioxidant activity comparison (DPPH, ABTS)

5.3 Antifungal Activity

Less research has been done on antifungal applications, but they are promising. Botrytis cinerea (gray mold) is a post-harvest pathogen of fruits and vegetables that is suppressed by 15–35% with a loading of 10–15% grapevine cane extract (Díaz-Galindo et al., 2020). Chicory root extract in starch films showed low growth inhibition of fungi overall, particularly of the yeast Candida albicans, whereas the effect on Aspergillus niger was more pronounced at 5% extract (Jaśkiewicz et al., 2020). Cinnamon oil and clove oil inhibit the sporulation of Penicillium, Rhizopus, and Aspergillus species, but are usually used in smaller quantities (0.5–2%) because of their strong sensory effects (Zende et al., 2025).

6. Mechanical Properties of PLA/Starch Composites with Plant Extracts

6.1 Tensile Properties

The addition of plant extracts generally affects mechanical properties in a concentration-dependent manner. Table 6 compares representative systems. The rows of Table 6 come from different matrices (PLA, a PLA/PBAT blend, and a nanofiber-coated PLA film) and different test conditions, so comparisons between rows are indicative only; the matrix and loading of each value are given in Section 7.4.

Table 6: Mechanical properties of PLA/starch composites with plant extracts

Some important patterns are apparent. First, concentrations above 8–10 wt% tend to decrease tensile strength as a result of plasticizing effects and decreased polymer crystallinity (Soltani et al., 2025) (Díaz-Galindo et al., 2020). In most cases, however, such a reduction results in an increase in elongation. For example, a 10 wt% loading of tannic/gallic acid in a PLA/PBAT blend reduced the strength to 8.6 MPa while increasing the elongation to 23.5%, making the film more flexible (S. Sharma et al., 2022). The sources compiled here do not report mechanical data for pomegranate peel extract in PLA, because the pomegranate peel study combined the extract with nano-ZnO and was concerned mainly with antimicrobial performance (Dai et al., 2022); this system is therefore shown as not reported in Table 6 and

in the comparison in Section 7.4. The strength–elongation trade-off of the four systems for which both values are available is examined in Section 7.4. Second, nanoparticles can be used to reinforce the composites, and this is the most important method for preventing the loss of strength, which was increased by 40–80% compared with non-reinforced composites (Nazrin et al., 2020) (Sun et al., 2023). Third, betel leaf extract at the lower concentration (2 wt%) showed significantly higher strength retention (34.5 MPa), but because this value was obtained for a PLA film coated with electrospun gelatin/chitosan nanofibers containing the extract (a contextual, non-PLA/starch system), the retention of strength may reflect the coating architecture and not better compatibility of the extract with a PLA/starch matrix; no conclusion on compatibility should be drawn (Tagrida et al., 2022). The influence of extract concentration on the tensile strength of PLA/starch composites is illustrated in Figure 8.

Figure 8: Effect of extract concentration on tensile strength

6.2 Factors Affecting Mechanical Properties

The dominant mechanical behavior factors are: (1) the concentration of the extract, which generally reduces strength and modulus, although the addition of plasticizers can increase the latter in some TPS formulations due to plasticizing effects; (2) the content of plasticizers, such as glycerol and sorbitol, which increases the free volume and chain mobility, thus increasing the elongation (up to 400% in some TPS formulations) but reducing the strength (Jayarathna et al., 2022) (Sadeghizadeh-Yazdi et al., 2019); (3) the addition of nanoparticles, which, if incorporated into the polymer matrices, generally improves interfacial adhesion and increases both strength and modulus (Nazrin et al., 2020) (Sun et al., 2023); and (4) the addition of compatibilizers, such as maleic anhydride-grafted PLA, which generally increases strength by 30–50% due to improved interfacial adhesion (Jayarathna et al., 2022) (Ilyas et al., 2022).

These factors are interdependent. For instance, higher plasticizer content results in greater flexibility, but the film has a higher tendency to lose strength with the addition of extracts. On the other hand, the use of both a compatibilizer and nanoparticles can maintain strength at high extract loadings (10–15 wt%) (Nazrin et al., 2020) (Sun et al., 2023).

Cellulose and nanocellulose have been found to be promising reinforcing materials for PLA/starch composites. Natural plant extracts (sea buckthorn leaves and pine bark) were used to coat paper as an antimicrobial packaging material, and (Brobbey et al., n.d.) found that the sea buckthorn extract maintained its antibacterial activity when used as a packaging coating material. The renovation and valorization of agro-waste (crop residues, fruit and vegetable wastes, animal wastes) for sustainable food packaging was reviewed by (Surendren et al., 2022), and the principles of the circular economy were emphasized. (Shoba et al., 2025) provided a detailed comparison of nonbiodegradable and biodegradable composites used for food packaging in terms of their mechanical strength, thermal stability, barrier properties, and antimicrobial activity. The biopolymer applications in nanoscience and nanotechnology reviewed by (Mohan et al., 2016) included starch, cellulose, chitin, chitosan, PLA, and PHA for packaging and biomedical applications. Beyond packaging, (Chen et al., 2021) explored the purification of medicinal plant extract for the removal of heavy metals (Cd^{2+}) using modified thermoplastic starch blends with PLA. To develop a sustainable route to reinforced biofilms, (De Nino et al., 2025) developed a catalytic transesterification of cellulose nanocrystals with waste oils and subsequently reinforced PLA with CNCs to create reinforced biofilms for packaging.

6.3 Nanotechnology-Enhanced Composites

Improvements in the performance of PLA/starch composites for antimicrobial packaging have been made with the help of nanotechnology (Souza et al., 2022). (Piryaei et al., 2025) produced PLA/nano-chitosan/iron nanoparticle films using a green synthesis process, which showed enhanced antioxidant and antibacterial properties. (Perera et al., 2022) compiled information about the modification of food packaging surfaces, antimicrobial sterilization, and barrier properties. Another extensive book on biopolymer-based bionanocomposites and hybrid materials for advanced applications was edited by (Ilyas et al., n.d.). (Estrada-Sotomayor et al., 2025) converted grass biomass into sustainable antimicrobial

bioplastics through alkaline hydrolysis and ε-polylysine as a plasticizer, which showed lower GHG emissions than conventional plastics when measured by LCA. (Nguyen Ngoc Son et al., 2025) prepared PLA/PVA/Ag nanocomposite films by ultrasound-assisted chemical reduction that exhibited a tensile strength of 5.77 MPa (20% higher than PLA) and also exhibited broad-spectrum antimicrobial properties against B. subtilis, E. coli, and S. cerevisiae. (Bruna et al., 2015) studied the antibacterial activity of nanocomposites based on MtCu and PLA that resulted in a 99% reduction of E. coli and L. innocua. (Lombardi et al., 2022) discussed natural active ingredients (polyphenols, essential oils, plant extracts) for PLA-based materials, their state of the art, and future perspectives. (Abdul Malek et al., 2025) reviewed the development of synergistic PLA-based nanocomposites containing nanofillers combined with antimicrobial agents such as metal/metal oxide nanoparticles, plant extracts, essential oils, and carbon nanomaterials for sustainable fruit packaging.

7. Thermal and Barrier Properties

7.1 Thermal Stability

PLA-based composites are thermally stable up to 200–250°C, which is enough for processing in the food packaging industry (typical processing temperature 150–190°C) (Soltani et al., 2025) (Díaz-Galindo et al., 2020). Neat PLA degrades with T_5% (5% weight loss) at 304–331°C and T_{max} at 350–370°C (Farah et al., 2016). Blends of PLA/starch have slightly lower thermal stability (T_5% 297–304°C) as a result of the lower thermal stability of starch (Díaz-Galindo et al., 2020). For most composites, the extracts only slightly decrease thermal stability. The glass transition temperature (Tg) of neat PLA is in the region of 55–65°C and is often decreased from 55–65°C (neat PLA) to ~40°C (composite), which can be interpreted as meaning that the extracts plasticize the PLA phase. These values are tolerable for packaging applications (which are used at refrigeration or ambient temperature), but may cause changes in dimensional stability at higher temperatures (Farah et al., 2016).

7.2 Barrier Properties

Barrier properties are critical for food packaging applications, particularly water vapor permeability (WVP) for moisture-sensitive foods and oxygen permeability for oxidation-sensitive foods. Table 7 summarizes key findings.

Table 7: Barrier properties of PLA/starch composites with plant extracts

The decrease in WVP for some extracts (olive leaf, grapevine cane, betel leaf) is counterintuitive, since hydrophilic extracts might be expected to enhance water absorption and permeability. The observed decrease is believed to be due to: (1) the more dispersed distribution of extract particles, which increases the tortuosity of the diffusion path; (2) decreased free volume, because of hydrogen bonding interactions between starch hydroxyl groups and the extract particles; and (3) a nucleating effect of the extract on PLA crystallization, because the higher the crystalline fraction, the lower the diffusivity of water vapor (Shi et al., 2022), which should be confirmed by DSC or XRD in each study. Reduced WVP is expected at low and intermediate loadings of the hydrophilic extract components, while at higher loadings, plasticization and phase separation might be expected to raise WVP. Figure 9b and Table 8 (Soltani et al., 2025) (Tagrida et al., 2022) compare the barrier properties reported in individual studies.

The oxygen permeability of a PLA film treated with electrospun gelatin/chitosan nanofibers was reported to decrease by 70% when the concentration of betel leaf extract added to the film was increased from 0 to 2 wt% (Tagrida et al., 2022). The barrier effect can thus be partly attributed to the coating layer and not the extract itself. The absolute permeability values and the test humidity and temperature are not given here, and thus no comparison is possible with high-barrier polymers such as EVOH, whose oxygen barrier is impaired significantly at higher relative humidity.

7.3 Optical Properties and UV Protection

The extracts obtained from such vegetable materials give them a characteristic color. Olive leaf extract is yellow-green, betel leaf extract is yellow-brown, chicory root extract is brown, and grapevine cane extract is yellow. These colors can influence the acceptance of a food product (Tagrida et al., 2022) (Soltani et al., 2025). More importantly, extracts offer substantial UV protection. Tannic acid incorporated in a

PLA/PBAT blend gave a 65–66% UV block (S. Sharma et al., 2022). Lignin nanoparticles provide excellent UV protection (close to 100% in the UV-B range) and are transparent to visible light (Sun et al., 2023). The UV-blocking effect is especially advantageous for the preservation of light-sensitive foods (such as dairy products, oils, and certain fruits) from photo-oxidation, which can result in off-flavors, nutrient degradation, and color changes (Tagrida et al., 2022) (Soltani et al., 2025).

7.4 Integrated Comparison of Extracts: Barrier versus Mechanical Performance

Sections 5 to 7 treated antimicrobial, mechanical, and barrier performance separately. Because packaging design depends on how these properties trade off against each other, Table 8 consolidates, for each extract, the matrix, loading, antimicrobial readout, mechanical properties, and barrier properties reported in the cited studies, and Figure 9 plots the mechanical trade-off (panel a) and the barrier gains (panel b). All values are taken from Tables 5–7 and from the studies cited there; "n.r." means not reported in the cited source and "n.q." means reported but not quantified. The two baseline rows give the reference ranges for neat PLA (Farah et al., 2016) and for unmodified PLA/starch blends (Jayarathna et al., 2022) (Ilyas et al., n.d.), against which the extract systems should be read. Because the matrices differ between rows, and because each value comes from a single study, Table 8 and Figure 9 are intended to show trends and trade-offs and not to rank extracts.

Strength. None of the extracts retains the strength of neat PLA (50–70 MPa). Relative to that range, the reported strengths correspond to about 12–17% for tannic/gallic acid in PLA/PBAT (S. Sharma et al., 2022), 23–32% for olive leaf extract (Soltani et al., 2025), 28–39% for grapevine cane extract, and 49–69% for betel leaf extract in a coated PLA film (Tagrida et al., 2022). Figure 9a shows that three of the four systems fall within or below the strength range of unmodified PLA/starch blends (10–30 MPa), so the extracts reduce strength to the level of a starch-containing blend while adding antimicrobial and antioxidant functionality. This is consistent with the mechanisms in Section 4.4: phenolic compounds that plasticise PLA and disturb its crystallinity lower the modulus and strength, and extract aggregates act as stress concentrators at higher loadings (Section 6.1).

Ductility. Figure 9a also shows that the systems separate into two groups. Olive leaf extract (WVP −55%) leaves elongation at about 4%, within the range of neat PLA, whereas grapevine cane extract (37.6%) and tannic/gallic acid (23.5%) raise elongation by roughly an order of magnitude, and betel leaf extract gives an intermediate 7%, with the best strength retention. High elongation is therefore obtained at low strength (tannic/gallic acid, 8.6 MPa), which is the usual plasticisation trade-off, whereas the combination of moderate strength and moderate elongation seen in the betel leaf system may reflect the nanofiber coating and not the extract itself (Section 6.1).

Barrier performance. Figure 9b compares the barrier gains: a 55% reduction of WVP for olive leaf and for grapevine cane extract, a 70% reduction of oxygen permeability for betel leaf extract in the coated film, and 65–66% UV blocking for tannic acid. These are different properties measured in different matrices and cannot be added or ranked, but they show that each extract contributes mainly one barrier function. Olive leaf and grapevine cane extracts, which are the most effective against water vapor, may reach this effect through their phenolic content and an associated increase in crystallinity (Section 7.2; (Shi et al., 2022)), whereas the UV protection of tannic acid follows from its strong absorption of UV light (Section 7.3). Taken with Figure 9a, the barrier gains are not accompanied by gains in strength, and no extract in Table 8 maximises strength, ductility, and barrier performance at the same time. The choice of extract should therefore be matched to the application: for example, olive leaf or grapevine cane extract for moisture-sensitive products in rigid trays, tannic acid for light-sensitive products in flexible films, and betel leaf extract in a coated film where oxygen is the main spoilage factor.

Antimicrobial data and the limits of the evidence. The antimicrobial columns of Table 8 show that the extracts for which mechanical and barrier data exist (olive leaf, grapevine cane, betel leaf, tannic/gallic acid) are characterized by film-level readouts (inhibition zones, percentage inhibition, shelf-life), whereas the extracts characterized by MIC (pomegranate peel, chicory root) have no mechanical or barrier data in the sources compiled here. This gap prevents a direct comparison of antimicrobial potency, strength, and barrier effect for any single extract, and it is a concrete target for future studies (Section 10.3). Finally, none of the extract-containing systems in Table 8 combines PLA and starch: they are PLA, PLA/PBAT,

coated PLA, or starch films, so the quantitative evidence for plant extracts in PLA/starch composites is thinner than the scope of this review implies. The PLA/starch literature supplies the matrix-level information (compatibility, biodegradation, and processing; Sections 3 and 8), and the extract literature supplies the functional data; combining the two in a single, well-characterized system remains to be done (Surendren et al., 2022) (Shao et al., 2022).

Table 8: Comprehensive comparison of extracts, loadings and their effects on antimicrobial, mechanical and barrier properties

Figure 9: Synthesis of (a) the strength–elongation trade-off and (b) the barrier gains reported for the extract systems in Table 8

8. Biodegradation Studies

8.1 Degradation Rates and Conditions

PLA/starch composites with plant extracts show enhanced biodegradation compared to neat PLA. Table 9 summarizes degradation behavior under different conditions.

Table 9: Biodegradation of PLA/starch composites with plant extracts

There are a few salient points to note. First, neat PLA is a slow degrader even under the best composting conditions (180 days at 58°C), and even slower (12–24 months) in soil or marine environments (X. Li et al., 2023) (Farah et al., 2016). Second, degradation is substantially faster when starch is added because starch is easily degraded and consumed by microorganisms, which leaves pores and channels for further degradation of PLA (Jayarathna et al., 2022) (Manabu Abe, n.d.). Third, degradation is accelerated even further for hydrophilic extracts such as olive leaf extract or tannic acid, but might be slowed for hydrophobic extracts such as essential oils because of the antimicrobial activity of the extracts against the microorganisms that degrade them (Soltani et al., 2025) (Sousa et al., 2025). Fourth, the composting conditions of high humidity, active microbial population, and 58°C (warmer than ambient) produce faster degradation than the soil burial conditions of variable moisture and ambient temperature (Manabu Abe, n.d.). The comparative degradation profiles of PLA/starch composites under composting and soil burial conditions are presented in Figure 10.

Figure 10: Biodegradation over time (compost vs. soil)

8.2 Factors Affecting Biodegradation

The degradation rates are controlled by five parameters: (1) starch content; the higher the content, the faster the degradation due to increased hydrophilicity and greater access for microorganisms; (2) crystallinity; the higher the crystallinity, the slower the degradation, because the chain mobility of PLA is reduced and the entry of water and microorganisms is hindered; (3) extract hydrophilicity; the more hydrophilic the extract is, the more water is absorbed and the faster the degradation; (4) compost temperature; degradation is faster when the temperature is in the range of 50–60°C because hydrolysis conditions and microbial activity are enhanced when the temperature is near the Tg of PLA, allowing greater mobility of the polymer chains; (5) soil moisture; degradation is faster above 30% moisture, as these are better conditions for microbial growth and hydrolysis (Jayarathna et al., 2022) (Farah et al., 2016) (Soltani et al., 2025) (Sousa et al., 2025) (Shi et al., 2022) (Manabu Abe, n.d.).

9. Food Preservation Applications

9.1 Overview of Real-Food Studies

Real-food validation is essential for translating lab-scale films to practical packaging. Table 10 summarizes representative applications across food categories.

Table 10: Food preservation applications of PLA/starch composites with plant extracts

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The valorization of food waste has been identified as one of the sustainable methods for the production of antimicrobial packaging materials. (Todhanakasem et al., 2022) produced an active thermoplastic starch film containing watermelon rind extract, which showed antioxidant and antimicrobial activities for biodegradable food packaging. (Muche et al., 2022) prepared an active packaging film using starch and root extract of Plumbago zeylanica (Amira) in which the extract (200 mg/mL) gave inhibition zones of 13.5 mm for S. typhi, 10.5 mm for S. aureus, and 27 mm for A. niger. (Darie-Niță et al., 2021) designed materials for ecological packaging based on PLA combined with bio-plasticizers and chitosan modified with rosehip seed oil. (Muche et al., 2022) optimized a starch-based active packaging film containing Plumbago zeylanica root extract, which resulted in optimum conditions for antimicrobial activity (glycerol/starch ratio 1.5, 1.5 g extract, 0.5 mm thickness). (Freitas et al., 2023) prepared active PLA films using aqueous extracts from rice straw (subcritical water extraction at 180°C) for meat preservation, which were effective for 16 days of pork quality preservation. (Thermo-Mechanical, Morphological and Water, n.d.) found that the water absorption, morphological, and thermo-mechanical properties of thermoplastic starch/cellulose foam composites containing PLA were enhanced by increasing the PLA content.

9.2 Meat, Poultry, and Seafood Preservation

In the case of meat products, rice straw extract, when used in PLA composites, preserved the quality of pork products (color, odor, and microbial levels) for a period of 16 days at 4°C, while the control packages preserved quality for 5–7 days (Freitas et al., 2023). Betel leaf extract improved the shelf-life of tilapia slices from 3 to 9 days at 4°C and decreased the total viable counts by 3 log CFU/g while inhibiting Pseudomonas and Shewanella growth (Tagrida et al., 2022). Both green tea polyphenols and oregano/cumin oils increased the shelf-life of beef and chicken by 2–3× compared with controls (Zende et al., 2025).

9.3 Fruit and Vegetable Preservation

Cherry tomatoes stored in the film made with olive leaf extract showed no fungal growth after 21 days at 4°C, and mold counts were below the detection limit during the storage period (Soltani et al., 2025). Tomato quality was also preserved for 20 days in tannic/gallic acid formulations when stored at room temperature, which is a challenging condition for perishable produce (S. Sharma et al., 2022). Chitosan/extract blends and PLA-based films extended the shelf-life of strawberries, grapes, and mushrooms (Motelica et al., 2020) (Zende et al., 2025) (H. Li et al., 2022).

10. Research Gaps and Future Opportunities

10.1 Identified Research Gaps

Analysis of all 91 publications reveals ten major research gaps, summarized in Table 11 with priority rankings.

Table 11: Summary of research gaps and future opportunities

10.2 Critical Analysis of Current Limitations

There are three systemic limitations that need to be highlighted, in addition to the above gaps. Most studies report their antimicrobial activity under idealized in vitro conditions (liquid media, high inoculum, direct contact) and not in actual food matrices, where fat, protein, and water content can bind, partition, or degrade the active compounds. Second, there is considerable variation in the methods used for testing, including different inoculum sizes (10^3 to 10^8 CFU/mL), contact times (1 hour to 14 days), temperature ranges (4°C to 37°C), and activity measures (zone of inhibition, log reduction, MIC). Third, there are very few migration studies – less than 15% – that are performed according to standardized migration tests as recommended by the FDA or EFSA; these data are important for regulatory approval. The proportions quoted here (fewer than 15% for migration testing and fewer than 5% for pilot scale) correspond to at most 13 and 4 of the 91 studies, respectively. Migration testing is the step that links the release behavior discussed in Section 4.4 (Figure 6, step 2) to regulatory acceptance, so its absence in most studies means

that the antimicrobial results in Tables 5 and 8 cannot yet be converted into compliance with migration limits (Vieira et al., 2022).

10.3 Future Perspectives

Based on the analysis of 91 publications, six key future directions emerge:

1. Advanced encapsulation technologies. Volatile active ingredients may be protected and released over a period of time via nanoencapsulation, microencapsulation, and liposome technologies (Sarkhel et al., 2025). Current burst-release profiles (60–80% release in 24–48 hours) need to be further extended over days or weeks to meet product shelf-life requirements. In preliminary studies, encapsulation in cyclodextrins, chitosan nanoparticles, and zein microspheres has proven to be promising.

2. Synergistic extract combinations. The potential of using different plant extracts in combination for synergistic and additive effects is underexplored (Pinto et al., 2023). Initial testing indicates that mixtures of agents that target different parts of the bacterial cell (e.g., a cell wall-degrading enzyme inhibitor and a membrane-disrupting phenolic) may be effective at lower concentrations per agent, which would lower both cost and sensory impact.

3. Smart and intelligent packaging. The next step (Korte et al., 2021) (Hu et al., 2023) is the combination of pH indicators, time-temperature indicators, and freshness sensors with antimicrobial properties. Early prototypes are based on anthocyanin colorimetric sensors (red at acidic pH, blue and purple at neutral pH) and PLA matrices, but stability (anthocyanins degrade within weeks) and reversibility are still challenges.

4. Green extraction methods. Sustainable recovery of bioactive compounds can be achieved by using supercritical CO_2, subcritical water, and enzyme-assisted extraction (Soltani et al., 2025) (Freitas et al., 2023). Cost reduction and process intensification, especially for subcritical water extraction, which requires high-pressure equipment, are required for industrial use.

5. Computational modeling. Computational modeling is almost absent from this field, and it is where a large gain in efficiency can be expected, as the number of possible combinations of extract, polymer ratio, compatibilizer, and plasticizer is too large to explore experimentally. A multiscale workflow is proposed (Table 12). (i) Quantum-chemical (DFT) calculations of the interaction energies between representative extract constituents (e.g., punicalagin, oleuropein, hydroxychavicol, tannic acid) and PLA and starch repeat units, to rank hydrogen-bond strength and to predict FTIR shifts that can be compared with measured spectra. (ii) All-atom molecular dynamics of PLA/TPS/glycerol/extract systems to calculate the Flory–Huggins interaction parameter, cohesive energy density, Hansen solubility parameters (extending the values for PLA and starch in Section 3.2), interfacial adhesion energy, Tg, and the diffusion coefficients of extract compounds as functions of water and plasticizer content; coarse-grained or dissipative-particle-dynamics models can then address phase morphology and the aggregation of extract above the optimum loading. (iii) Continuum models: Fickian and Peppas–Sahlin release models with moisture-dependent diffusivity solved by finite elements, tortuosity-based models for WVP and O_2 permeability, and micromechanical models (for example, Halpin–Tsai) for modulus, which can be coupled to microbial growth models to predict shelf life in food. (iv) Cell-level simulations: free-energy (umbrella-sampling) calculations of the permeation of phenolics through model Gram-positive and Gram-negative membranes, and docking followed by MD refinement for targets such as DNA gyrase and dihydrofolate reductase. (v) Data-driven models: QSAR and machine-learning models (for example, Gaussian processes, random forests, graph neural networks) trained on standardized datasets, with Bayesian optimization or active learning to choose the next formulation. These models need complete, machine-readable data, so the extraction of all reported loadings (Section 2.3) and the routine reporting of release curves are prerequisites. Every model should be paired with a defined validation experiment (Table 12) and its uncertainty reported.

Table 12 sets out how the five levels fit together. The electronic and atomistic levels address step 1 of Figure 6 (extract–matrix interaction): interaction energies and diffusion coefficients computed for ferulic acid or other phenolic acids in PLA and starch (the systems studied experimentally by (Hernández-García et al., 2022) (Ordoñez et al., 2022) and for thymol in PLA (Tawakkal et al., n.d.) can be compared directly with FTIR, DSC and sorption data, and the nucleating effect of biomass additives on PLA (Shi et

al., 2022) (Zhu et al., 2024) can be examined by simulating chain packing near the additive surface. The continuum level addresses step 2: release curves obtained from the atomistic diffusion coefficients can be checked against release measurements in food simulants (Vasile & Baican, 2021) and then used to predict the WVP and O_2 permeability and the modulus reported in Table 8. The cell-level and data-driven levels address step 3 and the whole system, respectively. Each level passes parameters to the next and receives validation data from the experiments in the right-hand column of Table 12, so that every model is tested before it is used for prediction.

Two practical requirements follow. First, the studies in Table 8 report different matrices, loadings, and assays, so the machine-learning level needs a harmonized dataset in which extract composition (for example, total phenolic content), loading, matrix, processing method, release data, and film properties are reported together; the extraction sheet of this review is a first step in that direction. Second, the first modeling targets should be the systems in which experimental data are most complete, namely the polyphenol–PLA and polyphenol–starch systems and the extracts in Table 8 that already have mechanical and barrier data (olive leaf, grapevine cane, betel leaf, and tannic acid), so that the models can be tested against measured strength, elongation, and permeability (Figure 9) before being applied to new extracts.

Table 12: Proposed multiscale computational workflow and its experimental validation

6. Industrial translation. There is a need for pilot-scale studies, continuous processing, and cost reduction strategies (Korte et al., 2021) (Foltynowicz, 2020). The vast majority of reported composites are only tested at the gram-to-kilogram scale. When produced on a ton scale, new issues of mixing homogeneity, thermal stability during extended extrusion, batch-to-batch reproducibility, and quality control will emerge.

The distribution of research focus areas across the 91 analyzed publications is presented in Figure 11, highlighting the current emphases and gaps in PLA/starch antimicrobial packaging research.

Figure 11: Distribution of research focus areas in analyzed papers

10.4 Limitations of This Review

The conclusions of this review should be read with the following limitations in mind. (i) Four databases were searched (Scopus, Web of Science, ScienceDirect and Google Scholar); Google Scholar results are not fully reproducible, and other databases were not searched. (ii) Only English-language publications were included. (iii) The review protocol was not prospectively registered. (iv) Publication bias is likely, because studies with positive antimicrobial results are more likely to be published. (v) The heterogeneity of matrices, extracts, loadings and test methods precluded meta-analysis, so the values quoted are descriptive ranges from individual studies, and not pooled estimates. (vi) Most of the quantitative mechanical and barrier data come from PLA-only, PLA/PBAT or starch-only systems (Table 8 and Figure 9), so extrapolation to PLA/starch composites is uncertain. (vii) Where one value per study is quoted, it is the value at the loading selected by the original authors (Section 2.3), which may favour favorable results; the loading and range are therefore always reported with it. (viii) Quality scoring was by consensus, and no chance-corrected agreement statistic is reported (Section 2.4). (ix) The search was last updated in December 2025, and later publications are not covered.

11. Conclusion

Ninety-one peer-reviewed publications addressing the properties of PLA/starch composites modified with plant extracts for their antimicrobial properties were analyzed in this systematic review. The main findings are:

Significant improvements in the antimicrobial and antioxidant properties of PLA/starch composites are reported for plant biomass extracts. Extract-level MIC values in the cited studies range from 1.25 to 3.0 mg/mL (pomegranate peel and chicory root), whereas film-level activity is reported separately as inhibition zones of about 9–16 mm (betel leaf and olive leaf extracts); the two measures are not

interchangeable. Most of the extracts with a high total phenolic content (>150 mg GAE/g) demonstrate the strongest activity; however, the composition of the phenolics is as important as the total amount.

The mechanical properties are generally reduced by the incorporation of the extracts (tensile strength 8.6–34.5 MPa in the studies compiled in Table 8, compared with 50–70 MPa for neat PLA). Strength loss can be effectively compensated for by adding nanoparticle reinforcement (1–5 wt% nanocellulose or lignin nanoparticles) and compatibilizers (5–10 wt% maleic anhydride-grafted PLA), which can increase the strength of unmodified composites by 30–80%.

Barrier properties are often improved, especially UV blocking (65–100% in the UV-B range) and oxygen reduction (70% reported). Extract-dependent behavior was observed for water vapor permeability with some extracts, such as olive leaf, grapevine cane, and betel leaf, which decreased by up to 55% due to an increase in tortuosity and hydrogen bonding. These are single-study values (tannic acid, 65–66% UV block; lignin nanoparticles, close to 100% in the UV-B range; oxygen permeability reduced by 70% in a nanofiber-coated PLA film), not pooled estimates.

Biodegradation is faster than that of neat PLA (180 days to 13–60 days under composting conditions for PLA-containing systems). The most important indicator of degradation rate is the starch content. Additionally, extracts containing hydrophilic compounds promote degradation, while extracts containing hydrophobic compounds (essential oils) may inhibit degradation because of their antimicrobial activity against the microorganisms that degrade them.

Shelf-life extension of real-food products was shown with meat (16 days at 4°C), fish (9 days vs. 3 days for the control), fruits (21 days fungus-free), and vegetables (20 days at room temperature). However, fewer than 5% of studies reached pilot scale, most remain at laboratory scale, and regulatory approval for market use has not yet been obtained.

There are still significant challenges: (a) incompatibility of PLA/starch, causing phase separation; (b) too little migration safety data for FDA/EFSA approval (fewer than 15% of studies tested migration); and (c) not enough pilot-scale or larger studies (<5%).

Future opportunities are: advanced encapsulation to achieve an extended-release profile, synergistic extract combinations to gain cost-effectiveness and improved efficacy, integration with smart packaging technology for real-time quality monitoring, green extraction methods (supercritical CO_2, subcritical water), and multiscale computational modeling (DFT, molecular dynamics, release-kinetics models, and machine learning, each paired with a validation experiment; Table 12) to accelerate formulation optimization, and pilot-scale validation for industrial translation.

Plant biomass extracts are promising natural ingredients for the formulation of PLA/starch composites as viable, eco-friendly packaging materials with antimicrobial properties, and thus with a reduced impact on the environment. Moving from lab demonstration to commercial application will, however, need to be achieved through concerted advances across materials, food engineering, regulatory science, industrial scale-up, and consumer research. Over the next five years, the potential of these laboratory results will have to be realized in commercially viable products that can outperform and outcompete conventional plastics in both performance and cost.

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Figures

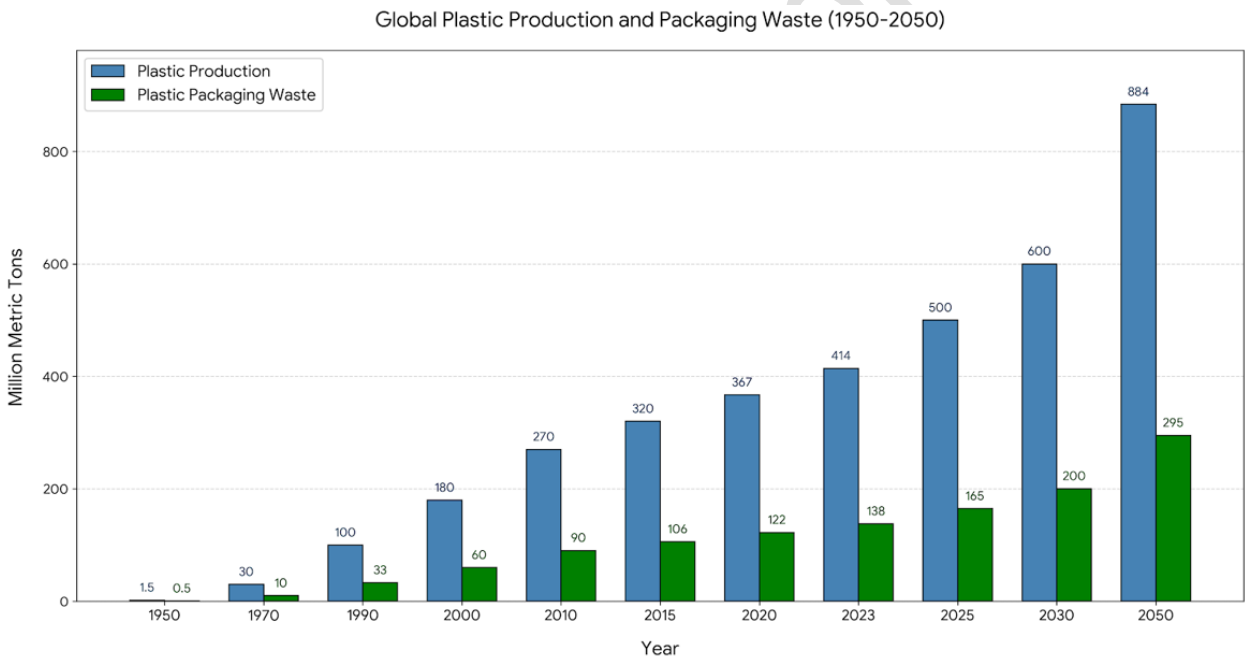


Figure 1: Global plastic production and packaging waste trends

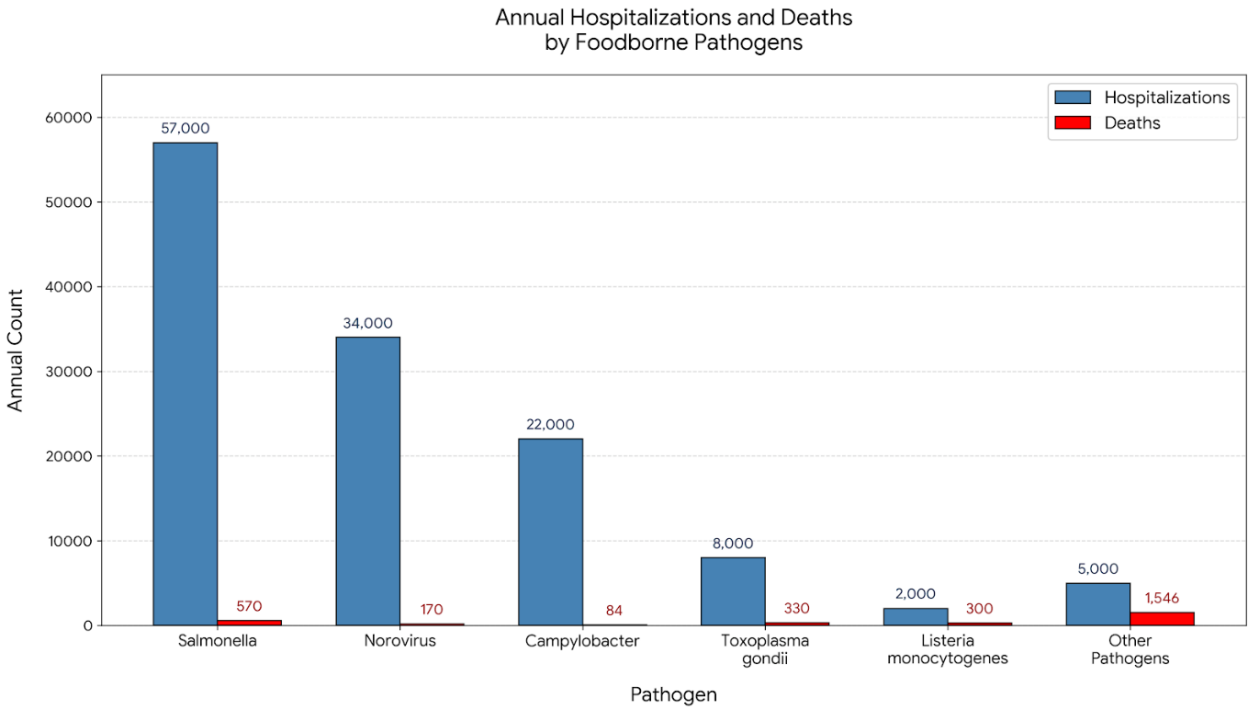


Figure 2: Major foodborne pathogens and associated illnesses

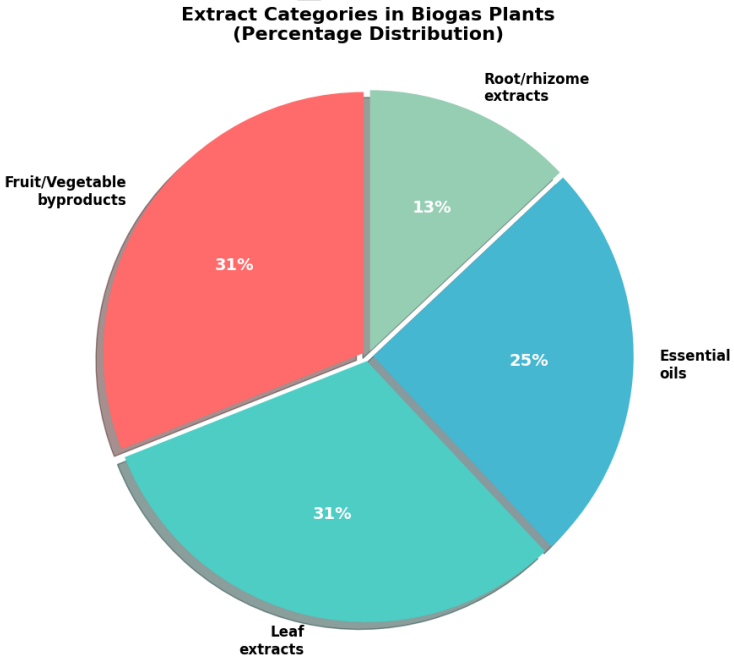


Figure 3: Distribution of plant biomass extract types used in PLA/starch antimicrobial packaging

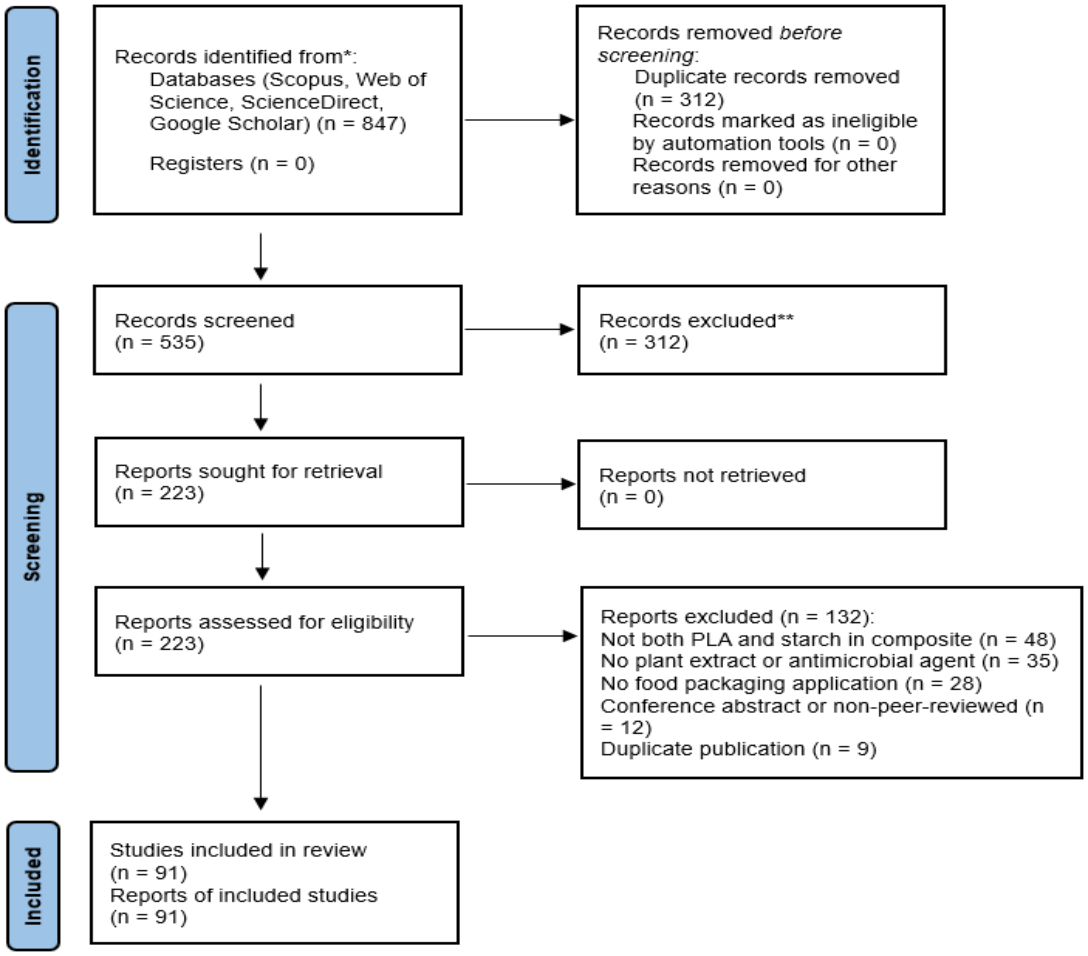


Figure 4: PRISMA flow diagram

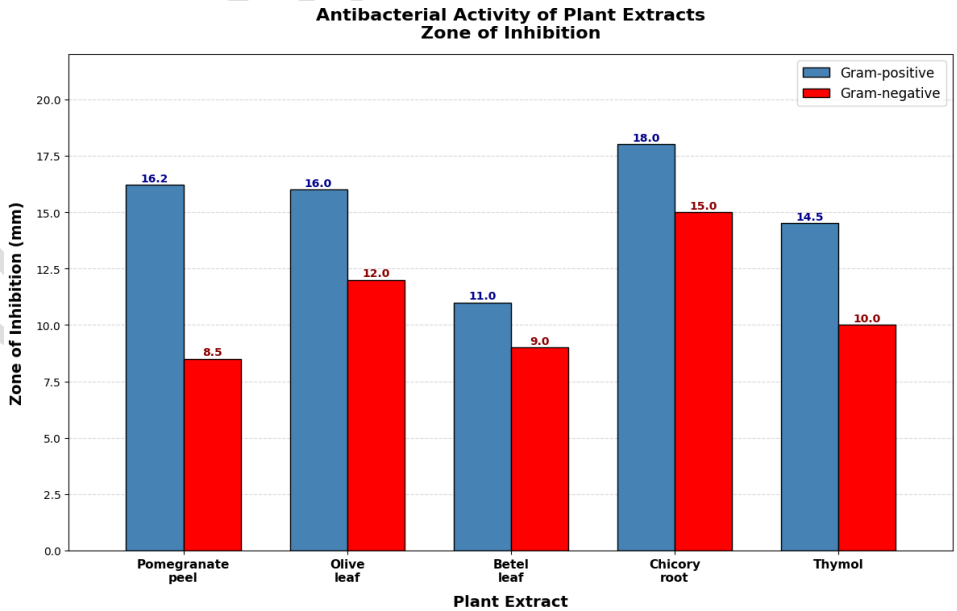


Figure 5: Antimicrobial activity comparison (Gram-positive vs. Gram-negative)

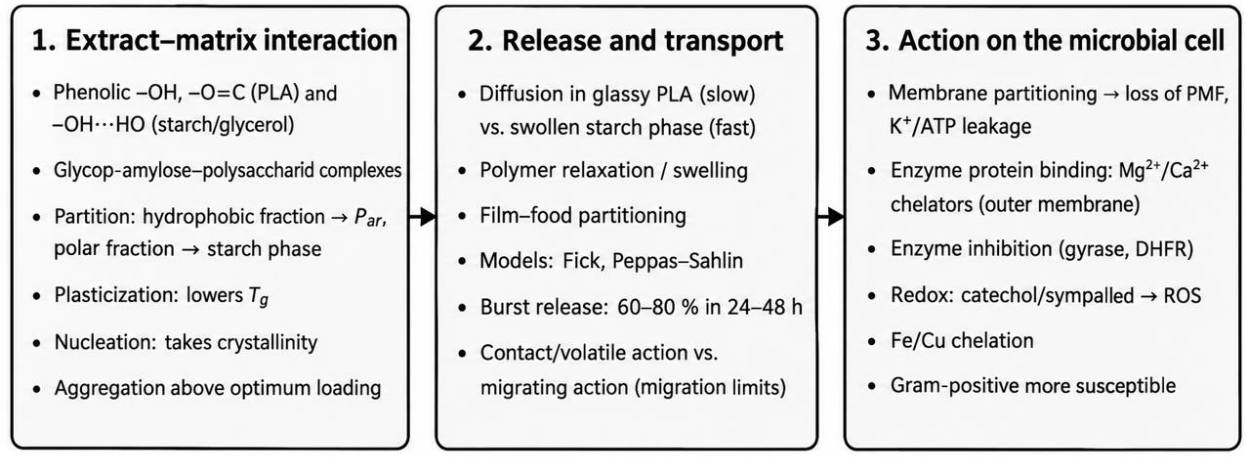


Figure 6: Conceptual scheme linking extract–matrix interaction, release and action on the microbial cell

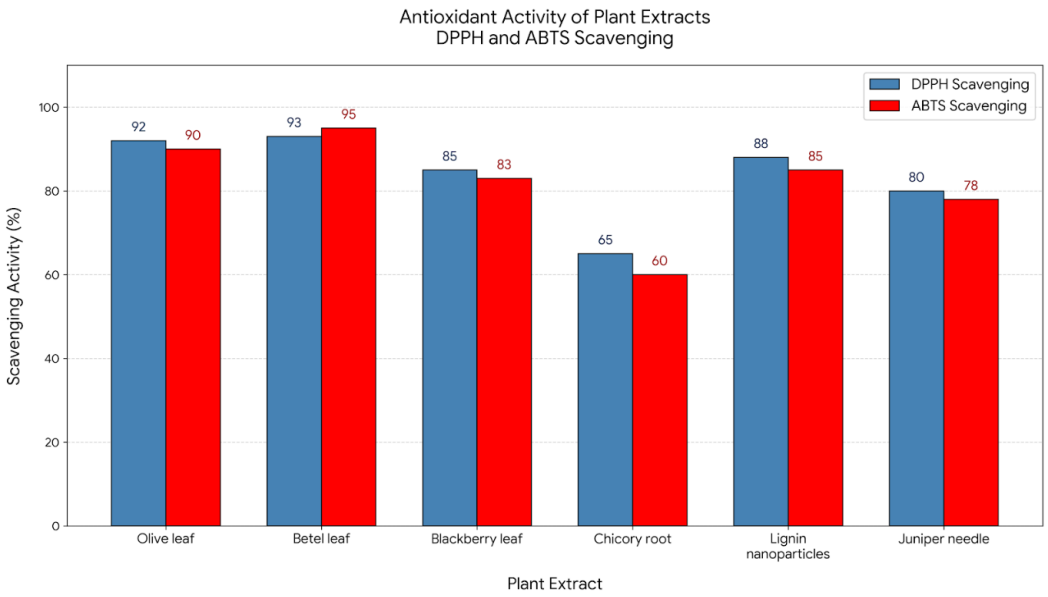


Figure 7: Antioxidant activity comparison (DPPH, ABTS)

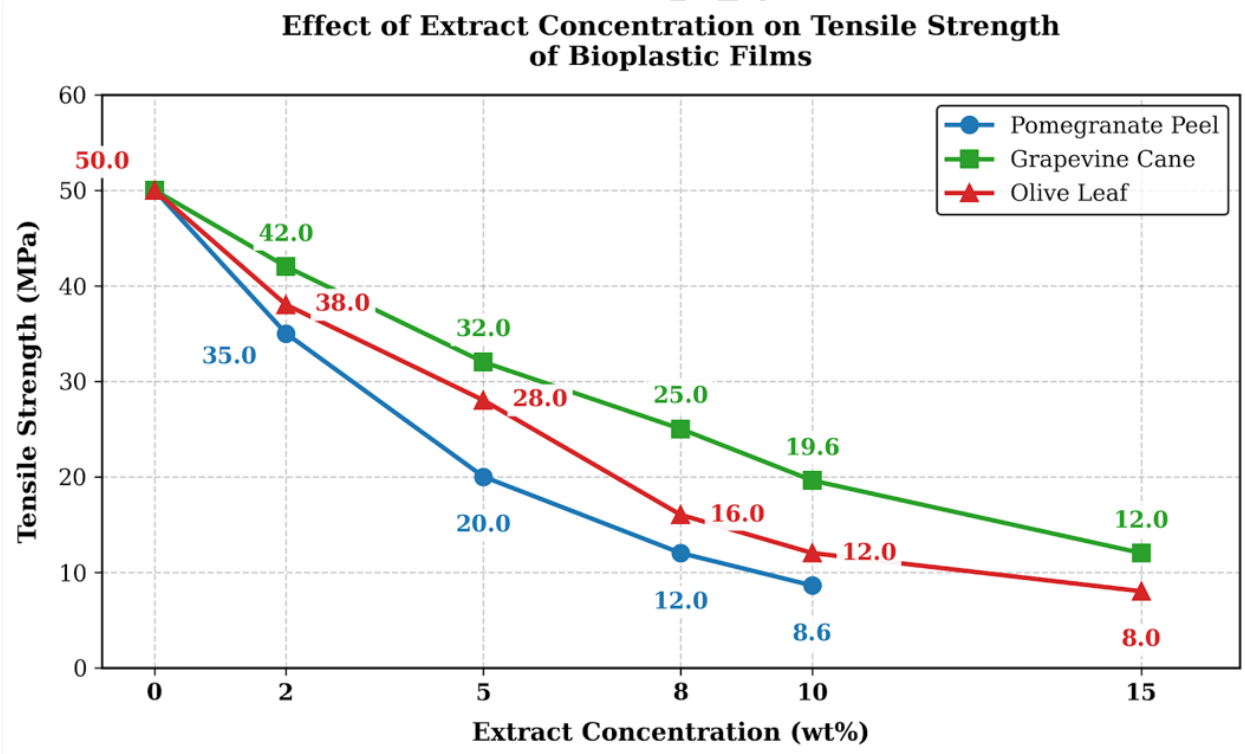


Figure 8: Effect of extract concentration on tensile strength

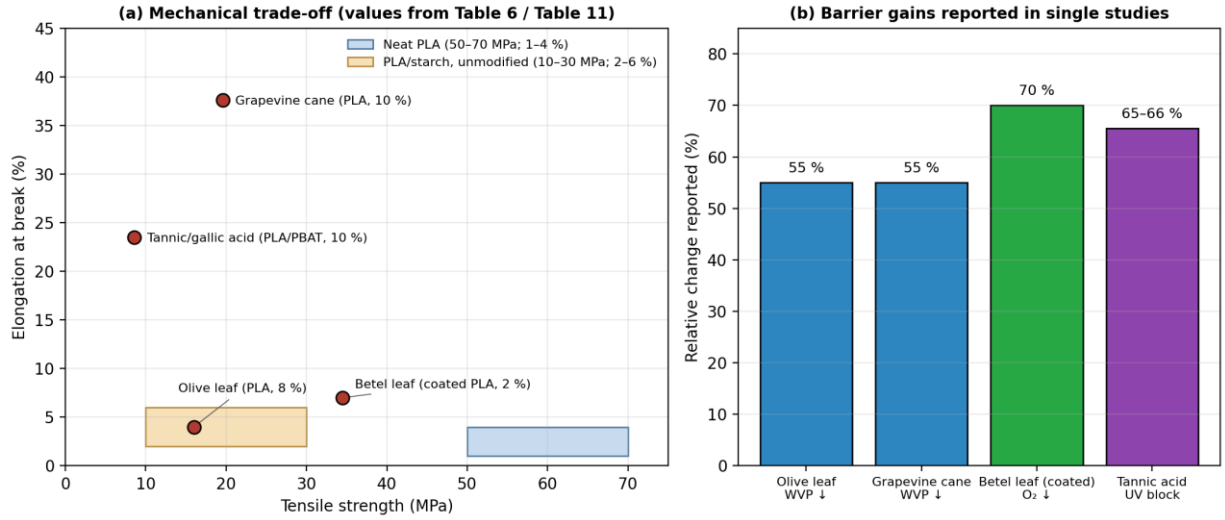


Figure 9: Synthesis of (a) the strength–elongation trade-off and (b) the barrier gains reported for the extract systems in Table 8

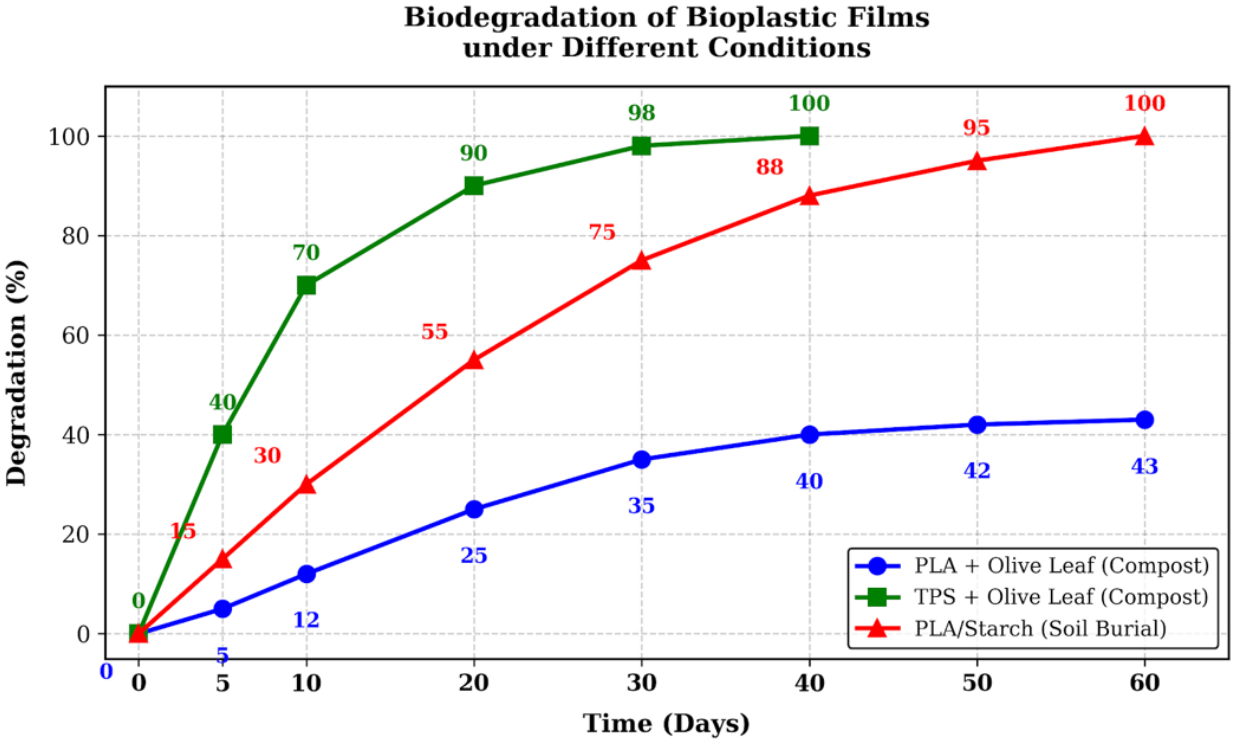


Figure 10: Biodegradation over time (compost vs. soil)

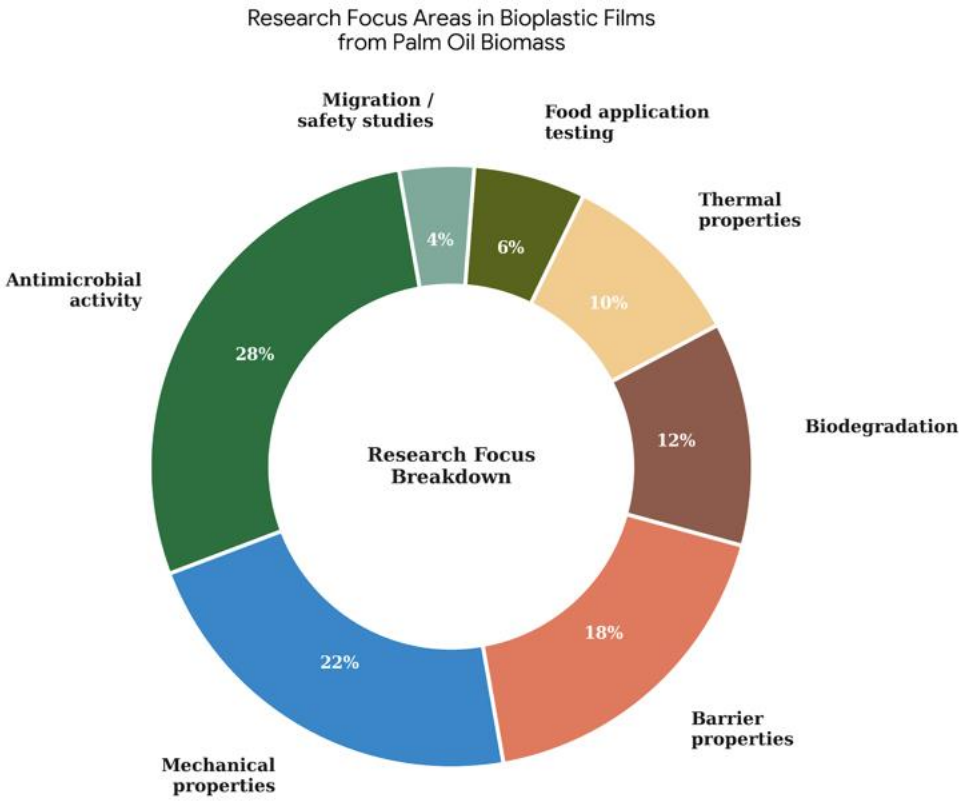


Figure 11: Distribution of research focus areas in analyzed papers

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Tables

Table 1: Comparison of PLA and starch properties

Property	PLA	Native Starch	TPS (30% glycerol)
Cost (USD/kg)	2.00–2.50	0.30–0.60	0.40–0.80

Tensile strength (MPa)	50–70	2–10	3–15
Elongation at break (%)	1–4	1–5	20–80
Water absorption (%)	0.5–1.0	20–40	30–60
Biodegradation (compost, days)	~180	30–60	20–40
FDA food contact	Yes	Yes	Yes
Key limitation	Brittle, high cost	Water sensitive	Very water sensitive

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Table 2: Compatibility enhancement strategies for PLA/starch composites

Strategy	Mechanism	Optimal Level	Strength Improvement	Reference
Maleic anhydride-grafted PLA	Covalent bonding with starch OH	5–10 wt%	30–50%	(Jayarathna et al., 2022) (Ilyas et al., 2022)
Glycerol plasticizer	Increased chain mobility	20–40 wt% (of starch)	-10 to +10% (elongation +100–400%)	(Jayarathna et al., 2022) (Sadeghizadeh-Yazdi et al., 2019)
Nanocellulose	Hydrogen bonding with both phases	1–5 wt%	40–80%	(Ilyas et al., 2022) (Nazrin et al., 2020)
Lignin nanoparticles	Amphiphilic bridge	1–3 wt%	30–60%	(Peng & Wang, 2025) (Sun et al., 2023)
Acetylation of starch	Reduced hydroxyl content	DS 0.5–1.5	20–35%	(Shi et al., 2022) (Zhu et al., 2024)

Table 3: Major plant biomass extracts and their bioactive compounds

Extract Source	Plant Part	Key Bioactive Compounds	TPC (mg GAE/g)	References
Pomegranate peel	Fruit peel	Punicalagin, ellagic acid, gallic acid	200–400	(Dai et al., 2022)
Olive leaf	Leaves	Oleuropein, hydroxytyrosol, verbascoside	100–250	(Soltani et al., 2025) (Sousa et al., 2025)
Betel leaf	Leaves	Hydroxychavicol, eugenol, chavibetol	150–300	(Tagrida et al., 2022)
Grapevine cane	Cane/shoot	Resveratrol, viniferin, stilbenes	50–150	(Díaz-Galindo et al., 2020)
Chicory root	Root	Sesquiterpene lactones, polyphenols	60–120	(Jaśkiewicz et al., 2020)
Thyme	Aerial parts	Thymol, carvacrol (essential oil)	100–200 (EO)	(Havelt et al., 2021) (Tawakkal et al., n.d.)

Table 4: Comparison of extraction methods for plant biomass

Method	Conditions	Time	Solvent Use	Green Score*	Key Advantage
Conventional solvent	25–80°C, 2–24 h	6–24 h	High (10–50 L/kg)	3-10	Simple, low cost
Ultrasound-assisted	20–40 kHz, 10–60 min	10–60 min	Medium (5–15 L/kg)	6-10	10–100× faster
Microwave-assisted	300–900 W, 2–10 min	2–10 min	Low (2–5 L/kg)	7-10	Very fast
Subcritical water	150–200°C, 10–50 bar	10–30 min	None (water only)	8-10	Green, no solvent residue
Supercritical CO_2	40–80°C, 150–500 bar	1–4 h	None (CO_2 only)	9-10	Clean, selective

Table 5: Antibacterial activity of PLA/starch composites with plant extracts

Extract	Concentration	Target Bacteria	Activity	Reference
Pomegranate peel	5–10 wt%	*E. coli*, *S. aureus*	MIC 2.5–3.0 mg/mL	(Dai et al., 2022)
Olive leaf	3–8%	*S. aureus*, *E. coli*, *Listeria*	16 mm zone	(Soltani et al., 2025)
Betel leaf	2%	*S. aureus*, *E. coli*, *L. monocytogenes*	9–11 mm zone	(Tagrida et al., 2022)
Grapevine cane	10–15%	*B. cinerea*, *L. monocytogenes*	35% inhibition	(Díaz-Galindo et al., 2020)

Chicory root	1–5%	*E. coli, B. subtilis*	MIC 1.25–2.5 mg/mL	(Jaśkiewicz et al., 2020)
Thymol	2–6%	*E. coli, S. aureus*	Contact-dependent	(Tawakkal et al., n.d.)

Table 6: Mechanical properties of PLA/starch composites with plant extracts

Composite	Tensile Strength (MPa)	Elongation (%)	Modulus (MPa)	Reference
Neat PLA	50–70	1–4	3000–4000	(Farah et al., 2016)
PLA/starch (unmodified)	10–30	2–6	1000–2000	(Jayarathna et al., 2022) (Ilyas et al., 2022)
PLA/PBAT + tannic/gallic acid (10%)	8.6	23.5	181	(S. Sharma et al., 2022)
PLA + grapevine cane (10%)	19.6	37.6	342	(Díaz-Galindo et al., 2020)
PLA + olive leaf (8%)	~16	~4	~900	(Soltani et al., 2025)
PLA + betel leaf (2%)	34.5	7	—	(Tagrida et al., 2022)
PLA/TPS + nanocellulose	Improved	Improved	Improved	(Nazrin et al., 2020)

Table 7: Barrier properties of PLA/starch composites with plant extracts

Composite	WVP Change	O_2 Permeability	UV Barrier	Reference
PLA + olive leaf (8%)	Reduced 55%	Reduced	Excellent (UV-B)	(Soltani et al., 2025)
PLA + grapevine cane (10%)	Reduced 55%	—	Moderate	(Díaz-Galindo et al., 2020)
PLA + betel leaf (2%)	Reduced	Reduced 70%	Excellent	(Tagrida et al., 2022)
PLA + tannic acid (10%)	Reduced	—	65–66% block	(S. Sharma et al., 2022)
Starch + lignin NPs	Reduced	—	Outstanding	(Sun et al., 2023)

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Table 8: Comprehensive comparison of extracts, loadings and their effects on antimicrobial, mechanical and barrier properties

Extract / active	Matrix (core vs. contextual)	Loading	Antimicrobial / antioxidant read-out	Tensile strength (MPa) / elongation (%) / modulus (MPa)	WVP	O_2 permeability / UV barrier	Barrier vs. mechanical outcome	Reference
Neat PLA (baseline)	PLA	–	No inherent antimicrobial	50–70 / 1–4 / 3000–4000	About 200–300	n.r.	Reference for strength and	(Farah et al., 2016)

			activity		g·mm/m²·day (Section 1.4)		ductility	
PLA/starch, unmodified (baseline)	PLA/starch (core)	–	n.a.	10–30 / 2–6 / 1000–2000	n.r.	n.r.	Reference for PLA/starch blends	(Jayarathna et al., 2022) (Ilyas et al., n.d.)
Olive leaf extract	PLA film (contextual)	3–8% (mechanics at 8%)	16 mm zone (*S. aureus*, *E. coli*, *Listeria*); DPPH/ABTS scavenging >90% at 8 wt%	~16 / ~4 / ~900	−55%	O_2 reduced (n.q.); UV-B excellent	Large barrier and antioxidant gain; strength 23–32% of neat PLA; elongation unchanged	(Soltani et al., 2025)
Grapevine cane extract	PLA film (contextual)	10% (10–15% in antifungal tests)	35% inhibition; antiadhesive; *B. cinerea* suppressed by 15–35% at 10–15%	19.6 / 37.6 / 342	−55%	O_2 n.r.; UV moderate	WVP gain with strong ductility gain; strength 28–39% of neat PLA	(Díaz-Galindo et al., 2020)
Betel leaf extract	PLA film coated with electrospun gelatin/chitosan nanofibres (contextual)	2%	9–11 mm zone (four pathogens); DPPH 93.5 TE; FRAP 2817 TE	34.5 / 7 / n.r.	Reduced (n.q.)	O_2 −70%; UV excellent	Best strength retention (49–69% of neat PLA) and O_2 barrier; possible coating effect	(Tagrida et al., 2022)
Tannic / gallic acid	PLA/PBAT blend (contextual)	10%	Cherry tomato quality kept for 20 days at room temperature	8.6 / 23.5 / 181	Reduced (n.q.)	O_2 n.r.; UV block 65–66% (tannic acid)	Highest UV protection and ductility; lowest strength (12–17% of neat PLA)	(S. Sharma et al., 2022)
Pomegranate peel extract	PLA film with nano-ZnO (contextual)	5–10%	MIC 2.5–3.0 mg/mL (*E. coli*, *S. aureus*)	n.r.	n.r.	n.r.	Antimicrobial data only; mechanical and barrier data not reported in the sources compiled here	(Dai et al., 2022)
Chicory root extract (with phytic acid)	Starch film (contextual)	1–5%	MIC 1.25–2.5 mg/mL (*E. coli*, *B. subtilis*)	n.r.	n.r.	n.r.	Antimicrobial data only	(Jaśkiewicz et al., 2020)
Thymol (essential-oil component)	PLA-based material with natural fibres (contextual)	2–6%	Contact-dependent	n.r.	n.r.	n.r.	Activity needs contact; no barrier data	(Tawakkal et al., n.d.)
Lignin nanoparticles (reinforcement, not an extract)	Starch film (contextual)	1–3%	Antioxidant activity >90% inhibition	Strength +40–80% vs. unreinforced composites (nanoparticle class)	Reduced (n.q.)	UV-B close to 100%	Barrier and strength improve together	(Sun et al., 2023) (Nazrin et al., 2020)
Nanocellulose (reinforcement, not an extract)	PLA/TPS (core)	1–5%	n.a.	Improved (+40–80% in the cited reviews)	n.r.	n.r.	Compensates the strength loss caused by extracts	(Nazrin et al., 2020) (Ilyas et al., n.d.)

n.r., not reported in the cited source; n.q., reported but not quantified; n.a., not applicable. “Contextual” means that the matrix does not contain both PLA and starch (Section 2.1), so rows with different matrices should not be compared directly. Loadings are as stated in the cited studies. Strength-retention percentages are calculated from the strength ranges of neat PLA (50–70 MPa) and the single values shown

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Table 9: Biodegradation of PLA/starch composites with plant extracts

Material	Condition	Time	Rate	Reference
Neat PLA	Compost (58°C)	180 days	Slow	(X. Li et al., 2023), (Farah et al., 2016)
PLA/starch	Soil burial	13–30 days	Fast	(Jayarathna et al., 2022)
PLA + olive leaf	Compost	40–60 days	43% at 60 days	(Manabu Abe, n.d.) (Soltani et al., 2025)
PLA/starch + xylan	Soil burial	13 days	Complete	(Manabu Abe, n.d.)
TPS + olive leaf	Compost	3–5 days	Complete	(Sousa et al., 2025)

Table 10: Food preservation applications of PLA/starch composites with plant extracts

Food Product	Extract	Condition	Shelf-Life Extension	Reference
Pork meat	Rice straw extract	4°C, 16 days	16 days quality maintained	(Freitas et al., 2023)
Tilapia slices	Betel leaf extract	4°C, 12 days	Extended to 9 days (vs. 3 control)	(Tagrida et al., 2022)
Cherry tomatoes	Olive leaf extract	4°C, 21 days	21 days of fungal decay reduced	(Soltani et al., 2025)
Cherry tomatoes	Tannic/gallic acid	RT, 20 days	20 days, pH 4.3	(S. Sharma et al., 2022)
Ground beef	Oregano/cumin oils	Refrigerated	12 days	(Zende et al., 2025)

Table 11: Summary of research gaps and future opportunities

Gap Area	Description	Priority	References
Mechanistic understanding	Limited molecular-level understanding of extract-polymer interactions and no validated multiscale or machine-learning models linking extract chemistry to film performance (Section 10.3, Table 12)	High	(Sarkhel et al., 2025), (Bose et al., 2023)
Controlled release kinetics	Few studies on release mechanisms or mathematical modeling	High	(Vasile & Baican, 2021)
Migration safety	Limited migration studies for regulatory approval (<15% of studies)	High	(Kamarudin et al., 2022), (Vieira et al., 2022)
Industrial scalability	<5% of studies at pilot scale or above	High	(Korte et al., 2021), (Foltynowicz, 2020)
Economic analysis	No cost comparisons with conventional plastics	Medium	(Korte et al., 2021)
Long-term stability	Limited data on aging and storage stability	Medium	(Farah et al., 2016) (Vasile & Baican, 2021)
Synergistic combinations	Under-explored combinations of multiple extracts	Medium	(Pinto et al., 2023)
Standardized testing	No standardized antimicrobial testing protocols	Medium	All
Life cycle assessment	No LCA of extract-based packaging	Low	(Korte et al., 2021)

Consumer acceptance	No studies on consumer perception or WTP	Low	(Korte et al., 2021)

Table 12: Proposed multiscale computational workflow and its experimental validation

Scale	Method	Quantity to be predicted	Experimental validation
Electronic	Density functional theory (binding energies, hydrogen-bond analysis, pKa and log P of extract constituents)	Extract–PLA and extract–starch interaction energies; expected FTIR shifts	FTIR (O–H and C=O bands); NMR where applicable
Atomistic	All-atom molecular dynamics of PLA/TPS/glycerol/water/extract systems	Flory–Huggins parameter, cohesive energy density and Hansen parameters, interfacial adhesion, Tg, diffusion coefficients of extract compounds	DSC (Tg); SEM/AFM morphology; sorption and desorption tests
Mesoscale	Coarse-grained molecular dynamics or dissipative particle dynamics	Phase morphology; aggregation of extract above the optimum loading	SEM and particle-size distribution; tensile tests at several loadings
Continuum	Fickian and Peppas–Sahlin release models; finite elements with moisture-dependent diffusivity; tortuosity models; Halpin–Tsai micromechanics	Release curves; WVP and O_2 permeability; modulus	Release in food simulants; WVP and oxygen-transmission measurements; tensile tests
Cell	Free-energy (umbrella-sampling) calculations of membrane permeation; docking with MD refinement	Relative affinity of extract compounds for Gram-positive and Gram-negative membrane models; binding to DNA gyrase and dihydrofolate reductase	MIC and time-kill assays; membrane-potential and leakage assays
Data-driven	QSAR and machine learning (Gaussian processes, random forests, graph neural networks); Bayesian optimisation or active learning	Antimicrobial, mechanical and barrier properties from composition and processing; next-best formulation	Hold-out experiments; challenge tests in food (log reduction, shelf life); uncertainty reported

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