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A narrative review of food packaging-related measures to reduce food loss and waste throughout the food supply chain

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ABSTRACT

Food loss and waste (FLW) pose a major global challenge with substantial environmental, economic, and social consequences. Packaging has a dual role in the food supply chain (FSC), so that inadequate design can contribute to FLW, whereas appropriate packaging can protect food, extend shelf-life, and support informed decision-making. However, existing reviews largely examine packaging technologies, waste-derived materials, or FLW drivers separately, leaving a gap in understanding how packaging interventions operate across the entire FSC. This narrative review introduces a stage-specific framework integrating two complementary but distinct pathways including prevention through innovative packaging (edible coatings, active and intelligent packaging) and valorisation of unavoidable FLW through biorefinery into polymer matrices, plasticisers, and functional additives. It maps packaging-related drivers and interventions from primary production to consumption and critically examines the life cycle and techno-economic performance of these strategies, relevant policy and regulatory frameworks, implementation barriers, and future directions. Most innovative packaging solutions target FLW prevention after harvest, particularly during storage, distribution, retail, and consumption, whereas biorefinery approaches valorise unavoidable residues generated mainly during primary production and processing. By positioning packaging as a strategic component of circular food systems, this review provides a systems-oriented basis for evaluating its contribution to FLW reduction.

1. Introduction

Food loss and waste (FLW) is a significant food system crisis. Globally, around one-third of the total food produced, equivalent to 1.3 billion tonnes, is lost and wasted along the food supply chain (FSC) (FAO, 2011; FAO, 2019). Within the European Union (EU), around 58 million tonnes of food waste are produced every year, which equals an average of 130 kg per person in 2023 (Eurostat, 2025). The FSC extends from agricultural production through processing, packaging, storage, distribution, and retail to final consumption. Within this chain, food loss (FL) mainly occurs before retail because of factors such as harvesting damage, processing failures, inadequate packaging, and inappropriate storage or transportation, whereas food waste (FW) occurs predominantly at the retail, food-service, and household stage (Rasines et al., 2023). Together, FLW have substantial social, environmental, and resource consequences as 29% of the global population experiences food insecurity (Food loss and waste, 2024). On the other hand, land, freshwater, and energy are expended to produce food that is never consumed. This challenge is likely to intensify as the global population increases from 8.2 billion in 2024 to approximately 9.7 billion by 2050, thereby leading to an increase in food demand and pressure on natural resources (DESA, 2024; Lutz et al., 2017).

Therefore, preventing FLW is essential for improving food security while avoiding unnecessary resource use and greenhouse gas (GHG) emissions. Although the drivers of FLW vary across the FSC, from surplus production to unsustainable consumer practices, packaging has a central and sometimes contradictory role. Packaging is introduced into the FSC immediately after postharvest operations and remains until household consumption. It supports transportation and storage, helps preserve food quality, reduces chemical, mechanical, and microbial

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spoilage, and provides important information to consumers (Robertson, 2016; Han, 2014). Conversely, inadequate packaging selection or design, poor sealing, unsuitable package sizes, and unclear information can contribute directly to FLW (Pauer et al., 2019). In recent decades, packaging functions have expanded beyond passive protection to include active systems that regulate conditions within the package and intelligent systems that monitor or communicate product quality and safety (Upadhyay et al., 2024; Poli et al., 2023).

Although these technologies, along with other practices can prevent and reduce FLW, the generation of FLW along the FSC is unavoidable, so that their mismanagement leads to environmental harm and wasteful resource depletion (Teigiserova et al., 2020). Biorefinery approaches are promising management strategy by converting FLW into higher-value products, including food packaging materials.

Packaging innovation directly supports Sustainable Development Goal (SDG) Target 12.3 by preventing FLW, while the biorefinery of unavoidable FLW into packaging materials contributes to Target 12.5 by promoting waste reduction and material recovery. These strategies may further support SDG 9, Industry, Innovation and Infrastructure through technological development and SDG 13, Climate Action by reducing emissions from FLW disposal and material production (United Nations, 2023).

Despite extensive research on the role of packaging in reducing FLW, existing review studies have largely focused on specific aspects rather than providing a comprehensive system-level perspective. For example, some studies emphasise the development of packaging materials derived from food waste and by-products, particularly in terms of fabrication methods and functional properties (Deotale et al., 2025; Xie et al., 2024). Others highlight sustainable and circular packaging innovations, including active and intelligent systems, mainly from a technological and sustainability perspective (De Oliveira et al., 2025; Rahman et al., 2026). Although some research considers packaging-related FLW across the FSC, it primarily addresses causes rather than linking them to targeted mitigation strategies (Uhlig et al., 2025). Consequently, a comprehensive review systematically connecting packaging-related mitigation strategies with each stage of the FSC remains lacking. Therefore, this narrative review examines recent advances in packaging-mediated FLW reduction, with particular attention to innovative packaging and biorefinery approaches. Relevant original research articles published in English between 2021 and 2026 were identified through Scopus using combinations of terms related to food loss and waste, packaging, valorisation, and biorefinery. Studies were selected based on their relevance to packaging-enabled FLW reduction across the FSC (further details in the Supporting Information). Furthermore, this review first identifies packaging-related drivers of FLW across the FSC (section 2). It then analyses advanced packaging technologies and biorefinery approaches that convert FLW into high-value packaging materials, highlighting their effectiveness at different FSC stages (sections 3 and 4). In addition, it examines life cycle assessment (LCA) and techno-economic assessment (TEA) of the proposed strategies (section 5). Finally, it addresses current actions, policies, and regulatory frameworks, as well as barriers that hinder implementation and outlines future pathways and emerging innovations, positioning packaging as a key driver of FLW reduction within circular and sustainable food systems (section 6).

2. Packaging-related drivers of food loss and waste

Packaging-related FLW generally arises when packaging fails to provide adequate physical protection, preserve product quality, or communicate appropriate handling and use information (Wohner et al., 2019). The importance of these functions changes along the FSC, as summarised in Table 1. At upstream stages, FL attributed to food packaging during primary stages and postharvest handling is mainly due to poor packaging choices and mechanical damage. Field containers and transport packages may contribute to contamination, crushing, or bruising when they are unclean, overfilled, insufficiently ventilated, or mechanically unsuitable. For fresh product, ventilation must correspond to the respiration requirements, and transport packaging must withstand compressive, impact, vibrational, and abrasive forces during handling and stacking (Fadiji et al., 2016; Verghese et al., 2015; Schudel et al., 2023; Mukama et al., 2020).

Table 1
Impact of conventional packaging on the generation and reduction of food loss and waste (FLW) across the food supply chain.

Food supply chain	FLW reduction	FLW drivers
Primary production	Protects products from mechanical damage and contamination	Contamination from unsuitable or unclean field containers, sharp edges or splinters in field crates, or overpacking of field crates
Processing/ packaging	Supports safe handling and prevents product contamination	Improper sealing and filling, and labelling errors
Storage	Extends shelf-life and slows spoilage	Poor mechanical protection, inappropriate packaging selection, incompatibility between package and food
Transport and distribution	Prevents physical damage and maintains temperature/gas conditions	Insufficient mechanical strength, inappropriate package selection or design, and damaged packaging
Retail	Maintains product quality and prevents early spoilage	Damaged packaging, unsuitable package size or format, packaging failure, and incorrect or unclear date labelling
Consumption	Portioning, resealability, and providing shelf-life information	Inappropriate package size, difficulty opening, resealing, or completely emptying the package, and unclear date or storage information

During processing, storage, and distribution, maintaining package integrity becomes the primary concern. Failures in filling and sealing can make products unsuitable for commercialisation, while incorrect or damaged labels can result in product rejection or improper handling (Canali et al., 2016; Dora et al., 2020). Mechanical stresses can also damage primary, secondary, and tertiary packaging, particularly when packages are combined with unsuitable pallet dimensions, poor stacking, or unfavourable environmental conditions such as high humidity (De Moraes et al., 2020). Once package integrity is compromised, exposure to oxygen, moisture, microorganisms, or physical damage can accelerate deterioration, reduce product acceptability, and potentially result in non-compliance with food-safety requirements (Ishangulyyev et al., 2019; Joardder and Hasan Masud, 2019; Priefer et al., 2016).

At the retail and consumption stages, packaging format, usability, and information become increasingly important. Damaged or unsuitable packages can contribute to early spoilage and product rejection at retail, whereas oversized portions, poor resealability, difficulty in completely emptying packages, and unclear date or storage information can increase household FW. Packaging-related factors have been associated with approximately 20–25% of household FW in Sweden. Other studies indicated that package sizes aligned with consumption needs, improved emptying and resealing functions, and clearer date and storage guidance can help consumers use food more efficiently and avoid FW (Wikström et al., 2019; Williams et al., 2012; Jörissen et al., 2015).

3. Innovative food packaging solutions

Although conventional food packaging plays an essential role in protecting products and maintaining quality throughout the FSC, its predominantly passive functions may be insufficient to address the diverse and dynamic drivers of FLW. Moreover, conventional packaging often relies on fixed expiration or “best before” dates, which may lead consumers and retailers to discard food that is still safe to consume.

Innovative packaging addresses these limitations through three distinct but complementary pathways including edible coatings that create a protective layer directly on the food, active packaging that modifies the package environment or inhibits deterioration, and intelligent packaging that monitors conditions or communicates product status. Under an EU 2050 scenario, it was estimated that shelf-life extending packaging innovations could halve retail and consumer FW, avoiding approximately 250 million tonnes of CO_2-eq. Replacing half of conventional packaging with organic waste-derived materials could avoid a further 120 million tonnes. The combined reduction of 370 million tonnes would represent nearly 10% of projected EU GHG emissions (Guillard et al., 2018).

Fig. 1 provides the conceptual framework for this section by linking packaging strategies to their potential intervention points across the FSC. Packaging interventions at the primary production stage are mainly introduced after harvesting. Although active packaging and edible coatings primarily reduce FLW by delaying deterioration after processing, intelligent packaging can generate information that supports decisions during distribution, retail and household storage. Their effectiveness therefore depends not only on material performance but also on integration with supply-chain management, stock-rotation practices and consumer behaviour. The following subsections examine these innovations, focusing on their mechanisms, applications and evidence of effectiveness in reducing FLW.

3.1. *Edible coatings*

Edible packaging refers to innovations developed using thin layers of edible ingredients, such as polysaccharides, proteins, lipids, and resins, or their composites applied directly to the food surface by dipping, spraying, or brushing. The coating is consumed with the product; therefore, its components must comply with applicable food-ingredient and additive requirements (European Commission, 2008). From an FLW perspective, the principal function of edible coatings is food preservation rather than simply the replacement of conventional plastic. The preservation performance of a coating is regulated by a balance between

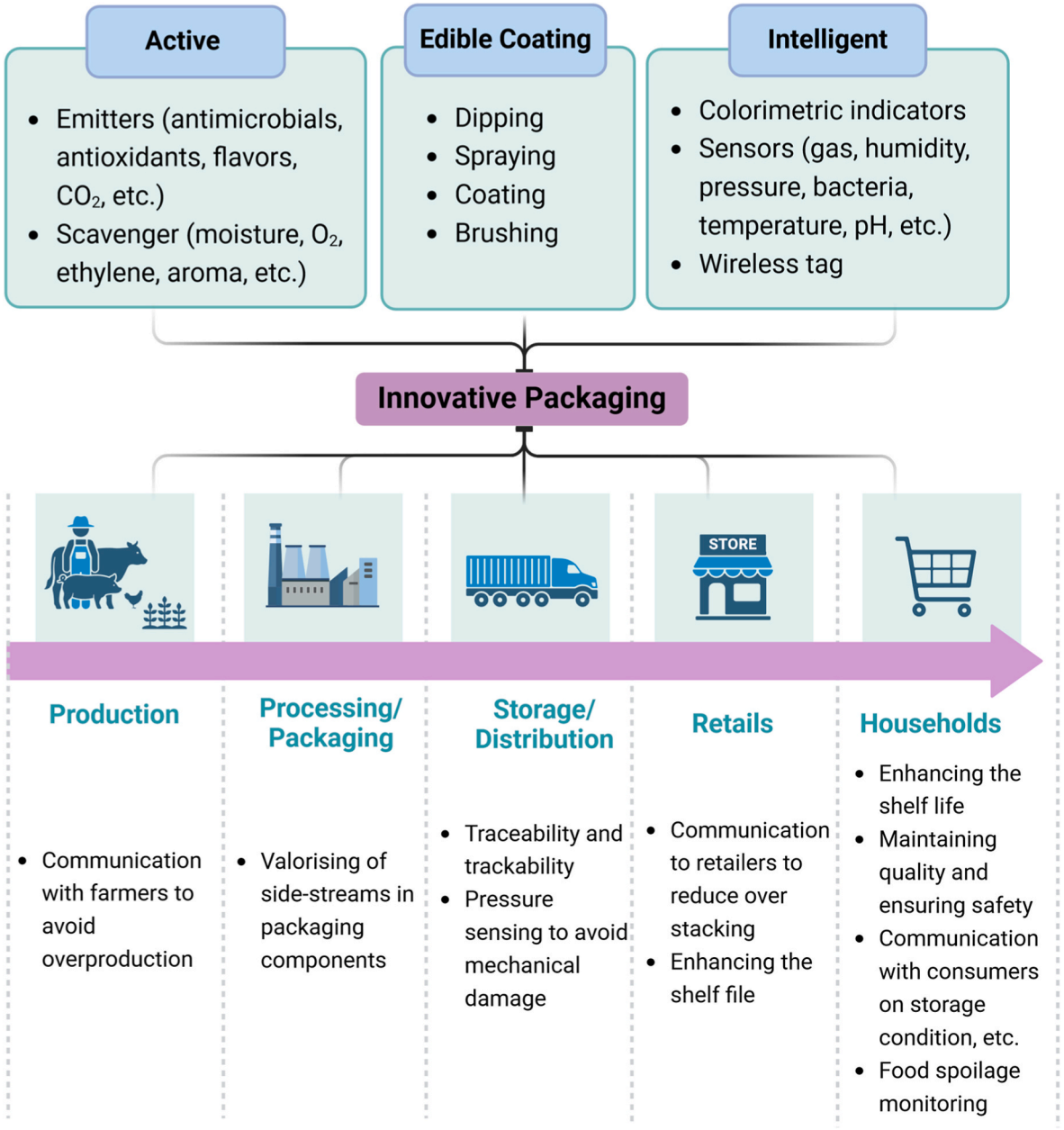


Fig. 1. Innovative packaging technologies and their roles in reducing food loss and waste across the food supply chain.

gas permeability, moisture resistance, adhesion, and sensory compatibility. Polysaccharide- and protein-based coatings can provide efficient oxygen and aroma barriers, but their hydrophilicity generally limits resistance to moisture. Lipids improve moisture resistance but may reduce coating uniformity, adhesion, transparency, or sensory acceptance. Composite coatings can balance these properties; however, their thickness and gas permeability must be optimised to avoid restricting respiration in fresh product, which can promote anaerobic metabolism and off-flavour development (Yaashikaa et al., 2023).

The studies summarised in Table 2 represent food-specific performance of coatings. In berries, vegetables, and climacteric fruits, the main benefits arise from limiting transpiration, respiration, softening, and surface microbial decay. Coatings for these products must remain sufficiently permeable to avoid unusual internal atmospheres. In contrast, meat, poultry, and seafood require stronger antimicrobial and antioxidant functions because microbial proliferation, protein deterioration, and lipid oxidation dominate quality loss. For lipid-rich nuts, oxygen and moisture control are generally important factors. Thus, the most suitable formulation differs by food category and its shelf-life requirement. Moisture- and gas-regulating composites are especially relevant to fresh products, whereas chitosan, essential oils, phenolics, postbiotics, or other active components are more relevant to protein- and lipid-rich foods.

Although coatings generally extended food shelf-life, the reported performance does not establish that one coating is intrinsically superior because storage conditions, endpoints, and rejection criteria differed. For example, in banana, responsive whey protein isolate-based coatings reduced weight loss to 5.93% versus 8.19% after 10 days at 10 °C, whereas prickly pear (*Opuntia spp*.) wax resulted in 9% versus 16% after 9 days at 25 °C. In contrast, *Opuntia ficus-indica* mucilage coating extended shelf-life from 8 to 16 days using a rejection-based criterion (Yang et al., 2026; Poomalaisundar et al., 2026; Chokoe et al., 2025). Comparability and reproducibility are further limited by inconsistent reporting of cultivar, maturity, humidity, replication, and coating concentration. Therefore, harmonised testing is needed to determine whether laboratory improvements translate into commercial FLW reduction. However, several pilot-scale and commercial examples already demonstrate their scale-up potential. Marketed products such as coated cucumbers (e.g., Saveggy AB coated cucumber, Sweden) indicate that edible coatings can be successfully implemented to maintain quality under real distribution and retail conditions. However, wider market adoption still requires addressing several important concerns. In cases where edible coatings are applied without secondary packaging, consumers may be unsure whether the product should be washed, peeled, or eaten directly. Therefore, clear labelling and effective communication are essential to explain the purpose, safety, and proper use of the coating. In addition, transparency regarding coating ingredients is important to address concerns about allergens, dietary restrictions, and the acceptance of insect- or animal-derived materials. Consumer perceptions of appearance, texture, odour, and possible changes in taste may also influence purchasing decisions.

3.2. Active packaging

Active packaging refers to packaging systems that interact with the food product or its surrounding environment to extend shelf-life, improve quality, and enhance safety (Tomadoni et al., 2025). Unlike conventional passive packaging, active packaging contains components that can either release substances, such as antioxidants or antimicrobial agents, or absorb compounds such as oxygen, moisture, and ethylene (Fig. 2a). By regulating the internal package environment, these systems help reduce FLW during storage, retail, and consumption stages (Ahmed et al., 2022).

The release behaviour of the active component is as important as its intrinsic bioactivity. Direct-contact films can deliver non-volatile compounds to the food surface but may produce rapid initial migration followed by early depletion. Headspace-releasing systems are suitable for volatile compounds and irregular food surfaces, although their efficacy depends on package volume, headspace composition, and temperature. Scavengers must similarly possess sufficient absorption capacity for the initial headspace concentration, package permeability, and compounds continuously generated by the food (Xu et al., 2025a; Yildirim et al., 2018). Nanostructured carriers including nanoemulsions, Pickering emulsions, electrospun fibres, and metal-organic frameworks can protect unstable compounds and reduce burst release (Riahi et al., 2025; Chen et al., 2025; Sun et al., 2026; Zhang et al., 2026a). However, controlled release must correspond to the deterioration kinetics of the food. Release that is too rapid causes early depletion or sensory effects, whereas release that is too slow may not reach an effective concentration before spoilage begins (Xu et al., 2025a).

Essential oils, plant extracts, chitosan, phenolics, and metal-oxide nanoparticles have been widely incorporated into active matrices (Moeini et al., 2026; Cerruti Da Costa et al., 2025; Li et al., 2026; Mobarraei et al., 2025; Shavisi and Shahbazi, 2025). FLW-derived compounds can also impart substantial bioactivity to packaging. In this regard, phenolic-rich cherry-pomace pectin films showed 85.33% DPPH scavenging, compared with <15% for conventional pectin, and better maintained strawberry quality; however, this outcome also reflected their antibacterial activity, barrier properties, and moisture regulation (Zhang et al., 2026b). In contrast, mandarin essential oil composites achieved up to 100% inhibition of *E. coli* and 97% of *S. aureus* and reduced growth of *B. cinerea;* however, they did not significantly improve fruit ABTS or FRAP values or most quality attributes (Parichanon et al., 2026). Therefore, *in vitro* activity should not be equated with shelf-life extension. Food-level effectiveness also depends on the concentration added, extraction method, matrix interactions, dispersion, stability, release kinetics, food composition, storage conditions, and the dominant spoilage mechanism.

Additionally, bio-based functional additives don't ensure safety, sensory neutrality, or regulatory acceptance (Xu et al., 2025a; Peng et al., 2024). Essential oils may impart strong odour or flavour at effective antimicrobial concentrations, plant extracts can vary with cultivar and extraction conditions, and nanoparticles require migration and toxicological assessment. These limitations are particularly relevant when laboratory formulations are transferred to industrial food-contact applications.

Table 3 shows that active systems have been evaluated across fresh products, oils, meat, poultry, seafood, and nuts. Antioxidant films are most relevant to lipid-rich products while antimicrobial systems are mainly relevant to moist protein-rich foods. These systems have mainly focused on FLW reduction in primary production and processing by valorisation, as well as retail and consumption by prolonging shelf-life.

Active technologies also differ in maturity. In this regard, oxygen scavengers (e.g., OxyGuard™) and antimicrobial technologies (e.g., Microban®) are commercially established, whereas many bioactive biopolymer films, nanocarriers, and FLW-derived additives remain at laboratory or pilot scale. These systems have demonstrated compatibility with extrusion-based processing, thereby improving their scale-up potential (Pereira et al., 2026).

3.3. Intelligent packaging

Intelligent packaging is developed to sense, record, and communicate information about the condition of food products or their surrounding environment (Fig. 2b). Unlike edible coatings and active packaging, it generally does not prevent deterioration directly. Its contribution to FLW reduction depends on whether the information generated changes stock rotation, distribution, purchasing, consumption, or disposal decisions (Palanisamy et al., 2025).

Principal technologies provide different types of information. Time-temperature indicators (TTIs) are among the most established intelligent packaging tools, providing visual signals when products experience

Table 2
Food- and stage-specific impact of edible coatings on food loss and waste reduction in the food supply chain.

Category	Foods	Coating systems	Key findings	Target FSC stage	Reference
Berries	Strawberry and blueberry	Insect and plant proteins, sericin-alginate, hemicellulose or protein containing nanocellulose, and soy protein-pectin containing phenolics	Protein- and polysaccharide-based coatings were particularly effective in limiting moisture loss, maintaining firmness and colour, and suppressing microbial growth. Reported shelf lives ranged from 7 to 14 days for strawberries and 12-30 days for blueberries, depending on storage conditions. The incorporation of phenolics and plant pigments also conferred antimicrobial potential and pH-responsive colour monitoring.	Primary production, processing, retail, household	(Guo et al., 2024; Gharibzahedi and Altintas, 2025; Zenasni et al., 2026; Pinheiro et al., 2026; Qazanfarzadeh et al., 2024)
Climacteric fruits	Banana	Whey protein–pectin Pickering emulsion containing thyme essential oil, *Opuntia* wax, *Opuntia ficus*-indica mucilage containing *Moringa oleifera* waste extract, and chitosan containing ZnO nanoparticles	The coatings delayed ripening by limiting respiration, transpiration, softening, browning and microbial spoilage. Shelf-life duration varied from 9 to 16 days depending on the storage condition and rejection criteria. Bioactive coatings combining moisture and gas barriers with antimicrobial or antioxidant compounds were particularly suitable for controlling the rapid ripening of bananas.	Primary production, distribution, retail, household	(Yang et al., 2026; Poomalaisundar et al., 2026; Chokoe et al., 2025; Molla et al., 2026)
Vegetables	Tomato, carrot, cucumber, and mushroom	Chitosan containing starfruit leaf extract, chicken-feet gelatin-lotus-stem starch, and cellulose-based emulsions	Chitosan-based coatings were especially promising for controlling microbial growth and moisture loss under ambient storage. Protein-polysaccharides coating delayed ripening and maintained firmness, colour, and overall sensory quality. Emulsion coatings were effective in reducing weight loss, respiration, delaying colour change, maintaining firmness, pH, and phenolics.	Primary production, processing, retail, household	(Rather et al., 2022; Mahin et al., 2025; Utama et al., 2022; Singkhonrat et al., 2023)
Seafood	Salmon cuts and smooth-hound shark fillets	Pea starch and fish-skin gelatin	The principal benefits were suppression of microbial growth and retardation of biochemical spoilage. Carbohydrate coatings reduced trimethylamine formation, whereas gelatin coatings reduced lipid oxidation, microbial growth, volatile basic nitrogen, colour deterioration and moisture loss and maintained texture better.	Processing, retail, household	(Salem et al., 2024; Vidal et al., 2024)
Meat	Pork loin, fresh pork, beef, and ostrich meat	Chitosan-furcellaran-gelatin hydrolysate, chitosan-cellulose nanofibre film containing gingerol loaded Pickering emulsions, chitosan film containing anthocyanin-zein-thymol-pullulan nanoparticles, and chia-seed mucilage containing *Lactococcus lactis* postbiotics	Chitosan-based active systems were particularly promising for meat preservation because of their intrinsic antimicrobial activity. Combining chitosan with proteins, other polysaccharides, and functional compounds has reduced microbial growth and lipid oxidation, while anthocyanins or other pH-sensitive indicators could additionally detect freshness. Postbiotic systems have also shown potential in reducing microbial growth, lipid oxidation, and colour deterioration.	Processing, distribution, retail, household	(Kulawik et al., 2024; Nosheen and Khan, 2026; Cai et al., 2026; Goudarzi Shams Abadi et al., 2026)
Poultry	Chicken breast and fillets	Persian-gum containing pennyroyal essential oil, flaxseed mucilage-bixin containing allicin or orange peel-essential oil, and chitosan nanoparticles containing ginger essential oil	Essential oil loaded polysaccharide coatings were particularly effective in controlling the microbial and oxidative spoilage of chicken. Nanoencapsulation improved the stability and sustained release of essential oils, while combining active coatings with oxygen scavenging provided additional protection against aerobic spoilage.	Processing, distribution, retail, household	(Hashemi et al., 2026; Musalem et al., 2025; Khalili et al., 2026)
Nuts	Chestnut, walnut, pistachio, and hazelnut	Carboxymethyl chitosan (CMC)-sodium alginate, oxidised bacterial cellulose with tea polyphenols, chickpea containing thyme essential oil microcapsules, guar-gum containing *Pycnocycla bashagardiana* essential oil, and gelatin	Antioxidant-rich coatings were particularly suitable for preventing rancidity in lipid-rich kernels. Polysaccharide-based coatings showed more greater potential for nut preservation. The blended-polysaccharide coatings led to lower respiration, weight loss, browning, and decay. Phenolic loading and essential oil addition controlled weight loss, lipid oxidation, and microbial growth.	Primary production, processing, distribution, retail, household	(Turan et al., 2024; Dong et al., 2026; Aldarraji et al., 2025; Chen et al., 2026; Camiletti et al., 2026)

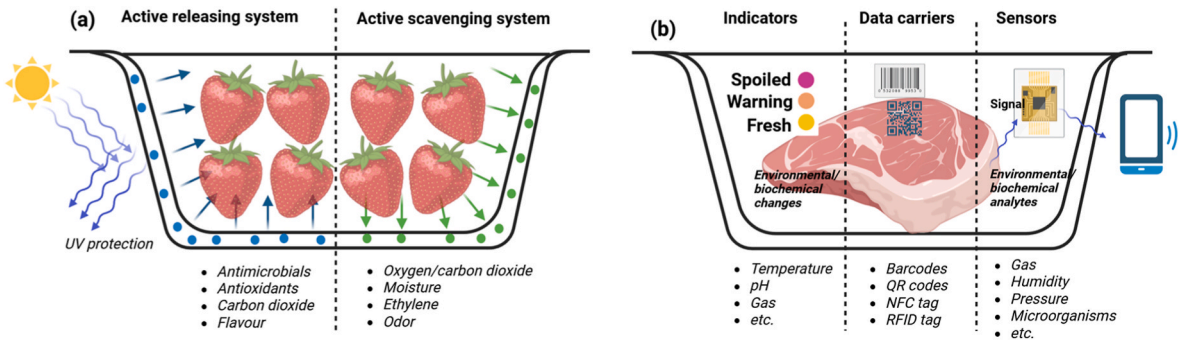


Fig. 2. Schematic representation of packaging technologies supporting food loss and waste reduction: (a) active packaging systems and (b) intelligent packaging systems.

Table 3
Summary of studies on the development of active and intelligent packaging aimed at reducing FLW.

Technology	Mechanism	Smart compound	Matrix	Food	Potential contribution to FLW reduction	Reference
Active	Direct contact migration of active compound	Polyphenolic extract and lignin nanoparticles from green walnut husk	Chitosan film	Walnut kernel	Delayed spoilage and extended shelf-life during *storage* and *retail*, and reduced walnut waste during *processing*	Liu et al. (2026)
Active	Direct contact migration of active compound and UV protection	Halloysite nanotubes functionalised with carbon dots	Alginate film	Apple and banana cut	Enhanced product stability, reduced spoilage and losses during *storage*, and reduced waste during *retail* while replacing petroleum-based plastics	Cinà et al. (2024)
Active	Direct contact migration of active compound	Phenolics extract from grape stalk	Polylactic acid film	Sunflower oil	Preserved oil against oxidation and reduced rancidity-related losses during *storage* and winery by-products during *processing*	De Freitas et al. (2024)
Active	Direct contact migration of active compound and UV protection	lignosulfonates	Beechwood xylans and cellulose nanofibres	Fresh-cut pears	Delayed browning due to antioxidant and UV-barrier properties during *retail* and *household* use	Silva et al. (2024)
Active	Direct contact migration of active compound and non-direct contact release	Grape marc, olive pomace, and *Moringa oleifera* leaf extract	Cellulose	Ground beef meat	Prevented lipid peroxidation during *distribution* and *retail*, and reduced *grape and olive processing* loss	Barzan et al. (2024)
Active	Direct contact migration of active compound	Zinc oxide nanoparticles	Bacterial nanocellulose film	Chicken	Reduced microbial growth and delayed spoilage in poultry during *retail* and *household* use	Soares Silva et al. (2023)
Active	Direct contact migration of active compound	Potato peel phenolic extracts	Starch film	Smoked seabream fillet	Slowed oxidation, preserved the sensory quality of seafood during *distribution*, *retail* and *consumption*, and reduced potato loss generated during *processing* and *food service*	Lopes et al. (2021)
Colorimetric indicator	Detecting NH_3, DMA, and TMA through anthocyanin colour shift	Purple corn anthocyanins	Alginate hydrogel beads	Muscle food	Improved early-stage spoilage detection through real-time monitoring of volatiles *across the supply chain*	Mohammadalinejhad et al. (2023)
Colorimetric indicator	Detecting spoilage metabolites via pH-dependent colour change	Red onion skin extract	Potato starch film with halloysite-based filler	Meat and milk	Real-time quality indication, along with antimicrobial functionality, reduced loss and waste in *storage*, *retail*, and *consumption*	Boccalon et al. (2022)
Oxygen sensor	Detecting package leakage or oxygen through reoxidation colour change	Toluidine blue and SnO_2 nanoparticles	Hydroxypropyl methylcellulose printed membrane	Uncooked ham in MAP system	Enabled rapid detection of package failure during *transport* and *distribution* as well as prevented unnoticed spoilage and reduced loss and waste in *storage* and *retail*	Fernández-Ramos et al. (2021)
Intelligent and active indicator	Detecting NH_3 via curcumin colour change, direct contact migration of active compound	Curcumin	PLA/polypropylene carbonate blend film	Shrimps	Detected spoilage through real-time freshness monitoring during *storage* and *retail*, and extended shelf-life to reduce seafood waste in *retail* and *consumption*	Cvek et al. (2022)
Intelligent colorimetric indicator	Detecting spoilage via pH change and volatile organic compounds	Black carrot anthocyanins	Whatman-42 filter paper	White button mushroom	Enabled timely use and reduced postharvest mushroom loss and waste by classifying freshness stages for *distribution*, retail, and *consumption*	Kumar et al. (2025)

temperature abuse during transport or storage stages. These systems commonly operate through chemical, enzymatic, microbial, or emerging mechanisms such as polymer-dye systems, photonic crystals, and electronic sensors, thereby helping to prevent spoilage and reduce the risk of foodborne illness (Gurunathan et al., 2024). These sensors have been reported to extend shelf-life by 25-40% in chilled meat and dairy products, representing a significant effect in reducing food waste (Park and Kwon, 2026). Freshness indicators provide more direct information by responding to metabolites associated with deterioration, including volatile amines in seafood, carbon dioxide in meat, or pH changes caused by microbial activity. Natural pigments such as anthocyanins, curcumin, betacyanins, and chlorophylls have shown promising potential for visible colour responses and compatibility with bio-based matrices (Ndwandwe et al., 2024). Indicator sensitivity and response time depend on several factors, including pigment loading, source and extraction method, matrix structure, exposure mode, food type, and storage conditions. Accordingly, anthocyanin-based indicators have shown different apparent responses. A red onion peel indicator changed colour within one min in buffer, whereas a black carrot indicator responded within some min and correlated with mushroom deterioration. A grape skin indicator responded to ammonia within 25 min and successfully monitored pork spoilage (Cai et al., 2026; Kumar et al., 2025; Piryaei et al., 2026). Besides, their response thresholds must correspond to microbiological and sensory acceptability for the intended food. Pigment degradation caused by light, oxygen, or humidity may be mistaken for spoilage. Immobilisation and protective fillers can improve stability, but may also slow analyte diffusion and delay the signal (Shao et al., 2021).

Besides, gas and humidity sensors constitute another category of intelligent packaging that may contain transducers, electronics, and software to effectively quantify biological, physical, and chemical changes during storage and distribution (Wei et al., 2025; Lu et al., 2025). Meanwhile, the development of RFID- and NFC-enabled packaging supports traceability and data sharing across the FSC. These devices can store and transmit information about origin, production conditions, and product status-features that align with smart logistics and “Internet of Things” ecosystems (Zuo et al., 2022).

The applications in Table 3 indicate that intelligent systems have been studied most extensively for meat, seafood, dairy products, and other foods that generate detectable spoilage metabolites. Bio-based indicators offer reduced material use and visible communication, but their moisture sensitivity, signal stability, early-spoilage sensitivity, and batch-to-batch reproducibility remain limitations (Boccalon et al., 2022; Cvek et al., 2022; Mohammadalinejhad et al., 2023). Furthermore, technical accuracy alone does not ensure FLW reduction. An unclear or unfamiliar colour transition may increase consumer uncertainty (Kamboj et al., 2025; Rahman et al., 2026).

In general, current evidence indicates that intelligent packaging is most effective in reducing FLW at the storage and retail stages, where monitoring conditions directly influence discard decisions. However, their effectiveness might be restricted if they are not combined with FSC management practices. While some intelligent packaging solutions are already commercially available, particularly TTIs such as Monitor-Mark™, Fresh-Check®, and OnVu™, and colorimetric ripeness indicators such as ripeSense®, as well as RFID- and NFC-based tracking systems, several challenges continue to hinder large-scale adoption of bio-based and FLW-derived biosensors, including sensor stability under varying environmental conditions and limited sensitivity at early spoilage stages (Boccalon et al., 2022). In addition, issues related to the integration of electronic components into cost-effective and scalable packaging systems, including standardisation, data interpretation, and consumer understanding, remain significant barriers. Therefore, broader implementation will depend on improving sensor reliability, reducing costs, and enhancing interoperability with digital logistics systems.

4. Upcycling food loss and waste into packaging materials

Although various practices can prevent and reduce FLW, unavoidable inedible fractions and processing side streams continue to rise throughout the FSC. However, material recovery out of FLW is primarily a management strategy for fractions that cannot remain within the food or feed chain (Teigiserova et al., 2020). Mismanagement through landfilling or uncontrolled disposal creates GHG emissions and other environmental burdens (Batool et al., 2024; Moult et al., 2018). Composting and anaerobic digestion recover nutrients or energy, whereas biorefinery approaches may recover higher-value polymers, chemicals, and functional compounds (Ranasinghe et al., 2024; Quan et al., 2024). However, a higher-value product does not necessarily provide a greater environmental benefit because collection, pretreatment, extraction, and purification can substantially influence the outcome (Caldeira et al., 2020; Scherhaufer et al., 2020).

Additionally, feedstock origin is an important aspect of biorefinery systems. Processing side streams are generally more homogeneous, traceable, and concentrated than waste collected from retail, food service, or households, making them more suitable for extraction and food-contact applications. However, many industrial side streams, including whey, oilseed cakes, molasses, and spent grain already have uses in feed, food ingredients, energy, or soil amendment. Converting them to packaging materials may therefore displace an existing product and create additional demand elsewhere. Consequently, feedstock availability should always be evaluated alongside environmental burden and economic feasibility (Caldeira et al., 2020; Moonsamy et al., 2024).

Fig. 3 presents the conceptual framework adopted in this section, illustrating how FLW generated throughout the FSC can be processed through biorefinery routes and returned to the FSC as sustainable packaging materials. In addition, it represents a closed-loop relationship between waste generation, material recovery and packaging production. Table 4 complements this framework by summarising the specific feedstocks, biorefinery methods, recovered compounds and packaging applications reported in recent studies. It also identifies their stage-specific contributions to FLW reduction across the FSC.

4.1. Biopolymers

In recent years, considerable research efforts have focused on developing biorefinery processes to convert FLW into biopolymeric matrices. These processes generally involve the extraction of biopolymers directly from biomass (e.g., polysaccharides, proteins, lipids) using conventional or green techniques, or the biotechnological production of polymers such as bacterial cellulose, lactic acid, polyhydroxyalkanoates (PHA), and polyhydroxybutyrate (PHB) from FLW biomass. Beyond food packaging, FLW-derived polymers also have potential in agriculture, biomedicine, and environmental remediation. Direct extraction preserves macromolecular structures but might require chemical solvents, fractionation, and purification. Green extraction techniques such as microwave- and ultrasound-assisted extraction, high pressure homogenization, enzymatic treatment, subcritical water extraction, and other methods are widely explored to enhance the extraction efficiency and reduce environmental burden. In contrast, fermentation can yield more compositionally consistent products but requires pretreatment, microbial control, nutrient balancing, and downstream product recovery.

Among various sources of FLW, fruit and vegetable residues are particularly suitable for direct extraction because they contain starch, pectin, cellulose, and other structural polysaccharides. Examples include thermoplastic starch from cassava bagasse (Akmeemana et al., 2026), pectin films from citrus and banana peels (Athanasopoulou et al., 2025; Zhang et al., 2024), and cellulose derivatives from cocoa shells (Qamar et al., 2025). Seafood-processing residues provide protein- and polysaccharide-based alternatives, including gelatin from fish by-products (Wang et al., 2025) and chitosan from shrimp shells (Orkhis

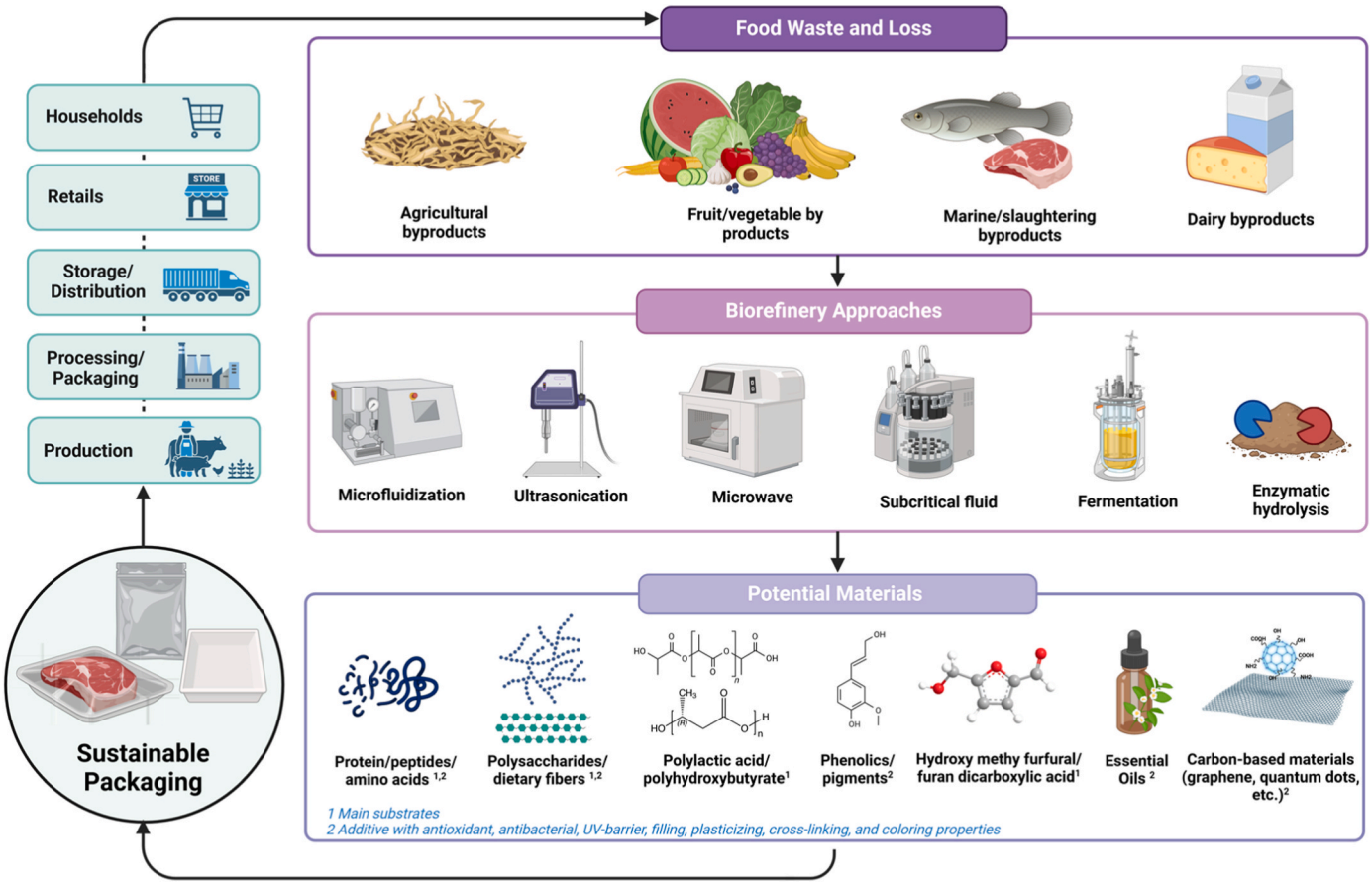


Fig. 3. Upcycling food loss and waste into sustainable packaging materials in a circular economy approach.

et al., 2024). However, source abundance alone does not establish packaging suitability. Polymer yield, molecular weight, purity, seasonal variability, odour, colour, and allergenicity can influence both processing and food-contact acceptance (Zhao et al., 2023; Ahmed et al., 2025).

On the other hand, fermentation can utilize carbohydrate-rich biomass and convert its sugars into more standardised polymer precursors. For instance, lactic acid was produced at 26.3 ± 0.3 g/L from a mixed food-waste substrate comprising rice, lentils, vegetables, bread, and various peels using *Lactiplantibacillus plantarum*, achieving 90% substrate utilisation (Swetha et al., 2025). Similarly, custard apple peel and seed waste have also been valorised for PHB production using *Bacillus megaterium*, yielding 7.92 g/L (Saravanan et al., 2024). Mixed-culture solid-state fermentation of food waste has also been shown to generate carboxylate-rich streams suitable for PHA synthesis by *Pseudomonas putida*, achieving 0.56 g PHA/g CDM (Chandra et al., 2023). In addition, FLW has been employed to produce pullulan from *Huangjiu lees*, bacterial cellulose from Kombucha waste, and grape pomace (Cáceres et al., 2025; Lu et al., 2024; Agha and Kati, 2025).

The effect of FLW-derived polymers on food shelf-life is generally indirect. Adequate mechanical strength and moisture and gas barrier properties help maintain package integrity, whereas polymers with intrinsic antimicrobial activity, particularly chitosan, may additionally suppress microbial deterioration. Despite these promising advances in valorising FLW, improving the mechanical and barrier properties of FLW-derived biopolymers remains a significant challenge. To meet industry standards, current research in materials science focuses on enhancing durability and resistance to moisture and oxygen, thereby ensuring the suitability of these materials for real-world food packaging applications (Kanwal et al., 2024).

4.2. Plasticisers

Plasticisers are key additives in polymeric packaging films that enhance flexibility, reduce brittleness, and improve processability by increasing polymer chain mobility. Plasticisers are typically colourless, odourless, and low molecular weight molecules that integrate well with polymers to optimise film performance (Lazaro-Hdez et al., 2025). Therefore, appropriate plasticisation may indirectly support shelf-life preservation by improving film flexibility and seal integrity and reducing cracking or package failure during handling. However, plasticiser effects are very dependent on the matrix and concentration used (Paudel et al., 2023). Among them, glycerol, sorbitol, and fructose are widely used plasticisers because of their compatibility with polysaccharide- and protein-based matrices (Zamanidehyaghoubi et al., 2025). Due to sustainability aspects, the production of plasticisers from FLW is increasingly being explored. This can reduce dependence on virgin sugars and lower environmental impact and production costs (Tan et al., 2013). For instance, glycerol, traditionally a by-product of biodiesel production, was produced using a mixture of starch-based pasta, vegetable residues, and plant/animal proteins via enzymatic saccharification and yeast fermentation, achieving 73.6% yield within 76 h (Zhu et al., 2024). In addition, sorbitol, typically produced from glucose via hydrogenation or microbial fermentation, was produced using sugarcane molasses and bagasse, abundant by-products of sugarcane processing via biological fermentation using *Zymomonas mobilis* (Phannarangsee et al., 2024).

In addition, vegetable oil-derived plasticisers including epoxidised soybean oil methyl ester, epoxidised linseed oil, and maleinised hemp seed oil offer greater hydrophobicity and may improve water resistance and compatibility with less polar polymers. However, compared to polyols, their efficiency depends strongly on chemical modification and

Table 4
Biorefinery of food loss and waste (FLW) into packaging materials and their contribution to FLW reduction.

FLW	Material	Application	Biorefinery method	Packaging formulation	Contribution to FLW reduction	Target FSC stage							Reference
						Production	Processing	Packaging	Distribution	Storage	Retail	Consumption	
Soybean oil deodoriser distillate	Isobutyl esters	Plasticiser	Chemical	PLA/10 wt% isobutyl esters	Reducing processing by-products and enabling flexible biodegradable packaging.		×	×					Najera-Losada et al. (2025)
Chia seed flour	Lignocellulose	Filler	Mechanical	PLA/15 wt% filler	Replacing synthetic fillers and lowering agro-food side-stream disposal.		×	×					Dominguez-Candela et al. (2022)
Cocoa pod husk and sugarcane bagasse	Cellulose and fibre	Main matrix and reinforcement	Chemical	Cellulose/fibre/ glycerol/sorbitol	Using crop-processing residues as structural biopolymer source and fillers for packaging, diverting bulky lignocellulosic waste from disposal.		×	×					Azmin et al. (2020)
Litchi shell waste	Extract	Bioactive agent	Microwave	Guar gum/CMC/litchi bioactive extract	Recovering antioxidants/ antimicrobials from fruit shell waste to create active films that can delay spoilage.		×	×			×	×	Deshmukh et al. (2022)
Red grape pomace	Pectin and extract	Main matrix and bioactive agent	Ultrasound-microwave assisted	Red kidney bean protein isolate/pectin/ bioactive extract/ glycerol	Valorising winery pomace into film-forming pectin and active molecules while extending shelf-life of packaged foods.		×	×			×	×	Amiri Samani et al. (2025)
Aegle marmelos fruit shell	Polysaccharides	Coating matrix	Ultrasound-assisted	Polysaccharides/ glycerol/acetic acid	Converting fruit shell waste into an edible coating matrix that can reduce moisture loss and spoilage of the product.		×	×	×		×		Sharma et al. (2024)
Banana peel	Magnetic iron oxide nanoparticles	Antioxidant and preservative	Maceration-chemical-thermal	Banana peel powder/ glycerine/iron oxide nanoparticles	Reusing banana peel residues in active packaging with preservative functionality, reducing peel disposal and food spoilage.		×	×			×	×	Abdullah et al. (2024)
Green walnut husk	Extract and cellulose nanocrystals (CNC)	Preservative and reinforcement	Ultrasonic-assisted solvent extraction and chemical	Paper coated with chitosan/CNC at the buttom and ethyl cellulose/extract at the top	Extracting high-value active molecules and CNC from walnut husk for multilayer coatings that improve barrier and preservation performance.		×	×	×		×	×	Liu et al. (2024b)
Banana bract and sugarcane bagasse	Cellulose fibres and active extract	Preservative and reinforcement	Solvent extraction and chemical	PVA/cellulose fibres/ banana bract extract/ nanosilver	Utilizing agro residues as reinforcement and active agents, reducing biomass waste and enhancing package protection.		×	×			×	×	Maroor and Badalamoole (2025)
Thymus infusions residue	Lignocellulose-based nanoparticles	Preservative and reinforcement	Aqueous extraction	PLA-PHB/Maleinised corn oil/thyme waste nanoparticles	Converting herbal infusion residues into functional nanoparticles for compostable packaging with active protection.		×	×			×	×	Sempere-Torregrosa et al. (2025)
Cocoa shells	CMC	Main matrix	Chemical	CMC coated with natural waxes (bees and carnauba)	Recovering polysaccharides from cocoa shells to form coated packaging materials that can improve moisture barrier and reduce product losses.		×	×	×		×		Qamar et al. (2025)
Artichoke leaves	Active extract	Active coating	Subcritical water	PLA coated with a blend of CMC and extract	Converting non-edible parts of artichoke harvesting to an active coating that improves barrier and preservation performance.	×		×			×	×	Qazanfarzadeh and Jiménez-Quero (2025)

compatibility with the polymer, oil migration, odour, and oxidative stability (Lerma-Canto et al., 2021; Liu et al., 2024a; Zych et al., 2021).

FLW-derived plasticisers are also relevant to non-food packaging polymers. For example, waste soybean cooking oil has been used to produce benzyl-based ester plasticisers for flexible PVC films via a lipase-mediated process (Sabi et al., 2025). Waste cooking oil has also been directly used as a plasticiser. In this regard, substitution of glycerol with waste cooking oil in carrageenan/corn starch bioplastics was shown to improve tensile properties, enhance water resistance, and accelerate biodegradation (Mangala et al., 2025).

4.3. Functional additives

FLW-derived additives can be divided into three functional groups including reinforcing fillers that improve mechanical or barrier properties, active compounds that inhibit microbial or oxidative deterioration, and responsive compounds that indicate changes in food condition. Unlike polymer matrices, additives are generally used at low concentrations, but they may provide a large contribution to packaging performance and economic value. Their effectiveness depends on compatibility and dispersion within the matrix, stability during processing and storage, and migration or release at an appropriate rate.

Cascade biorefinery is particularly relevant for functional additives because different fractions of one side stream can serve complementary packaging functions. For example, coffee leaf waste was fractioned to produce multiple additives, such as essential oils for antimicrobial Pickering emulsions, lignin nanoparticles as emulsion stabilisers, and cellulose nanocrystals as reinforcing agents in gelatin films (Sun et al., 2026). Similarly, nanochitosan produced from shrimp shells and the nanocellulose and bioactive extract derived from orange peel waste were applied as an edible coating for apples (Hasanin et al., 2025).

Phenolic, flavonoid, anthocyanin, and essential oil fractions recovered from fruit and vegetable production and processing residues provide more direct active or sensing functions. In this regard, edible coatings formulated with chitosan-lignin matrices enriched with banana, mango, and pomegranate peel extracts effectively extended apple shelf-life, with pomegranate peel extract showing the highest antimicrobial and quality-preserving performance (Waseem et al., 2025). Anthocyanins extracted from fruit residues such as pitaya peel have been widely used as natural pH-sensitive indicators in smart packaging systems (Ma et al., 2026). Inedible parts of vegetables such as leaves and stems also offer rich sources of antioxidants. Extracts derived from different anatomical parts of konjac waste (leaf blade, petiole, corm) were incorporated into chitosan films, with leaf blade extract exhibiting the highest phenolic content and antioxidant activity (Zhong et al., 2025).

Essential oils can provide strong antimicrobial and antioxidant activity, but direct incorporation may cause volatility, rapid release, and sensory changes. Encapsulation can improve stability and prolong release; for example, sweet orange essential oil encapsulated in whey protein isolate–peach gum complexes improved the storage quality of fresh-cut pears (Xu et al., 2025b). Likewise, incorporating mandarin essential oil (2%) into polylactic acid (PLA)/poly(butylene succinate-co-adipate) (PBSA) films with chitosan produced strong antibacterial activity, inhibiting *E. coli* by 100% and *S. aureus* by 97% (Parichanon et al., 2026).

Besides, carbon quantum dots (CQDs), multifunctional additives with fluorescence, UV-shielding, antioxidant, antimicrobial, or sensing properties, are increasingly being produced using FLW streams (Esmaeili et al., 2025). In this way, precursors such as palm-kernel shells, oyster residues, fruit and potato peels, and bread waste have been investigated for CQD production (Qazanfarzadeh et al., 2025; Kumar et al., 2024; Krishnaiah et al., 2025; Siva Kumar et al., 2024; Zhu et al., 2025; Koç Keşir and Yılmaz, 2024).

FLW-derived additives also have several non-food applications. For example, CQDs produced from food waste have been evaluated for biomedical and water purification applications (Esmaeili et al., 2025). Among the three material groups, functional additives have the most direct relationship with food shelf-life. Antimicrobial and antioxidant additives can suppress microbial growth and oxidation, while freshness-responsive additives may help prevent premature disposal by providing information about product condition.

5. Life cycle and techno-economic assessments

Life cycle assessment (LCA) and techno-economic assessment (TEA) provide complementary information for evaluating packaging-based FLW reduction and waste valorisation pathways. LCA identifies environmental hotspots and quantifies impacts across the product life cycle, whereas TEA assesses technical scalability and economic feasibility. Their integration is essential because an environmentally favourable technology may remain economically uncompetitive, while a profitable process may generate considerable impacts through energy use, chemical consumption, transportation, or end-of-life treatment (Wunderlich et al., 2021).

At the packaging level, fruit and vegetable distribution systems were assessed using reusable plastic crates (RPC) and conventional cardboard packaging from the farm to the retail stage (Gao et al., 2026). The results showed that RPC systems could significantly reduce FL and energy consumption during storage and transportation, which in turn reduced the global warming potential by 32.4–50.4%, freshwater ecotoxicity by 3.1–16.8%, eutrophication potential by 1.9–13.4%, and water consumption by 3.4–16.9% compared with cardboard packaging. In addition, direct packaging impacts were estimated at 0.56 kg CO_2-eq per RPC use cycle, assuming 72 uses over three years and 1.23 kg CO_2-eq per use of a single-use cardboard box. However, the commercial viability of RPC also depends on other factors such as purchase cost and washing requirements. The importance of evaluating these balances was demonstrated for smart Tetra Pak incorporating an antioxidant layer and a spoilage sensor. Under the average food waste prevention scenario, smart packaging reduced climate change impacts by 29.2%, although its production cost increased by EUR 9.3×10^{-2} per unit, or 38.7%, compared with conventional packaging (Stramarkou et al., 2025). However, this was a preliminary cost analysis that excluded equipment, labour, and depreciation, indicating that a complete TEA is still required before commercial implementation.

A more comprehensive assessment of cellulose-nanofibril coatings on moulded-pulp trays demonstrated how food preservation can be integrated directly into LCA and TEA. The economically preferred configurations differed among cherry tomatoes, raspberries, and blueberries because the added coating cost was balanced against fruit value and reductions in weight loss. The corresponding minimum selling prices (MSP) of packaged fruit after 10 days were USD 5.73, 41.40, and 18.75 kg^{-1}, while their global warming potentials were 0.85, 1.65, and 1.92 kg CO_2-eq kg^{-1}, respectively. Sensitivity and Monte Carlo analyses identified fruit wholesale price and weight loss as the main economic drivers, demonstrating that packaging functionality and avoided FLW, rather than packaging cost alone, should be included in TEA (Bangalore Ashok et al., 2026).

Material choice and collection infrastructure also strongly influence economic viability. A comparative TEA of PET, recycled PET, and PLA packaging in Australia found that recycled PET collected through return-deposit systems was cost-competitive compared to virgin PET (AUD 0.80 kg^{-1}), whereas PLA cost AUD 2.82 kg^{-1} because of its high feedstock, energy, and fermentation costs (Taskhiri and Symons, 2026).

Integrated assessments are also important for FLW-derived packaging materials. In this regard, LCA and TEA investigation of starch-cellulose bioplastics produced from sweet potato peel, banana pseudostems, and waste cooking oil as plasticiser were combined with end-of-life recycling into biochar. This integrated approach improved economic performance by reducing the payback period from 13.3 to 6.8 years and increasing the internal rate of return to 12.1% through profits

from bioplastic, biochar, carbon credits, and pollution reduction (Senga et al., 2024). Similarly, agro-waste-derived starch films showed a climate-change impact of 1220 kg CO_2-eq per tonne of film and an MSP of USD 1.67 kg^{-1}. Raw-material cost and production capacity were the main economic drivers, whereas chemical inputs and electricity dominated environmental impacts, identifying process conditions that could simultaneously reduce cost and emissions (Singh et al., 2026).

For cellulose-based packaging components, an industrial-scale process producing 8000 tonnes per year of carboxylated cellulose nanocrystals achieved an MSP of EUR 4.3 kg^{-1} and a global warming potential of 1705 kg CO_2-eq per tonne. Pulp price and production capacity controlled economic performance, while pulp, sodium hypochlorite, sodium hydroxide, and electricity dominated environmental impacts (Forssell et al., 2026). However, using such systems to reduce FLW does not guarantee simultaneous economic and environmental benefits. For example, producing the bio-based plastic precursor 2,5-furandicarboxylic acid from lignocellulosic biomass had an estimated MSP of USD 1024 per tonne and 53% lower fossil depletion than petroleum-derived terephthalic acid, but a 29% higher climate change impact due to electricity-intensive processing (Kim et al., 2020).

6. Actions, challenges, and future perspective

Packaging can contribute to FLW reduction through two interconnected pathways, including innovative packaging and biorefinery processes. These pathways are not equivalent, so that prevention remains the priority under the waste hierarchy, whereas material valorisation provides a circular route for unavoidable residues.

6.1. Policies and regulations for FLW reduction and packaging

At the global level, FLW reduction is framed by SDG 12.3, which aims to halve per-capita FW at retail and consumer stages and reduce FL throughout FSC by 2030 (United Nations). The Food and Agriculture Organization (FAO) Voluntary Code of Conduct for FLW Reduction provides a general framework of actions for governments, FSC actors, research institutions, and other stakeholders (Voluntary code of conduct for, 2022). The FAO Food Waste Index and United Nations Environment Programme (UNEP) provide complementary methods for monitoring FL before retail and FW at retail, food service, and household stages, respectively. However, international frameworks establish broad targets rather than requirements for particular packaging interventions, and their implementation remains dependent on national policies, data availability, and monitoring capacity (UNEP and Food Waste Index Report, 2024).

In North America, regulatory approaches are more decentralised and rely strongly on national strategies, voluntary commitments, and state or provincial initiatives. The United States has adopted a national objective of reducing FLW by 50% by 2030 (EPA, 2025). The National Strategy for Reducing Food Loss and Waste and Recycling Organics coordinates activities among the Environmental Protection Agency (EPA), United States Department of Agriculture (USDA), and Food and Drug Administration (FDA), including upstream prevention, date-labelling initiatives, consumer education, food donation, and recovery of remaining organic materials (EPA, 2024). Although the strategy does not specifically require packaging innovation or conversion of FLW into packaging, it follows the same general sequence of preventing waste before recovering value from unavoidable residues.

The EU has developed one of the most comprehensive frameworks linking FLW prevention, packaging management, and resource circularity. The Circular Economy Action Plan and Farm to Fork Strategy identify food waste prevention and sustainable packaging as components of a circular food system (European Commission, 2020a, 2020b). The Waste Framework Directive establishes a hierarchy in which prevention is prioritised over reuse, recycling, and material recovery (European Union, 2008). This hierarchy provides a logical connection between the two pathways considered in this review. Packaging should first prevent food from becoming waste, while unavoidable residues may subsequently be recovered as secondary raw materials. Beside, the revised Waste Framework Directive, (EU, 2025/1892), introduces binding national targets to reduce FW by 10% in processing and manufacturing and by 30% per capita across retail, restaurants, food services, and households by 2030 (European Parliament, 2025). Packaging can support these targets through shelf-life extension, portion optimisation, improved emptying and resealing, and clearer date and storage information. EU food-information legislation is particularly relevant because misunderstanding “use by” and “best before” dates can contribute to premature disposal (Cliceri et al., 2025). On the other hand, the Packaging and Packaging Waste Regulation (EU, 2025/40) strengthens requirements for packaging minimisation, reuse, and design for recycling and sets a target of recycling 70% of total packaging waste by 2030. However, reducing packaging should not compromise food protection and increase the overall environmental burden through additional FLW.

Policy support for FLW-derived materials is less direct and operates mainly through provisions concerning by-products, end-of-waste criteria, industrial symbiosis, and secondary raw materials. The Waste Framework Directive and Industrial Emissions Directive can facilitate the exchange and valorisation of food-industry side streams (European Commission, 2020b; European Union, 2010). However, recovered materials intended for food packaging must comply with food-contact, migration, traceability, and safety requirements irrespective of their renewable origin.

6.2. Barriers to implementation

Several technological, economic, regulatory, and behavioural barriers limit the contribution of packaging to FLW reduction. For innovative packaging, a major limitation is the gap between laboratory performance and demonstrated reductions in discarded food under commercial conditions (Wohner et al., 2020). Shelf-life extension does not necessarily translate into lower FLW if the packaging is incompatible with distribution systems, retail practices, consumer needs, or waste-management infrastructure. Active and intelligent packaging also requires safety and migration assessments, reliable operation under variable temperature and humidity, scalable manufacturing, and acceptable costs (European Commission, 2009). Under EU Regulation No. 10/2011, plastic food-contact materials must not exceed an overall migration limit of 10 mg dm^{-2} of food-contact surface, while specific migration limits depend on the individual substance (European Union, 2011).

Consumer behaviour is particularly important at retail and household stages. In a household study, approximately 20–25% of recorded FW was associated with packaging-related factors, particularly excessive package size, difficulty emptying packages, and expired “best before” dates (Williams et al., 2012). Consumer acceptance of active, edible, or intelligent packaging may also be constrained by concerns regarding safety, cost, convenience, unfamiliar materials, and correct disposal (Brennan et al., 2021; Cliceri et al., 2026). Unclear environmental claims such as “green” or “eco-friendly” can further create confusion and weaken consumer trust (Ada et al., 2023; Ketelsen et al., 2020).

FLW biorefinery faces a different but related set of challenges. Feedstock composition can vary according to season, geographical origin, processing, and storage conditions, affecting extraction yield and material consistency. Collection, transportation, drying, extraction, and purification may also require substantial energy and resources (Carpentieri et al., 2025). Many FLW-derived polymers and composites still show limitations in mechanical strength, moisture resistance, thermal stability, or industrial processability (Zhao et al., 2023). Moreover, residual allergens, contaminants, odours, colours, or migrating compounds may restrict their use in direct food-contact applications (European Union, 2011). The impact of innovative packaging

on end-of-life performance is equally important and depends on package design and composition, food contamination, and available collection and treatment infrastructure (European Commission, 2022). Multi-layers, active additives, and nanomaterials may hinder recycling or composting, while electronic components require separation and dedicated recovery. Without appropriate design and infrastructure, energy recovery or landfill may remain the only available routes. Thus, bio-based or FLW-derived origin alone does not ensure circular end-of-life management.

In addition, economic competitiveness remains a common obstacle. Low prices for virgin materials, high initial investment, insufficient processing infrastructure, and delayed returns can discourage industrial adoption (European Environment Agency, 2024; Kirchherr et al., 2017). Therefore, the use of an FLW feedstock cannot itself be considered evidence of environmental or economic sustainability. LCA and TEA must include feedstock collection, pretreatment, extraction, purification, processing, co-product value, food-preservation performance, and end-of-life management (Pérez-Almada et al., 2023). Where food-contact requirements cannot be achieved, non-food applications may offer more technically and economically realistic valorisation routes.

6.3. *Future pathways*

Future progress requires coordinated action among farmers, food processors, packaging manufacturers, retailers, policymakers, waste managers, and consumers (Voluntary code of conduct for, 2022). Packaging interventions should be designed around food-specific FLW hotspots rather than material novelty. Commercial validation should then quantify not only shelf-life extension but also reductions in product rejection and the amount of food actually saved (Pauer et al., 2019).

Assessment frameworks must similarly move beyond packaging mass, biodegradability, or recyclability alone. Integrated LCA, social LCA, life-cycle costing, and TEA can provide a more comprehensive evaluation of environmental, social, and economic performance (Molina-Besch et al., 2019). Existing food- and FLW-oriented LCA resources differ substantially in their objectives, system boundaries, geographical datasets and level of methodological detail as shown in Table 5.

Additionally, intelligent packaging combined with artificial intelligence may improve condition monitoring and dynamic shelf-life estimation. A prototype combining convolutional neural networks with gas, temperature, and humidity sensors classified the condition of fruits and vegetables with 95% accuracy (Sonwani et al., 2022). A relative-humidity-responsive label coupled with deep learning achieved 95.65% classification accuracy and was validated for monitoring packaged silver carp and apples (Zeng et al., 2026). Machine-learning models have also predicted potato shrinkage and sprouting and microbial and physicochemical changes in coated ostrich meat (Goudarzi Shams Abadi et al., 2026; Jubayer et al., 2025). These technologies could support first-expired first-out stock rotation and reduce disposal based only on fixed dates.

For FLW biorefinery, future development should prioritise cascade and multiproduct processes that recover several valuable fractions from the same side stream (Ebikade et al., 2020). Standardised feedstock characterisation, green extraction, continuous processing, and early safety assessment will be required to produce consistent polymers, plasticisers, and additives (Carpentieri et al., 2025). LCA and TEA should be integrated during process development to identify energy-intensive operations, appropriate production scales, valuable co-products, and realistic markets (Pérez-Almada et al., 2023).

7. Conclusion

This review provides a stage-specific framework linking packaging-related FLW drivers to two complementary but distinct interventions

Table 5
Food- and FLW-oriented LCA resources and their limitations for packaging-enabled FLW assessment.

Tool/resource	Primary scope	Main limitation	Reference
HESTIA	Open-source models and harmonised data for assessing the environmental impacts of agricultural production, farms, food products and selected food-processing operations	Coverage generally extends only from input production to the farm or processor gate. Downstream packaging, storage, retail, consumption, and packaging end-of-life are not comprehensively represented.	(HESTIA LCA models)
JRC Food Waste Prevention Calculator	LCA-based calculator for estimating the environmental, economic and nutritional benefits of FLW-prevention interventions, while considering the additional burdens associated with implementing the intervention.	Relies primarily on predefined European food profiles and prevention scenarios. It does not provide detailed modelling of packaging configurations, food-specific shelf-life responses, or FLW collection.	Laurentiis Valeria et al. (2023)
FORKLIFT	Simplified LCA and life-cycle-costing tool for selected valorisation routes involving food-processing side streams	Focuses mainly on processing side flows, GHG emissions, and costs under predominantly European conditions.	Östergren et al. (2018)
AGRIBALYSE	Public database covering more than 2500 agricultural and food products from production to consumption	Primarily represents foods produced or consumed in France and provides only background inventory data.	(AGRIBALYSE)
Kerry food waste estimator	Screening tool estimating reductions in food waste and associated CO_2 emissions, water use, and nutritional losses resulting from shelf-life extension. It includes manufacturer and consumer scenarios and the North American region	Provides indicative estimates rather than a complete LCA. It covers limited food categories, relies partly on regional averages and proprietary data.	(Kerry Food Waste Estimator)
FAO food loss and waste database	Global compilation of food-loss and waste quantities and rates by commodity, supply-chain stage and geographical region, useful for establishing baseline mass flows in LCA	Data originate from heterogeneous studies and methodologies.	(Food and Agriculture Organization of the United Nations)
ReFED impact calculator	Quantifies the life cycle GHG emissions, methane, water use, social cost of carbon and recoverable meals associated with U.S. food waste by supply	Does not directly convert additional shelf-life days into FLW reduction. Its underlying factors and waste profiles are primarily specific to the US.	(ReFED and Impact Calculator)

(*continued on next page*)

Table 5 (*continued*)

Tool/resource	Primary scope	Main limitation	Reference
	chain sector, food category and management pathway		

across the FSC. It includes prevention through edible coatings and active and intelligent packaging, and valorisation of unavoidable FLW through biorefinery into polymer matrices, plasticisers, and functional additives. Integrating these pathways clarifies where each operates and how its contribution should be evaluated.

Innovative packaging can prevent food from becoming waste after harvest, particularly during storage, distribution, retail, and consumption. In contrast, biorefinery adds value to residues already generated, mainly during primary production and processing. Consequently, shelf-life extension, antioxidant or antimicrobial activity, sensor responsiveness, or bio-based material production should not automatically be interpreted as FLW reduction; this requires evidence that less food is discarded under realistic FSC conditions.

The effectiveness of these strategies depends on food-specific performance, the amount of food saved, supply-chain and consumer responses, process inputs, and safety and migration. Prevention should therefore remain the priority, while material recovery provides a complementary pathway for unavoidable residues.

Future research should move beyond film characterisation and *in vitro* functionality towards package-food-system validation under realistic commercial conditions. Integrated LCA and TEA should be applied early and incorporate food preservation benefits, collection and pre-treatment, scale-up, co-product value, displaced uses, and end-of-life pathways. Intelligent packaging should be evaluated according to its ability to improve stock rotation and consumer decisions, while biorefinery research should prioritise feedstock standardisation, cascade processing, safety assessment, and realistic markets. This combined stage-specific and life-cycle perspective represents the review's principal methodological contribution and provides a basis for selecting packaging strategies that reduce FLW without shifting burdens between food, packaging, and waste-management systems.

CRediT authorship contribution statement

Zeinab Qazanfarzadeh: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Formal analysis, Conceptualization. **Pamela Freire De Moura Pereira:** Writing – original draft. **Rodrigo Oliver-Simancas:** Writing – original draft. **Michele Pedrotti:** Writing – original draft, Conceptualization. **Danny Cliceri:** Writing – original draft. **Daemon Ortega Froysa:** Writing – original draft. **Amparo Jiménez-Quero:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) to enhance readability and improve language. Following its use, the authors carefully reviewed and edited the content as necessary and accept full responsibility for the final publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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