

Sustainable valorization of agri-food by-products for smart packaging with innovations, challenges, and future directions within a circular bioeconomy: A systematic review

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42 **Abstract**

43 This systematic review explores the sustainable valorization of agri-food by-products
44 for innovative smart packaging within a circular bioeconomy framework. It emphasizes the
45 escalating environmental and economic impacts of agricultural waste, highlighting its
46 potential as a rich source of bioactive compounds, biopolymers, and natural antioxidants.
47 The review critically examines recent advancements in converting residues—such as peels,
48 husks, seeds, and processing by-products—into functional materials like biodegradable
49 films, sensors, and active packaging systems. It discusses the integration of
50 nanotechnology, biosensors, and digital tools, including AI and IoT, to develop intelligent
51 packaging capable of monitoring food freshness, microbial safety, and spoilage indicators
52 in real time. The paper also addresses fabrication techniques, challenges related to raw
53 material variability, stability of bioactives, scalability, and regulatory considerations.
54 Importantly, it underscores the environmental benefits of replacing conventional plastics with
55 bio-based, biodegradable materials derived from waste streams, aligning with sustainability
56 goals and reducing ecological footprints. Future perspectives suggest that combining
57 advanced technologies with circular economy principles can revolutionize food packaging—
58 enhancing safety, extending shelf life, and promoting resource efficiency. Despite existing
59 barriers such as regulatory hurdles, high costs, and consumer acceptance, ongoing
60 innovations promise to foster a more sustainable and resilient food system. Overall, this
61 review advocates for multidisciplinary efforts to harness agri-food by-products, supporting a
62 transition toward eco-friendly, smart packaging solutions that address global sustainability
63 challenges and contribute to a circular bioeconomy.

64 **Keywords:** Agri-food by-products, AI-assisted packaging, Circular bioeconomy,
65 Nanotechnology, Smart packaging, valorization

66

67 **Graphical Abstract**

68

69

Graphical Abstract

70

71 **1. Introduction**

72 **Global scale of agri-food by-products (peels, pomace, husks, shells, bran)**

73 Annually, about one-third of global food production—around 1.3 billion tons—is
74 wasted, accounting for over 20% of greenhouse gas emissions. A significant portion—30-
75 50% of raw materials—comprises post-harvest and processing by-products like shells,

skins, and seeds, which are rich in bioactive compounds and nutrients (Roy et al., 2023a). While vital for food security and economic growth, the agri-food sector also generates substantial organic waste (Fig. 1), costing over US\$1 trillion annually, with nearly 30% of food discarded yearly. Developed nations waste around 670 million tons due to consumer and retail habits, whereas developing regions waste approximately 630 million tons, mainly because of infrastructural limitations in storage and transportation (Berenguer et al., 2022; Tariq et al., 2025).

Fig. 1 (A) Household food waste in selected regions (million tons per year) (Leverenz et al., 2021) (B) Global distribution of food waste by category (%), with fruits and vegetables as the major contributors, followed by roots and tubers, fish and seafood, cereals, dairy and oilseeds and pulses.

Agri-food by-products—including plant residues, animal waste, and processing leftovers—are abundant throughout the supply chain. Once considered low-value waste, they were mainly landfilled, incinerated, or used as animal feed, limiting resource recovery and harming the environment. However, recent advances in green technologies and bioprocessing now reveal these residues as valuable, low-cost sources of bioactive compounds like phenolics, flavonoids, antioxidants, fatty acids, fibers, amino acids, and proteins. Their valorization enhances waste reduction, resource efficiency, and supports sustainable, circular food systems.

Environmental and economic burden of food waste

Food waste poses a critical environmental challenge, constituting large landfills and releasing methane and CO₂, which account for nearly 8% of human-generated greenhouse gases, with about 25% of global agricultural resources—land, water, fertilizers, and energy—placing immense pressure on ecosystems and biodiversity. Improper disposal causes air pollution, groundwater contamination, and nutrient runoff, exacerbating environmental degradation. As global food demand grows, reducing waste is vital for creating sustainable food systems and mitigating environmental impacts (Kohli et al., 2024).

Global food waste costs over USD 2.6 trillion annually, with more than USD 1 trillion in direct expenses and USD 1.6 trillion in environmental and social damages, driven by inefficiencies throughout the supply chain. This results in significant financial losses for producers, household waste for consumers, and hefty waste management costs for governments, while also depleting vital resources like energy, water, and land. Addressing

110 this requires a strategic shift toward waste prevention and resource recovery to bolster
111 economic and environmental sustainability (Tariq et al., 2025).

112 **Evolution from conventional to smart packaging**

113 Food packaging has evolved from simple containers to advanced, eco-friendly
114 systems driven by technological innovation, safety, and sustainability. Influenced by
115 industrialization, material science, and growing concerns about food waste and safety, this
116 shift has given rise to smarter, environmentally responsible solutions that meet modern
117 consumer and regulatory needs (Fig. 2).

118

119 **Fig. 2** Timeline illustrating the evolution of food packaging technologies from conventional
120 passive systems (canning, paper, glass, plastics) to advanced active, intelligent, and smart
121 packaging solutions (Davidescu et al., 2025).

122

123 **Historical development of packaging technologies**

124 Food packaging has evolved from primitive natural materials—leaves, animal skins,
125 shells, and fibers—that offered minimal protection, to durable ceramics and metals like clay
126 vessels and cans, introduced through innovations such as Nicolas Appert’s 1805 canning
127 method, which pioneered sterilization and sealing. The 19th century’s mass production of
128 glass, metal, and paper enhanced preservation and logistics, while the 20th century saw the
129 rise of synthetic polymers like cellophane and plastics (PE, PP, PET), revolutionizing flexible
130 and barrier packaging. Advances in aseptic techniques extended shelf life but raised
131 environmental concerns. Recent innovations include multifunctional systems: active
132 packaging with antimicrobials, intelligent packaging with sensors and RFID (Radio-
133 Frequency Identification), and integrated smart solutions enabling real-time monitoring and
134 traceability. Current focus shifts toward sustainable, biodegradable materials, aligning with
135 global efforts toward environmentally responsible food packaging (Alamri et al., 2021;
136 Hassoun, 2025; Petrenko et al., 2024; Tas et al., 2017; Tripathi et al., 2023).

137 **Rationale for using agro-food by-products in eco-friendly packaging**

138 The heavy dependence on petroleum-based food packaging fuels environmental
139 pollution and depletes resources, underscoring the urgent need for sustainable alternatives.
140 Agro-food processing generates abundant, underutilized by-products rich in functional
141 polysaccharides—renewable materials with biodegradability, biocompatibility, and wide
142 availability—ideal for eco-friendly packaging (Zhu, 2021). These polysaccharides can be
143 chemically modified to enhance strength, barrier properties, and functionality, supporting a
144 circular economy by converting waste into valuable resources and reducing fossil plastic

dependence (Li et al., 2024). Despite challenges like moisture sensitivity, recent advances in blending and composite development have improved their practicality. Valorizing agricultural by-products into packaging offers a promising, environmentally responsible path toward high-performance, sustainable solutions minimizing waste and conserve resources.

Emergence of smart packaging systems and scope of review

This systematic review explores recent advances in smart food packaging, emphasizing biodegradable and nanomaterial-enhanced materials that enhance barrier properties, antimicrobial efficacy, and environmental sustainability. It covers embedded sensing systems, indicators, and data carriers for real-time quality and safety monitoring, along with their integration with IoT, blockchain, and digital platforms. The review also evaluates consumer-driven innovations, economic and regulatory factors, and sustainability assessments to provide a comprehensive overview of current trends, challenges, and future directions in sustainable, intelligent food packaging.

2. Methodology

The current comprehensive review was carried out in a rigorous methodological manner using the evidence-based approach to confirm the inclusion of high-quality relevant material, applying the following steps:

2.1. Literature search strategy

A comprehensive search was conducted using several electronic databases with official online search engines, involving PubMed, Scopus, Web of Science, and Google Scholar, with other official sources for agri-food data. The search terms included “sustainable valorization of agri-food by-products”, “biopolymers from food waste”, “biodegradable packaging materials”, “edible films from agri-food waste”, “circular economy in food packaging”, “smart packaging systems”, “active packaging”, “intelligent packaging”, “food safety packaging”, “nanotechnology in food packaging”, “digital technologies in food supply chain”, “sensors for food freshness”, “RFID, QR codes in food packaging” and “bioactive compounds in food packaging” among others. Boolean operations like AND, OR, and NOT were used to narrow the search results which were limited to English-language articles published in last 22 years, i.e. between 2005-2026.

2.2. Inclusion and exclusion criteria

The inclusion criteria encompassed well-documented, peer-reviewed original research and review articles, as well as high-quality gray literature such as theses, policy papers, government reports, and conference proceedings. These sources provided valuable, often unpublished insights with reduced bias, relevant to the review's core topics. Studies were selected based on their significance, methodological rigor, and contribution to

180 the field. Exclusion criteria included publications in languages other than English with
181 insufficient data, non-peer-reviewed articles, and studies unrelated to the main topics.

182 **2.3. Selection process**

183 All retrieved records were subjected to rigorous screening via a reference
184 management system, with other manual screening for works not referenced, where
185 duplicates were rejected. Two reviewers individually examined thoroughly the titles and
186 abstracts to determine which articles were suitable and eligible for inclusion.

187 **2.4. Data extraction and synthesis**

188 Data from selected articles were extracted systematically using a standardized form,
189 included details like study design, sample size, key findings, and limitations. The collected
190 data were synthesized qualitatively, and thematic analysis was performed to detect repeated
191 patterns, topics, and gaps in the literature.

193 **3. Results and discussion**

194 **3.1 Study selection**

195 As demonstrated in Fig. 3, the initial search resulted in 10,761 records. Following the
196 removal of duplicates and ineligible entries, 417 unique records were available for further
197 screening. From these, 297 reports were selected for retrieval, and ultimately, 127 reports
198 were included in the review.

199
200 **Fig. 3 PRISMA flow diagram including searches of databases and registers (2005-2026)**

202 **3.2 Agri-food by-products: Sources and composition**

203 **3.2.1 Major sources**

204 Agri-food by-products from various stages of the food supply chain (Fig. 4) present
205 both environmental challenges and opportunities, as they are rich sources of valuable
206 bioactive compounds like fibers, phenolics, proteins, and antioxidants. These residues, often
207 discarded, can be sustainably managed and valorized for applications in food,
208 pharmaceuticals, and packaging, due to their health-promoting properties such as
209 antioxidant and anti-inflammatory effects. Understanding their sources and composition is
210 crucial for developing innovative, sustainable uses of these by-products (Chen & Lou, 2025;
211 Gueboudji et al., 2023; Hrelia et al., 2025; Ivanović et al., 2023; Perrone et al., 2025).

212
213 **Fig. 4 Sources of agri-food by-products**

215 3.2.1.1 Fruits and vegetable waste (peels, pomace, seeds)

216 Agricultural and food processing residues are classified based on their origin,
217 including field residues—such as leaves, stalks, straw, seed pods, and stems remaining
218 after harvest—and process residues generated during crop processing for value-added
219 products (Pandey et al., 2025). These residues from fruits, vegetables, cereals, and related
220 sources accumulate in billions of tonnes across all stages of the food supply chain—
221 production, handling, storage, processing, packaging, distribution, marketing, and
222 consumption—posing environmental and health challenges. A significant portion comprises
223 lignocellulosic biomass like straw, stalks, husks, bagasse, leaves, and seeds, mainly
224 composed of cellulose (40–60%), hemicellulose (10–40%), and lignin (15–30%) (Campos
225 et al., 2020; Sindhu et al., 2019).

226 Additionally, residues such as peels, pulp, shells, husks, bark, bran, and leaves from
227 fruits and vegetables are rich sources of organic matter and phytonutrients, including
228 phenolics, polyphenols, tannins, flavonoids, anthocyanins, carotenoids, terpenes, essential
229 oils, and secondary metabolites (Haq et al., 2021; Paritosh et al., 2017; Prasad et al., 2020).
230 These bioactive compounds (Fig. 5) exhibit beneficial physiological effects, while the
231 residues also contain carbohydrates, dietary fibers, enzymes, fatty acids, lipids,
232 biopolymers, minerals, vitamins, and amino acids. This diverse chemical profile underscores
233 the immense potential of agri-food waste for sustainable valorization in food,
234 pharmaceutical, nutraceutical, and bio-based material applications (Ben-Othman et al.,
235 2020; Berenguer et al., 2022).

236

237 **Fig. 5** Different types of compounds present in agri-food waste (AFW) and value-added
238 applications

239

240 3.2.1.2 Cereal by-products

241 Cereal by-products like bran, germ, husks, and brewer's grains are rich in valuable
242 nutrients but are often underutilized or discarded. As focus shifts toward reducing food waste
243 and promoting sustainability, these low-cost, renewable resources are increasingly
244 recognized for their potential. Advanced processing and biotechnological methods enable
245 their transformation into high-value ingredients for food, nutraceuticals, bio-packaging, and
246 energy, advancing circular economy principles (Skendi et al., 2020).

247 Major cereal by-products such as rice bran, rice germ, wheat bran, corn bran, barley
248 bran, oat bran, finger millet seed coat, and proso millet bran are produced in large quantities
249 during milling. These materials exhibit health-promoting properties, including antioxidant,

250 anti-inflammatory, cholesterol-lowering, antimicrobial, prebiotic, and glycemic-regulating
251 effects (Luithui et al., 2019), making them suitable for diverse functional foods, natural
252 preservatives, and biodegradable packaging materials. Additionally, cereal husks from
253 wheat, rice, corn, barley, and millet are abundant lignocellulosic resources composed mainly
254 of cellulose, hemicellulose, and lignin, along with silica, proteins, phenolics, and minerals.
255 Their high structural strength, chemical stability, porosity, and surface reactivity enable their
256 application in food systems, energy production, and environmental remediation. Due to their
257 renewability, biodegradability, and affordability, cereal husks play a crucial role in
258 sustainable waste management and pollution mitigation. Overall, effective utilization of
259 cereal by-products offers significant economic, environmental, and sustainability benefits
260 across food, feed, nutraceutical, packaging, cosmetic, and pharmaceutical industries within
261 a circular bioeconomy framework.

262 **3.2.1.3 Oilseed by-products**

263 Oilseed by-products from canola/rapeseed, sunflower, flaxseed, and sesame
264 processing are nutrient-rich yet underutilized resources. Valorizing these residues aligns
265 with sustainable development and circular economy objectives by transforming waste into
266 functional ingredients. For example, rapeseed meals, especially from cold pressing, are high
267 in proteins (cruciferin and napin), dietary fibers, minerals, and bioactive compounds.
268 Preprocessing methods like dehulling enhance oil quality and increase the meal's protein
269 content and functional properties. These high-quality proteins possess health-promoting
270 effects and exhibit balanced amino acid profiles, making them suitable for functional foods
271 and nutraceuticals.

272 Similarly, sunflower meal contains 40–50% proteins, phenolic acids (chlorogenic and
273 caffeic acids), and minerals with potent antioxidant activity, supporting its use in health-
274 oriented products. Flaxseed cake is rich in proteins, dietary fiber, lignans, phenolic acids,
275 and minerals, offering antioxidant and anti-inflammatory benefits for bakery and fermented
276 foods. Sesame oil cake is notable for its proteins, lignans, tocopherols, phenolics, and
277 minerals like calcium and iron, with high antioxidant potential and versatile applications.

278 These plant-based by-products present low-cost, sustainable sources of bioactives
279 and nutrients for functional foods, natural antioxidants, and value-added formulations.
280 Advances in green extraction technologies, such as bio-based solvents, have improved
281 recovery efficiency, expanding opportunities for product innovation and economic growth.
282 Despite challenges related to standardization and regulation, ongoing research supports
283 their integration into food systems, promoting a circular economy, enhancing public health,
284 and advancing sustainable food production (Nemli et al., 2025).

285 **3.2.1.4 Dairy and meat by-products**

286 **Animal by-products:** The dairy and meat industries generate substantial volumes of
287 undervalued by-products—over 20 million tons annually in the EU alone—from
288 slaughterhouses, meat processing, and dairy operations. Proper disposal is expensive and
289 poses environmental and health risks, prompting efforts to valorize these residues into
290 valuable products, both edible (bioactive compounds) and non-edible (fertilizers, biodiesel)
291 (León et al., 2019).

292 **Dairy by-products:** Whey, a major by-product of cheese manufacturing, is abundant yet
293 environmentally challenging to manage. It is rich in proteins and bioactive peptides with
294 antioxidant and antihypertensive effects. Whey permeate contains carbohydrates and
295 oligosaccharides, which can be processed into prebiotics like galacto-oligosaccharides,
296 enhancing gut health (Corrêa et al., 2019). Colostrum, produced postpartum, is highly
297 nutritious, containing immunoglobulins, lactoferrin, and bioactive oligosaccharides with
298 antioxidant, antimicrobial, anti-inflammatory, and neuroprotective properties (Christiansen
299 et al., 2010). While most research focuses on cow, buffalo, sheep, and goat milk,
300 underutilized sources like camel and donkey milk offer additional potential.

301 **Meat by-products:** Meat processing yields blood, bones, skin, horns, fatty tissues, and
302 viscera, which are often repurposed as feed, pet food, biodiesel, and fertilizers (Toldrá et
303 al., 2016). Proteins from trimmings, blood, bones, and collagen can be hydrolyzed into
304 bioactive peptides exhibiting antioxidant, antihypertensive, and antimicrobial activities (Mora
305 et al., 2014). Despite this promising potential, research on the valorization of animal by-
306 products remains limited compared to plant residues, emphasizing the need for further
307 investigation.

308 **3.2.1.5 Seafood by-products and their valorization**

309 The global fishing industry yields over 170 million tons of seafood annually, with 40–
310 50% generated as by-products such as fish bones, skin, shells, and cartilage. These
311 residues, often regarded as waste, are rich sources of bioactive compounds with nutritional
312 and therapeutic benefits. For example, shrimp waste contains chito-oligosaccharides,
313 astaxanthin, and omega-3 fatty acids; salmon cartilage offers proteoglycans with anti-
314 angiogenic, joint-protective, and wound-healing properties. Fish skin provides collagen,
315 which can be hydrolyzed into peptides with antioxidant, anti-hypertensive, anti-diabetic, and
316 cognitive-enhancing effects. Edible seaweeds, extensively consumed in Asia, are valuable
317 sources of sulfated polysaccharides, carotenoids, polyphenols, vitamins, and phlorotannins,
318 exhibiting antioxidant, antimicrobial, anti-inflammatory, anticancer, antidiabetic, and anti-
319 obesity activities. Notable species include *Ulva*, *Sargassum*, *Laminaria*, *Gracilaria*, and

320 *Porphyra*. However, further research is needed to fully characterize bioactive profiles,
321 especially of underutilized or wild-harvested seaweeds (Ben-Othman et al., 2020).

322 Effective management and valorization of seafood discards are crucial for
323 sustainability. Green extraction methods such as enzymatic hydrolysis, supercritical CO₂,
324 and subcritical water extraction facilitate the recovery of bioactive compounds for use in
325 food, pharmaceutical, and cosmetic industries. Despite associated challenges and costs,
326 consumer demand for these bioactives is increasing, supporting waste reduction, the
327 development of the blue economy, and the promotion of a circular, zero-waste approach in
328 fisheries (Roy et al., 2023b).

329 **3.3 Valuable components**

330 **3.3.1 Polyphenols**

331 Polyphenols are plant secondary metabolites, including flavonoids, phenolic acids,
332 tannins, and stilbenes, acting as defense agents against environmental stresses like
333 pathogens, UV radiation, and oxidative damage. Rich sources include fruit peels, vegetable
334 residues, cereal husks, and especially olive mill wastes, which contain high concentrations
335 of these compounds. Polyphenols exhibit strong antioxidant activity, scavenging reactive
336 oxygen species and protecting cells from oxidative stress. They also possess anti-
337 inflammatory effects, antimicrobial properties, and anticancer potential by inducing
338 apoptosis and inhibiting tumor growth. Agro-industrial by-products such as apple peels,
339 grape skins, and olive leaves are abundant in bioavailable phenolics like quercetin, gallic
340 acid, and hydroxytyrosol, which offer significant health benefits. Efficient extraction enables
341 their incorporation into innovative products, supporting circular economy principles by
342 reducing waste. Notably, olive mill wastewater (OMW) is a concentrated source of water-
343 soluble polyphenols with potent bioactivity, making extracts suitable for nutraceuticals,
344 functional foods, and cosmeceuticals due to their antioxidant and anti-aging effects.
345 Valorizing these by-products not only alleviates environmental pollution but also drives
346 sustainable innovation in health and wellness sectors.

347 **3.3.2 Dietary fibers**

348 Dietary fibers, including soluble types like pectins, gums, and inulin, and insoluble
349 forms such as cellulose, hemicellulose, and lignin, are abundantly found in agri-food by-
350 products like cereal bran, fruit pomace, and oilseed cakes (Plakantonaki et al., 2023). These
351 fibers serve multiple functions in food formulation as thickeners, gelling agents, stabilizers,
352 and texture enhancers, improving mechanical and rheological properties. Physiologically,
353 soluble fibers delay gastric emptying and regulate glucose absorption, helping to mitigate
354 post-meal blood sugar spikes and supporting metabolic health and diabetes management.

Both soluble and insoluble fibers facilitate lipid metabolism by promoting bile acid excretion and reducing serum cholesterol, thus lowering cardiovascular risk (Plakantonaki et al., 2023). Additionally, soluble fibers act as prebiotics, fostering the growth of beneficial gut bacteria such as *Bifidobacteria* and *Lactobacilli*, which enhance digestion, boost immune function, and promote overall health. Valorization of these fiber-rich by-products offers a sustainable strategy for developing functional, health-promoting foods (Bhatia et al., 2024).

3.3.3 Proteins and bioactive peptides

Agri-food by-products, including oilseed cakes from soy, sunflower, and rapeseed, residual grains from brewing, and dairy whey, are sustainable sources of high-quality proteins. These proteins can be enzymatically hydrolyzed into bioactive peptides, typically comprising 2–20 amino acids, with activities influenced by their amino acid sequence, structure, and the enzymes used. These peptides offer various health benefits, such as antihypertensive effects through ACE inhibition, antioxidant activity that reduces oxidative stress, immune modulation, and antimicrobial properties. Consequently, bioactive peptides are increasingly investigated for use in functional foods, nutraceuticals, and clinical nutrition. Recent research aims to optimize hydrolysis processes, enhance peptide purification, improve stability, and increase absorption to maximize their efficacy in promoting overall health and managing conditions like cardiovascular and inflammatory diseases.

3.3.4 Bioactive lipids

Lipid-rich agri-food residues such as olive pits, avocado peels, and nut processing wastes contain monounsaturated and polyunsaturated fatty acids, tocopherols, and phytosterols. These bioactive lipids exhibit antioxidant, anti-inflammatory, and cholesterol-lowering properties, making them valuable for high-value applications. Extracts derived from these residues are increasingly used in nutraceutical oils to support metabolic and cardiovascular health, in cosmetic formulations for skin protection and rejuvenation, and as lipid carriers in drug delivery systems to improve bioavailability and enable targeted release of pharmaceuticals.

3.3.5 Polysaccharides (Pectin)

Citrus peels and apple pomace, abundant agro-industrial by-products, are primary sources of pectin—a complex heteropolysaccharide mainly composed of galacturonic acid with varying degrees of branching and methylation. Pectin's gel-forming, thickening, and emulsifying properties make it a versatile ingredient in food products such as jams, jellies, dairy items, and confections. Beyond its technological functions, pectin offers notable health benefits, including glycemic regulation, cholesterol reduction through bile acid binding, immune modulation, and promotion of colon health by increasing stool bulk. Enzymatic or

acid hydrolysis can convert pectin into pectic oligosaccharides, which serve as prebiotics by selectively stimulating beneficial gut bacteria like *Bifidobacterium* and *Lactobacillus*. This enhances short-chain fatty acid production and supports gut microbiome balance. Such bioconversion improves pectin’s nutritional and functional value, making it suitable for functional foods, nutraceuticals, and dietary interventions aimed at metabolic and gastrointestinal health (Table 1).

Table 1. Agri-food by-products with valuable bioactive components and applications

No.	Agri-food by-products sources	Valuable bioactive components	Applications/ Research findings	References
1	Apple pomace	Phenols, flavanols, phloridzin, chlorogenic acid	Functional foods, nutraceuticals, beverages, and pharmaceutical industries	(Du et al., 2019; Guiné et al., 2021)
2	Apple fruit and peel	Polyphenols, polysaccharides (pectin), phytosterols, pentacyclic triterpenes, vitamins, trace elements	Potential to prevent or manage cardiovascular disease, diabetes, inflammation, and cancer; contributes to overall human health	(Patocka et al., 2020)
3	Rice brans, rice hulls, liquid rice hull smoke	Phenolic acid	Antioxidant, Rice bran oil	(Friedman, 2013)
4	Avocado seeds	Proteins, fats, dietary fiber, total phenolics, flavonoids, antioxidants	Avocado seed flour enhances nutritional content, antioxidant capacity, acts as a functional food ingredient	(Fufa et al., 2025)
5	Jumbo squid (<i>Dosidicus gigas</i>) by-products – skin, head, fins, viscera, tentacles, unclaimed mantle	Proteins, lipids, minerals, vitamins, enzymes, biopolymers	Extraction and valorization of by-products for use in food, medicine, agrochemical, and pharmaceutical industries; enhances economic value and reduces environmental impact	(Ezquerria-Brauer & Aubourg, 2019)

398 **3.4. Functional roles of agri-food by-products in smart packaging**

399 **3.4.1 Anti-microbial agents**

400 Plant-based phenolic extracts from by-products like peels and pomace are emerging
401 as natural alternatives to synthetic preservatives in food packaging. Rich in bioactive
402 compounds—such as flavonoids, phenolic acids, tannins, resveratrol, catechins, and
403 proanthocyanidins—these extracts exhibit broad antimicrobial properties. For example,
404 grape pomace incorporated into polypropylene films creates bactericidal surfaces effective
405 against *E. coli* and *B. subtilis*, with low water vapor permeability suitable for food contact.
406 They also contain organic acids, vitamin C, and dietary fibers that enhance antimicrobial
407 activity by lowering pH and disrupting microbial membranes. These phenolics can be
408 integrated into plastics (e.g., pomegranate peel in polyethylene) or embedded in edible
409 coatings and biopolymer films to provide controlled release, inhibit spoilage, and extend
410 shelf life (da Silva et al., 2022; Galante et al., 2025; Oulahal & Degraeve, 2022).

411 **Essential oils (EOs)** from herbs and spices such as oregano, thyme, clove, and
412 cinnamon possess strong antimicrobial properties, with key compounds like carvacrol,
413 thymol, eugenol, and cinnamaldehyde effectively targeting foodborne pathogens like *E. coli*,
414 *S. aureus*, and *L. monocytogenes*. Incorporated into biopolymer-based packaging as free
415 oils, emulsions, or microcapsules, they benefit from encapsulation, which enhances stability,
416 masks intense aromas, and allows sustained release—maximizing antimicrobial action
417 while reducing sensory impact. For instance, chitosan films with basil EO microcapsules
418 inhibit Gram-positive bacteria and lower microbial growth in cooked ham, while ginger EO-
419 loaded films target various pathogens, highlighting the promising role of EO-infused
420 biopolymer systems as active, edible packaging solutions (Carpena et al., 2021; Casalini &
421 Giacinti Baschetti, 2023; Ribeiro-Santos et al., 2017).

422 **Mechanism of microbial inhibition**

423 The antimicrobial activity of phenolic compounds and essential oil constituents is
424 primarily attributed to disruption of microbial cell membranes leading to leakage of
425 intracellular contents and cell lysis due to increased permeability leading to leakage of
426 cellular contents. Essential oil residues also exhibited protein and enzyme inactivation
427 through binding/denaturation, impairing essential metabolic pathways and oxidative damage
428 to DNA, proteins and lipids which are enhanced by co-factors such as vitamin C.
429 Environmental acidification by co-present organic acids (tartaric, malic), reducing pH,
430 denaturing enzymes and disturbing membrane potential (Bibow & Oleszek, 2024; Varghese
431 et al., 2020).

432 The antimicrobial action of EOs is mainly related to their hydrophobic nature. EO
433 components partition into the lipid bilayer of cell membranes and mitochondria, increasing
434 permeability, disrupting membrane structures and causing leakage of ions and cell
435 constituents. Many EO constituents contain hydroxyl groups able to damage cell
436 membranes and interfere with membrane-bound proteins. At higher levels, EOs can
437 collapse membrane potential, inhibit energy generation, and ultimately cause cell death. In
438 packaging systems, controlled migration of phenolics from films/coatings maintains
439 inhibitory concentrations at the food surface over time (Devi et al., 2024; Schmitz & Moura,
440 2025; Tomić et al., 2023).

441 **3.4.2 Antioxidant activity**

442 Lipid oxidation is a key factor in food deterioration, causing off-flavors, nutrient loss,
443 and shortened shelf life. Natural antioxidants from fruit and vegetable by-products—such as
444 grape pomace, apple peels, and berry residues—are rich in polyphenols, carotenoids,
445 tocopherols, and fibers, making them potent agents against oxidation. Incorporating these
446 bioactive compounds into biodegradable packaging or edible coatings can significantly
447 extend the freshness of meat, dairy, and bakery products by delaying rancidity and
448 preserving sensory qualities. These antioxidants neutralize free radicals, chelate metals,
449 and inhibit peroxide formation, effectively slowing lipid oxidation in high-fat foods. As an
450 alternative or supplement to traditional methods like direct addition or modified atmosphere
451 packaging, active packaging utilizing natural by-products offers a sustainable solution to
452 combat food spoilage (Dilucia et al., 2020; Matthes & Schmid, 2024; Messinese et al., 2024).

453 Fruit and vegetable by-products, cereal bran and other residues can be incorporated
454 into biopolymers (chitosan, starch, cellulose, proteins, PLA) to produce films and coatings
455 with increased total phenolic content and radical-scavenging activity. Grape by-products
456 (seeds, skins, stalks) are particularly attractive because their phenolic-rich composition
457 provides antioxidant, antimicrobial, UV-blocking and pH-sensitive properties; films with
458 grape extracts can both preserve foods and act as smart indicators for meat and seafood
459 spoilage. Broader smart packaging concepts focus on encapsulating natural antioxidants or
460 carbon dots into films to enhance stability and control release, thereby sustaining antioxidant
461 activity over storage. Essential oils obtained from agro-industrial residues (leaves, seeds,
462 peels, unused pulp) can be incorporated free or encapsulated into biodegradable films,
463 providing antioxidant and antimicrobial actions that delay spoilage and extend shelf life
464 (Barzan et al., 2024; Bhat et al., 2024; Ganiari et al., 2017; Lante & Momayezhaghghi,
465 2025).

466

467 Edible coatings and films infused with antioxidants from agricultural by-products are
468 emerging as cost-effective, sustainable solutions to control lipid oxidation and extend the
469 shelf life of animal-derived foods. In seafood and meat packaging, biopolymers and extracts
470 derived from food waste are being developed into active, intelligent materials that preserve
471 freshness and provide visual indicators of quality—though scaling up production and
472 consumer acceptance pose challenges. Broadly, polysaccharide- and protein-based active
473 films incorporating plant extracts, essential oils, and nanofillers enhance oxidative stability
474 and microbial safety by combining barrier properties with controlled antioxidant release. This
475 antioxidant active packaging is crucial for prolonging shelf life, reducing food waste, and
476 supporting extended distribution, especially when paired with oxygen scavengers. Utilizing
477 agricultural residues for these applications promotes circular economy principles,
478 transforming low-value by-products into functional ingredients and packaging solutions that
479 improve food stability and lessen environmental impact (Dilucia et al., 2020; Domínguez et
480 al., 2018; Jamróz & Kopel, 2020; Yin et al., 2023).

481 **3.4.3 pH and freshness indicators**

482 Natural pigments derived from agricultural by-products—such as red cabbage, grape,
483 berry wastes, flower, and vegetable residues—can be integrated into biopolymer films as
484 colorimetric indicators responsive to pH and spoilage gases, enabling real-time food
485 freshness monitoring. Rich sources of anthocyanins, including red and purple cabbage,
486 grape pomace, berry wastes, banana bracts, and certain flowers (*Clitoria*, *Ipomoea*), exploit
487 their pH-sensitive color-changing (halochromic) properties—shifting from red in acidic to
488 purple/blue and green/yellow in alkaline environments. Beyond sensing, these extracts
489 impart antioxidant and antimicrobial benefits, creating “triple-action” films that protect,
490 monitor, and potentially extend shelf life. Berry-derived anthocyanin films exemplify dual
491 functionality: acting as pH-responsive freshness indicators while reducing lipid oxidation in
492 packaged foods (Ma et al., 2025; Marangon et al., 2022; Nadi et al., 2023; Neves et al.,
493 2022).

494 **Color change in response to spoilage gases**

495 During food spoilage, volatile basic compounds such as ammonia and amines are
496 released, causing an increase in pH. Anthocyanin-based indicators undergo visible color
497 transitions (e.g., red to purple, blue, or green) in response to these changes, providing a
498 real-time visual indication of food freshness. This makes them effective tools for monitoring
499 spoilage in meat, fish, and seafood products (Table 2).

500

501

502 **Table 2. Color response & performance**

By-product pigment & matrix	Target food / trigger	Color response & performance
Red cabbage anthocyanins in basil seed gum/chitosan	Fish spoilage, pH & NH ₃	Red → blue → green; strong DPPH activity; correlates with TVB-N/TVC (Nadi et al., 2023)
Grape pomace anthocyanins in PVA/starch	Fish (gilthead sea bream), volatile amines	Pink-red → pale green-blue; sensitive to TMA, DMA, NH ₃ ; tracks spoilage under cold chain abuse (Basdeki et al., 2025)
Red cabbage / dragon fruit (anthocyanin–betacyanin) films	Beef, lamb, fish, pork	pH-sensitive; ammonia-responsive; color strongly correlates with TVB-N and pH (Ma et al., 2025)
Grape seed/peel extract + lignin in chitosan	Fish, NH ₃	Yellow → orange; antimicrobial + antioxidant + halochromic “waste-only” film (Liu et al., 2022)
Banana bract anthocyanin in banana starch/chitosan	Chicken	pH-driven color changes; reduced TVB-N, TVC and TMA-N (Kumar et al., 2024)

503

504 **3.4.4 Gas and moisture control**

505 Fibrous agro-industrial by-products like cellulose, hemicellulose, and lignin—sourced
506 from residues such as wheat bran, rice husk, and sugarcane bagasse—are increasingly
507 employed in food packaging for enhanced oxygen and moisture control. Incorporating
508 sugarcane bagasse and asparagus peel fibers (0–40% w/w) into sweet potato starch trays
509 markedly reduces water absorption— trays with ≥20% bagasse absorb less than 34.4 g/100
510 g compared to 55.4 g/100 g for pure starch—while improving flexibility and strength. In
511 commercial pads, cellulosic fibers create a porous network that quickly absorbs liquids,
512 managing surface moisture and humidity. Additionally, these fibers serve as bio-based
513 matrices that bolster barrier properties; combining starch or polysaccharides with
514 nanocellulose enhances film density and reduces gas permeability. Hydrophobic
515 modifications further diminish water vapor and oxygen transmission, stabilizing the package
516 atmosphere. By regulating gas exchange and moisture migration, these by-products inhibit
517 microbial growth, slow oxidation, and preserve texture, thereby extending shelf life and
518 promoting sustainability through waste valorization (Chen et al., 2025; Dilucia et al., 2020;
519 Kalita et al., 2025; Muñoz-Gimena et al., 2023; Ribeiro et al., 2025; Siriwong et al., 2024).

520 **3.5. Agri-food by-products as film-forming materials**

521 Agri-food by-products are increasingly recognized as valuable renewable resources
522 for the development of sustainable packaging materials. These by-products originate from
523 agricultural production and food processing industries and include fruit peels, vegetable
524 pomace, cereal husks, seed coats, and sugar industry residues such as bagasse.
525 Traditionally considered waste, these materials are now being valorized due to their high
526 content of biopolymers such as cellulose, hemicellulose, starch, and pectin. The utilization
527 of agri-food by-products contributes to waste reduction, promotes circular economy
528 principles, and decreases reliance on petroleum-based plastics, which are associated with
529 environmental pollution and non-biodegradability. Their abundance, low cost, and
530 biodegradability make them attractive candidates for film-forming applications in food
531 packaging and coating technologies (Abdul Khalil et al., 2012).

532 Cellulose is one of the most abundant biopolymers found in agri-food residues such
533 as cereal straw, fruit peels, corn cobs, and sugarcane bagasse. It is typically extracted
534 through a series of chemical and mechanical treatments involving alkaline pretreatment,
535 bleaching, and purification steps to remove lignin and hemicellulose. The resulting cellulose
536 exhibits excellent film-forming properties due to its high crystallinity, tensile strength, and
537 barrier performance against oils and fats. Native cellulose is poorly soluble in water, which
538 has led to the development of cellulose derivatives, such as carboxymethyl cellulose and
539 hydroxypropyl methylcellulose, that are more suitable for film production. These cellulose-
540 based films are transparent, flexible, and biodegradable, making them suitable for food
541 packaging applications. Hemicellulose, another major polysaccharide present in plant cell
542 walls, is commonly extracted from agricultural residues using alkaline extraction or
543 hydrothermal treatments. Sources such as wheat bran, rice husk, and corn fiber are rich in
544 hemicellulose (Farhat et al., 2017; Santhosh et al., 2024).

545 Compared to cellulose, hemicellulose has a lower molecular weight and amorphous
546 structure, which allows easier film formation but results in weaker mechanical strength.
547 Hemicellulose films generally exhibit good oxygen barrier properties but poor moisture
548 resistance due to their hydrophilic nature. To overcome these limitations, hemicellulose is
549 often blended with other biopolymers or plasticizers to enhance film flexibility and durability.
550 Starch is widely extracted from agri-food by-products such as potato peels, cassava
551 residues, maize waste, and rice processing by-products. Starch extraction typically involves
552 wet milling, filtration, and drying processes. Starch-based films are colorless, odorless, and
553 edible, which makes them highly suitable for food applications. However, their high
554 sensitivity to moisture and relatively poor mechanical strength limit their standalone use,

555 encouraging the development of starch-based composites and blends. Due to its
556 thermoplastic behavior in the presence of heat and plasticizers like glycerol or sorbitol,
557 starch can be processed into films using casting or extrusion methods (Benito-González et
558 al., 2022).

559 Pectin is a complex heteropolysaccharide primarily extracted from fruit processing
560 by-products such as citrus peels, apple pomace, and mango peels. Extraction is usually
561 performed using acidified hot water followed by precipitation with alcohol. Pectin exhibits
562 excellent film-forming ability due to its gel-forming nature, especially in the presence of
563 divalent cations or sugars. Pectin films are transparent and flexible but show high water
564 permeability. Nevertheless, their edible nature and ability to carry bioactive compounds such
565 as antioxidants and antimicrobials make them ideal for active and edible food packaging
566 applications (Espitia et al., 2014).

567 Bio-based polymer blends have gained significant attention as a strategy to overcome
568 the individual limitations of single biopolymers. By blending polymers such as starch-
569 cellulose, starch-chitosan, or pectin-protein systems, films with improved mechanical
570 strength, barrier properties, and thermal stability can be achieved. These blends allow
571 synergistic interactions between polymers, resulting in enhanced performance and broader
572 application potential. Additionally, incorporating natural plasticizers, lipids, or nanofillers
573 from agri-food by-products further improves film flexibility, moisture resistance, and
574 functional properties.

575 Edible and biodegradable films derived from agri-food by-products play a crucial role
576 in sustainable food packaging. Edible films can be consumed along with food and are
577 commonly used for coating fruits, vegetables, meat, and confectionery products to extend
578 shelf life and reduce moisture loss. Biodegradable films, on the other hand, decompose
579 naturally under environmental conditions, minimizing plastic pollution. These films not only
580 act as physical barriers but can also serve as carriers for antimicrobial agents, antioxidants,
581 and probiotics, thereby enhancing food safety and quality. The development of such films
582 aligns with global sustainability goals and regulatory efforts aimed at reducing synthetic
583 plastic waste (Azeredo et al., 2017; Khuntia et al., 2022; Rhim & Ng, 2007; Sorrentino et al.,
584 2007).

585 **3.6 Smart packaging: Concept and classification**

586 **3.6.1 Conventional vs smart packaging**

587 Conventional food packaging plays a critical role in protecting food products from
588 physical, chemical, and biological damage while maintaining quality and safety throughout
589 distribution and storage. For several decades, petroleum-based plastics, particularly

polyethylene and copolymers, have been the dominant materials used in food packaging due to their low cost, flexibility, versatility, and satisfactory mechanical and barrier properties. As a result, plastic packaging has become the most widely adopted packaging solution within the global food industry (Rahman et al., 2026; Siciliano et al., 2024).

Despite these advantages, conventional plastic packaging materials present significant limitations, particularly in terms of environmental sustainability. Most plastic food packaging is designed for single use and disposal, with only a small fraction being recycled. Consequently, large volumes of plastic waste accumulate in landfills, where these materials persist for extremely long periods due to their non-biodegradable nature. The limited availability of landfill space, especially in densely populated regions, further exacerbates waste management challenges. In addition, increasingly stringent environmental regulations place pressure on existing waste disposal systems, raising concerns about the long-term feasibility of plastic waste handling.

Another major limitation of conventional packaging is its reliance on non-renewable petroleum resources. The production of plastic packaging is closely linked to fossil fuel availability and price volatility, creating economic and sustainability concerns. As petroleum resources decline and costs rise, the continued dependence on petroleum-based materials becomes increasingly unsustainable. This reliance also contributes to greenhouse gas emissions and environmental degradation throughout the material life cycle.

Furthermore, traditional plastic packaging systems primarily provide passive protection and lack advanced functionalities such as antimicrobial activity, antioxidant protection, or real-time monitoring of food quality. In the context of modern food distribution systems—characterized by global supply chains, extended shelf-life requirements, and increasing consumer demand for fresh, safe, and minimally processed foods these limitations have become more apparent. Consumers are also increasingly demanding packaging solutions that are recyclable, biodegradable, or derived from natural sources.

Collectively, the environmental persistence, dependence on fossil resources, limited recyclability, and lack of functional performance highlight the inherent shortcomings of conventional food packaging materials. These limitations have driven growing interest in biodegradable, bio-based, and functional packaging alternatives that can meet both industrial performance requirements and sustainability goals (Rahman et al., 2026).

2.2 Limitations of traditional packaging and its impact on food waste

Traditional food packaging systems often provide only basic physical protection and lack the ability to effectively control factors that influence food deterioration after opening. Once exposed to air and environmental conditions, packaged foods become highly

625 susceptible to oxidation, microbial growth, and moisture imbalance, frequently resulting in
626 spoilage within a short period, typically 7–10 days. This limited post-opening shelf life is a
627 major contributor to household and retail food waste (Cutter, 2006).

628 Inadequate protection against environmental factors further accelerates food quality
629 degradation. Oxygen permeation promotes oxidative reactions that cause off-flavors,
630 nutrient loss, and color changes. Insufficient barrier properties also allow microbial
631 contamination, increasing the risk of foodborne spoilage and safety concerns. Additionally,
632 uncontrolled moisture transfers either loss or absorption negatively affects texture, sensory
633 quality, and overall product acceptability.

634 Beyond food quality concerns, traditional packaging poses serious environmental
635 challenges. Most conventional packaging materials are designed for single use, generating
636 large volumes of waste that persist in the environment. Limited recyclability and non-
637 biodegradable nature of these materials complicate waste management and contribute to
638 pollution. Collectively, the inability of traditional packaging to adequately preserve food
639 quality and its negative environmental footprint underscore the need for advanced,
640 sustainable packaging solutions that can extend shelf life while minimizing food waste and
641 environmental impact (de Sousa et al., 2023).

642 **2.3 Advantages of smart system**

643 The most recent phase in packaging evolution is the development of smart
644 packaging, which integrates both active and intelligent functionalities into a single system.
645 Smart packaging systems are capable of sensing, responding, and communicating, often
646 incorporating printed electronics, biosensors, nanomaterials, and IoT-enabled platforms.
647 These systems improve traceability, reduce food waste, enhance consumer engagement,
648 and support sustainability objectives (Drago et al., 2020; Müller & Schmid, 2019).

649 Contemporary smart packaging research increasingly emphasizes bio-based
650 materials, biodegradable polymers, and circular economy principles, aligning technological
651 innovation with environmental responsibility. This progression reflects a paradigm shift from
652 packaging as a passive container to packaging as an interactive, information-rich, and
653 sustainable component of modern food systems.

654 **2.4 Types of smart packaging**

655 **2.4.1 Classification of packaging systems**

656 Advancements in food packaging technologies have led to the development of smart
657 packaging systems that integrate monitoring, communication, and product-responsive
658 functionalities. Smart packaging systems are commonly classified into active, intelligent and
659 responsive packaging based on their functional principles and operating characteristics

660 (Davidescu et al., 2025). Evaluating the application of these smart packaging systems in the
661 food industry is essential for understanding their contribution to enhanced food safety, shelf-
662 life extension, and supply-chain transparency. A structured classification of smart packaging
663 technologies supports comparative analysis and aids in identifying future research and
664 technological development opportunities.

665 **2.4.2 Active packaging**

666 Active packaging interacts directly with the packaged food or its surrounding the
667 packaging, controlling factors such as humidity and oxygen (D’Almeida & de Albuquerque,
668 2024). The primary objectives of these systems are to prolong shelf life, preserve sensory
669 attributes, and improve food safety. To achieve these goals, active packaging incorporates
670 biological, chemical, or physical components into the packaging matrix, allowing internal
671 conditions to be dynamically managed over time. Packaging functions not merely as a
672 containment system but as an active tool for food preservation (Davidescu et al., 2025).

673 Active packaging technologies can be broadly grouped into functional categories
674 such as scavenging, releasing, blocking, and regulating systems. These systems utilize
675 diverse mechanisms to modify the internal atmosphere of packaged foods. Scavenging
676 approaches are designed to eliminate undesirable constituents, including oxygen, moisture,
677 carbon dioxide, ethylene, and other volatile compounds. Many food products are highly
678 sensitive to oxygen, as its presence accelerates oxidative deterioration, loss of sensory
679 quality, nutrient degradation, and microbial growth. Vacuum and modified-atmosphere
680 packaging can lower oxygen levels and extend shelf life, they cannot completely prevent
681 oxygen ingress during storage, making oxygen scavengers a critical component of active
682 food packaging systems.

683 Oxygen scavengers, are incorporated into packaging in various formats, including
684 sachets, films, labels, and closures, often based on iron oxidation or titanium dioxide–
685 mediated reactions, effectively reduce oxidative degradation and inhibit microbial growth. In
686 addition to scavengers, synthetic antioxidants are commonly used to inhibit lipid oxidation in
687 fat-rich foods, Safety and compatibility concerns related to food safety, metal detection
688 interference, and microwave incompatibility have encouraged the development of
689 alternative metal-based and polymer-integrated scavenging technologies (Drago et al.,
690 2020).

691 Moisture-control systems, such as desiccant inserts or moisture-absorbing polymer
692 layers, help prevent quality defects, including loss of crispness in dry foods and
693 agglomeration in powdered products (Davidescu et al., 2025; Drago et al., 2020; Lee & Lee,
694 2024). Beyond scavenging functions, releasing systems are engineered to introduce

695 beneficial substances into the food or its headspace in a controlled manner. Antimicrobial
696 agents, including silver-based nanomaterials, organic acids, nisin, and zinc oxide, have
697 been shown to limit the growth of spoilage and pathogenic microorganisms. In addition,
698 carbon dioxide–releasing systems formulated using compounds such as citric acid and
699 sodium bicarbonate are commonly applied in modified-atmosphere packaging of products
700 like fish and poultry, where regulated gas generation contributes to the maintenance of
701 freshness and product quality (Drago et al., 2020).

702 The advancement of active packaging has enabled the development of innovative
703 strategies to extend the shelf life of perishable foods while preserving their microbiological
704 safety and sensory quality. Recent research highlights the use of bioactive materials and
705 natural compounds, including nanofibers, essential oils, biopolymers, and metal–organic
706 frameworks (MOFs), to create packaging systems capable of moisture regulation, gas
707 adsorption, and controlled release of antimicrobial agents. Studies have demonstrated that
708 such systems effectively delay spoilage, regulate ethylene levels, prevent microbial
709 contamination, and, in some cases, provide insect-repellent functionality. Collectively, these
710 developments emphasize the potential of active packaging technologies to improve food
711 quality and safety while offering sustainable solutions to reduce post-harvest losses and
712 food waste (D’Almeida & de Albuquerque, 2024).

713 **2.4.3 Smart packaging**

714 Smart packaging systems provide real-time or visual information regarding food
715 condition, safety, and freshness through indicators and sensing elements (Fig. 6).

716

717 **Fig. 6 Smart packaging system framework**

718

719 This capability is especially important in modern logistics, where unpredictable
720 environmental fluctuations during transportation can significantly affect product quality and
721 safety. Intelligent or smart packaging systems are built upon three main technological
722 components: indicators, sensors, and data carriers (D’Almeida & de Albuquerque, 2024;
723 Davidescu et al., 2025). Indicators provide rapid, typically visual information on specific
724 product attributes, such as color changes associated with cumulative temperature exposure
725 in time–temperature indicators (TTIs) or responses to volatile compounds that signal
726 microbial spoilage. Sensors extend beyond basic indication by detecting a broader range of
727 parameters, including temperature profiles, relative humidity, oxygen concentration, carbon
728 dioxide composition, and pH changes within the package environment (Dirpan et al., 2022).

729 Data carriers include technologies such as RFID tags and barcodes, which are designed to
730 store and transmit product-related information throughout the supply chain.

731 A key application of intelligent packaging is TTI predictor technology, which enables
732 the estimation of dynamic shelf life based on initial reference temperature values. By
733 incorporating spectrophotometric measurements from indicator labels at each distribution
734 stage, real-time updates to the remaining shelf life can be made. This detailed level of
735 monitoring allows decision-makers to redirect products that are nearing expiration to nearby
736 markets or to initiate rapid sales promotions. TTIs effectively connect laboratory-based shelf-
737 life models with real-world conditions through simple visual indicators or digital integration
738 (Cheng et al., 2022; Dirpan et al., 2022).

739 Intelligent or smart packaging systems can detect microbial contamination by binding
740 target microorganisms to engineered virus-like structures within enclosed sensing zones.
741 The resulting microbial interaction generates electronic signals that can be detected using
742 portable devices at inspection points, making these systems particularly suitable for high-
743 risk foods such as ready-to-eat meat and seafood products. In addition, intelligent packaging
744 increasingly incorporates bio-based sensing approaches that use natural polymers and
745 pigments responsive to biological changes. For example, freshness indicators based on pH-
746 sensitive anthocyanins undergo visible color changes in response to acids produced during
747 protein degradation in fish during storage (Wu et al., 2021).

748 The advantages of intelligent or smart packaging include improved transparency in
749 product quality assessment across different handling and distribution conditions, as well as
750 enhanced capacity to reduce food waste through early intervention. These systems provide
751 supply-chain stakeholders with timely warnings when storage conditions deviate from
752 optimal ranges, helping to prevent spoiled products from reaching consumers and
753 supporting compliance with regulatory requirements for cold-chain monitoring and
754 documentation. Recent developments have further combined intelligent indicators with
755 active preservation technologies, resulting in hybrid smart packaging systems that are
756 capable of both extending product freshness and continuously reporting quality degradation.
757 Overall, intelligent packaging functions both as a diagnostic tool and as an enabler of
758 adaptive logistics strategies, integrating sensory science with digital traceability systems that
759 can respond to changes in product condition within hours rather than days during
760 transportation or storage (D’Almeida & de Albuquerque, 2024; Wu et al., 2021).

761 **2.4.4 Responsive/ stimuli sensitive packaging**

762 Responsive food packaging is an emerging and innovative approach in modern food
763 packaging, designed to dynamically respond to changes in the food product or its

764 surrounding environment. Unlike conventional active packaging systems that rely on
765 predefined interactions, responsive packaging senses specific stimuli such as temperature
766 variations, microbial activity, gas composition, or pH changes and triggers targeted
767 responses in real time. These responses may include visual indicators, data generation, or
768 controlled release of functional agents, enabling timely monitoring and intervention to
769 maintain food quality and safety (Brockgreitens & Abbas, 2016; Gao et al., 2019).

770 Growing interest in responsive packaging reflects increasing demands for intelligent
771 and sustainable solutions that enhance food safety, quality monitoring, and environmental
772 responsibility. By providing accurate, real-time, and non-destructive information on product
773 condition, responsive systems improve shelf-life management, support supply-chain
774 decision-making, and help reduce food waste. Freshness indicators are among the most
775 widely studied responsive systems, as they undergo visible color changes in response to
776 pH shifts caused by spoilage-related compounds such as volatile amines, carbon dioxide,
777 and sulfides.

778 Responsive freshness indicators commonly consist of polymer matrices combined
779 with pH-sensitive pigments. Natural polymers and pigments are increasingly favored due to
780 their biodegradability, biocompatibility, and functional advantages. Starch-based films,
781 particularly when blended with chitosan or reinforced with nanoparticles, show enhanced
782 mechanical, barrier, and antimicrobial properties, while nanoencapsulation strategies further
783 improve pigment stability and sensitivity. To overcome limitations associated with low gas
784 permeability, porous materials such as silica-based aerogels are incorporated to enhance
785 gas adsorption, thereby accelerating color response and improving detection sensitivity
786 (Brockgreitens & Abbas, 2016; Gao et al., 2019).

787 Overall, responsive food packaging systems integrating natural polymers, stimuli-
788 sensitive pigments, nanocomposites, and porous materials offer a promising strategy for
789 real-time freshness monitoring. These technologies improve quality control, reduce food
790 waste, and enhance food safety across the supply chain, although challenges related to
791 scalability, regulatory compliance, material stability, and cost must still be addressed to
792 enable widespread commercial adoption.

793 **7. Fabrication techniques for smart packaging**

794 Smart packaging systems are designed to enhance food quality, safety, and shelf life
795 by incorporating functional components such as sensors, indicators, antimicrobials, and
796 antioxidants into packaging materials. The fabrication techniques used for smart packaging
797 play a crucial role in determining the mechanical strength, barrier performance,
798 responsiveness, and stability of these systems. Common fabrication approaches include

799 solvent casting, extrusion, electrospinning, coating and lamination, and nanocomposite
800 incorporation.

801 Solvent casting is one of the most widely used laboratory-scale techniques for
802 producing smart packaging films. It enables excellent dispersion of additives and precise
803 control over film thickness, making it particularly suitable for research and development of
804 smart films. In this method, biopolymers or synthetic polymers are dissolved in an
805 appropriate solvent, followed by the incorporation of active or intelligent components such
806 as pH indicators, antimicrobial agents, or nanoparticles. The resulting solution is poured
807 onto a flat surface and allowed to dry under controlled temperature and humidity conditions
808 to form a uniform film. However, the technique is time-consuming, difficult to scale up, and
809 may involve the use of toxic organic solvents, which limits its industrial application (Hu & Li,
810 2024; Sistani & Shekarchizadeh, 2025).

811 Extrusion is a highly efficient and scalable fabrication technique commonly used in
812 the packaging industry. This technique is compatible with a wide range of thermoplastic
813 materials, including polyethylene, polypropylene, polylactic acid, and thermoplastic starch.
814 In extrusion processing, polymer pellets or powders are melted under high temperature and
815 pressure and forced through a die to produce films or sheets. Smart packaging
816 functionalities are introduced by blending active compounds, sensors, or nanoparticles
817 directly into the polymer melt. the high processing temperatures can degrade heat-sensitive
818 bioactive compounds, requiring careful selection of additives or encapsulation strategies.
819 Extrusion offers high production rates, consistent film quality, and cost-effectiveness,
820 making it ideal for commercial-scale manufacturing (Realini & Marcos, 2014).

821 Electrospinning is an advanced fabrication technique used to produce ultrafine fibers
822 with diameters ranging from nanometers to micrometers. Electrospun materials exhibit
823 excellent porosity, breathability, and controlled release properties, making them suitable for
824 active and intelligent packaging systems. During the process, a polymer solution or melt is
825 subjected to a high-voltage electric field, resulting in the formation of continuous fibers
826 collected on a grounded surface. Despite these advantages, electrospinning faces
827 challenges related to low production yield, high energy consumption, and limited scalability
828 for mass production. In smart packaging applications, electrospinning enables the creation
829 of nanofibrous mats with high surface area-to-volume ratios, which enhance the
830 effectiveness of antimicrobial agents, antioxidants, and sensing materials. Electrospun
831 biopolymer nanofiber mats are also explored as smart moisture adsorbent pads, where high
832 surface area of fibrous membranes enhances water vapor uptake and can be combined with
833 antimicrobial agents (Mathew et al., 2025).

Coating and lamination techniques are widely employed to incorporate smart functionalities onto conventional packaging materials. Coating and lamination are highly versatile, compatible with existing industrial equipment, and suitable for large-scale applications. However, issues such as poor adhesion, delamination, and uneven distribution of active agents must be carefully managed. In coating processes, active or intelligent substances are applied as thin layers onto the surface of films or containers using methods such as dipping, spraying, or roll coating. Lamination involves bonding multiple layers of materials together to combine structural support with functional performance. These techniques allow smart components to be localized at the packaging–food interface, enhancing their effectiveness without compromising the bulk properties of the packaging material (Hu & Li, 2024; Realini & Marcos, 2014; Sistani & Shekarchizadeh, 2025).

Nanocomposite incorporation represents a key strategy for enhancing the performance of smart packaging materials. Nanocomposites can be fabricated using solvent casting, extrusion, or in situ polymerization techniques. While nanocomposite-based smart packaging offers significant advantages, concerns related to nanoparticle migration, toxicity, and regulatory approval remain important considerations for food-contact applications. This approach involves embedding nanoscale fillers such as nanoclays, metal oxide nanoparticles, carbon-based nanomaterials, or nanocellulose into polymer matrices. The incorporation of nanocomposites improves mechanical strength, thermal stability, and barrier properties while enabling additional functionalities such as antimicrobial activity, UV protection, and sensing capabilities (Al-Tayyar et al., 2020; Rhim & Ng, 2007; Sorrentino et al., 2007).

8. Role of nanotechnology in by-product-based smart packaging

Nanocellulose has emerged as a promising bio-based material for sustainable food packaging, thanks to its renewable origin, biodegradability, impressive mechanical strength, and excellent barrier properties. It can be derived from plant sources like wood and agricultural residues or produced through microbial processes, offering a more environmentally friendly alternative to conventional petroleum-based packaging. Rising concerns over plastic waste have further fueled research into nanocellulose-based packaging solutions.

Nanocellulose exists in three main forms: cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC), each with unique characteristics. CNCs, produced via acid hydrolysis, are rod-shaped and highly crystalline, providing outstanding rigidity, tensile strength, and stiffness, making them ideal as reinforcing fillers in polymer composites. CNFs, obtained through mechanical, enzymatic, or chemical

869 processes, form long, flexible fibrils that create dense networks within films, enhancing both
870 strength and flexibility. BNC, synthesized by specific bacteria, offers high purity, a nanoscale
871 fibrous structure, and excellent water-holding capacity, making it suitable for high-value
872 packaging applications.

873 Incorporating nanocellulose into biopolymers improves mechanical properties by
874 enabling efficient stress transfer through strong hydrogen bonding and uniform dispersion.
875 It also enhances barrier performance by creating tortuous pathways that slow gas and
876 aroma diffusion, crucial for maintaining food quality. While its hydrophilic nature can limit
877 moisture resistance, surface modifications and optimized composites can overcome this.
878 Moreover, nanocellulose's reactive surface allows functionalization with antimicrobial,
879 antioxidant, or UV-protective agents, enabling active packaging that prolongs shelf life and
880 safeguards food from microbial and oxidative damage (Reddy et al., 2025).

881 These nanomatrix-based composites are generally prepared using methods like
882 mechanical grinding, high-pressure homogenization, or ionic gelation. As an example,
883 chitosan nanocomposites formed through ionic gelation have been reported to possess
884 significantly improved antibacterial activity and barrier performance when compared with
885 traditional, non-nanoscale systems. Such findings clearly demonstrate that using nanoscale
886 matrices can offer distinct performance advantages over materials structured at the micro-
887 or molecular level, making them highly attractive for advanced food packaging applications
888 (Peng et al., 2025).

889 Cellulose is a naturally occurring polymer that is widely available in nature and is
890 valued for its excellent biocompatibility, renewability, and biodegradability. It is a major
891 structural component of plant cell walls and can be obtained from various agricultural and
892 plant-based sources, including oat husks, wood, wheat straw, corn stalks, sugarcane
893 bagasse, and cotton stalks. By applying mechanical, chemical, or combined treatment
894 methods, cellulose can be broken down into nanoscale materials, which greatly increases
895 its specific surface area and enhances its chemical reactivity. Based on their origin and
896 structural morphology, treated cellulose materials are generally categorized into cellulose
897 nanocrystals and cellulose nanofibers. Both forms exhibit unique fibrous characteristics at
898 the nanoscale, making them highly suitable for use as reinforcing agents or functional
899 components in composite systems.

900 In food packaging applications, nanocellulose primarily contributes to improvements
901 in mechanical strength and barrier performance. The incorporation of nanocellulose
902 significantly enhances the tensile strength of composite films, while its compact and well-
903 organized structure effectively limits the permeation of gases and moisture, thereby helping

904 to prolong the shelf life of packaged foods. In addition, nanocellulose-based composites are
905 recognized for their high transparency and environmentally friendly nature. For instance, the
906 development of a composite film incorporating silver-loaded nanocellulose and collagen
907 peptides, which showed a 64.28% improvement in tensile strength compared to a
908 nanocellulose–collagen peptide film without silver, although a reduction of 35.18% in
909 elongation at break was observed (Zhao et al., 2025).

910 Similarly, Yadav et al. (2019) employed cellulose nanocrystals as reinforcing fillers in
911 a cellulose nanocrystal/silver/alginic acid bio-nanocomposite film. The presence of silver
912 nanoparticles imparted effective UV-blocking properties, indicating its potential application
913 as UV-protective food packaging material. Furthermore, genipin as a natural crosslinking
914 agent was utilized to combine cellulose nanofibers with chitosan, resulting in a chitosan–
915 cellulose nanofiber composite film with a uniform, bubble-free surface and enhanced water
916 vapor barrier performance, which successfully extended the storage life of chicken.

917 Chitosan is a naturally occurring polysaccharide obtained from chitin and is widely
918 appreciated for its strong film-forming capability, biodegradability, and pronounced
919 antibacterial and antioxidant activities. These properties enable chitosan to effectively
920 suppress the growth of a broad spectrum of bacteria and fungi. At the nanoscale, chitosan
921 exhibits enhanced antibacterial activity, which is mainly attributed to its positively charged
922 surface. This cationic nature allows nano chitosan particles to interact strongly with the
923 negatively charged bacterial cell membranes, leading to membrane destabilization, leakage
924 of intracellular components, and subsequent inhibition of microbial growth. Reducing
925 chitosan to the nanoscale further improves its functional performance by increasing
926 antibacterial efficiency, mechanical strength, and barrier properties.

927 In this context, researchers have developed composite films based on sodium
928 alginate, chitosan, and zinc oxide, demonstrating that these films possess good tensile
929 characteristics. The inclusion of zinc oxide nanoparticles significantly enhanced the
930 antibacterial activity of the composite, making it particularly effective against *Escherichia*
931 *coli*. In another study, a biodegradable food packaging film was fabricated using
932 polyurethane and chitosan, where the resulting composite exhibited markedly higher tensile
933 strength and improved thermal stability compared to the pure polymer and conventional
934 blended films. Additionally, the inherent biodegradability of chitosan underscores its
935 importance in the development of sustainable and environmentally friendly food packaging
936 materials (Zhao et al., 2025).

937 Bioactive compounds are widely present in plant-based sources such as vegetables,
938 fruits, cereals, legumes, roots, rhizomes, and other botanical materials, where they

939 contribute important functional, nutritional, and protective benefits. Despite their potential,
940 the direct incorporation of these compounds into food and agricultural systems is often
941 limited by their high sensitivity to environmental factors, including light, oxygen, moisture,
942 temperature, and pH. Exposure to such conditions can result in rapid degradation, loss of
943 biological activity, and reduced effectiveness during processing, storage, and application.
944 To overcome these challenges and enhance both stability and usability, encapsulation has
945 emerged as an effective and widely adopted strategy.

946 Among the various approaches, microencapsulation and nanoencapsulation are the
947 most extensively applied technologies for protecting bioactive compounds and enabling
948 controlled delivery. The success of encapsulation largely depends on the careful selection
949 of encapsulating materials and techniques, as these directly influence protection efficiency,
950 release behavior, and functional performance. Several encapsulation methods have been
951 reported, including emulsification, antisolvent precipitation, electrospinning, and
952 coacervation, each offering distinct advantages depending on the physicochemical
953 properties of the active compound and its intended application. Coating or wall materials
954 play a critical role in determining emulsion properties such as droplet size, viscosity, and
955 stability, as well as the physical characteristics and handling behavior of the final
956 encapsulated product. In microencapsulation systems, the bioactive core is embedded
957 within a homogeneous or heterogeneous matrix that serves as a protective barrier against
958 external stresses (Zabot et al., 2022).

959 Encapsulation enables the efficient incorporation of a wide range of active
960 ingredients, including polyphenols, carotenoids, natural pigments, fatty acids, phytosterols,
961 probiotics, vitamins, minerals, and bioactive peptides, into suitable carrier matrices.
962 Encapsulation efficiency (EE), defined as the proportion of core material successfully
963 retained within the carrier system, is a key parameter used to evaluate encapsulation
964 performance and is influenced by the physical and chemical interactions between the core
965 and wall materials. Advanced techniques such as lyophilization are particularly valuable for
966 preserving heat-sensitive bioactive compounds, while extrusion is widely used to produce
967 stable formulations with controlled release characteristics. In agricultural applications,
968 essential oils such as rosemary oil have shown strong potential as natural insecticidal
969 agents. Microencapsulation of rosemary oil using spouted bed drying systems and carriers
970 like maltodextrin, Tixosil and microcrystalline cellulose enhances stability, handling, and
971 controlled release, thereby expanding its practical use in sustainable food and agricultural
972 systems (Munteanu & Vasile, 2021).

973 The controlled and sustained release of active ingredients through advanced
974 technologies is increasingly driving growth in both the pharmaceutical and food industries.
975 Microencapsulation has emerged as a reliable solution for protecting sensitive compounds
976 and improving their functional performance. In the pharmaceutical sector, it enhances drug
977 stability, bioavailability, and therapeutic effectiveness by enabling controlled release.
978 Similarly, in food and beverage applications, microencapsulation improves the incorporation
979 of flavours and fragrances by preventing losses caused by evaporation, oxidation, and heat,
980 while ensuring uniform mixing and appealing aroma and taste. This technology also plays a
981 crucial role in the development of functional foods, as it allows for the safe inclusion of
982 bioactive compounds such as phenolics, polyphenols, anthocyanins, vitamins, and
983 polyunsaturated fatty acids, which are highly sensitive to environmental conditions. By
984 isolating and protecting these components, microencapsulation extends shelf life, improves
985 stability, and enables the creation of innovative food formulations without compromising
986 quality or effectiveness (Borah et al., 2023).

987 Indicators, sensors, and biosensors are key tools in smart food packaging for
988 monitoring quality and safety. Indicators display visible changes, such as color shifts, to
989 show the presence of specific substances, food freshness, or package integrity, with
990 examples including time temperature and freshness indicators. Sensors detect and measure
991 physical or chemical changes, converting them into signals; for instance, electronic noses
992 use chemical sensor arrays and pattern-recognition systems to identify odors. Biosensors
993 are highly precise, especially for meat freshness, combining a selective bioreceptor with a
994 transducer that converts biochemical interactions into measurable electrical signals,
995 enabling accurate detection, recording, and transmission of information about biological
996 reactions (Ahmed et al., 2018).

997 **9. Sustainability, circular bioeconomy and life cycle assessment**

998 The rapid growth of industrial activity and consumer-driven markets has resulted in
999 an unprecedented rise in plastic production, with food packaging emerging as one of the
1000 major sources of plastic waste. Packaging acts as a vital link between food products and
1001 consumers, playing an essential role in ensuring food safety, extending shelf life, supporting
1002 transportation, conveying product information, and shaping brand identity. From a supply-
1003 chain perspective, effective food packaging is crucial for maintaining product quality and
1004 minimizing losses during storage and distribution.

1005 However, the environmental burden of plastic packaging has become increasingly
1006 evident. Global plastic production reached hundreds of millions of metric tons in recent
1007 years, and a large proportion of this material is used only once before being discarded. Such

single-use practices have intensified issues related to waste accumulation, environmental pollution, and the overuse of non-renewable resources. Traditional linear business models in food packaging typically follow a “take–make–dispose” pattern, where raw materials are extracted, converted into packaging, and rapidly thrown away after use. This approach places significant pressure on ecosystems and contributes to landfill overflow and long-term environmental degradation.

In response to these challenges, the food packaging sector is undergoing a shift toward more sustainable business models. This transition is being driven by advances in packaging technologies, stricter regulatory policies, and growing consumer awareness of environmental issues. Modern consumers increasingly expect brands to demonstrate environmental responsibility, and their purchasing decisions often reflect these values. As a result, companies are compelled to rethink packaging design, material selection, and end-of-life management. Investments in biodegradable and bio-based materials, reusable packaging systems, and waste-reducing innovations are becoming essential for maintaining competitiveness. Embracing sustainable packaging strategies not only addresses environmental concerns but also strengthens corporate social responsibility, enhances brand trust, and fosters long-term loyalty in an increasingly eco-conscious marketplace (Pavón Losada et al., 2025).

Within the framework of a circular bioeconomy, agricultural residues and food waste such as vegetable scraps and processing by-products can be transformed into high-value materials like bioplastics by utilizing their natural chemical composition. Bioplastics are commonly grouped as bio-based and biodegradable, bio-based but non-biodegradable, or biodegradable but not bio-based, depending on the origin and degradation behavior of the polymer. Bio-based plastics are derived from renewable biological sources, while biodegradable plastics are those that can be broken down by microorganisms into simple end products such as water, carbon dioxide, and biomass. Recent studies have demonstrated the potential of biopolymer films produced from food-derived components; for example, films developed from persimmon pectin combined with sodium alginate, guar gum, and baobab seed oil have shown improved mechanical strength, enhanced water resistance, and biological activity, successfully extending the shelf life of mushrooms. Among food waste constituents, cellulose is particularly abundant, accounting for nearly one-third to half of total biomass and occurring in materials such as rice husks, sugarcane bagasse, wheat straw, banana peels, and spent mushroom substrates. Cellulose-based films, unlike conventional petroleum-derived plastics, are sourced from renewables and are compostable, reducing long-term environmental burden. Starch-rich waste, including potato

1043 peels, corn husks, and banana skins, are also valuable for film formation due to their
1044 transparency, flexibility, biodegradability, and gas-barrier properties. Protein-based films
1045 further contribute by offering excellent oxygen barrier performance along with edible and
1046 biodegradable characteristics. Overall, converting food and agricultural waste into
1047 bioplastics supports waste valorization, reduces reliance on fossil resources, lowers
1048 greenhouse gas emissions, and offers a sustainable solution to plastic pollution while
1049 addressing environmental and economic challenges simultaneously (Fig. 7) (Vatieri et al.,
1050 2025).

1051
1052 **Fig. 7 Circular economy and environmental impact**
1053

1054 The assessment of packaging-related environmental impacts has evolved
1055 considerably (Fig. 8), with life cycle assessment (LCA) increasingly recognizing not only the
1056 direct effects of packaging materials but also their indirect influence on overall product
1057 sustainability. In addition to stand-alone packaging LCAs, many food product LCAs now
1058 include packaging within their system boundaries, providing valuable insights into how
1059 packaging interacts with food production, distribution, and consumption. This integrated
1060 approach has led to the perception that food LCAs offer a more holistic evaluation of
1061 packaging impacts, as they account for both the environmental burdens associated with
1062 packaging itself and its role in protecting food and preventing losses along the supply chain
1063 (Arfelli et al., 2024).

1064
1065 **Fig. 8 LCA flow diagram**
1066

1067 The direct environmental impacts of packaging primarily stem from the extraction,
1068 processing, and manufacturing of materials used for primary, secondary, and tertiary
1069 packaging. For food products with relatively low production impacts, such as soft drinks or
1070 minimally processed foods, packaging can represent a substantial share of the total
1071 environmental footprint. In contrast, for products derived from resource-intensive
1072 ingredients, such as dairy products or cheese, the relative contribution of packaging is
1073 smaller, though it remains an important factor in the overall life cycle. Beyond production,
1074 the end-of-life management of packaging constitutes another significant source of
1075 environmental impact. Ideally, packaging would be the only waste generated after food
1076 consumption; however, in practice, approximately one-third of food produced globally is lost

1077 or wasted before reaching the consumer. This inefficiency dramatically amplifies
1078 environmental burdens by coupling food waste with additional packaging waste (Molina-
1079 Besch et al., 2019).

1080 The short functional lifespan of packaging materials, combined with the large volumes
1081 generated, creates substantial challenges for waste management systems. Plastic
1082 packaging, in particular, poses serious environmental concerns due to insufficient collection
1083 infrastructure, low recycling rates, and the risk of accumulation in landfills and natural
1084 ecosystems. In LCA modeling, mechanical recycling is therefore most commonly applied to
1085 plastic packaging, reflecting its current industrial prevalence and the limited availability of
1086 consistent and reliable life cycle data for emerging chemical recycling technologies.

1087 In this context, smart packaging has emerged as a promising strategy to reduce the
1088 environmental footprint of agri-food systems, especially by addressing food loss and waste.
1089 Smart packaging technologies such as time temperature indicators, freshness and gas
1090 sensors, RFID tags, and QR-code-based traceability system enable continuous monitoring
1091 of food quality and storage conditions throughout the supply chain. By providing accurate,
1092 real-time information on product freshness and exposure to environmental stress, these
1093 systems help prevent the premature disposal of food that is still safe for consumption. As a
1094 result, the resources invested in food production, including water, energy, land, and
1095 agrochemicals, are used more efficiently, and greenhouse gas emissions associated with
1096 food production, transportation, and disposal are significantly reduced (D'Almeida & de
1097 Albuquerque, 2024).

1098 Beyond waste prevention, smart packaging enhances overall supply chain efficiency
1099 by enabling early detection of temperature abuse, handling errors, and logistical delays. This
1100 is particularly valuable for agri-food by-products and highly perishable materials, where
1101 timely interventions can extend shelf life and create new opportunities for reuse, recycling,
1102 or valorization within circular economy frameworks. When intelligent monitoring systems are
1103 combined with bio-based, biodegradable, or recyclable packaging materials, the
1104 environmental advantages are further amplified by reducing plastic waste and improving
1105 end-of-life outcomes. Moreover, consumer-oriented smart features promote informed
1106 purchasing decisions, responsible consumption behavior, and correct disposal practices,
1107 ultimately contributing to higher recycling rates and lower environmental impacts.
1108 Collectively, smart packaging represents an integrated and forward-looking solution that not
1109 only safeguards food quality but also plays a crucial role in minimizing the environmental
1110 footprint of modern agri-food systems (Yam et al., 2005).

1111 The agriculture and food processing sectors have historically played a pivotal role in
1112 driving technological advancement, contributing substantially to improvements in
1113 productivity, operational efficiency, and economic development. The progressive shift from
1114 traditional farming practices to mechanized systems has enabled large-scale production,
1115 reduced dependence on manual labor, and enhanced consistency across agricultural
1116 operations. Despite these achievements, continued technological evolution is essential to
1117 address persistent global concerns, particularly those related to food security, environmental
1118 sustainability, and the efficient management of natural resources.

1119 Recognizing these challenges, the United Nations adopted the Sustainable
1120 Development Goals (SDGs) in 2015, establishing 17 interlinked objectives aimed at
1121 fostering a sustainable, inclusive, and resilient global future by 2030. These goals span
1122 critical domains such as poverty alleviation, zero hunger, health and well-being, clean water
1123 and sanitation, affordable energy, economic growth, industrial innovation, responsible
1124 consumption, climate action, and ecosystem protection. The agriculture and food supply
1125 chain (AFSC) is intrinsically connected to the achievement of many SDGs, as it directly
1126 influences food availability, nutritional quality, environmental stewardship, and socio-
1127 economic stability (Sridhar et al., 2023).

1128 Recent advancements in automation and artificial intelligence (AI) are rapidly
1129 transforming agri-food systems, enabling a transition toward data-driven and precision-
1130 based operations. Technologies such as unmanned aerial vehicles, smart sensors, and
1131 digital analytics platforms facilitate real-time monitoring of critical parameters including soil
1132 health, moisture content, weather conditions, and nutrient status. These tools support
1133 informed decision-making, optimize resource utilization, and minimize environmental
1134 impacts. The broader concept of smart farming and smart food systems seeks to enhance
1135 global food production capacity, improve supply chain resilience, and support the
1136 development of innovative, health-oriented food products (Sarker et al., 2024).

1137 The integration of sensor-based technologies represents a cornerstone of digital
1138 agriculture. In recent years, sensors have been widely explored across farming, food
1139 processing, and quality control applications. In the context of food safety, advanced
1140 biosensing technologies such as electrochemical and immunosensor-based systems have
1141 demonstrated exceptional sensitivity in detecting foodborne pathogens at trace levels.
1142 Concurrently, precision agriculture has emerged as a sustainable production strategy that
1143 leverages site-specific data and advanced information technologies to maximize crop yields
1144 while reducing input costs, labor intensity, and environmental footprints.

1145 Within this evolving technological landscape, digital transformation presents both
1146 opportunities and challenges for the agriculture and food supply chain. Barriers such as high
1147 initial investment costs, limited technical expertise, infrastructure constraints, data
1148 management issues, and regulatory uncertainties can hinder large-scale adoption.
1149 Addressing these challenges is critical for fully realizing the potential of digital technologies
1150 to support the SDGs and to build a resilient, efficient, and sustainable agri-food ecosystem.

1151 Parallel to advances in digital agriculture, the development of smart packaging
1152 systems derived from agri-food byproducts has gained significant attention as a sustainable
1153 solution aligned with global environmental and policy agendas. Agricultural and food
1154 processing residues such as fruit and vegetable peels, pomace, seeds, husks, and bagasse
1155 are increasingly valorized into biodegradable and bio-based packaging materials. This
1156 approach reduces dependence on petroleum-based plastics, mitigates plastic pollution, and
1157 lowers greenhouse gas emissions associated with conventional packaging production and
1158 disposal (Baraketi & Khwaldia, 2024).

1159 The utilization of agri-food byproducts in smart packaging directly supports SDG 12
1160 (Responsible Consumption and Production) by promoting waste reduction and circular
1161 economy principles, and SDG 13 (Climate Action) through decreased lifecycle
1162 environmental impacts. Moreover, sustainable packaging technologies contribute to SDG 2
1163 (Zero Hunger) and SDG 3 (Good Health and Well-being) by extending shelf life, improving
1164 food safety, and reducing post-harvest losses. The incorporation of active and intelligent
1165 components such as natural antimicrobial agents and sensing elements further enhances
1166 food quality monitoring and preservation.

1167 From an ecological perspective, bio-based smart packaging systems play a vital role
1168 in protecting terrestrial and aquatic ecosystems (SDGs 14 and 15) by minimizing landfill
1169 accumulation and environmental contamination. In response, international and national
1170 policies increasingly encourage the adoption of renewable materials, waste valorization
1171 strategies, and life-cycle-based sustainability assessments. These policy frameworks are
1172 driving innovation, industrial uptake, and green procurement practices within the packaging
1173 sector.

1174 Despite their considerable potential, the transition of agri-food byproduct-based smart
1175 packaging technologies from laboratory research to commercial implementation remains
1176 challenging. Key obstacles include regulatory ambiguities, cost-competitiveness,
1177 performance limitations compared to conventional plastics, and the need for greater
1178 consumer awareness and supportive policy enforcement. Overcoming these challenges
1179 through interdisciplinary research, policy alignment, and stakeholder collaboration is

essential to fully harness the sustainability benefits of smart packaging and to advance the achievement of the Sustainable Development Goals (Carnaval et al., 2024).

10. Regulatory and safety considerations

Food contact materials (FCMs) are a broad category of products and substances that are intended to come into direct or indirect contact with food during processing, packaging, transport, storage, and consumption. They include plastics, glass, metals, paper, ceramics, and rubber, among others. Because they interact with food, there is potential for components of these materials both intentionally added substances and non-intentionally added substances (NIAS) such as impurities or degradation products to migrate into the food and potentially be ingested by consumers. Therefore, regulatory oversight and safety assessments are essential to ensure that such migration does not pose health risks, alter food quality, or compromise consumer safety (European Food Safety Authority, 2016).

In the European Union (EU), FCMs are regulated under a harmonized legal framework designed to protect public health and ensure a high level of consumer safety. The cornerstone of EU regulation is Regulation (EC) No. 1935/2004, often called the “Framework Regulation,” which states that FCMs placed on the market must be sufficiently inert so that substances do not transfer to food in quantities that could endanger human health, change food composition unacceptably, or deteriorate its organoleptic properties. This framework applies to all materials intended to contact food and is supported by more specific measures for particular material types, such as plastics, ceramics, and recycled materials. The EU also uses a “positive list” approach for plastics only substances listed in Commission Regulation (EU) No. 10/2011 may be used, with specified conditions and restrictions. Good Manufacturing Practices are mandated, and national authorities may adopt additional recommendations under mutual recognition principles where specific EU measures do not exist.

In contrast, the U.S. Food and Drug Administration (FDA) regulate food contact substances (FCSs) under the Federal Food, Drug and Cosmetic Act (FD&C Act). The FDA requires that substances intended to contact food be authorized through pre-market review mechanisms such as Food Contact Notifications (FCNs), food additive regulations, or exemptions like the Threshold of Regulation when exposures are sufficiently low. The FDA’s review process involves a rigorous analysis of submitted data, including toxicological evidence and migration testing, to determine whether the intended use of a substance is safe. Migration data must demonstrate how much of a substance could reach food under intended use conditions, and toxicological data are assessed to ensure that consumer exposure at those levels does not present a safety concern (U.S. Food and Drug

Administration. Understanding How the FDA Regulates Substances That Come into Contact with Food.

A central component of safety evaluation for FCMs is toxicological assessment. Both regulators require evidence that substances migrating from materials will not harm human health at anticipated exposure levels. Toxicological evaluations examine potential health effects such as genotoxicity, carcinogenicity, reproductive toxicity, and other adverse endpoints. In the EU, scientific bodies like the European Food Safety Authority (EFSA) provide expert risk assessments that incorporate toxicology data and exposure estimates to guide regulatory decisions and set specific migration limits (SMLs) based on acceptable daily intake (ADI) or tolerable daily intake (TDI) values. EFSA also emphasizes that even non-intentionally added substances should be assessed using appropriate approaches, including genotoxicity testing, to ensure comprehensive safety evaluation (European Food Safety Authority. (2016). Potential Impact on the Safety Assessment of Substances Used in Food Contact Materials. EFSA Journal).

Migration studies are laboratory tests that simulate the contact between FCMs and food to quantify how much of a substance can transfer from the material into food or food simulants. These studies are crucial because migration is affected by several factors such as temperature, contact time, food type, and the chemical properties of both the material and food. Standardized protocols use food simulants (e.g., ethanol or Tenax) that represent different food categories (aqueous, acidic, fatty, dry) to approximate real-world conditions. Migration limits such as overall migration limits (e.g., 60 mg/kg food in the EU) and specific migration limits established for individual chemicals protect consumers by ensuring that migration remains within safe thresholds. Accurate migration testing is vital because it influences exposure estimates and helps validate safety assessments for compliance with regulatory limits.

Finally, consumer acceptance plays a significant role in the real-world success of safe FCMs. Research shows that consumers' perceptions and understanding of food packaging safety influence their choices and behaviors. Many consumers are concerned about chemical migration and food contamination but may lack detailed awareness of what regulatory systems and safety assessments entail, and these perceptions can affect their trust and acceptance of novel materials like edible packaging or active packaging systems. Studies highlight that safety perceptions often rank highly among factors influencing consumer preferences for cookware or food contact materials, and that higher consumer literacy regarding food contact risks can improve acceptance of safe innovations (Kourkopoulos et al., 2025).

Overall, regulatory frameworks in both the EU and U.S. integrate toxicology, migration science, and risk assessment principles to safeguard public health. Simultaneously, understanding and addressing consumer perceptions and acceptance of food contact materials ensures that safety regulations translate into confidence and continued success in the marketplace.

11. Challenges and limitations

Agri-food waste is increasingly recognized as valuable, biodegradable resources rich in bioactive compounds, natural pigments, and functional biomolecules that can be converted into high-value products. They contain important phytochemicals such as phenolics, carotenoids, and tocopherols, which offer antioxidant, nutritional, and therapeutic benefits for food, pharmaceutical, and cosmetic applications. Recently, these residues have gained attention in smart and sustainable packaging as eco-friendly alternatives to petroleum-based plastics. By-products such as fruit peels, seeds, and bran provide biopolymers and bioactive agents that can impart antioxidant, antimicrobial, and freshness-indicating functions to packaging systems. Such applications help enhance food safety and extend shelf life. However, industrial adoption is constrained by variability in raw material composition and the instability of sensitive bioactive compounds. Additional challenges include scale-up limitations and strict food-contact regulatory requirements (Berenguer et al., 2022).

Variability in by-product composition

One of the most fundamental challenges in valorizing agri-food residues for smart packaging lies in the inherent variability of the raw materials themselves. Agricultural by-products differ widely in their chemical composition depending on factors such as crop variety, geographic origin, cultivation practices, seasonality, and processing conditions. For example, polysaccharide, protein, and phenolic content which critically influence how a material forms films or interact with other packaging components can vary from batch to batch. This variability makes it difficult to standardize processing methods and predict the performance of materials derived from these sources. Without consistent feedstock quality, it becomes challenging to develop reproducible packaging products with predictable mechanical and functional properties, such as barrier performance or sensor reliability. This inconsistency is a major barrier to scaling up from laboratory formulations to reliable industrial production (Marotta et al., 2025).

Stability of bioactive compounds

Smart packaging frequently relies on bioactive compounds extracted from food by-products such as polyphenols, carotenoids, and natural antioxidants to provide antimicrobial

activity or to serve as quality indicators within the packaging system. However, many of these compounds are chemically sensitive: they can degrade when exposed to heat, oxygen, light, or changes in humidity during processing and storage. This instability complicates efforts to integrate them into packaging films or sensor components without losing their functionality. Additionally, manufacturing processes such as drying, extrusion, or film casting can alter the structure and activity of sensitive bioactives. Ensuring that these compounds retain their beneficial properties throughout the life of the packaging and that they do so consistently across production lots remains a significant research and engineering challenge (Yin & Woo, 2024).

Scale-up and industrial feasibility

Translating successful lab-scale innovations into commercially viable industrial processes is not straightforward. Many promising techniques for extracting, modifying, or incorporating by-product-derived materials into sensors or films have been validated only at small scales. Scaling up often requires specialized equipment, rigorous quality controls, and optimization of heat and mass transfer to achieve continuous production without compromising material function. For instance, producing continuous films with uniform thickness, a requirement for industrial packaging is far more complex than casting a few samples in the lab. These technical challenges are compounded by high capital investment needs, as the infrastructure for collecting, preprocessing, and transforming food waste at large scales is often inadequate or non-existent. Without significant investment both in technical optimization and industrial infrastructure, many agro-by-product-based smart packaging technologies may remain confined to research setting (Yin & Woo, 2024).

Regulatory hurdles

Finally, the regulatory landscape presents substantial hurdles for introducing new materials derived from food industry by-products into packaging applications. Packaging materials in contact with food must meet strict safety standards that govern chemical migration, toxicological profiles, allergenicity, and microbiological safety. These regulatory evaluations are often time-consuming and expensive. In many regions, there is a lack of harmonized standards specifically tailored to bio-based, intelligent, or hybrid packaging systems that incorporate sensors or electronic components alongside biodegradable materials. This regulatory ambiguity creates uncertainty for manufacturers and can delay product approvals or market entry. Moreover, global differences in regulatory frameworks can complicate international commercialization strategies, making it harder for innovators to scale solutions across markets (D'Almeida & de Albuquerque, 2024).

12. Future perspectives

Smart packaging in the agri-food sector is rapidly evolving from conventional passive materials to active, intelligent systems capable of sensing, communicating, and interacting with both products and stakeholders throughout the supply chain. A key driver of this transformation is artificial intelligence (AI), whose integration with sensors, the Internet of Things (IoT), and digital indicators is redefining what packaging can do not merely protect food, but monitor, predict, and respond to changes in product quality.

AI-assisted smart packaging design

Future smart packaging designs increasingly embed AI algorithms directly into packaging systems to enable real-time evaluation and decision-making. Rather than relying on fixed “best-before” dates, AI-enabled smart packaging uses machine learning, computer vision, and fusion of multiple sensor inputs (gas, temperature, humidity) to accurately predict spoilage and shelf life. This allows packaging to dynamically assess conditions inside or around produce such as respiration rates or microbial signals then communicate that status to supply chain actors or consumers.

For example, smart packaging systems can leverage AI to:

- **Predict spoilage trends** by analyzing sensor data streams instead of static thresholds, enabling proactive interventions like rerouting near-spoilage batches.
- **Enhance quality control** by using deep learning models trained on large datasets from real supply chains.
- **Integrate with cloud analytics** to improve traceability and decision support across distributed networks.

These AI capabilities will be critical in handling the complexity of perishable agri-food by-products, such as fruit waste or vegetable trims, where traditional packaging cannot provide granular quality data (Madhu, 2025).

Hybrid intelligent systems

Future packaging solutions will not rely on a single technology but on hybrid intelligent systems combining several advanced layers:

- **Sensor arrays** (e.g., gas sensors, freshness indicators) that detect the biochemical state of packaged products.
- **AI engines** that interpret multi-sensor data and make context-aware predictions about spoilage or quality risks.
- **Connectivity modules** (Wi-Fi, RFID, Bluetooth) for real-time data exchange.

The synergy between these components allows systems to act not just as information collectors but as intelligent decision-making nodes. For instance, data from sensors could be processed by embedded AI to generate actionable alerts such as notifying warehouse

1355 managers of cold chain breaches or feed into algorithms that optimize inventory rotation
1356 (Mkhari et al., 2025).

1357 **Commercialization potential**

1358 The smart packaging market is projected to grow significantly in the coming decade,
1359 driven by consumer demand for quality, safety, and sustainability. Market analysts forecast
1360 substantial growth from the tens of billion USD range currently to even larger valuations by
1361 mid-2030s underscoring strong commercialization potential. Key commercialization
1362 opportunities includes;

- 1363 - **Subscription-based quality analytics services** that leverage AI insights for
1364 retailers and producers.
- 1365 - **IoT connectivity solutions** that bundle hardware (sensors) with cloud platforms,
1366 suitable for cold chain logistics and smart retail.
- 1367 - **Sustainable material integration** such as biodegradable substrates equipped with
1368 digital indicators to appeal to consumers and regulatory demand for eco-friendly
1369 solutions.
- 1370 - **Value-added services** like supply chain optimization tools that use real-time
1371 packaging data for reducing waste and improving routing.

1372 However, barriers include cost of components, regulatory requirements for food-
1373 contact electronics, and consumer education on interpreting digital freshness indicators
1374 (Jaiswal & Jaiswal, 2026).

1375 **Integration with IoT and digital indicators**

1376 In Agri-Food 4.0, the integration of the Internet of Things (IoT) plays a central role in
1377 connecting sensors, devices, and control systems across the agricultural value chain. IoT-
1378 enabled sensors continuously monitor environmental and operational parameters such as
1379 soil moisture, temperature, and crop health, providing real-time data for smarter decision-
1380 making. This connectivity allows automated systems, like irrigation controllers and
1381 greenhouse regulators, to respond dynamically to changing conditions, enhancing efficiency
1382 and productivity. The data collected through these networks serve as digital indicators,
1383 offering measurable insights into performance, sustainability, and resource use.
1384 Additionally, these indicators improve traceability and transparency, ensuring better
1385 management, quality control, and informed decision-making across the entire supply chain
1386 (Miranda et al., 2019).

1387 **Challenges and future perspectives**

1388 Despite the promising advancements in the valorization of agri-food by-products for
1389 smart packaging systems, several challenges must be addressed to facilitate their

1390 widespread industrial adoption and commercialization. While smart packaging offers
1391 revolutionary benefits, several challenges remain:

1392 - **Cost and scalability:**

1393 Embedded AI and sensor systems currently add to packaging costs, hindering
1394 adoption of low-margin products.

1395 - **Standardization:**

1396 Lack of unified international standards for IoT and intelligent packaging makes
1397 interoperability difficult.

1398 - **Variability in raw material composition:**

1399 A significant obstacle lies in the inherent heterogeneity of agri-food residues, which
1400 vary widely depending on crop variety, geographic origin, harvest season, and processing
1401 conditions. This variability affects the consistency of bioactive compounds, biopolymer
1402 content, and physical properties, complicating standardization and scale-up processes.
1403 Developing robust extraction, purification, and formulation protocols that accommodate raw
1404 material fluctuations remains a priority.

1405 - **Stability of bioactive components:**

1406 Many bioactive compounds derived from agri-food waste, such as phenolics,
1407 carotenoids, and antioxidants, are sensitive to environmental factors like light, oxygen, heat,
1408 and moisture. Their instability during processing, storage, and application can diminish
1409 functionality, undermining the efficacy of active and intelligent packaging systems.
1410 Innovative encapsulation and stabilization techniques are needed to preserve bioactivity
1411 over the product's shelf life.

1412 - **Scalability and industrial implementation:**

1413 Translating laboratory-scale innovations into commercially viable products poses
1414 technical and economic challenges. Current fabrication methods such as electrospinning or
1415 nanocomposite formation require optimization for large-scale production, ensuring
1416 uniformity, cost-effectiveness, and process efficiency. Infrastructure investments and
1417 technological advancements are essential for bridging this gap.

1418 - **Regulatory and safety considerations:**

1419 The incorporation of bioactive extracts, nanomaterials, and sensors raises regulatory
1420 concerns related to safety, migration, and toxicity. Harmonization of standards across
1421 regions and comprehensive toxicological assessments are crucial to ensure consumer
1422 safety and gain regulatory approval. Additionally, transparency and consumer education
1423 regarding the safety and benefits of these novel materials are vital for market acceptance.

1424 - **Consumer acceptance and market penetration:**

1425 Public perception and acceptance of packaging derived from food waste and
1426 nanotechnology influence market success. Educating consumers about the safety,
1427 sustainability, and functional benefits of these innovations can foster trust and demand.
1428 Moreover, aligning product design with consumer preferences for eco-friendly,
1429 biodegradable, and smart features will be key. Users must understand and trust digital
1430 signals and AI predictions to act on them effectively.

1431 - **Future perspectives:**

1432 Looking ahead, integrating emerging technologies such as artificial intelligence, IoT,
1433 and big data analytics with bio-based smart packaging holds great potential. AI-driven
1434 predictive models can optimize material formulations, monitor product quality, and enhance
1435 supply chain efficiency. The development of cost-effective, scalable, and multifunctional
1436 materials—combining bioactive compounds, nanomaterials, and digital sensors—will
1437 accelerate commercialization. Additionally, policy support, interdisciplinary collaborations,
1438 and consumer engagement are critical to overcoming current barriers and realizing the full
1439 potential of agri-food by-product-based smart packaging. Future research must focus on
1440 low-cost, scalable sensor technologies, interoperable communication frameworks, and user-
1441 centered design that ensures signals (e.g., freshness indicators) are intuitive for diverse
1442 consumer groups. Broader adoption will also depend on regulatory frameworks that
1443 accommodate digital and sensor-based packaging without compromising safety (M.
1444 Rahman et al., 2026). In conclusion, while considerable progress has been made, concerted
1445 efforts in research, regulation, and industry adoption are essential to harness the
1446 sustainable, functional, and economic benefits of agri-food by-products in the next
1447 generation of smart packaging systems.

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1451 **Novelty impact statement**

1452 This paper presents a pioneering synthesis of interdisciplinary research emphasizing
1453 sustainable food and pharmaceutical packaging by converting agri-food byproducts into
1454 bioactive, biodegradable, and smart materials. It develops the integration of circular
1455 economy principles with cutting-edge technologies including nanotechnology, artificial
1456 intelligence, the Internet of Things, and biosensors. This novel approach not only improves
1457 package functionality—such as antimicrobial activity, freshness monitoring, and shelf-life
1458 extension—but also addresses major environmental issues by reducing dependency on
1459 fossil-based plastics and minimizing waste. The findings pave the path for safer, more

sustainable, and intelligent packaging solutions that are consistent with global sustainability goals and will transform the future of food and pharmaceutical systems.

Aligning the study with the United Nations' sustainable development goals (17 SDGs)

The current study promotes the valorization of agri-food by-products into sustainable, bioactive, and biodegradable materials for smart packaging, which aligns with the United Nations' Sustainable Development Goals (SDGs), particularly SDGs 12 (Responsible Consumption and Production) and 13 (Climate Action). This technique decreases food and packaging waste, reduces dependency on fossil-based plastics, and promotes circular economy concepts using resource-efficient strategies. It also helps to achieve SDG 2 (zero hunger) by increasing food shelf life and improving food safety, as well as SDG 15 (life on land) by reducing environmental pollution. Overall, the research improves eco-friendly packaging technologies that promote environmental sustainability, resource conservation, and responsible manufacturing and consumption.

1473

4. Conclusion

This review underscores the transformative potential of agri-food by-products as sustainable resources for next-generation smart packaging systems. Key findings highlight that valorization of residues such as peels, husks, seeds, and processing by-products can yield functional materials—including bioactive compounds, natural antioxidants, biopolymers, and nanomaterials—that enhance food safety, extend shelf life, and support circular economy principles. The integration of advanced fabrication techniques, nanotechnology, and digital tools like sensors, RFID, and AI-driven analytics has significantly improved the performance, sensitivity, and real-time monitoring capabilities of these ecofriendly packaging solutions.

Industrial applications are rapidly expanding across sectors such as meat, seafood, dairy, and fresh produce, where active and intelligent packaging systems effectively inhibit microbial growth, prevent lipid oxidation, and provide visual freshness indicators. These innovations not only reduce food waste and environmental pollution but also align with global sustainability goals by decreasing reliance on fossil-based plastics and promoting resource-efficient practices.

Environmental benefits are profound, with life cycle assessments demonstrating substantial reductions in carbon footprint, energy consumption, and plastic waste when utilizing biobased, biodegradable materials derived from agri-food residues. Such approaches foster a sustainable, resilient food system capable of meeting the demands of a growing population while conserving natural resources.

1495 Future research should focus on overcoming current barriers such as raw material
1496 variability, bioactive compound stability, scalability, regulatory frameworks, and consumer
1497 acceptance. Emphasis on developing cost-effective, scalable manufacturing processes,
1498 harmonized safety standards, and consumer education will be critical. Additionally, the
1499 integration of AI and IoT technologies promises to further revolutionize smart packaging,
1500 enabling predictive analytics and autonomous quality management.

1501 In summary, harnessing agri-food by-products for innovative smart packaging offers
1502 a promising pathway toward environmentally responsible, safe, and efficient food systems—
1503 paving the way for sustainable industrial practices and global food security.

1504 **Abbreviations**

1505 ADI: acceptable daily intake

1506 AFSC: agriculture and food supply chain

1507 AI: artificial intelligence

1508 BNC: bacterial nanocellulose

1509 CNCs: cellulose nanocrystals

1510 CNFs: cellulose nanofibrils

1511 EE: Encapsulation efficiency

1512 EFSA: European Food Safety Authority

1513 EO: Essential oil

1514 EU: European Union

1515 FCMs: Food contact materials

1516 FDA: Food and Drug Administration

1517 IoT: Internet of Things

1518 LCA: life cycle assessment

1519 NIAS: non-intentionally added substances

1520 OMW: Olive mill wastewater

1521 PE: polyethylene

1522 PET: polyethylene terephthalate

1523 PP: polypropylene

1524 RFID:

1525 SDGs: sustainable development goals

1526 SMLs specific migration limits

1527 TDI: tolerable daily intake

1528 TTI: time–temperature indicator

1529 UN: United Nations

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1536 The authors confirm that the data supporting the findings of this study are available within

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1538 **Clinical trial number**

1539 Not applicable.

1540 **Declarations**

1541 **Ethics approval and consent to participate**

1542 Not applicable.

1543 **Consent for publication**

1544 Not applicable.

1545 **Competing interests**

1546 The authors declare that they have no competing interests.

1547

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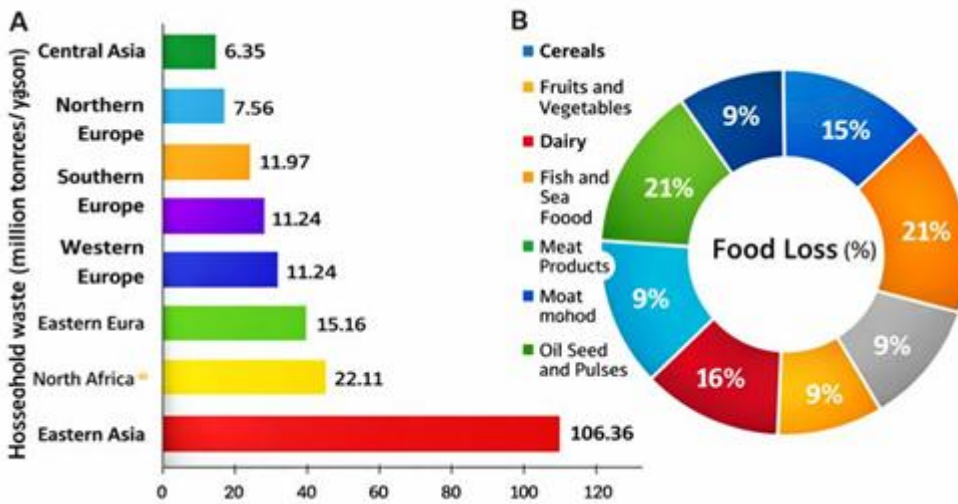
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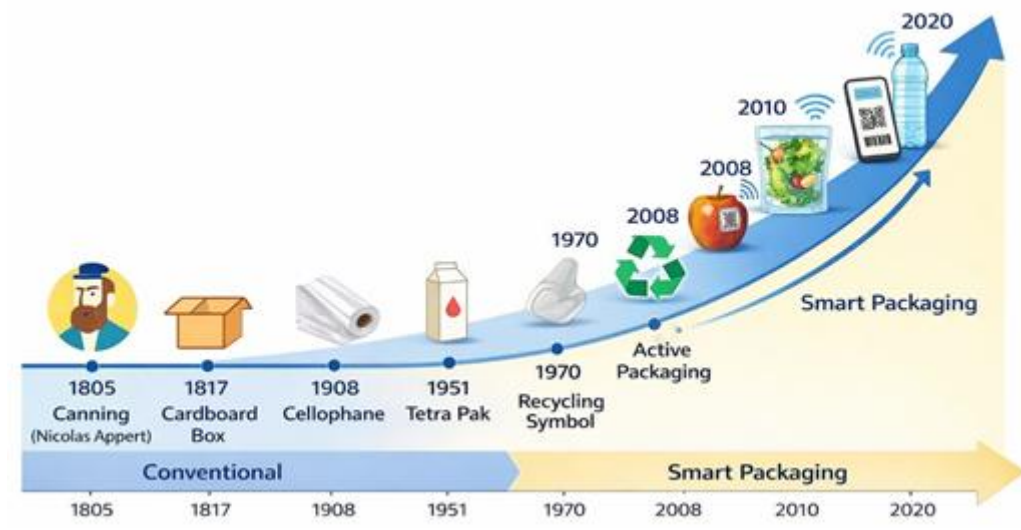
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1994



1995

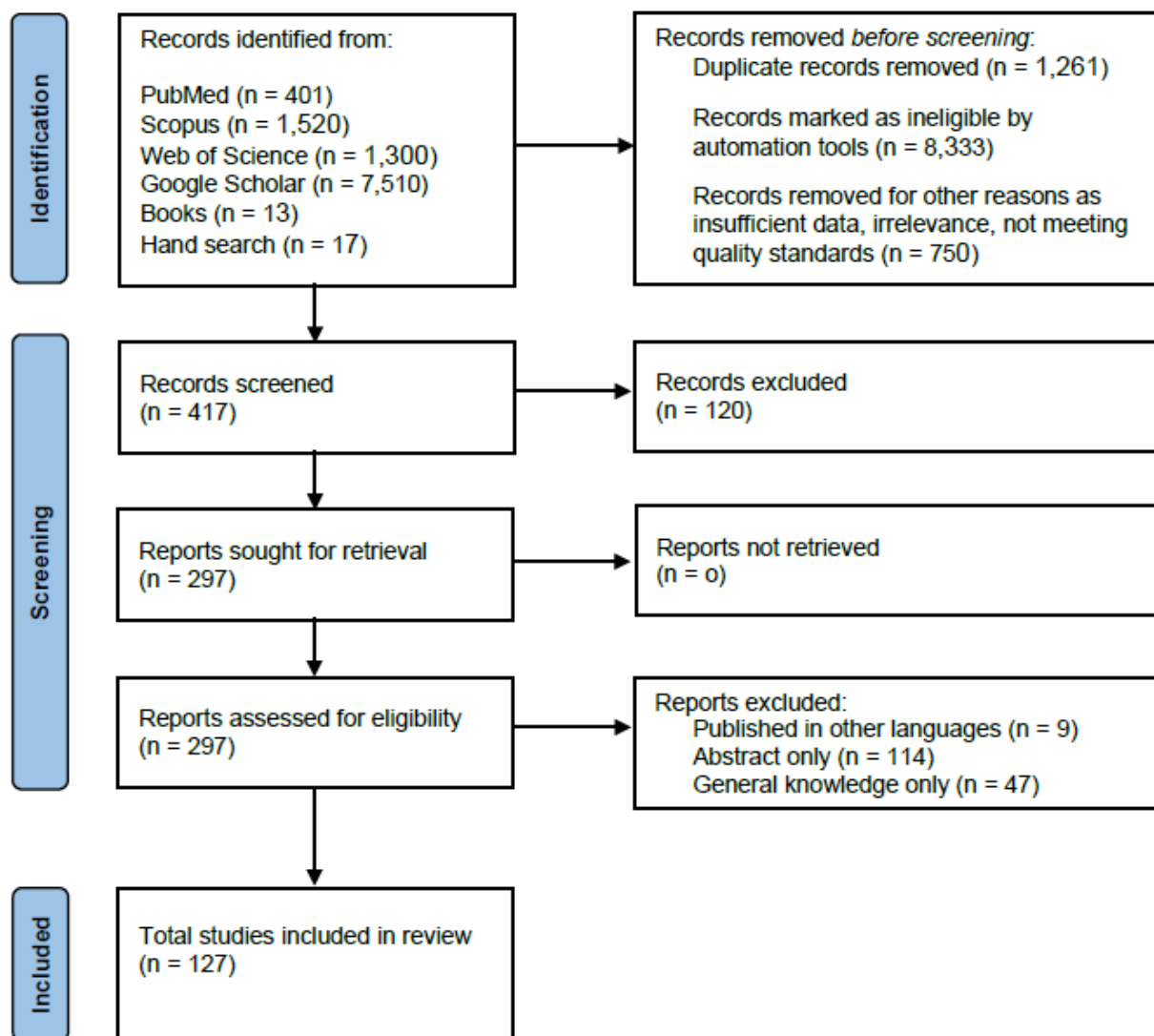
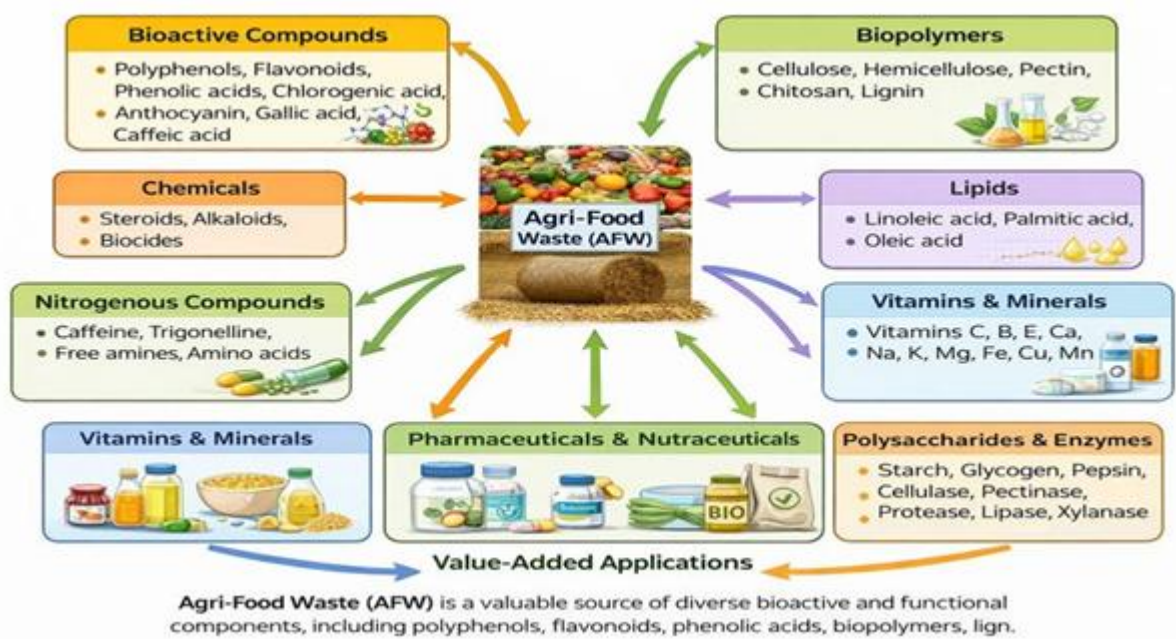


Fig. 3 PRISMA flow diagram including searches of databases and registers (2005-2026)





1998



1999

