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COMPREHENSIVE REVIEW

Food packaging solutions in the post-per- and polyfluoroalkyl substances (PFAS) and microplastics era: A review of functions, materials, and bio-based alternatives

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Abstract

Food packaging (FP) is essential for preserving food quality, safety, and extending shelf-life. However, growing concerns about the environmental and health impacts of conventional packaging materials, particularly per- and polyfluoroalkyl substances (PFAS) and microplastics, are driving a major transformation in FP design. PFAS, synthetic compounds with dual hydro- and lipophobicity, have been widely employed in food packaging materials (FPMs) to impart desirable water and grease repellency. However, PFAS bioaccumulate in the human body and have been linked to multiple health effects, including immune system dysfunction, cancer, and developmental problems. The detection of microplastics in various FPMs has raised significant concerns regarding their potential migration into food and subsequent ingestion. This comprehensive review examines the current landscape of FPMs, their functions, and physicochemical properties to put into perspective why there is widespread use of PFAS and microplastics in FPMs. The review then addresses the challenges posed by PFAS

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and microplastics, emphasizing the urgent need for sustainable and bio-based alternatives. We highlight promising advancements in sustainable and renewable materials, including plant-derived polysaccharides, proteins, and waxes, as well as recycled and upcycled materials. The integration of these sustainable materials into active packaging systems is also examined, indicating innovations in oxygen scavengers, moisture absorbers, and antimicrobial packaging. The review concludes by identifying key research gaps and future directions, including the need for comprehensive life cycle assessments and strategies to improve scalability and cost-effectiveness. As the FP industry evolves, a holistic approach considering environmental impact, functionality, and consumer acceptance will be crucial in developing truly sustainable packaging solutions.

KEYWORDS
food packaging, food safety, microplastics, PFAS, sustainability

1 | OVERVIEW OF FOOD PACKAGING MATERIALS (FPMS)

From the moment a food product is created until it reaches the consumer plate, food packaging (FP) is needed for warranting the product quality, maintaining its safety, and defending its integrity throughout the entire journey (Amoroso et al., 2021; Li et al., 2021; Rigotti et al., 2021). Although food packaging materials (FPMs) are typically classified based on their material composition, FPMs can also be organized based on their primary use-purposes, which include containment, protection, convenience, and communication (A. Kumar, Hasan, et al., 2022; Jayakumar et al., 2022; Shlush & Davidovich-Pinhas, 2022). This review primarily focuses on primary packaging, which is defined as the first wrap or containment that directly holds the food product for sale, serving as the most critical interface between the product and the consumer (Soroka, 2022).

Containment function involves FPM that holds and encloses the food product, preventing spillage and facilitating transportation (Chan, 2023; Hounsou et al., 2022). Examples of containment packaging include bags such as plastic bags, paper bags, aluminum foil bags, vacuum bags, stand-up pouches, retort pouches, gusseted bags, zipper bags, and produce bags (Alak et al., 2024; Chan, 2022; Gulcimen et al., 2023; Siddiqui et al., 2023). Preservation function as a selective barrier to mitigate the permeation and transmission of environmental factors, including water vapor, oxygen, UV light, and extraneous substances (Carullo et al., 2023; A. Khan, Priyadarshi, et al., 2023; T. Gao, Yan, et al., 2024; Sani et al., 2024).

From a scientific perspective, FPM serves various functions to preserve and protect its contents. Polymeric stretch films act as a semi-permeable membrane, allowing selective gas exchange while providing a barrier against contaminants and moisture loss (de Oliveira Mariano Pilger et al., 2024; Gupta et al., 2022). Rigid FPM, including thermoplastic containers, silica-based glass jars and bottles, metallic cans composed of aluminum or steel, lignocellulosic paperboard boxes, expanded polystyrene (EPS) foam trays, aluminum trays, thermoformed plastic clamshells, and molded cups and plates made from various polymers, provide mechanical strength and structural integrity (Banerjee & Ray, 2022; Sierra & Jha, 2023; Zheng et al., 2023).

Convenience function refers to packaging features that enhance the ease of use, handling, and storage of food goods (Chen, Brahma et al., 2020; Khedkar & Khedkar, 2020). Examples of convenience packaging include resealable zipper bags, microwaveable containers, single-serve portions, and dispensing systems such as pump bottles or squeeze tubes (Alves et al., 2023; Huyghe et al., 2017; Shin et al., 2024). Flexible packaging configurations, such as plastic wraps and zipper bags, enhance user accessibility and offer reclosable functionality, thereby optimizing product preservation and consumer utility throughout multiple usage cycles (Dudeja et al., 2023; Jo et al., 2022; Taylor & Sapozhnikova, 2022).

The communication function of packaging, while not directly influencing the inherent physical characteristics of FPMs, is significant for effectively conveying essential information to consumers (Nemat et al., 2022; Schifferstein et al., 2021). Packaging labels, printed directly on the material or applied as stickers, convey important details such as product identification, nutritional information, preparation instructions, and expiration dates (Batista et al., 2023; Thøgersen, 2023).

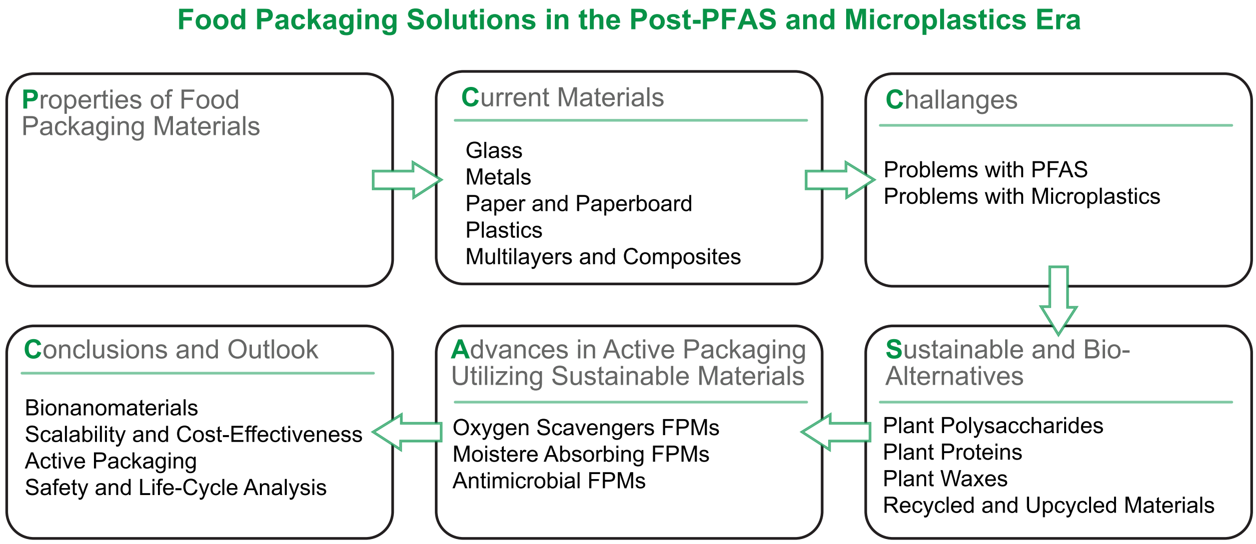

FIGURE 1 Schematic overview of food packaging solutions in the post-per- and polyfluoroalkyl substances (PFAS) and microplastics era. The figure illustrates the progression from traditional packaging materials and their properties to current challenges with PFAS and microplastics. It then highlights sustainable and bio-based alternatives, advances in active packaging utilizing sustainable materials, and concludes with future outlook and emerging solutions.

Given the pressing need to address the environmental and health concerns associated with conventional FPMs, particularly per- and polyfluoroalkyl substances (PFAS) and microplastics, this comprehensive review aims to critically examine the current landscape of FP and explore innovative, sustainable solutions. The scope of this review encompasses several key areas: (i) an overview of traditional FPMs and their physicochemical properties; (ii) an in-depth analysis of the challenges posed by PFAS and microplastics in FP; (iii) an exploration of sustainable and renewable materials as alternatives, including plant-derived polysaccharides, proteins, and waxes; (iv) recent advances in active packaging utilizing these sustainable materials; and (v) a discussion of future perspectives and challenges in the field. By synthesizing the latest research and developments in sustainable FP, this review seeks to provide a comprehensive resource for researchers, industry professionals, and policymakers working toward more environment-friendly and health-conscious FP solutions. Figure 1 provides a visual overview of the key concepts and scope covered in this review.

2 | PHYSICOCHEMICAL PROPERTIES OF FOOD PACKAGING MATERIALS

Considering different types of FPMs, their main functions include providing a barrier against physical, chemical, and biological contaminants; maintaining the desired atmosphere inside the package; and facilitating the distribution and storage of edible commodities (Manzoor et al., 2023; Thirupathi Vasuki et al., 2023). The selection of appropriate construction materials is based on an interplay of considerations such as the nature of food commodities, the intended shelf-life, the distribution and storage specifications, and the desired functionality (Bamps et al., 2023; Frigerio et al., 2023). To understand the current reliance on PFAS and plastics as FPMs, we first review their physicochemical and mechanical property requirements and considerations.

2.1 | Contaminant barrier properties

FP is responsible for preventing the entry of biological, physical, and chemical contaminants that can adversely affect food quality, safety, and shelf-life. Inadequate packaging exposes food to various contamination risks during processing, storage, transportation, and handling (Kawecka & Cholewa-Wójcik, 2023). Physical contaminants, such as particulate matter and foreign objects, can enter food through multiple pathways such as tears or punctures in packaging, inadequate sealing, and poor handling practices (Pakdel et al., 2023). Chemical contaminants, including pesticide residues, heavy metals, and cleaning agents, can also contaminate food without proper packaging (Mazzoleni et al., 2023). Biological contaminants, such as pathogenic microorganisms, pose a significant food safety hazard and can proliferate rapidly in the absence of appropriate packaging (Jafarzadeh et al., 2023). These microorganisms can enter food through various routes, such as contact with contaminated surfaces, exposure to air or water, or cross-contamination from other contaminated food products (Khan et al., 2024). To prevent the entrance of physical, chemical, and biological contaminants, FPMs are designed with specific barrier properties (Tumu et al., 2023).

2.2 | Gas diffusion control properties

The selection of FPM must account for their capacity to preserve the optimal atmospheric conditions inside the package. This is achieved through the utilization of barrier properties that impede the mass transfer of gases, vapors, and other small molecules across food products and the exterior environment. The transport of gases through polymeric FPM is generally described by the solution-diffusion model, which encompass both physical and chemical processes (Fang & Vitrac, 2017). This model outlines the gas permeation mechanism as a tripartite process involving: (i) adsorption of gaseous species at the polymer-gas interfacial boundary, (ii) molecular diffusion through the polymeric matrix, and (iii) subsequent desorption at distal side of the interface (Adibi et al., 2023; Monsalve-Bravo et al., 2024). The diffusive flux of gaseous permeants through the polymeric matrix is fundamentally modulated by the kinetic diameter of the permeant and the polymer characteristic mesh size (Xue et al., 2023). This interchain spacing is dictated by the molecular nanoarchitecture and the level of crystallinity of the polymer (J. Li, Wang, et al., 2024; Li et al., 2023). Within the non-crystalline regions of the polymer, the stochastic arrangement of macromolecular chains engenders increased free volume elements, facilitating enhanced diffusive transport of gaseous permeants through these regions of diminished polymer chain packing density (Mansuri et al., 2023). Conversely, the highly ordered structure of crystalline regions restricts the mobility of gas molecules, causing lower permeability.

The diffusive transport of permeant molecules through the polymeric matrix is predominantly governed by the spatiotemporal fluctuations of the macromolecular chain segments, particularly the localized conformational rearrangements that modulate the formation and dissipation of transient free volume elements (Deng et al., 2024; Jeong et al., 2024). Thermal excitation of the polymer system beyond its glass transition temperature imparts enhanced segmental mobility to macromolecular chains, accompanied by free volume fluctuations and dynamic percolation pathways, thereby facilitating augmented diffusive transport of gaseous permeants through the polymeric matrix (Joardder et al., 2024; T. Jin, Coley, et al., 2022). The frequency and temporal extent of macromolecular segmental relaxations are modulated by several factors, including the chemical architecture of the polymer, the presence of low-molecular-weight diluents acting as plasticizers, and the thermodynamic state variables of temperature and pressure, collectively influencing the viscoelastic behavior and consequent permeation characteristics of the polymeric system (Alebrahim et al., 2022; Gainaru & Sokolov, 2022). The intrinsic permeability of a polymeric FPM to a specific gaseous permeant is quantitatively determined from the thermodynamic solubility parameter and the kinetic diffusion coefficient (Idris et al., 2022). Common polymeric diffusive barrier materials used in FP include polypropylene (PP), polyethylene terephthalate (PET), and polyethylene (PE) (Hosono et al., 2023; Velásquez et al., 2024). To enhance the barrier characteristics of FPMs, various strategies can be employed, such as increasing the crystallinity of the polymer, incorporating inorganic fillers with high aspect ratios (e.g., nanoclays), or using multilayer structures with alternating layers of high- and low-barrier materials (El Mouzahim et al., 2023; Guivier et al., 2023; Mao et al., 2023; Petrovics et al., 2023).

Inorganic barrier materials, such as aluminum foil and silicon oxide coatings, display lower gas permeabilities than polymeric materials due to their dense, ordered atomic structures (Körner et al., 2010; Lamberti & Escher, 2007). Aluminum foil employed in FP applications exhibits superior barrier properties against gaseous permeants, vaporous species, and moisture due to its densely packed face-centered cubic crystal structure and the spontaneous formation of a passivating nanoscale aluminum oxide layer at the metal–air interface, which impede molecular diffusion through the material matrix (Dong et al., 2021; Dutems et al., 2024). Similarly, silicon oxide coatings, deposited on polymer substrates via physical or chemical vapor deposition, offer superior barrier properties due to their dense and defect-free structure. Gas permeation through inorganic layers is significantly inhibited due to the absence of free volume elements and restricted atomic mobility, resulting in permeability coefficients much lower than those observed in polymeric matrices (Faramarzi et al., 2023). However, the barrier performance of these inorganic layers can be compromised by defects, such as pinholes or microcracks, which can arise from processing conditions or mechanical stresses (Hering et al., 2020). To overcome this limitation, multilayer structures that combine inorganic barrier layers with polymeric layers have been developed, exploiting the high barrier characteristics of the inorganic layer while maintaining the mechanical compliance and durability of the polymeric substrate (Hering et al., 2020).

2.3 | Mechanical properties

The design of FPMs must consider various aspects of statics, dynamics, and material properties to ensure that the packaged food products remain safe and intact throughout the distribution process. An important consideration in the design of FPM is their ability to withstand static loads, such as the weight of the food product and the stacking of multiple packages. The stress-strain behavior of the FPM, as described by its tensile strength, compressive strength, and flexural strength, must be carefully considered to prevent deformation or failure under static loads. In addition to static loads, FPM must also withstand dynamic loads arising from the motion and acceleration of the package during transportation such as vibration, shock, and impact loads. The damping properties of FPMs, as well as their capacity to absorb and dissipate energy, are important in reducing the impact of dynamic loads on the packaged food product. The mechanical interactions at the packaging-food interface during logistics and storage constitute an important factor in the design and optimization of FP, influencing both product quality and shelf-life (El Bourakadi & Bouhfid, 2022). The surface characteristics of the packaging material, such as its roughness, hardness, and coefficient of friction, must be optimized to minimize the damage to the food product caused by abrasion or adhesion (Y. Kumar, Roy, et al., 2022).

Polymeric materials are known for their excellent mechanical flexibility, which allows them to be easily processed into various packaging formats, such as bags, pouches, and wraps. Flexibility is necessary for producing packaging that adapts to food shape and resists stresses during transport and handling. In contrast, metal foils and ceramic coatings are inherently brittle and can crack or fracture under mechanical stress, limiting their use in flexible packaging applications.

2.4 | Thermal properties

In addition to the mechanical aspects, the design of FPM must carefully consider the thermal and heat transfer characteristics that affect the distribution and storage of the packaged foodstuff. Maintaining the optimal temperature range for the food product is essential to prevent spoilage, maintain quality, and ensure food safety. FPM must exhibit adequate thermal resistance to mitigate external temperature fluctuations, thereby preventing undesirable thermodynamic and kinetic changes in the physicochemical characteristics of the enclosed foodstuff (Kurd et al., 2024; Zeng et al., 2022). Another important consideration is the prevention of phase separation within the food product due to temperature fluctuations. Many food goods, such as emulsions (e.g., salad dressings) and suspensions (e.g., beverages), are thermodynamically unstable systems that can undergo phase separation when exposed to temperature changes. The separation of phases can lead to a loss of product homogeneity, changes in texture and appearance, and potential spoilage. FPM should provide adequate thermal insulation to minimize temperature fluctuations within the package and prevent phase separation. To address these thermal and heat transfer challenges, some FPMs are designed with specific thermal properties in mind. FPMs with low thermal conductivity, such as foams and vacuum-insulated panels, are commonly used to provide thermal insulation.

Other important thermal considerations are the glass transition temperature (T_g) and melting temperature (T_m), which are critical thermal properties that significantly influence the performance of polymeric FPMs. In semi-crystalline polymers, the degree of crystallinity and lamellar thickness distribution, modulated by thermal history, significantly influence gas barrier properties and mechanical resilience (Durand & De Almeida, 2024). For instance, the presence of a rigid amorphous fraction at the crystal–amorphous interface can complicate the thermal behavior, affecting molecular mobility and consequently, diffusion kinetics of permeants (Coelho et al., 2024). Moreover, thermal cycling around Tg can lead to physical aging, characterized by densification of the amorphous phase and consequent changes in free volume distribution (Zhang, Jariyavidyanont et al., 2023). This phenomenon, often overlooked in FP design, can result in time-dependent changes in barrier properties and mechanical performance.

2.5 | Interfacial properties

The interfacial properties of FPM determine their interactions with the packaged food product, as well as their resistance to various surface-related phenomena such as grease spreading and water repellency. These properties are governed by the interfacial chemistry and topography of FPM, which can be tailored through the use of specific surface treatments, coatings, or additives. Grease spreading, also known as oil wetting, is a common issue in FP, particularly for high-fat content products (e.g., meat, cheese, and baked goods) (Rovera et al., 2020; Thuy et al., 2021). When grease or oil touches FPM, it can spread across the surface, leading to a loss of product quality, unsightly appearance, and potential leakage. To prevent grease spreading, FPMs are often designed with low surface energy and high oleophobicity. This is often achieved through the use of fluoropolymers, such as polytetrafluoroethylene or perfluoroalkoxy alkanes, which exhibit ultralow surface energy and excellent resistance to oil and grease. Water repellency is another critical interfacial property for FPM, especially for products that are sensitive to moisture or require a robust steam barrier function (Arshad et al., 2024; Pasquier et al., 2022). To achieve water repellency, FPMs are often treated with hydrophobic coatings or additives, such as silicones, waxes, or fluorochemicals (Basak et al., 2024; Long et al., 2022). Interfacial properties of FPMs are also related to their ability to adhere and repel bacteria, viruses, and contaminants (Mu, Liu, et al., 2023; Oh et al., 2018).

2.6 | Optical properties

The optical characteristics of FPM govern the appearance, quality, and consumer appeal of the packaged food product. These properties include transparency, gloss, and color, which can be tailored to suit specific product requirements and marketing goals. Transparency is an important optical property for many FP applications, as it allows consumers to view the contents of FP and assess the quality and freshness of the product (Bou-Mitri et al., 2021). Clear transparency is often desired for fresh produce where visual appeal is a key factor in consumer purchasing decisions (Vermeir & Roose, 2020). To optimize optical transmittance in FPM, amorphous silica-based glasses and semi-crystalline thermoplastics such as PET and PP are frequently employed due to their favorable refractive indices and minimal light scattering characteristics (Guzman-Puyol et al., 2022; Tsironi et al., 2022). Surface specular reflectance, quantified as gloss, is another critical optical parameter that influences the visual aesthetics and perceived organoleptic quality of packaged foodstuff, impacting consumer perception and market acceptance (Rim et al., 2022). Color is another significant optical property for FPMs, as it can modulate consumer perceptions of product quality, freshness, and taste (Steiner & Florack, 2023).

The optical properties of FPMs can also serve functional purposes, such as providing light protection for light-sensitive products (Intawiwat et al., 2012). Many food products (e.g., dairy, meat, and beer) are susceptible to light-induced oxidation and degradation, which can lead to off-flavors, nutrient loss, and diminished shelf-life (Mortensen et al., 2004; Passaretti et al., 2019). To prevent these issues, FPMs with high opacity or UV-blocking properties can be used, such as aluminum foil, metalized films, or materials with UV absorbers or blockers.

3 | CLASSES OF FOOD PACKAGING MATERIALS

Over the years, different categories of materials were used to satisfy the requirement for the physicochemical properties of FPMs. These materials can be classified into several categories, each with its own unique set of properties (Kim et al., 2014; Piergiovanni & Limbo, 2016; Videira-Quintela et al., 2021).

3.1 | Glass

Glass is an amorphous solid material composed of a network of silica (SiO_2) tetrahedra, where each silicon is covalently bonded to four oxygens, and the oxygen atoms bridge the silicon atoms to form a continuous, random network (Y. Yuan, Kim, et al., 2022). Vitreous silica-based materials, as traditional FPMs, exhibit chemical inertness, negligible gas and moisture permeability, and high optical transmittance, rendering them desirable in FP applications (Lee et al., 2023). Glass is also reusable and recyclable, making it an environment-friendly option. However, glass is heavy, brittle, and more expensive compared to other FPMs (Driscoll & Rahman, 2020).

The primary network former in most FP glass is silica, which is typically derived from sand or quartz. The high bond strength of the Si–O covalent bonds (approximately 800 kJ/mol) contributes to the excellent thermal stability and chemical resistance of glass (Rouxel, 2007). However, pure silica glass has a high melting point and is difficult to process. To lower the melting point and improve the workability of the glass, network modifiers, such as sodium oxide (Na_2O) and calcium oxide (CaO), are added (Fu et al., 2018). These modifiers disrupt the silica network by creating non-bridging oxygens (NBOs), which are oxygen atoms that are bonded to only one silicon atom (Serra et al., 2002). The existence of NBOs weakens the glass structure, lowering the melting point and viscosity of the glass melt. The inclusion of network intermediates, such as aluminum oxide (Al_2O_3) and boron oxide (B_2O_3), can further modify the properties of the glass (Osipov et al., 2016). These intermediates can act as both network formers and modifiers, depending on their coordination number and the presence of other ions in the glass composition.

Recent research has centered on developing and characterizing novel vitreous glass materials with diverse compositional profiles, aimed at expanding the functional properties of glass for potential applications in food containment and preservation systems (Oh et al., 2015; Ruzi et al., 2022). A notable study by Sadeq et al. (2023) explored the effects of ZnO incorporation on the physicochemical characteristics and antimicrobial efficacy of chromium-doped sodium borosilicate glass systems. The incorporation of increasing concentrations of zinc oxide in sodium borosilicate glass matrices yielded a dose-dependent enhancement of antibacterial activity versus *Staphylococcus aureus*, *Escherichia coli, Bacillus subtilis*, and *Klebsiella pneumoniae* (Figure 2) (Sadeq et al., 2023). The glass with the highest ZnO content (7 mol%) demonstrated the most promising antibacterial properties. The glasses also exhibited inhibitory effects on bacterial biofilm formation, demonstrating greater efficacy versus *S. aureus* relative to *E. coli*. Additionally, the ZnO-containing glasses

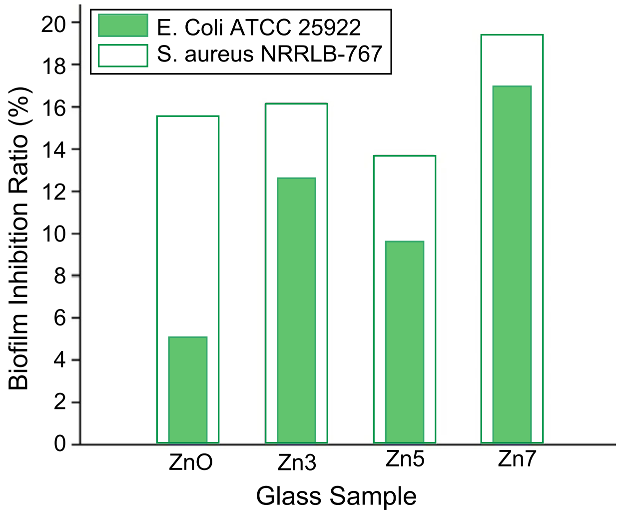

FIGURE 2 Comparison of antibiofilm activity of all ZnO-modified glass samples against *Staphylococcus aureus* NRRLB-767 and *Escherichia coli* ATCC-25922. The figure displays the effectiveness of various compounds in inhibiting biofilm formation by these two bacterial strains. *Source*: Image courtesy of Sadeq et al. (2023).

exhibited antioxidant action, as determined by DPPH and H_2O_2 free radical scavenging assays, which could be useful in FP applications.

Naseri et al. (2019) synthesized and characterized argentiferous borate glasses (AgBGs) via sol–gel methodology, investigating their antimicrobial properties. The study elucidated that Ag+ ion liberation from AgBGs in aqueous media was contingent upon both fabrication methodology and glass stoichiometry, with sodium-deficient formulations exhibiting significantly enhanced ion release kinetics. A dose-dependent bactericidal efficacy versus *E. coli* and *S. aureus* was observed, correlating positively with solubilized Ag+ ion concentration.

Ren et al. (2018) developed a superhydrophobic and transparent coating for glass with antibacterial characteristics. They achieved this by spray-coating a blend of hydrophobic silica sol and CuO nanoparticles onto glass substrates. This coating exhibited a maximum transmittance of 96.6%, showcasing its transparency. The superhydrophobic nature of the coating reduced *E. coli* adhesion by 3.2 log cells/cm^2 compared to bare glass. Moreover, the incorporated CuO nanoparticles imparted a significant bactericidal effect versus *E. coli*. Importantly, the coating demonstrated robustness, maintaining its superhydrophobicity even after undergoing sand impact tests.

Overall, recent advances in experimental characterization techniques and molecular dynamics simulations are providing new insights into the atomic-level structure and properties of glass, enabling the coherent design, fabrication, and optimization of glass compositions for specific food containment systems. As the need for secure, eco-friendly, and superior FPMs surges, glass will probably endure as an important component in FP, and current studies will persist in expanding the limits of this fascinating material.

3.2 | Metals

Metallic substrates, notably aluminum, tinplate steel, and chromium-coated steel (ECCS), find extensive utility in FP systems because of their exceptional gas and moisture impermeability, high mechanical strength, and superior resistance to environmental degradation (Deshwal & Panjagari, 2020). These materials offer excellent protection against light, oxygen, and moisture, thus prolonging the shelf-life of packaged foodstuff (Sarkar & Aparna, 2020).

Aluminum, with its low density, high tensile strength, and good formability, is commonly used in the production of cans, trays, and foils for packaging various food items, including beverages, seafood, and snacks (S. Liu, Ulugun, et al., 2021; Shin & Selke, 2014). Aluminum establishes a thin oxide layer on its outer side when exposed to air, which further enhances its barrier properties against gas and moisture permeation (Struller et al., 2014). The oxide layer, with a thickness of 1–10 nm, comprises amorphous and crystalline zones, with the latter being dominated by the thermodynamically stable α-Al_2O_3 phase (Xie et al., 2020). Tinplate steel, another common metal FPM, is produced by electrolytically coating low-carbon steel with a thin layer of tin (Pandey et al., 2023). Tin layer serves as sacrificial anode, shielding steel substrate from corrosion, maintaining packaged food integrity. ECCS, a tinplate steel alternative, features thin metallic chromium layer deposited on steel substrate (Piergiovanni et al., 2016).

Recent progress in metal FPMs has aimed to boost their sustainability and functionality. Moreover, the creation of functional coatings, such as antimicrobial and antioxidant coatings, has shown potential in improving the hygiene and quality of packaged food. Morselli et al. (2021) reported a notable innovation in sustainable FP technology: the synthesis of zinc polyaleuritate ionomer coatings. This material was fabricated through the chemical interaction between nanoscale zinc oxide particles, generated via heat-induced breakdown of zinc acetate, and aleuritic acid, a bio-derived polyhydroxylated long-chain carboxylic acid. This development represents a significant advance toward bisphenol A-free, eco-compatible metallic food containment systems. The presence of zinc in the coatings was found to provide some antibacterial activity, further enhancing food preservation.

Regarding the improved functionality, researchers have also developed durable, superhydrophobic nanodiamond

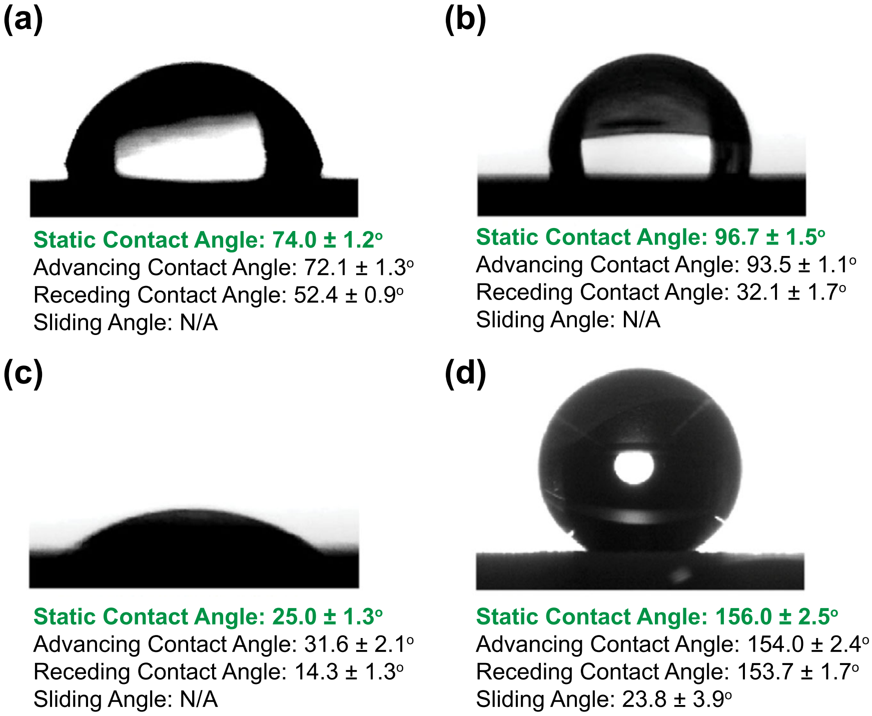

FIGURE 3 Water contact angle measurements on various aluminum surfaces: (a) bare aluminum, (b) CND-coated aluminum, (c) CND/L-DOPA-coated aluminum, and (d) FDPS-coated aluminum. The FDPS coating successfully transformed the wettability of the aluminum surface from hydrophilic to superhydrophobic, as evidenced by the significant increase in water contact angle compared to the bare aluminum surface. *Source*: Image courtesy of S. Liu, Ulugun et al. (2021).

coatings on aluminum to enhance food contact surface hygiene. S. Liu, Ulugun et al. (2021) engineered a novel surface modification for aluminum substrates, comprising successive deposition of ultrahard nanodiamond particles, self-assembled dopamine, and organofluorosilane functionalization. The resultant coating exhibited exceptional superhydrophobicity, with a static water wetting angle of about 160° (Figure 3). This surface modification demonstrated remarkable bacterial antiadhesion properties, inhibiting 99.5% of *E. coli* O157:H7 and 99.0% of *S. aureus* cell attachment relative to unmodified aluminum surfaces. The synergistic combination of superhydrophobicity, bacterial repulsion, and mechanical resilience renders this coating technology highly promising for FP applications.

Similarly, Zhou et al. (2024) developed a nanotextured antifouling coating for galvanized steel, applicable to food containment systems, to enhance hygienic properties and corrosion resilience against microbial and environmental contaminants. The coating was synthesized via a bi-phasic process: initial adherence of silica nanoparticles followed by chemisorption of a low surface energy organosilane layer. The resultant surface exhibited superhydrophobic characteristics, with a static water wetting angle of about 160°. During 7-day period, the coating demonstrated significant antimicrobial efficacy, achieving logarithmic reductions of 2.6 ± 0.1 and 2.9 ± 0.1 in the adherence of *Salmonella enterica* and *Listeria innocua*, respectively. Furthermore, the coating substantially inhibited *Aspergillus niger* fungal adherence. Electrochemical analysis of the coated steel in the presence of *S. enterica* revealed a ∼60% ± 10% reduction in corrosion rate relative to unmodified steel substrates. This coating technology could be implemented on galvanized steel surfaces, including storage units and containers for foodstuff.

Despite their excellent barrier and mechanical properties, metal FPMs have some limitations. They are opaque, which prevents consumers from visually inspecting the inside content. Additionally, the production and processing of metal FPMs are energy-intensive and can be more expensive compared to other FPMs (Akram et al., 2023).

3.3 | Paper and paperboard

Paper and paperboard, often employed in FP, are affordable, biodegradable, and versatile materials made from cellulose fibers sourced from wood pulp or plants (Zaidi et al., 2022). Intermolecular forces, specifically van der Waals attractions and hydrogen bonding, facilitate cohesion among individual paper fibers, resulting in a three-dimensional matrix characterized by high porosity, flexibility, and conformability (Barbash et al., 2022; Semple et al., 2022). The hierarchical framework of paper and paperboard determines its properties at various length scales. At the nanoscopic level, cellulose fibers consist of extended polymeric chains composed of glucopyranose monomers, exhibiting a heterogeneous ultrastructure characterized by alternating regions of high molecular order and reduced structural regularity (Sharma et al., 2019). The crystallinity degree and cellulose microfibril orientation within the fibers significantly affect the mechanical properties (Jakob et al., 2022).

Paper and paperboard FP often fails to effectively block moisture, gases, and grease. Surface treatments and coatings can improve the performance of such FPMs. For example, the application of a thin layer of PE or PP can significantly ameliorate the moisture and grease resilience of paper and paperboard (Basak et al., 2024). The coating thickness and composition can be customized for specific FP needs to achieve desired barrier properties (Paul & Heredia-Guerrero, 2021). Incorporating nanocellulose, like cellulose nanofibrils or nanocrystals, into paper and paperboard enhances barrier properties (Hu et al., 2021). Nanocellulose significantly reduces porosity and increases tortuosity, improving moisture and gas barrier properties (Wu et al., 2022). Modifying nanocellulose surface chemistry introduces hydrophobic or oleophobic functionality, further enhancing water and grease resistance (Wen et al., 2024).

Ozcan et al. (2023) described the fabrication of an active FPM utilizing a composite coating of chitosan (CH) and titanium dioxide nanoparticles (TiO_2 NPs) on paper substrates. Their methodology involved the sol–gel synthesis of thiol-functionalized TiO_2 NPs and the chemical modification of CH through allylation with glycidyl ether. The coated papers were characterized in terms of their color ($\Delta E00 < 1.6$), gloss (up to 12.8 GU at 75°), contact angle (25–44°), surface energy (49.1–56.0 mJ/m^2), and air permeability (reduction compared to base paper). Antimicrobial efficacy, assessed via the Kirby-Bauer disk diffusion assay, revealed a cooperative effect between the modified CH and TiO_2 nanoparticles. The composite coating demonstrated enhanced bacteriostatic action versus *E. coli* and *S. aureus* compared to the individual constituents. Paper substrates coated with 5% (w/w) CH-functionalized TiO_2 nanoparticles exhibited maximum zones of inhibition measuring 11.3 and 12.0 mm in diameter for *E. coli* and *S. aureus*, respectively.

Koshani et al. (2021) described the synthesis and characterization of a photobactericidal hairy nanocrystalline cellulose derivative for application as a bio-inspired nanofiller in self-disinfecting FPMs (Figure 4). Rose Bengal (RB), a natural photosensitizer, was covalently conjugated to these amine moieties via an aqueous-phase bioconjugation reaction. The antimicrobial efficacy of the RB-amorphous nanocellulose crystal (ANCC) conjugate was gauged versus *Listeria monocytogenes* and *S. enterica* serovar Typhimurium. Upon exposure to normal light irradiation, the conjugate demonstrated significant photodynamic inactivation, effectively reducing viability by over 80% for both bacterial species. Notably, the RB-ANCC conjugate exhibited superior photoinactivation of *S. typhimurium* compared to free RB, which showed no measurable effect. The RB-ANCC conjugate was successfully incorporated into two distinct cellulose-based matrices: carboxyl-modified cellulose films and electrospun cellulose acetate nanofibers.

3.4 | Plastics

Plastics, the most relied on FPMs, offer low cost, light weight, and versatility (Boone et al., 2023). They are easily molded into various shapes and sizes, with properties tailored to specific product requirements. Polypropylene, PET, PE, and polystyrene are common plastics in FP (Tajeddin & Arabkhedri, 2020). Advances in polymer synthesis and processing have enabled novel plastic materials with enhanced functionality and sustainability. Controlled radical polymerization techniques, such as atom transfer radical polymerization or reversible addition-fragmentation chain transfer polymerization, allow for precise control over polymer molecular weight, architecture, and composition (Keddie, 2014). Incorporating nanofillers, such as clay, silica, or cellulose nanocrystals (CNCs), into plastic matrices enhances their mechanical, thermal, and barrier properties (Peerzada et al., 2024).

Regarding some specific examples, Beigmohammadi et al. (2016) synthesized and characterized PE-based nanocomposite layers integrating silver, CuO, and ZnO nanoparticles, evaluating their antimicrobial efficacy for potential application in ultra-filtered cheese packaging. The 45 ± 5 µm thick nanocomposite films, produced by melt extrusion, significantly reduced coliform bacteria by ~4 log cfu/g in 4-week study at 4°C, compared to a 1.0 log cfu/g reduction for virgin low-density polyethylene (LDPE) films (Figure 5). Migration testing of the optimum 1% CuO nanocomposite film into a food simulant showed CuO nanoparticle migration of 0.23 ± 0.005 mg/kg. This study highlights the potential of LDPE nanocomposite films with CuO nanoparticles as an effective antibacterial packaging for UF cheese.

Kim and Cha (2014) engineered polymer-based nanocomposite films by incorporating organically modified layered silicates to a copolymer matrix made from ethylene–vinyl alcohol. The addition of up to 5% by weight of nanoclay particles resulted in significant improvements across multiple material properties, including thermal resilience, mechanical strength, optical clarity, and permeability resistance. Thermal analysis revealed an increase in the temperature at which 50% mass loss occurred, rising from 386°C for the unmodified copolymer to 392°C for the composite containing 7% nanoclay, indicating enhanced thermal stability. Optical measurements demonstrated

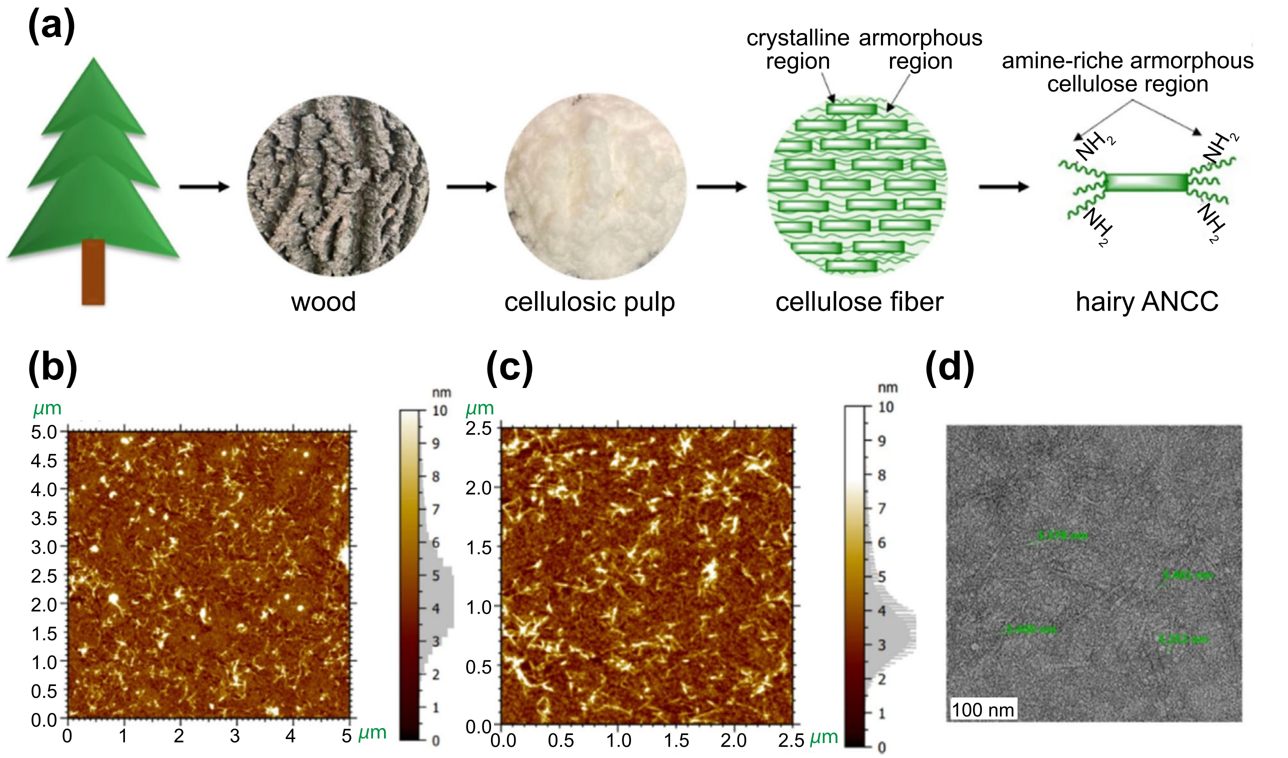

FIGURE 4 (a) The schematic diagram portrays the overall process for extracting hairy amorphous nanocellulose crystals (ANCC) from cellulosic biomass. This process involves a two-step method consisting of an oxidation phase followed by a reduction phase. (b and c) Atomic force microscopy (AFM) images of the ANCC particles, captured at two different scales of 5 × 5 μm and 2.5 × 2.5 μm, reveal the crystalline core structure of the nanowhiskers. These nanowhiskers closely resemble traditional nanocrystalline cellulose (NCC) in appearance. (d) Transmission electron microscopy (TEM) imaging shows individual ANCC particles with approximate dimensions of 120 nm in length and 5 nm in width. *Source*: Image courtesy of Koshani et al. (2021).

that films with 5% nanoclay content maintained high transparency, allowing transmission of approximately 92% of visible light in the 650–850 nm spectral range. Notably, the nanocomposite films exhibited exponential drops in both oxygen and steam permeance as the nanoclay concentration increased. At 3% nanoclay content, dramatic reductions of 59.4% and 90.1% were observed for oxygen and steam transmission, respectively, relative to the unmodified copolymer.

Arcot et al. (2021) developed a novel surface modification technique for high-density polyethylene (HDPE). The resulting coatings exhibited superhydrophobic properties, with a static water wetting angle of ~150°. The modified surfaces demonstrated superior durability, maintaining their water-repellent characteristics after simulated food processing abrasion tests and multiple cycles of sand abrasion. Microbial adhesion studies revealed significant reductions in bacterial attachment compared to untreated HDPE. Specifically, the coated surfaces reduced the adhesion of *S. typhimurium* LT2 and *L. innocua* by 2.1 ± 0.4 (>99.3%) and 1.6 ± 0.6 (>97.8%) log-cycles, respectively. Furthermore, the modified substrata showed efficacy in minimizing bacterial cross-contamination to food items such as spinach leaves.

Researchers employed extrusion-blowing techniques to fabricate multifunctional nanocomposite films using low-density PE as the primary matrix, incorporating extract of grapefruit seeds, melanin, and ZnO nanomaterials (Shankar et al., 2019). The resulting materials exhibited enhanced physical and functional properties, including increased thickness, improved UV-shielding capabilities, greater elongation at break, and superior thermal resistance. The composite films also demonstrated significant antimicrobial effectiveness versus *E. coli* and *L. monocytogenes*. When applied as a coating to paper substrates, these nanocomposite materials substantially reduced both aqueous and lipophilic fluid absorption.

The investigation by Zhang et al. (2014) demonstrated the capability of ultrathin polyethylene glycol (PEG) films as a novel strategy to prevent bacterial contamination on tomato surfaces. They reported that complete PEG surface coverage significantly reduced the attachment of *S. enterica* serovar Typhimurium LT2 and *E. coli* O157:H7 by approximately 90% or greater compared to unmodified

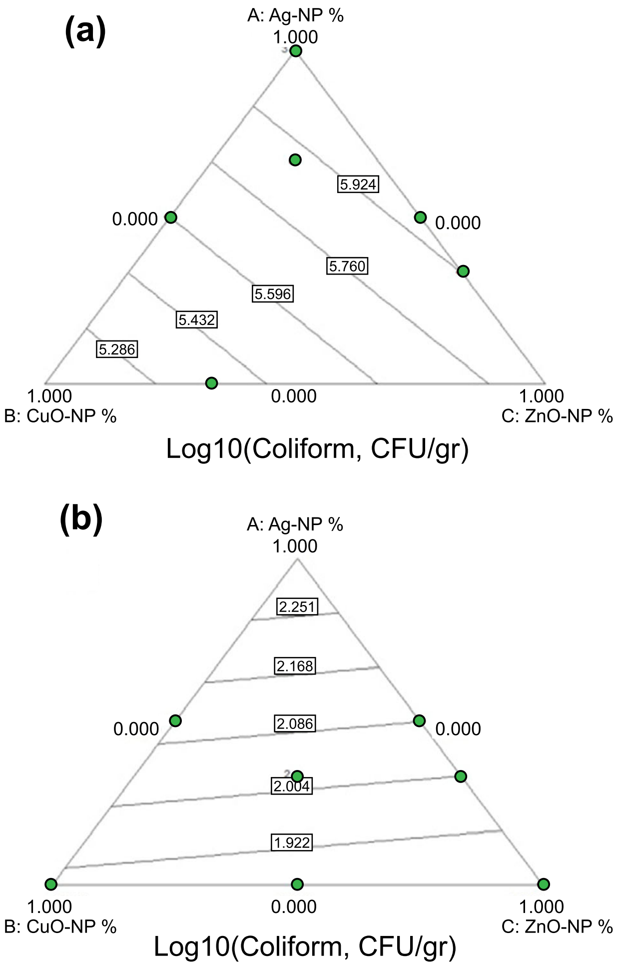

FIGURE 5 Contour plots depicting the coliform load in cheese packed with nanocomposite films using a combined design. (a) Coliform count at the beginning of storage (Week 1). (b) Coliform count at the end of storage (Week 4). The red spots on the contour plots represent the logarithmic colony-forming units per gram (log_{10} cfu/g) of coliforms in the cheese samples packed with the nanocomposite films. *Source*: Image courtesy of Beigmohammadi et al. (2016).

tomato surfaces. This antiadhesion property was attributed to the PEG film acting as a steric barrier and reducing attractive interactions between the bacteria and the tomato surface, offering a promising approach for enhancing the safety of fresh produce.

3.5 | Multilayer and composite materials

Multilayer and composite materials are designed to combine the advantages of different FPMs while overcoming their individual limitations. Composite packaging structures typically comprise multiple layers of heterogeneous materials, including polymeric films, metallic foils, and cellulose-based substrates. These layers are bonded through lamination or co-extrusion processes. The resulting multilayer composites exhibit superior gas and moisture barrier properties, enhanced mechanical strength, and improved flexibility in diverse food containment systems (Alias et al., 2022; DeFlorio et al., 2024; Liu, Ieoure, et al., 2024).

Regarding the recent progressions in multilayer and composite FPMs, a study performed by Huang et al. (2017) investigated the efficiency of a laminated clay/polyvinyl alcohol (PVA) nanocomposite film for FP applications. They fabricated the composite material by depositing a montmorillonite (MMT)/PVA suspension (4% w/w solids) onto PET substrate, followed by lamination with linear low-density polyethylene. Results demonstrated that incorporating a 30% w/w MMT coating layer into the polymer matrix significantly enhanced barrier performance, with oxygen transmission rates (OTRs) reduced by up to 99%. To assess practical efficacy, the researchers conducted food shelf-life studies using tomato paste as a model system. Monitoring of physicochemical changes revealed that the nanocomposite film pouches notable inhibited the oxidation of key nutritional compounds. Specifically, ascorbic acid (AA) and lycopene degradation were reduced by up to 88% and 37%, respectively, compared to the control packaging.

In another study, Nacas et al. (2019) explored the integration of boron nitride (BN) into a two-component reactive polyurethane (PU) adhesive to augment the barrier characteristics and peel resistance of flexible laminated FP for food. The study examined two different BN particle size distributions: micro- and nanostructured BN. These BN variants were incorporated into the PU adhesive at various concentrations to assess their impact on packaging performance. Their water vapor permeation tests showed that adding BN reduced PU sample permeability by up to 50%. Micro BN particles significantly reduced permeability with only 1 wt% filler, whereas nano BN particles needed 2 wt% filler for a similar reduction.

Winotapun et al. (2021) investigated the reliance of laser technique to create microperforation in PET/PE laminates for fresh produce packaging. The study utilized a carbon dioxide (CO_2) laser operating in the infrared spectrum to generate microholes in the film structure. They examined the effects of varying pulse durations ranging from 3 to 200 μs and explored perforation from both the PET and PE sides of the laminate. Their findings revealed that increasing laser fluence led to surface deformation and microhole formation. Furthermore, they established correlations between the area of a single microhole and the oxygen and carbon dioxide transmission rates. To demonstrate practical applicability, the team packaged a mixed vegetable salad in plastic trays sealed with microperforated lidding films. The results showed that all perforated packages achieved equilibrium gas compositions of 10%–13% O_2 and 8%–10% CO_2, in contrast to non-perforated controls.

4 | CHALLENGES WITH CURRENT FOOD PACKAGING MATERIALS

4.1 | Problems with PFAS (per- and polyfluoroalkyl substances)

PFAS are a group of synthetic compounds employed in FPMs (FPMs) to impart grease, water, and thermal resistance (US Food and Drug Administration, 2022). They are commonly added to paper, board, and plastics that are relied on the production, processing, transport, handling, and storage of foods. Migration of PFAS from food contact materials (FCMs) into food can occur in several ways, including diffusion, abrasion, and mechanical stress. They can migrate as individual molecules or as particles or fragments that detach, a process that is influenced by the type and composition of the FPM. Migration typically increases with increasing temperature, contact duration, and surface area as well as with the presence of acidic or fatty foods (Begley et al., 2008). The PFAS that have most commonly been used in FPM include perfluoroalkyl carboxylic acids (e.g., perfluorooctanoic acid [PFOA] and PFHxA), perfluoroalkanesulfonic acids (e.g., PFBS), fluorotelomer sulfonates (FTS) (e.g., 6:2 FTS), fluorotelomer alcohols (FTOHs), and phosphate esters (PAPs and diPAPs), with more recent studies indicating the utilization of polymers such as side chain fluorinated polymers (Barhoumi et al., 2022; Phelps et al., 2024; Schaider et al., 2017; Schultes et al., 2019; Zabaleta et al., 2016, 2017).

PFAS are highly stable and resistant to breakdown thanks to bonding strength of the carbon–fluorine bonds (Buck et al., 2011). Their stability, a sought-after packaging trait for consumer use, also translates to environmental persistence. Upon release, PFAS contaminate soil, water, and air where they can travel long distances. Furthermore, PFAS bioaccumulate in living organisms (B. Khan, Burgess, et al., 2023), meaning that they can accumulate in the body gradually through repeated exposure. This bioaccumulation occurs because PFAS bind to proteins in the blood and liver (Smeltz et al., 2023), are retained by the kidney, and undergo enterohepatic recirculation. As a result, many PFAS have a long elimination half-life in the body that's on the order of years (Bartell et al., 2010; Hölzer et al., 2009; Olsen et al., 2007). In addition to bioaccumulation, they also biomagnify in the food chain, with higher concentrations found in living beings at the summit of the food chain, such as predatory fish and humans (B. Khan, Burgess, et al., 2023). This is of concern due to their demonstrated capacity to affect multiple physiological systems, with substantial research linking their exposure to a spectrum of negative health consequences, including hypercholesterolemia, increased risk of specific malignancies, developmental abnormalities, immunological dysfunction, and endocrine dysregulation (National Academies of Sciences, Engineering, & Medicine, 2022).

Exposure to PFAS used in FCM and other products can occur via multiple pathways for consumers, workers, and through the environment (Eze et al., 2024; Phelps et al., 2024). PFAS released from chemical and product manufacturing enters the environment via stack emissions, deep well injection, and effluent. Wastewater treatment plants do not remove PFAS inputs and discharge it as effluent into water bodies as well as in biosolids (Blaine et al., 2013; Lindstrom et al., 2011; Yu et al., 2009), which are typically applied to agricultural land, incinerated or landfilled. PFAS in FCM waste can be released into the environment following disposal *in* landfills via leachate that often goes to wastewater treatment plants (Benskin et al., 2012; Lang et al., 2017), runoff, consumption by local wildlife, and into groundwater if the landfill lining is compromised. FCM waste may also be composted, and elevated PFAS has been reported in industrial compost containing plant fiber-based FCM treated with PFAS coatings (Choi et al., 2019; Yuan et al., 2016). Many PFAS are highly mobile and migrate easily in the environment, including surface water, through soils into groundwater, into plants and animals—thus contributing to environmental exposures via drinking water and diet (Sunderland et al., 2019).

Use of PFASs in FCM is estimated up to 9000 tons per year (Minet et al., 2022). Owing to health and environmental concerns associated with PFAS, there has been heightened scrutiny and regulatory measures against their use. The US Environmental Protection Agency initiated the PFOA Stewardship Program in 2006, targeting PFOA, its long-chain homologues, and precursors. Subsequently, PFAS manufacturers in North America and Europe predominantly transitioned to other PFAS such as 6:2 FTOH. In 2020, the US Food and Drug Administration and manufacturers of grease-proofing agents for paper and paperboard FP reached a voluntary agreement to phase out 6:2 FTOH by 2024, following new toxicological evidence suggesting significant potential health risks associated with chronic dietary exposure (https://www.fda.gov/food/environmental-contaminants-food/and-polyfluoroalkyl-substances-pfas). Worldwide regulatory agencies have implemented regulations on use of specific PFAS in FCMs and limits on PFAS levels in food products. Thus, developing safer and more sustainable PFAS alternatives is an active research area, aiming to find materials that provide similar performance benefits without the associated environmental and health risks.

4.2 | Problems with microplastics

Microplastics, plastic particles under 5 mm, have become a major environmental and health issue recently (Luo et al., 2024; Winiarska et al., 2024; Yang et al., 2024). Microplastics are generated through multiple pathways, including the crumbling of larger plastic debris via physical, chemical, and biological degradation processes (de Oliveira et al., 2023). The presence of microplastics in FPMs instigates worries about potential migration into food and ingestion by humans (Al Mamun et al., 2023; Emenike et al., 2023; Muhib et al., 2023).

Microplastics can be generated in FPMs through several mechanisms: (i) Degradation of plastic FP (Figure 6): Plastic FP can degrade over time due to exposure to heat, light, and mechanical stress, triggering the occurrence of microplastics (Hussain et al., 2023; Sutkar et al., 2023). This degradation can occur during the production, transport, and storage of the packaged foodstuff. (ii) Abrasion and wear: The use and handling of plastic FP can result in the abrasion and wear of the material, generating microplastics (Cole et al., 2024; Sobhani et al., 2020; Su et al., 2024). This can occur during the opening and closing of containers, as well as during the transportation and stacking of packaged foods. (iii) Migration from recycled materials: The incorporation of recycled polymeric materials in food contact applications may result in the unintentional transfer of pre-existing microplastic particles from the source material to the final packaging product (Lehel & Murphy, 2021). If not properly filtered out during the recycling process, these microplastics can migrate into the food product. Some of these mechanisms are listed in Figure 6 with examples from common FPMs.

Microplastic generation from grocery bags can occur through friction, wear, and rubbing motions experienced by the bags during their use and handling. The primary mechanism behind this process is known as mechanical degradation or abrasion. When grocery bags are subjected to repeated mechanical stresses, such as rubbing against other surfaces (e.g., products, other bags, or the user's hands), the polymeric material of the bag can undergo microscopic damage. This damage can manifest as small cracks, fractures, or surface abrasions on the bag surface. As the mechanical stresses continue, these micro-damaged areas can grow and propagate, yielding the formation of small plastic fragments or fibers. Over time, these fragments can detach from the surface, causing the release of microplastics into the environment. Plastic soda cups and water bottles can also contribute to microplastic generation through similar mechanisms of mechanical degradation, friction, and wear. However, the extent and nature of microplastic formation may differ due

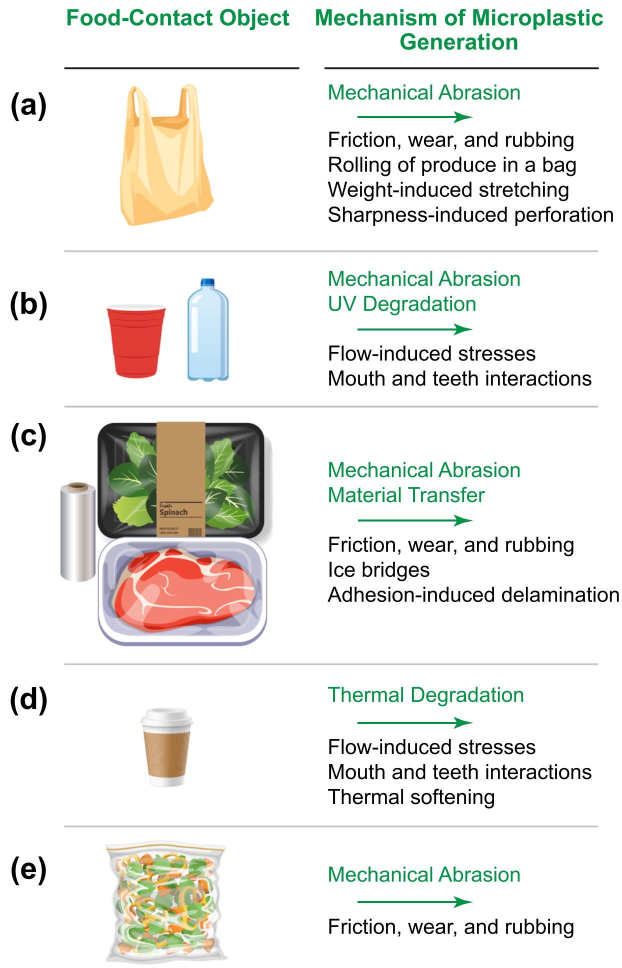

FIGURE 6 Mechanisms of microplastic generation from common food packaging materials. (a) Grocery bags: Friction, wear, and rubbing motions during use and handling can cause mechanical degradation and abrasion, leading to the formation and release of microplastics. (b) Plastic soda cups and water bottles: Mechanical stresses, such as contact with the user's mouth, opening and closing of bottle caps, and stacking of cups, can contribute to surface wear and microplastic generation. (c) Stretch wrap films for packaging meat and produce: Repeated stretching, handling, and friction against food products can cause microscopic tears and surface abrasions, leading to microplastic formation. Delamination and material transfer can occur when frozen food adheres to the film during removal. (d) Expanded polystyrene cups for hot drinks: Surface abrasion from handling and stacking, and temperature-related degradation can cause fragmentation and the release of microplastics from the brittle expanded foam material. (e) Vacuum seal bags for storing fresh and cut produce: The process of vacuum sealing can cause mechanical stress on the bag material, potentially leading to the formation of microplastics. Additionally, friction between the produce and the bag, especially for products with rough surfaces, can cause surface abrasion and contribute to microplastic generation.

to alterations in material properties, usage patterns, and environmental influences. Soda cups and water bottles are often subjected to different types of mechanical stresses compared to grocery bags. For example, they may experience more direct contact with the user's mouth, leading to additional friction and potential microplastic release. Additionally, the repeated opening and closing of bottle caps or the stacking of cups can cause localized stresses and contribute to mechanical degradation. Exposure to UV radiation can degrade the plastic material of water bottles, making them more susceptible to mechanical degradation and microplastic formation. For instance, leaving a water bottle in a hot car or exposing it to direct sunlight for extended periods can accelerate the degradation process. Stretch wrap films, commonly used for packaging meat and produce, can also be a source of microplastics through mechanical degradation, friction, and wear. Stretch wrap films are designed to be stretched tightly around food products to create a secure and protective seal. During the wrapping process, the film experiences mechanical stresses that can cause microscopic tears and surface abrasions. Repeated stretching and handling of the film can exacerbate this damage and yield the release of microplastics. When stretch wrap films are used to package meat and produce, they directly contact the food surface. Friction between the film and the food product can cause additional surface abrasion and contribute to microplastic generation. This is particularly relevant for products with rough or irregular surfaces, such as certain fruits and vegetables. When opening packaged food items, consumers often cut or tear the stretch wrap film. This action can create small plastic fragments or fibers that can seep into the environment or potentially contaminate the crops. When frozen meat and produce are packaged using stretch wrap films, the adhesion between the food and the film can lead to additional challenges related to microplastic generation. As the food adheres to the film, it can cause delamination or material transfer during the removal process. EPS foam, commonly used for hot drinks, can also contribute to microplastic generation through various mechanisms, including mechanical degradation, friction, and wear. When such plastic cups are handled, stacked, or transported, they can experience surface abrasion due to friction against other cups, surfaces, or the user's hands. This abrasion can cause small particles or fragments of plastic cups to break off from the cup's surface, contributing to microplastic generation. Exposure to high temperatures can cause the EPS to soften, making it more prone to deformation and potential microplastic release. Additionally, temperature fluctuations during use and disposal can lead to thermal degradation, which can further contribute to fragmentation and microplastic formation.

Microplastics in food can enter humans via ingestion. Their small size enables translocation through the gastrointestinal tract and potential absorption into the body (Fournier et al., 2021; Krasucka et al., 2022). Studies detected microplastics in human stool, confirming exposure and internalization (Barceló et al., 2023; Schwabl et al., 2019; Yan et al., 2021). The health effects of microplastic internalization remain unclear, but proposed toxicity mechanisms include as follows: (i) Physical damage: Microplastics may inflame and abrade the gastrointestinal tract due to their size and sharp edges (Prata et al., 2021; Xie et al., 2021; Z. Yuan, Nag, et al., 2022). (ii) Chemical toxicity: Microplastics can transport toxic chemicals, including plasticizers, flame retardants, and POPs (Fred-Ahmadu et al., 2020; Okoye et al., 2022; Song et al., 2022). These chemicals can leach from microplastics and cause toxicity. (iii) Immune response: Microplastics in the body may trigger inflammation and oxidative stress (Cui et al., 2023; Kim et al., 2021; Qiao et al., 2019). (iv) Gut microbiome disruption: Microplastics may disrupt the gut microbiome, important for human health (Blackburn & Green, 2022; Fackelmann & Sommer, 2019; Lu et al., 2019). Gut microbiome alterations are linked to various diseases, including metabolic disorders and inflammatory bowel disease.

Although the current evidence suggests that humans are exposed to and can internalize microplastics (Table 1), the full extent of their health impacts remains an active area of research. Given the increasing prevalence of polymeric materials in food contact applications, it is imperative to develop and implement multifaceted strategies to mitigate microplastic formation and migration, conduct comprehensive toxicological and exposure assessments, and establish evidence-based risk management protocols to address potential human health implications associated with microplastic exposure via FP.

5 | SUSTAINABLE AND RENEWABLE MATERIALS FOR FOOD PACKAGING

The vast utilization of petrochemical-derived FPMs has brought about global environmental challenges, prompting a shift toward sustainable and eco-friendly alternatives. Renewable resources, such as biomaterials from plants and valorized industrial waste streams, have emerged as promising candidates for novel FP solutions. Bio-based substrates exhibit attractive physicochemical properties and environmental attributes, making them suitable substitutes for conventional fossil fuel-derived plastics. The biodegradability, renewability, and reduced carbon footprint of these plant-derived materials align with circular economy principles and sustainable development,

TABLE 1 A systematic compilation of diverse microplastic types detected in various human tissues and biological samples, indicating the pervasive presence of microplastic contaminants throughout the human body.

Microplastic type	Anatomical site of detection	References
Polyethylene Polyvinyl chloride Polyethylene terephthalate Polymethylmethacrylate Polyurethane Polycarbonate Polypropylene Polystyrene Nylon Styrene–butadiene rubber Acrylonitrile butadiene styrene	Human brain	Campen et al. (2024)
Polyethylene terephthalate Polyethylene Polyurethane Polymethylmethacrylate Polyamide Polypropylene Polyvinyl chloride Polycarbonate Polystyrene	Human heart tissues	Yang et al. (2023)
Polyethylene Polyvinyl chloride Polyethylene terephthalate Polymethylmethacrylate Polyurethane Polycarbonate Polypropylene Polystyrene Nylon Styrene–butadiene rubber Acrylonitrile butadiene styrene	Human kidney and liver	Horvatits et al. (2022) Campen et al. (2024)
Polypropylene Polyethylene terephthalate Resin (epoxy/alkyd) Polyethylene Polytetrafluoroethylene Polystyrene Polyacrylonitrile	Human lung	Jenner et al. (2022)
Polycarbonate Polyamide Polypropylene	Human colon	Ibrahim et al. (2021)
Polypropylene Polyethylene Polyurethane Polystyrene	Human placenta	Braun et al. (2021) Liu et al. (2023)
Acrylate copolymer Polyethylene Polyethylene terephthalate Polypropylene Polystyrene Polyurethane Polyvinyl chloride Butadiene rubber Chlorinated polyethylene	Human endometrium and uterus	Sun et al. (2024) Qin et al. (2024)

(Continues)

TABLE 1 (Continued)

Microplastic type	Anatomical site of detection	References
Ethylene–acrylic acid Fluororubber Ethylene vinyl acetate Phenolic epoxy resin		
Polypropylene Polyethylene Polyethylene terephthalate Polystyrene Polyvinylchloride Polycarbonate Polyoxymethylene	Human testis and semen	Zhao et al. (2023) Montano et al. (2023)
Nylon Polyvinyl chloride Polypropylene Polyethylene Polymethyl methacrylate Polystyrene	Human vitreous humor/eye	Zhong et al. (2024)
Polyethylene terephthalate Rayon polyester polypropylene polyamide polyvinylchloride polystyrene polycarbonate	Human joints	Z. Li, Zheng et al. (2024)
Polyethylene terephthalate Polyamide Polyvinylchloride Polyethylene	Human arteries	Liu, Wang et al. (2024)
Polymethylmethacrylate Polypropylene Polystyrene Polyethylene Polyethylene terephthalate	Human blood	Leslie et al. (2022) Liu, Yang et al. (2024)
Polyurethane Polyester Polypropylene Polyethylene Polyacetal Polymethylmethacrylate	Human sputum	Huang et al. (2022)
Polyamide Polyethylene Polyvinyl chloride Polystyrene Polyethylene terephthalate Polymethylmethacrylate Polycarbonate Polypropylene Polybutylene adipate terephthalate	Human thrombi	Wang et al. (2024)
Polystyrene Polyethylene terephthalate Polyethylene Polyvinylchloride Ethylene–vinyl acetate	Human gallstones	Zhang et al. (2024)

(Continues)

TABLE 1 (Continued)

Microplastic type	Anatomical site of detection	References
Polypropylene Polyethylene terephthalate Polystyrene Polyethylene Polyoxymethylene Polycarbonate Polyamide Polyurethane Polyvinyl chloride	Human stool/feces	Schwabl et al. (2019) Yan et al. (2021) Zhang et al. (2021)
Polyethylene vinyl acetate Polyvinyl chloride Polypropylene Polyethylene	Human urine	Pironti et al. (2022) Massardo et al. (2024)

addressing the need for environmentally benign packaging options in the food industry.

5.1 | Plant polysaccharides

Polysaccharides are mixed-carbohydrates composed of long-chain monosaccharides connected by α or β glycosidic bonds (Ullah et al., 2021). They are abundant in nature, non-toxic, and hydrophilic due to carboxyl, hydroxyl, and amino groups, making them suitable for FP applications. Plant-derived polysaccharide materials are often categorized based on the extraction processes: Starch, gum, and mucilage are extracted directly from plant tissues, whereas cellulose requires a multi-stage extraction process (Cakmak et al., 2023; Lira et al., 2023; Saji et al., 2022). Plant-derived starches, cellulose, gums, and mucilage are increasingly used in biopolymers for FP (Martins et al., 2022). Edible films/coatings made from polysaccharides can also provide additional functional benefits such as supplying essential nutrients, stimulating the immune system, providing antioxidants, and reducing weight (Janaswamy et al., 2022; Xu et al., 2016).

5.1.1 | Cellulose, hemicellulose, and lignin

Cellulose, hemicellulose, and lignin are the fundamental components of plant cell walls, forming a complex and hierarchical structure that provides mechanical strength, structural framework, and protection to the plant (Ilyas et al., 2022). The long chains of cellulose are arranged in a highly ordered manner, forming microfibrils stabilized by intra- and intermolecular hydrogen bonds. This ordered structure contributes to the superior mechanical behavior, thermal stability, and chemical resistance of cellulose (Khalil et al., 2012). In plant cell walls, cellulose microscale filaments are surrounded by a medium of hemicellulose and lignin, which provide additional strength and rigidity to the plant tissue.

Cellulose extraction from plants removes lignin and hemicellulose through pulping, bleaching, and purification (Chopra, 2022). The cellulose fibers are processed into microfibers, microcrystalline cellulose, nanofibers, nanowhiskers, and nanocrystals for FP (Wasim et al., 2021). Cellulose nanofibers (CNFs) are flexible, lightweight, transparent materials with nanometer diameters (1–100 nm) and micrometer lengths. High-pressure homogenization, microfluidization, or TEMPO oxidation defibrillate cellulose fibers, exposing nanoscale fibrils (Wang et al., 2021). The large aspect ratio and specific surface area of CNFs confer superior gas and moisture barrier properties, resulting from their ability to create a tortuous path for permeant molecules (Al-Gharrawi et al., 2022). Cellulose nanowhiskers (CNWs) and CNCs are rod-like nanoobjects from acid hydrolysis of cellulose fibers, removing amorphous regions, leaving crystalline domains. CNWs have 5–20 nm diameters and hundred-nanometer lengths, whereas CNCs are smaller with 2–10 nm diameters and 50–500 nm lengths (Nagarajan et al., 2021). The high crystallinity and rigid structure of CNWs and CNCs reinforce biopolymer matrices, improving mechanical characteristics (Tanpichai et al., 2022).

The integration of cellulose nanomaterials into FP has shown hopeful results for augmenting the functionality and performance of FPMs. For example, Lu et al. (2020) developed a nanocellulose hydrogel smart packaging from sugarcane bagasse as a pH-dependent colorimetric indicator of chicken freshness. The hydrogel matrix was functionalized with halochromic indicators, specifically bromothymol blue and methyl red, which exhibit colorimetric responses to volatile biogenic amines generated during microbial spoilage processes. This intelligent packaging system enabled in situ assessment of food

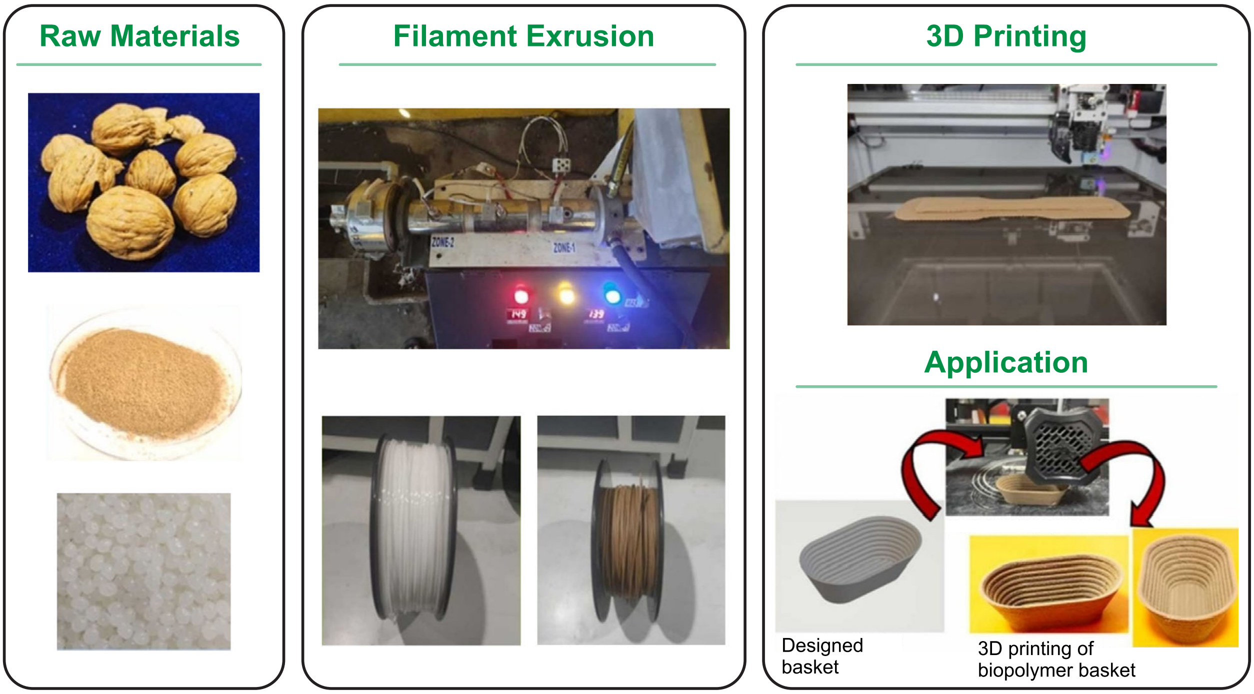

FIGURE 7 Three-dimensional (3D) printed polylactic acid (PLA) composites incorporating silane-treated walnut shell particles show promise for sustainable food packaging, exhibiting enhanced mechanical and barrier properties. *Source*: Image courtesy of Palaniyappan et al. (2024).

quality and freshness through visual indicators. Chawla et al. (2023) fabricated an antimicrobial nanocellulose film from corn husk-extracted cellulose impregnated with eugenol, a natural antimicrobial compound. The incorporation of eugenol (0.5%–5%) into the nanocellulose film provided antibacterial efficacy against bacteria of differing nature, demonstrating the potential of cellulose-based FPM for food preservation.

In another study, Palaniyappan et al. (2024) explored the feasibility of utilizing walnut shell, a readily available agricultural byproduct, as a reinforcement material for 3D printed polylactic acid (PLA) composites targeted for FP applications (Figure 7). Silane grafting treated walnut shell particles to improve compatibility and adhesion with PLA matrix. Studied impact of walnut shell concentrations (0, 5, 10, and 15 wt%) on properties of untreated and organosilane-modified composites. Walnut shell reduced tensile and flexural strength but enhanced modulus and heat deflection temperature, especially in silane-treated samples. Silane treatment improved interfacial bonding, resulting in better hemicellulose and lignin, the other major plant cell wall components, also significantly impact sustainable FPM development. Hemicellulose, a heterogeneous polysaccharide group composed of various sugar units like xylose, mannose, galactose, and arabinose, has degrees of polymerization from 50 to 200 (Qaseem et al., 2021). Hemicellulose branched and amorphous structure yields water solubility and lower thermal stability compared to cellulose (Rao et al., 2023). Lignin, an aromatic polymer of phenylpropanoid units linked with various covalent bonds such as *β*-*O*-4, *β*–*β*, and *β*-5 linkages (del Río et al., 2020), establishes structural rigidity, water impermeability, and microbial degradation resistance in plant cell walls. Kraft or sulfite pulping processes typically extract lignin from plant materials by solubilizing it and separating it from cellulose and hemicellulose (Erdocia et al., 2021). Researchers have explored lignin as a natural antioxidant and antimicrobial material in FP applications and as a reinforcing filler in biopolymer composites (Anushikha & Gaikwad, 2024).

The utilization of wood-based materials, which contain cellulose, hemicellulose, and lignin, has been a conventional practice in FP for a long time. Molded pulp, produced from wood fibers or other fibrous plant materials such as sugarcane bagasse, wheat straw, corn stalk, and bamboo, is widely used for single-use takeout containers, tableware, and packaging applications (Semple et al., 2022). The processing of molded pulp involves various methods, such as one-shot molding, thermoforming, dry thermoforming, and transfer molding, which allow for the production of packaging items with different shapes, sizes, and properties (Rangappa et al., 2020).

Recently, bamboo has received interest as a sustainable source of cellulose for preparing nanofibrillated cellulose and its application in food containment systems (Ahmad et al., 2022). Bamboo cellulose has exceptional mechanical features, low density, good thermal stability, and high crystallinity, making it an attractive raw material for designing high-performance FPMs (Ren et al., 2022). Among various other recent efforts, Janaswamy and coworkers have recently been working on the development of novel extraction procedures for cellulosic residue from agricultural biomass and agricultural processing byproducts. They have developed processes for the extraction of cellulosic residues and materials from switchgrass (Bhattarai & Janaswamy, 2024a, 2024b), wheat straws (Ahmed et al., 2024), corncob (Paudel & Janaswamy, 2024), spent coffee grounds (Bhattarai & Janaswamy, 2023), avocado peel (Ahmed & Janaswamy, 2023), and banana peel (Hoque & Janaswamy, 2024). In addition to the extraction technologies, our groups have also developed various protocols for transforming such cellulosic materials into thin films for FP applications (Ahmed & Janaswamy, 2023; Bhattarai & Janaswamy, 2023; Hoque & Janaswamy, 2024; Paudel et al., 2023).

5.1.2 | Starch

Starches are semi-crystalline polymers of amylose and amylopectin arranged in a helical structure (Li & Gong, 2021). Starches are abundant in nature, are cost-effective, have film-forming ability, and possess good degradability (Rashwan et al., 2024). Although they are commonly sourced from corn, potatoes, cassava, wheat, rice, and sago, arrow root, sorghum, barley, and low graded fruits and vegetables show promise as alternative sources of starch (Nath & Dutta, 2024). Although there are variations in methods for starch extraction due to type of plant tissue, most starches are extracted by cleaning and cutting, grinding, or crushing soaked plant materials to release starch granules, followed by separation, and drying (Dorantes-Fuertes et al., 2024).

Starches can replace resins from non-renewable sources in thermoplastics or be used in electrospinning (Cao et al., 2022). They can also be blended with other biopolymers using chemical modifications and micro- or nanosized reinforcements, developed into intelligent FP solutions, or fabricated into biodegradable films (García-Guzmán et al., 2022). Starch films have high potential but poor mechanics (tensile strength, shear stress, elasticity, and brittleness), water vapor permeability, and hygroscopicity, limiting FP use (Lauer & Smith, 2020). Research on starch-based films has focused on strengthening the film properties with chemical modifications (Marta et al., 2022), plasticizers (Tan et al., 2022), nanoparticles (Ahmad et al., 2020), and crosslinkers (Lipatova & Yusova, 2021) for broader FP applications. For example, Cheng et al. (2022) found dual modified starch had better compactness, water resistance, tensile strength, transparency, and steam barrier capacity than native cassava starch, performing well as pH sensitive quality indicators in intelligent FP. Zhang et al. (2023) reported composite film blends by casting, electrospinning, and thermoplastic extrusion enhanced mechanical and barrier properties.

5.1.3 | Gum

Gums are water-soluble polysaccharides derived from various plant sources, characterized by their ability to form viscous solutions and gels in aqueous media. They are composed of complex mixtures of monosaccharides, primarily D-mannose and D-galactose, arranged in a backbone of β-1,4-linked mannose units with side chains of α-1,6-linked galactose units (Vijayanand et al., 2020). The abundance of hydroxyl moieties on the constituent saccharide units imparts hydrophilicity to gum polymers, facilitating their capacity for water retention and the formation of stable, viscous colloidal dispersions across a wide pH spectrum spanning from 4 to 10 (Barak et al., 2020). The chemicomolecular structure of gums dictates their functional properties and suitability for FP applications. The linear backbone of mannose units provides a rigid and stable structure, whereas the galactose side chains contribute to the flexibility and water solubility of gums (Su et al., 2021). The level of branching and the abundance of side chains along the main backbone influence the rheological properties of gum solutions, such as viscosity, shear-thinning behavior, and gel formation (Bercea et al., 2024; Nsengiyumva & Alexandridis, 2022).

Gums serve as film-forming agents in FP, especially for edible films/coatings (Hashemi Gahruie et al., 2020). The hydroxyl groups in gums enable hydrogen bonding, yielding cohesive, flexible films with good mechanical strength (Kirtil et al., 2021). Gums high water-binding capacity maintains packaged food moisture content, preventing dehydration and preserving quality during storage (X. Gao, Pourramezan, et al., 2024). Gums also enhance FPM barrier characteristics versus moisture, oxygen, and other gases (Khezerlou et al., 2021). Incorporating gums into starch or CH improves the oxygen and steam barrier characteristics of the resulting films (Sultan et al., 2023; Wang et al., 2023).

However, gum as FPM faces challenges, including moisture sensitivity, which affects film mechanical and barrier characteristics, and potential interactions with food components, influencing the packaged product sensory attributes (Amin et al., 2021). Current research focuses on modifying and functionalizing gums through chemical crosslinking, grafting, or nanocomposite formation to improve performance and stability in FP applications.

5.1.4 | Mucilage

Mucilage, a hydrophilic and viscous substance from plants, stores water, disperses seeds, and protects against pathogens (Goksen et al., 2023). It contains polysaccharides, proteins, minerals, lipids, and uronic acids (Amicucci et al., 2019; Kurzyna-Szklarek et al., 2022; Lira et al., 2023). Protein side chains provide high water-holding capacity, whereas methyl and ethyl side chains enable oil–water and air–water emulsions (Soukoulis et al., 2018; Y. Liu, Liu, et al., 2021). Flaxseed, chia seeds, maize roots, okra fruits, and cactus plants yield mucilage (Lira et al., 2023). Extraction involves maceration in water or ethanol, agitation, precipitation, and centrifugation or drying (Andrade et al., 2024; Tosif et al., 2021).

Mucilage is non-toxic, biodegradable, gels well, swells highly, and has bioactivity and antioxidant properties, making it attractive for FP (Araújo et al., 2018; Ayquipa-Cuellar et al., 2021; Hajivand et al., 2020; Kassem et al., 2021). It yields edible films/coatings with good gas barrier characteristics to lengthen shelf-life of fresh produce (Olawuyi et al., 2021). High water-holding capacity maintains moisture content, whereas antioxidant properties preserve quality and nutritional value (Cakmak et al., 2023; López-Díaz & Méndez-Lagunas, 2023). Polysaccharide chain interactions and cohesive matrix formation improve mechanical properties (Guadarrama-Lezama et al., 2018). Plasticizers, such as glycerol or sorbitol, can ameliorate their handleability (Gheribi et al., 2018; Urbizo-Reyes et al., 2020).

Despite the promising potential of mucilage as a FPM, challenges remain for widespread commercial adoption. Variability in chemico-structural composition and functional properties from different plant sources affects reproducibility and consistency. Sensitivity to temperature, pH, and humidity influences stability and performance over time. Standardizing extraction and characterization methods, optimizing processing and formulation parameters, and evaluating long-term stability and safety in food contact applications require further research.

5.2 | Plant proteins

Plant proteins are promising sustainable alternatives to synthetic polymers as FPMs. Proteins from plant sources, such as soybeans, peas, corn, and wheat, have gained recognition thanks to their abundance, renewability, biodegradability, and potential to produce films/coatings with desirable mechanical and barrier characteristics. The extraction of plant proteins for FP applications typically involves wet extraction, dry extraction, or enzymatic hydrolysis, followed by purification and processing to attain the protein in liquid or powder form (Chandran et al., 2023; Mondor & Hernández-Álvarez, 2022). The extraction of proteins from soybeans commonly involves wet methods, including alkaline extraction and isoelectric precipitation, whereas proteins from peas and wheat are frequently obtained through dry extraction methods, such as milling and air classification (Amin et al., 2022). The functional properties of plant proteins, including their solubility, emulsification, and film-forming ability, can be altered through enzymatic hydrolysis, which involves the cleavage of specific peptide bonds, producing smaller peptide fragments (Galante et al., 2020; Klost et al., 2020).

Diverse technologies have been developed to synthesize microfibers and nanofibers from plant proteins for utilization in FP applications (Hadidi et al., 2022). Electrospinning is one such technique that employs an electromagnetic force ranging from 20 to 30 kV to induce ionization in macromolecular solutions. This process results in the generation of fibers with a high surface-to-volume ratio, desirable mechanical characteristics, and tunable features (Aghababaei et al., 2023). Parameters, including the protein source, extraction method, pH, electrolyte concentration, and processing conditions, can influence the extent of β-sheet formation in protein films (Meng et al., 2022).

In FP, plant proteins find applications as film-forming agents, adhesives, and coatings, utilizing their distinctive structural and functional properties (Zubair & Ullah, 2020). The film-forming ability of plant proteins is primarily attributed to their secondary structure, which comprises α-helices, β-sheets, and random coils (Nasrabadi et al., 2021; Sim et al., 2021). The β-sheet structure is particularly important for the materialization of stable and cohesive protein films, as it yields a network of intermolecular hydrogen bonds amongst the polypeptide chains (Kang et al., 2023). The extent of β-sheet formation in protein films can be influenced by various factors, such as the protein source, extraction method, pH, ionic strength, and processing conditions (Meng et al., 2022).

Plant protein films/coatings have the potential to boost the barrier characteristics of FPMs against moisture and oxygen, owing to their hydrophobic nature and their ability to form a dense and compact network (Hadidi et al., 2022). The amino acid constituents, the extent of crosslinking, and the presence of hydrophobic moieties, such as lipids and long-chain aliphatic groups, influence the stream permeability of protein films (Rawat & Saini, 2024). Although the oxygen barrier characteristics of protein films are generally poorer than those of synthetic polymers, they can be improved by increasing the film thickness, incorporating nanofillers, or applying surface treatments, such as plasma or UV radiation (Das et al., 2022; Mihalca et al., 2021).

5.3 | Plant waxes

Plant waxes, which are naturally occurring and water-repellent substances, have attracted considerable interest as environment-friendly and decomposable substitutes for artificial FPMs (Zubair et al., 2021). These waxes are obtained from a variety of plant origins, including carnauba, candelilla, rice bran, and beeswax, and consist of an intricate blend of long-chain alkanes, fatty acids, fatty alcohols, and esters (Pashova, 2023). The chemical makeup and physical attributes of plant waxes render them auspicious substances for utilization in FP, especially as edible coatings/films (Soleimanian et al., 2020).

The chief purpose of plant waxes in FP is to enhance the barrier characteristics of FPMs, thereby prolonging the shelf-life of the contained foodstuff. The water-repellent quality of plant waxes enables them to create a water-resistant layer on the surface of the food or FPM, diminishing moisture loss and hindering the infiltration of water vapor (Duan et al., 2023; Mu et al., 2024). Apart from their moisture barrier attributes, plant waxes can also ameliorate the gas barrier characteristics of FPMs. The tightly arranged, crystalline structure of plant waxes can impede the permeance of oxygen and carbon dioxide through themselves (Mehraj et al., 2023). This is vital for thwarting oxidative deterioration and preserving the desired atmosphere within the package, particularly for oxygen-sensitive foods, such as meats, fruits, vegetables, and nuts (Yousef et al., 2021; Zhu et al., 2023).

Contemporary research has concentrated on the advancement of nanostructured plant wax-based coatings and films, utilizing the unique properties of nanoparticles to augment the barrier and mechanical attributes of FPMs. The assimilation of nanomaterials, such as CNCs, clay nanoplatelets, or metal oxide nanoparticles, into plant wax matrices can generate a more convoluted path for the diffusion of gas and moisture molecules, thereby improving the barrier attributes of the resulting films (Lisuzzo et al., 2021; Moradi Ganjeh et al., 2020; Zhu et al., 2022). Furthermore, the interactions between nanoparticles and wax matrix can result in the creation of a reinforced network, augmenting the mechanical stability of the films.

Notwithstanding the promising potential of plant waxes in FP applications, several challenges must be addressed to facilitate their extensive commercial adoption. The variability in the chemico-molecular composition and physical characteristics of plant waxes from different sources can influence the reproducibility and consistency of the obtained coatings and films. The sensitivity of plant waxes to temperature changes, particularly their low melting points, can also affect the stability and integrity of FPMs during storage and transportation. Another challenge is the limited mechanical strength and flexibility of plant wax-based films, which can restrict their application in certain packaging formats, such as pouches or wraps. Future research is necessary to mitigate these challenges.

5.4 | Recycled and upcycled materials

Agrofood-based industries generate a large number of byproducts and waste materials that have utility in developing new FPMs. The employment of recycled paper in FP has increased significantly thanks to consumer demand and policy directions. In recycling paper, considerations need to be made for contaminated paper, greasy paper, and ink printed paper. Prior to milling, paper containing printed ink and additives needs to be removed (Hu et al., 2021). Moreover, during recycling, the pulp fibers are damaged due to hornification, that is, swelling loss by fiber walls, making it unsuitable for high grade paper. Nonetheless, recycled paper has utility in FP applications (H. Jin, Kose, et al., 2022).

Numerous agricultural byproducts that typically end up in landfills or are incinerated have the promise to be repurposed as ingredients in the production of FPMs. These discarded materials could serve as valuable sources of polysaccharides, bioactive compounds, and proteins, which can be redirected toward the manufacturing of FPMs. According to a study conducted by Srivastava et al. (2023), the incorporation of rice husk fiber at a concentration of 20% as a reinforcing agent, along with the addition of 0.05% benzalkonium chloride as an antimicrobial material, in the fabrication of a composite antimicrobial corn starch film resulted in significant improvements in the film's properties. These enhancements included increases in thickness, tensile strength, elasticity, water solubility, and thermal stability, with improvements reaching up to 61%. Various researchers have explored the utilization of other agricultural waste materials, such as brewery spent grain fiber (Mendes et al., 2021), sugar palm nanocrystalline cellulose (Syafiq et al., 2021), empty fruit bunch cellulose fiber (Salehudin et al., 2014), and microfibrillated cellulose (Sharma et al., 2022) as reinforcement in starch-based biopolymers to enhance mechanical and barrier attributes. Benhamou et al. (2022) reported on the valorization of cactus fruit waste seed, which is the fibrous byproduct generated after the extraction of virgin oil from cactus seeds. The researchers employed a process involving crushing the cactus fruit waste seed, heating it in distilled water for an hour, and subsequently subjecting it to alkali, bleaching, and sulfuric acid treatments to extract cellulose microfibers and nanocrystals. Other agro-processing byproducts that have been repurposed for packaging solutions include wheat straw, which serves as a source of biodegradable cellulose (Bangar et al., 2023) as well as papaya plant waste and spent green tea, which have been successfully incorporated into starch and pectin composite FP films (Sethulakshmi & Saravanakumar, 2024).

Chemical recycling and enzymatic depolymerization are advanced technologies that enable the breakdown of polymeric materials into their monomeric or oligomeric constituents, which can then be repurposed to synthesize new polymers or other valuable chemicals (Thiyagarajan et al., 2022). Chemical recycling involves processes such as pyrolysis, gasification, or solvolysis, where heat, catalysts, or solvents are used to depolymerize plastics, including petroleum-based polymers and bioplastics (Liu et al., 2024). Enzymatic depolymerization, on the other hand, utilizes specific enzymes to selectively break down polymers under mild conditions (Chen et al., 2020). Recent research has demonstrated the use of engineered enzymes to depolymerize PET plastics back into their monomers, which can be recycled into new PET products (Shi & Zhu, 2024).

The shift toward sustainable and renewable materials in FP aims to address the environmental and health challenges posed by PFAS and microplastics. Unlike PFAS, which persist in the environment and bioaccumulate in living organisms, many bio-based materials, such as cellulose derivatives, CH, and plant-derived waxes (e.g., carnauba wax), undergo biodegradation through enzymatic and microbial processes (Altun et al., 2020; Zhu et al., 2024). These materials typically degrade into their constituent monomers and simpler organic compounds—for example, cellulose-based materials can be broken down by cellulases into glucose units, whereas proteins degrade into amino acids through proteolysis. However, further research is needed to fully characterize the degradation pathways and intermediate products formed during the breakdown of novel bio-based packaging materials under different environmental conditions. Although these materials show promise in reducing PFAS-related risks and microplastic accumulation, comprehensive safety evaluations are still required to ensure their degradation products do not introduce unexpected environmental or health impacts. Particularly important areas for investigation include: (i) the kinetics and mechanisms of degradation in various disposal environments, (ii) the potential formation and fate of micro- and nanosized particles during material breakdown, and (iii) the biocompatibility and potential toxicity of both the materials and their degradation products. This cautious approach acknowledges that although bio-based alternatives offer theoretical advantages over conventional materials, their long-term environmental and health implications must be rigorously assessed through continued research.

Although the development of sustainable and renewable materials for FP offers significant environmental benefits, their integration into advanced packaging technologies can further enhance food preservation and safety. In the following section, we focus on recent advancements in active packaging utilizing these sustainable materials, highlighting how they contribute to innovative and eco-friendly packaging solutions.

6 | ADVANCES IN ACTIVE PACKAGING UTILIZING SUSTAINABLE MATERIALS

The increasing need for environment-friendly FP options has incited the creation of innovative materials sourced from renewable resources, including polysaccharides, proteins, and waxes derived from plants, as well as materials that have been recycled or repurposed. These sustainable alternatives present an opportunity to mitigate the ecological footprint associated with traditional FPMs while simultaneously delivering improved functionality and performance. Relying on the progress made in the development of sustainable FPMs, scientists have additionally concentrated their efforts on incorporating active elements into these packaging systems to further augment the safety, quality, and prolongation of foodstuff.

6.1 | Oxygen scavengers and moisture-absorbing films made from sustainable materials

Active packaging systems rely on the important roles played by oxygen scavengers and moisture-absorbing films, which work together to manage the internal atmosphere of the package. The primary objective of these systems is to lengthen the shelf-life and preserve the desirable attributes of the contained foodstuff. The active FPMs are engineered to eliminate or decrease the concentrations of oxygen and/or moisture within the package (Chang et al., 2021; Thuy et al., 2021), thus alleviating the adverse consequences of oxidative and moisture-related degradation processes on the food contents. The most widely utilized oxygen scavengers operate on the basis of oxidation–reduction reactions, in which a reducing agent, such as iron, AA, or photosensitive dyes, is integrated into the FPM and subsequently undergoes oxidation when exposed to oxygen (Alves et al., 2023).

The effectiveness of these active FPMs in removing oxygen is frequently assessed by employing a range of methods, including the monitoring of the OTR, which provides a numerical metric of the quantity of oxygen that passes through FPM per unit area and time (Gupta, 2024). The solubility and diffusivity of oxygen within the polymer matrix, in combination with the reactivity and concentration of the oxygen scavenger, dictate the OTR (Zabihzadeh Khajavi et al., 2020). The oxygen-scavenging kinetics can be modeled using reaction-diffusion equations, which describe the coupled processes of oxygen diffusion through the polymer matrix and its consumption by the scavenger (Di Giuseppe et al., 2022; Oliveira et al., 2022). These models can help optimize the design of oxygen-scavenging materials by predicting the effect of various parameters, such as the scavenger loading, film thickness, and storage conditions, on the overall oxygen-scavenging performance.

Oxygen hastens metabolic processes, triggering chemical reactions that bring about the rancidification of fats, the degradation of flavor, the modification of color, the proliferation of molds and aerobic bacteria, and, in the end, the decrease in nutritional value (Moschopoulou et al., 2019). In the past, modified atmosphere packaging and vacuum packaging have been frequently employed to eliminate surplus oxygen from FP. Nevertheless, these techniques possess constraints and might not completely remove oxygen. Recent progress in oxygen-scavenger technology derived from sustainable materials involves the incorporation of oxygen scavengers into biopolymers. For instance, Mahieu et al. (2015) engineered an oxygen-scavenging film based on thermoplastic starch (TPS) containing AA as a reducing compound and iron powder (Fe) as catalysts. The TPS-AA-Fe film displayed encouraging oxygen-scavenging attributes, which could be activated by elevating the water quantity in the film. The material possessed the capability to decrease the oxygen concentration in the measurement device from ~21% to 1% in 15 days at 80% relative humidity. The oxygen-scavenging mechanism entails the oxidation of AA, which is catalyzed by the transition metal ions (Fe), utilizing the oxygen molecules and generating an oxygen-depleted environment within the package.

As another example, Singh et al. (2021) engineered active oxygen barrier layers based on CH containing gallic acid (GA) as an oxygen scavenger and sodium carbonate as a catalyst. The influence of GA on the mechanical, structural, physicochemical, and oxygen-scavenging attributes of the layers was scrutinized. The occurrence of GA in the CH lowered water and oxygen permeability of the layers. The film containing 20% GA exhibited the highest oxygen absorbance rate and capacity of ~3 mL O_2/g day and ~20 mL O_2/g, respectively, at room temperature. As another example, Dey et al. (2023) engineered oxygen-scavenging layers by incorporating zero-valent metal nanoparticles into cellulose acetate matrices for active FP applications. Cellulose acetate layers synthesized using dimethyl sulfoxide demonstrated the highest scavenging rate of 0.03 day^{-1}. Subsequently, zero-valent iron (Fe), copper (Cu), and aluminum (Al) nanoparticles were synthesized using wet-chemical methods and incorporated into the cellulose acetate layers. The resulting layers containing zero-valent metal nanoparticles exhibited enhanced oxygen-scavenging properties. The layer with zero-valent iron nanoparticles showed the highest scavenging rate of 0.99 day^{-1}, followed by layers with zero-valent copper and aluminum nanoparticles, with rates of 0.60 and 0.35 day^{-1}, respectively.

Moisture-absorbing films are, conversely, designed to control the humidity within the package by removing excess moisture from the headspace or the product surface. These films typically contain hygroscopic materials, such as desiccants, humectants, or superabsorbent polymers, which can absorb and retain water molecules through various mechanisms, such as adsorption, absorption, or capillary condensation (Ebadi et al., 2021; Jeong et al., 2023). The most commonly relied on desiccants in FP are silica gel, calcium oxide, and molecular sieves, which have high surface areas and pore volumes that allow for efficient moisture adsorption (Shamim et al., 2021). The moisture absorption performance of these films is usually evaluated using gravimetric methods, such as the water vapor sorption isotherm, which measures the equilibrium moisture content of the material with respect to the relative humidity (Turan, 2021). The water vapor (steam) permeability of the films can also be determined using standard test methods, such as the ASTM E96 or the ISO 2528, which measure the steady-state rate of water vapor transmission through the material under specific temperature and humidity gradients (Khuntia et al., 2022).

Recently, there has been a building interest in developing moisture-absorbing films from sustainable and biodegradable materials to reduce the environmental impact of traditional petroleum-based FPM. Researchers have explored the use of various biopolymers, such as starch, cellulose, and natural gums, as matrices for moisture-absorbing films, often incorporating hygroscopic fillers or modifying the biopolymers to enhance their water absorption capacity and mechanical compliance (Alipour et al., 2023; Ebadi et al., 2021; Wang et al., 2018). For example, Acevedo-Puello et al. (2023) explored sustainable hydrogels as effective moisture absorbers for FP applications. Their study focused on gelatin-based hydrogels incorporating micro- and nano-crystalline cellulose. By integrating these cellulose components, the hydrogels exhibited enhanced mechanical strength, critical for preventing deformation when absorbing moisture. Moreover, their research observed significant improvements in preserving food quality, evident through observed color changes in chicken breast samples packaged with these hydrogels.

In another study, Pirsa (2021) aimed to prolong banana shelf-life using an active hydrogel. They prepared a carboxymethylcellulose/nanofiber cellulose/potassium permanganate hydrogel film to absorb humidity and ethylene in banana packaging. Over 30 days, this hydrogel-maintained banana quality at both 0 and 25°C, enhancing flavor and texture while reducing humidity inside packages compared to controls. Chen et al. (2018) constructed an FP film incorporating PVA and green tea extract (GTE) to address moisture-related issues in food preservation. Their study revealed that the PVA film containing 2% GTE exhibited exceptional moisture-absorbing capabilities alongside potent antioxidant attributes. When utilized to package dried eel, this specialized film significantly mitigated moisture-induced weight changes and lipid oxidation during storage, ensuring prolonged product freshness and quality.

Escobar et al. (2023) introduced an innovative approach to lengthen the shelf-life of lulo fruits through active FP. By combining modified atmospheres with active oxygen removal and moisture adsorption, they aimed to mitigate rapid deterioration and extend the short shelf-life of fruit. Their method involved utilizing a mixture of iron filings (Fe) and sodium polyacrylate (SPA) powder in sachets to effectively remove moisture. Notably, the optimal ratio of Fe/SPA at 1/1 (w/w) exhibited a significant oxygen removal capacity at 12°C, resulting in a shelf-life extension of over 25 days for lulo fruits.

In the development of oxygen scavengers and moisture-absorbing films for FP applications, researchers have made significant strides in incorporating sustainable and biodegradable materials to lessen the environmental impact of traditional petroleum-based FP. However, it is essential to recognize that the successful integration of oxygen scavengers and moisture-absorbing films into FP systems necessitates a comprehensive understanding of the compound interactions and phenomena occurring at the interface among the active components, the FPM, and the food product itself. The potential migration of the active compounds from the packaging into the food matrix must be carefully assessed and quantified to ensure the hygiene and regulatory compliance of the FP system, as stipulated by the relevant FCMs regulations. Moreover, the impact of the active packaging on the sensory properties and consumer acceptance of the foodstuff must be thoroughly investigated.

6.2 | Antimicrobial food packaging utilizing sustainable materials and natural compounds

The amalgamation of antimicrobial agents into sustainable FPMs offers a promising tactic to reduce the reliance on synthetic preservatives and address the growing concerns over the environmental impact of conventional FP. The antimicrobial activity of FPMs has been achieved through various mechanisms, such as the leaching of antimicrobial compounds from the FP to the contained foodstuff, the immobilization of antimicrobial compounds on the FP surface, or the inherent antimicrobial properties of the FPM itself (Motelica et al., 2020; Mu, Wang, et al., 2023). The choice of antimicrobial compounds and their mode of action depends on several factors, including the target microorganisms, the food product characteristics, and the desired release kinetics. Among many of such options, natural compounds, such as essential oils, enzymes, bacteriocins, and organic acids, offer several advantages, including their natural origin, biodegradability, and comprehensive antimicrobial potency (Arcot, Mu, Taylor et al., 2024; DeFlorio et al., 2021; Hashemi et al., 2022).

The antimicrobial action of essential oils is ascribed to their competence to disrupt the cell membrane integrity, interfere with cellular metabolism, and induce oxidative stress in microbial cells (Hou et al., 2022; Yegin et al., 2016). The amalgamation of essential oils into biopolymer matrices, such as CH, alginate, or cellulose, has been shown to impart antimicrobial properties to the resulting FPMs. For instance, recently, Arcot, Mu, Lin et al. (2024) developed a novel hybrid edible wax coating formulation containing nano-encapsulated cinnamon essential oil for application on red apples. The nano-encapsulation of cinnamon essential oil in whey protein concentrate significantly delayed its release, extending the half-life by 61 h compared to unencapsulated counterparts, and the coatings demonstrated enhanced antibacterial and antifungal properties against foodborne pathogens. In separate investigation, Basumatary et al. (2023) engineered antimicrobial films based on CH, which were fortified with a nanoemulsion of eugenol (EuNE), gel derived from Aloe vera, and nanoparticles composed of zinc oxide (ZnONPs) for utilization in FP. The integration of EuNE dramatically enhanced the composite films' ability to obstruct UV light by a factor of three to six while preserving their transparent nature. Furthermore, the inclusion of ZnONPs substantially augmented the films' antibacterial efficacy against bacteria commonly associated with foodborne illnesses and nearly doubled their tensile strength.

In another study, Khalil et al. (2023) developed cost-effective active edible layers for FP applications using entirely citrus peel waste. High-methoxyl pectin was efficiently isolated from grapefruit peels, exhibiting superior physicochemical properties versus citrus pectin (Figure 8). The pectin films were enhanced by incorporating free grapefruit peel extract and maltodextrin-encapsulated lemon peel extract, yielding films with potent antioxidant and antimicrobial characteristics. This bioactive ingredient combination amended the tensile strength, thermal stability, water vapor and UV barrier attributes of the films, and biodegradability, making them promising antimicrobial FP candidates for extending fresh produce shelf-life,

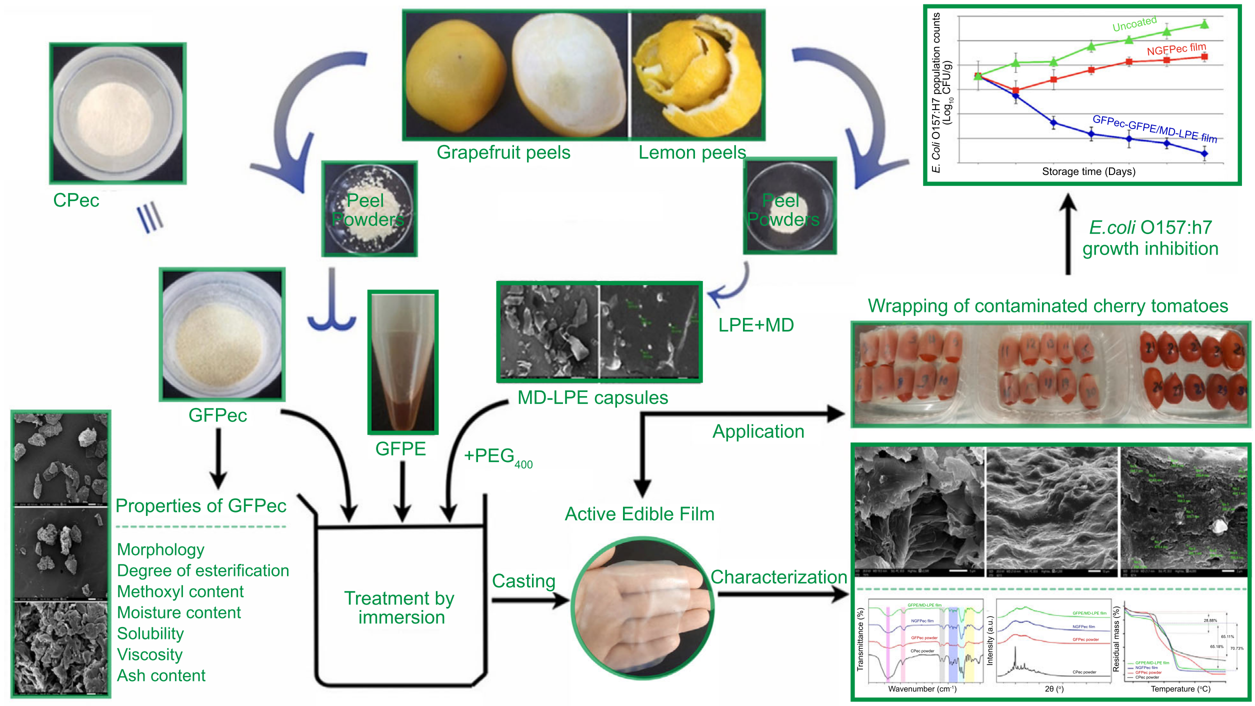

FIGURE 8 Active edible films developed entirely from citrus peel waste, offering a sustainable and eco-friendly alternative to conventional food packaging materials. The films are composed of methoxyl pectin extracted from grapefruit peels, demonstrating superior physicochemical properties compared to commercial citrus pectin. To enhance their functionality, the films incorporate both free grapefruit peel extract, rich in antioxidants, and maltodextrin-encapsulated lemon peel extract, providing sustained antimicrobial activity. CPec, citrus pectin; GFPE, grapefruit peel methanolic extract; GFPec, grapefruit pectin; LPE, lemon peel extract; MD, maltodextrin; MD-LPE, maltodextrin-encapsulated lemon peel extract. *Source*: Image courtesy of Khalil et al. (2023).

as demonstrated by their *E. coli* O157:H7 growth inhibition on wrapped cherry tomatoes.

Enzymes are another class of natural antimicrobial agents that have been explored for their probable application in active FP. Enzymes, such as lysozyme (LZM), lactoperoxidase, and glucose oxidase, have been shown to exhibit antimicrobial activity through various mechanisms, including cell wall hydrolysis, the generation of antimicrobial compounds, and the depletion of essential nutrients (Lee et al., 2020; Liu et al., 2020). Recently, the immobilization of enzymes on the surface of FPMs or their incorporation into biopolymer matrices has received increasing attention as a means to develop antimicrobial packaging. For example, Shokri et al. (2015) investigated the effect of incorporating lactoperoxidase at various concentrations into whey protein solution as an antimicrobial coating strategy for preserving rainbow trout (*Oncorhynchus mykiss*) fillets at 4°C for a 16-day period. The results showed that lactoperoxidase-whey protein coating effectively restrained the growth of spoilage microorganisms, including mesophilic bacteria, psychrotrophic bacteria, *Pseudomonas* spp., and specific spoilage bacteria (*Shewanella putrefaciens* and *Pseudomonas fluorescens*), and lengthened the shelf-life of the trout fillets from approximately 12 days to at least 16 days. In another study, Zhang et al. (2022) fabricated a composite coating comprising tea polyphenol liposomes and LZM incorporated into a CS matrix using tape casting. The coating exhibited gradual, sustained release properties, enabling prolonged preservation. Mechanistic studies revealed synergism between TP and LZM in their antibacterial action, whereas the liposomal and coating components of the slow-release system extended the duration of activity of both TP and LZM.

Bacteriocins are antimicrobial peptides produced by certain strains of bacteria that have a narrow spectrum of activity against closely related bacterial species. Nisin, a bacteriocin produced by *Lactococcus lactis*, has been widely studied for its potential application in antimicrobial packaging due to its effectiveness against Gram-positive bacteria, including *Listeria monocytogenes* (Lan et al., 2021; Settier-Ramírez et al., 2021). Recently, the incorporation of nisin into biopolymer matrices, such as zein, gelatin, or CH, has been demonstrated to impart antimicrobial attributes to the resulting FPMs (Chen et al., 2022; Yan et al., 2024; Yu et al., 2023).

The development of antimicrobial packaging utilizing sustainable materials and natural compounds requires a thorough understanding of the interactions among the antimicrobial agents, the FPM, and the food product. The release kinetics of the antimicrobial compounds from the FP into the food matrix must be carefully studied to ensure the desired antimicrobial activity is achieved throughout the shelf-life of the product. The diffusion of antimicrobial agents through FPMs and their partition into the food matrix is often modeled using mathematical equations, such as Fick's second law of diffusion or the Weibull model (Malekjani & Jafari, 2021). The physicochemical attributes of FPMs, such as their hydrophobicity, crystallinity, and porosity, can significantly influence the release behavior of the antimicrobial agents. The compatibility between the antimicrobial agents and the FPM must be carefully considered to ensure the stability and functionality of the active FP system. The incorporation of antimicrobial agents into the FPM can alter its mechanical, thermal, and barrier properties, which must be evaluated to ensure the packaging maintains its integrity and functionality throughout the shelf-life of the contained foodstuff.

7 | CONCLUSIONS AND OUTLOOK

The pervasive use of PFAS and the emergence of microplastics in FPMs present significant environmental and health challenges that necessitate urgent attention. PFAS, due to their strong carbon–fluorine bonds, are highly resistant to degradation, leading to bioaccumulation and adverse health effects in humans and wildlife. Microplastics, generated from the degradation of conventional plastics, pose risks through ingestion and potential toxicity. Addressing these issues requires a fundamental shift in the materials and strategies used in FP.

This review has highlighted the potential of sustainable and renewable materials, such as plant-derived polysaccharides (cellulose, hemicellulose, starch, gums, and mucilage), proteins, waxes, and recycled or upcycled materials, to replace traditional, harmful FPMs. These bio-based materials offer inherent biodegradability and non-toxicity, reducing environmental persistence and health risks associated with PFAS and microplastics. They also provide functional properties suitable for FP, such as mechanical strength, barrier properties, and the ability to form films and coatings.

Despite these promising alternatives, several critical gaps and challenges remain. One significant challenge is enhancing the performance of bio-based materials to match or surpass that of conventional plastics. Many sustainable materials exhibit limitations in mechanical strength, thermal stability, moisture sensitivity, and barrier properties against gases and vapors. Future research may need to focus on: (i) Developing methods to modify and enhance the properties of bio-based materials. This includes chemical modifications, incorporation of nanomaterials (e.g., CNFs, nanoclays), and blending with other biopolymers to improve mechanical strength, thermal stability, and barrier properties. (ii) Addressing the scalability of production processes for bio-based materials to meet industrial demands. This includes optimizing extraction methods from plant sources and agricultural waste, reducing production costs, and enhancing manufacturing efficiencies. (iii) Investigating the degradation pathways and environmental fate of bio-based FPMs. Understanding how these materials decompose in various environments (e.g., composting, landfills, and marine settings) is crucial for assessing their true environmental impact. Research into enzymatic degradation and microbial processes can inform strategies for effective waste management. (iv) Conducting comprehensive safety evaluations to ensure that bio-based materials do not introduce new health risks. This includes assessing potential allergenicity, migration of substances into food, and interactions with food components. (v) Studying consumer perceptions and acceptance of bio-based packaging. Understanding consumer willingness to adopt and potentially pay a premium for sustainable packaging can guide marketing strategies and policy development. (vi) Performing thorough LCAs to quantify the environmental impacts of bio-based FPMs throughout their lifecycle, from raw material extraction to end-of-life disposal. LCAs will help identify trade-offs, optimize resource use, and ensure that sustainable materials truly offer environmental benefits over conventional options. (viii) Advocating for policies that support the development and adoption of sustainable packaging materials. This includes incentives for research and development, subsidies for sustainable materials, and regulations that limit the use of harmful substances like PFAS in FP.

Although the shift to sustainable FPMs is promising, it is not without challenges. The complexity of FP requirements means that a one-size-fits-all solution is unlikely. Tailored approaches that consider the specific needs of different food products, supply chain logistics, and regional environmental conditions are necessary. Additionally, the economic implications for manufacturers, especially small and medium-sized enterprises, must be considered to ensure equitable and widespread adoption. There is also a need to be cautious about unintended consequences. For example, increasing the use of agricultural resources for packaging materials may have implications for food security and land use. A balance must be struck to ensure that the pursuit of sustainable packaging does not inadvertently create new environmental or social issues.

Addressing the challenges posed by PFAS and microplastics in FP requires a concerted effort to develop and implement sustainable and renewable materials. By focusing on enhancing material properties, standardizing testing methods, and fostering interdisciplinary collaboration, the FP industry can transition toward solutions that safeguard both human health and the environment. The path forward involves not only technological innovation but also policy support, consumer engagement, and a commitment to sustainability at every stage of the packaging lifecycle.

AUTHOR CONTRIBUTIONS

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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