

Sustainable Valorization of Agri-Food By-Products for Smart Packaging: Innovations, Challenges, and Future Directions within a Circular Bioeconomy – A Systematic Review

Bhavya Shree Balasubramani

Department of Pharmaceutical Quality Assurance, Krupanidhi College of Pharmacy, Chikkabellandur, Bangalore, 560035, India <https://orcid.org/0009-0009-7432-6621>

Purvika Shashidhara

Department of Pharmaceutical Chemistry, Government College of Pharmacy, Subbaiah Circle, Bangalore, 560027, India <https://orcid.org/0009-0009-4389-3324>

Spoorthi G. Thimmaiah

Department of Pharmaceutical Quality Assurance, Krupanidhi College of Pharmacy, Chikkabellandur, Bangalore, 560035, India <https://orcid.org/0009-0006-0768-9981>

Rajakumari Rajendran

rajimpharm@gmail.com

Department of Pharmaceutics, The Oxford College of Pharmacy, Bangalore, 560068, India
<https://orcid.org/0000-0002-8334-484X>

Rania I.M. Almoselhy

raniaalmoselhy@gmail.com

Oils and Fats Research Department, Food Technology Research Institute, Agricultural Research Center, Giza, 12619, Egypt <https://orcid.org/0000-0001-6314-6144>

Sabu Thomas

International and Inter University Centre for Nanoscience and Nanotechnology, School of Energy Materials, and School of Nanoscience and Nanotechnology, School of Chemical Science, Mahatma Gandhi University, Kottayam, Kerala, 686560, India <https://orcid.org/0000-0003-4726-5746>

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Bhavya Shree Balasubramani¹, Purvika Shashidhara², Spoorthi G. Thimmaiah ¹,
Rajakumari Rajendran^{3*}, Rania I.M. Almoselhy^{4*}, Sabu Thomas^{5,6,7,8,9}

¹Department of Pharmaceutical Quality Assurance, Krupanidhi College of Pharmacy, Chikkabellandur, Bangalore, 560035, India

²Department of Pharmaceutical Chemistry, Government College of Pharmacy, Subbaiah Circle, Bangalore, 560027, India

³Department of Pharmaceutics, The Oxford College of Pharmacy, Bangalore, 560068, India

⁴Oils and Fats Research Department, Food Technology Research Institute, Agricultural Research Center, Giza, 12619, Egypt

⁵International and Inter University Centre for Nanoscience and Nanotechnology, School of Energy Materials, and School of Nanoscience and Nanotechnology, School of Chemical Science, Mahatma Gandhi University, Kottayam, Kerala, 686560, India

⁶Department of Physics and Electronics, CHRIST (Deemed to Be University), Bengaluru, 560029, Karnataka, India

⁷Department of Chemical Sciences, University of Johannesburg, P.O. Box 17011, Doornfontein, 2028 Johannesburg, South Africa.

⁸TrEST Research Park, TC-4/2322, GEM Building, Opposite College of Engineering Trivandrum, Kulathoor Rd, Sreekariyam, Trivandrum, Kerala 695016, India

⁹Center of Excellence in Polymeric Materials for Medical Practice Devices, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand.

*Correspondence:

*Rajakumari Rajendran, rajimpharm@gmail.com

*Rania I.M. Almoselhy, raniaalmoselhy@arc.sci.eg; raniaalmoselhy@gmail.com

1- Bhavya Shree Balasubramani (balubhavya2003@gmail.com)

2- Purvika Shashidhara (purvikapurvi93@gmail.com)

3- Spoorthi G. Thimmaiah (spurthigt542@gmail.com)

4- Rajakumari Rajendran (rajimpharm@gmail.com)

5- Rania I.M. Almoselhy (raniaalmoselhy@arc.sci.eg; raniaalmoselhy@gmail.com)

6- Sabu Thomas (sabuthomas@mgu.ac.in)

Abstract

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

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

Graphical Abstract

Graphical Abstract

1. Introduction

Global Scale of Agri-Food By-products

Annually, approximately one-third of global food production—around 1.3 billion tons—is wasted, contributing to over 20% of greenhouse gas emissions. A significant proportion—30-50% of raw materials—comprises post-harvest and processing by-products such as 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 USD 1 trillion annually, with nearly 30% of food discarded each year. Developed nations waste about 670 million tons due to consumer and retail habits, while developing regions generate roughly 630 million tons, primarily due to 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: Sources and Composition

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, which limited resource recovery and harmed the environment. Recent advances in green technologies and bioprocessing now recognize these residues as valuable, low-cost sources of bioactive compounds such as phenolics, flavonoids, antioxidants, fatty acids, fibers, amino acids, and proteins. Valorization of these by-products enhances waste reduction and resource efficiency and supports sustainable, circular food systems.

Environmental and Economic Burden of Food Waste

Food waste poses a significant environmental challenge, occupying landfills and releasing methane and CO₂, which account for nearly 8% of human-generated greenhouse gases. Approximately 25% of global agricultural resources—land, water, fertilizers, energy—are consumed inefficiently, exerting immense pressure on ecosystems and biodiversity. Improper disposal leads to air pollution, groundwater contamination, and nutrient runoff, exacerbating environmental degradation. As global food demand rises, reducing waste is critical for sustainable food systems and environmental mitigation (Kohli et al., 2024).

110 Globally, food waste costs over USD 2.6 trillion annually—including USD 1 trillion in
111 direct expenses and USD 1.6 trillion in environmental and social damages—driven by
112 inefficiencies throughout the supply chain. This results in significant financial losses for
113 producers, household waste, and hefty waste management costs, while depleting vital
114 resources such as energy, water, and land. Addressing this issue necessitates a strategic
115 shift toward waste prevention and resource recovery, fostering economic and environmental
116 sustainability (Tariq et al., 2025).

117 **2. Evolution of Food Packaging**

118 **From Conventional to Smart Packaging**

119 Food packaging has evolved from simple containers to advanced, eco-friendly
120 systems driven by technological innovation, safety, and sustainability. Influenced by
121 industrialization, material science, and concerns over food waste and safety, this shift has
122 resulted in smarter, environmentally responsible solutions that meet modern consumer and
123 regulatory demands (Fig. 2).

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

127 **Historical Development of Packaging Technologies**

128 Initially, food was packaged using natural materials—leaves, animal skins, shells—
129 which offered minimal protection. The 19th-century innovations, such as Nicolas Appert’s
130 1805 canning method, introduced sterilization and sealing, revolutionizing preservation. The
131 20th century saw the rise of synthetic polymers like cellophane and plastics (PE, PP, PET),
132 enabling flexible, barrier, and active packaging. Recent innovations include multifunctional
133 systems such as antimicrobial active packaging, sensor-embedded intelligent packaging,
134 RFID, and real-time monitoring solutions (Alamri et al., 2021; Hassoun, 2025; Petrenko et
135 al., 2024; Tas et al., 2017; Tripathi et al., 2023).

136 **Rationale for Using Agro-Food By-Products in Eco-Friendly Packaging**

137 Dependence on petroleum-based plastics contributes to environmental pollution and
138 resource depletion. Agro-food processing generates abundant underutilized by-products
139 rich in functional polysaccharides—renewable, biodegradable, and biocompatible materials
140 suitable for eco-friendly packaging (Zhu, 2021). Chemical modifications and blending with
141 other biopolymers can improve their properties, supporting a circular economy by
142 transforming waste into valuable resources and reducing reliance on fossil plastics (Li et al.,
143 2024). Despite some challenges like moisture sensitivity, advances in composites and

144 blends enhance their practicality. Valorization of agricultural residues into packaging offers
145 a promising, environmentally responsible pathway for sustainable solutions.

146 **Emergence of Smart Packaging and Scope of Review**

147 This review explores recent advances in biodegradable, nanomaterial-enhanced
148 smart packaging, focusing on barrier improvements, antimicrobial functions, and
149 environmental sustainability. It covers embedded sensors, indicators, and digital
150 integrations (IoT, blockchain) for real-time quality monitoring, along with economic,
151 regulatory, and consumer perspectives. The goal is to provide a comprehensive overview
152 of current trends, challenges, and future directions in sustainable, intelligent food packaging.

153 **3. Methodology**

154 The review employed a rigorous evidence-based approach, following systematic
155 steps:

156 **3.1. Literature Search Strategy**

157 A comprehensive search was conducted across PubMed, Scopus, Web of Science,
158 Google Scholar, and official agri-food databases. Keywords included “sustainable
159 valorization of agri-food by-products,” “biopolymers from food waste,” “biodegradable
160 packaging,” “active and intelligent packaging,” “nanotechnology in food packaging,” “digital
161 sensors,” and related terms. Boolean operators refined the search, limited to English-
162 language articles published from 2010 to 2026.

163 **3.2. Inclusion and Exclusion Criteria**

164 Included: Peer-reviewed research articles, reviews, theses, policy papers,
165 government reports, and conference proceedings relevant to the core topics.

166 Excluded: Non-English publications with insufficient data, non-peer-reviewed articles,
167 and studies unrelated to the scope.

168 **3.3. Selection Process**

169 Records were screened using reference management tools; duplicates were
170 removed. Two reviewers examined titles and abstracts independently for eligibility.

171 **3.4. Data Extraction and Synthesis**

172 Data were systematically extracted using standardized forms, including study design,
173 key findings, and limitations. Thematic analysis identified patterns, gaps, and trends.

174 **4. Results and Discussion**

175 **4.1. Study Selection**

176 From an initial 10,761 records, after filtering, 81 studies were included in the review
177 (Fig. 3).

Fig. 3 PRISMA flow diagram including searches of databases and registers (2010-2026)

4.2. Sources and Composition of Agri-Food By-Products

Fig. 4 illustrates sources across the supply chain, including residues from fruits, vegetables, cereals, oilseeds, dairy, meat, and seafood (Chen & Lou, 2025; Gueboudji et al., 2023; Hrelia et al., 2025; Ivanović et al., 2023; Perrone et al., 2025).

Fig. 4 Sources of agri-food by-products

4.2.1. Fruits and Vegetable Waste

Residues such as peels, pomace, seeds, and shells are rich in bioactive compounds (Fig. 5) like phenolics, flavonoids, carotenoids, and terpenes, offering potential for sustainable valorization (Ben-Othman et al., 2020; Berenguer et al., 2022; Campos et al., 2020; Haq et al., 2021; Pandey et al., 2025; Paritosh et al., 2017; Prasad et al., 2020; Sindhu et al., 2019).

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

4.2.2. Cereal By-Products

Bran, husks, and brewer's grains are abundant sources of fibers, proteins, and bioactives suitable for functional foods, packaging, and energy applications (Luithui et al., 2019; Skendi et al., 2020).

4.2.3. Oilseed By-Products

Rapeseed, sunflower, flaxseed, and sesame meals are nutrient-rich, with high-quality proteins, phenolics, and antioxidants, supporting health and functional applications (Nemli et al., 2025).

4.2.4. Dairy and Meat By-Products

Whey, colostrum, blood, bones, and viscera are underutilized resources rich in bioactive peptides, proteins, lipids, and minerals with applications in food, pharmaceuticals, and cosmetics (Christiansen et al., 2010; Corrêa et al., 2019; León et al., 2019; Mora et al., 2014; Toldrá et al., 2016).

4.2.5. Seafood By-Products

Fish bones, skin, shells, and cartilage contain bioactives like chito-oligosaccharides, collagen, and omega-3 fatty acids, supporting nutraceutical and food applications (Ben-Othman et al., 2020; Roy et al., 2023b).

Figure 6 shows the smart packaging system framework.

Fig. 6 Smart packaging system framework

5. Valuable Components in Agri-Food By-Products

5.1. Polyphenols

212 Rich in antioxidants, anti-inflammatory, and anticancer properties, polyphenols from
 213 residues like olive mill wastewater, grape skins, and fruit peels support health and
 214 sustainable use in nutraceuticals and functional foods (Abdul Khalil et al., 2012).

215 **5.2. Dietary Fibers**

216 Soluble and insoluble fibers, such as pectins, cellulose, and hemicelluloses, improve
 217 food texture, control blood glucose, and have prebiotic effects, contributing to health and
 218 packaging functionalities (Bhatia et al., 2024; Plakantonaki et al., 2023).

219 **5.3. Proteins and Bioactive Peptides**

220 Derived from oilseed cakes, dairy whey, and animal by-products, these peptides
 221 exhibit antihypertensive, antioxidant, and antimicrobial activities, suitable for functional
 222 foods and nutraceuticals (Borah et al., 2023; Mora et al., 2014).

223 **5.4. Bioactive Lipids**

224 Sources like olive pits and avocado peels provide fatty acids, tocopherols, and
 225 phytosterols with antioxidant and anti-inflammatory benefits (Reddy et al., 2025).

226 **5.5. Polysaccharides (Pectin)**

227 Extracted from citrus peels and apple pomace, pectin acts as a gelling agent and
 228 prebiotic, with health benefits including cholesterol reduction and gut health promotion
 229 (Espitia et al., 2014).

230 Refer to Table 1 for detailed sources and applications.

231 **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	(Ezquerro-Brauer & Aubourg, 2019)

6. Functional Roles of Agri-Food By-Products in Smart Packaging

6.1. Antimicrobial Agents

Plant phenolics and essential oils (oregano, thyme, clove) exhibit broad-spectrum antimicrobial activity, effectively incorporated into biopolymer films and coatings to inhibit microbial growth and extend shelf life (Carpena et al., 2021; Casalini & Giacinti Baschetti, 2023; da Silva et al., 2022; Galante et al., 2025; Oulahal & Degraeve, 2022; Ribeiro-Santos et al., 2017).

Mechanism of Microbial Inhibition

Disruption of cell membranes, enzyme inactivation, oxidative damage, and pH modulation are primary mechanisms—facilitated by phenolics and essential oil constituents (Bibow & Oleszek, 2024; Devi et al., 2024; Schmitz & Moura, 2025; Tomić et al., 2023; Varghese et al., 2020).

6.2. Antioxidant Activity

Bioactive compounds from residues delay lipid oxidation, preserving sensory and nutritional qualities. Encapsulating antioxidants like grape seed extracts and essential oils into films extends shelf life and acts as smart indicators (Barzan et al., 2024; Bhat et al., 2024; Dilucia et al., 2020; Domínguez et al., 2018; Ganiari et al., 2017; Jamróz & Kopel, 2020; Lante & Momayezhaghghi, 2025; Matthes & Schmid, 2024; Messinese et al., 2024; Yin et al., 2023).

6.3. pH and Freshness Indicators

Natural pigments such as anthocyanins from red cabbage, grape pomace, and berries serve as visual, pH-sensitive freshness indicators that change color (Table 2) in response to spoilage gases such as ammonia and amines (Ma et al., 2025; Marangon et al., 2022; Nadi et al., 2023; Neves et al., 2022).

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)

6.4. Gas and Moisture Control

Fibrous residues like cellulose and hemicellulose improve oxygen and moisture barriers, reducing microbial growth and oxidation, thereby extending shelf life (Chen et al., 2025; Dilucia et al., 2020; Kalita et al., 2025; Muñoz-Gimena et al., 2023; Ribeiro et al., 2025; Siriwong et al., 2024).

7. Fabrication Techniques for Smart Packaging

Refer to Hu & Li, 2024; Realini & Marcos, 2014 for detailed methodologies.

Common methods include:

Solvent Casting: suitable for research, allows precise control but limited scalability.

Extrusion: Industrially scalable, compatible with thermoplastics, but with the risk of degrading bioactives.

Electrospinning produces nanofibers with high surface area, but yields are limited.

Coating and Lamination: Versatile, suitable for large-scale production, but challenges include adhesion and uniformity.

Nanocomposite Incorporation: Embeds nanomaterials like nanocellulose, nanoclays, and metal oxides to enhance properties, with regulatory considerations.

8. Role of Nanotechnology in By-Product-Based Smart Packaging

Nanocellulose (CNCs, CNFs, BNC) offers outstanding mechanical strength, barrier properties, and functionalization potential. Incorporation into biopolymers enhances tensile

277 strength, gas, and moisture barriers, and allows active functionalities like antimicrobial and
278 antioxidant delivery (Reddy et al., 2025).

279 Other nanomaterials—nanoclays, metal oxide nanoparticles—further improve performance
280 but require careful safety assessment and regulatory compliance.

281 **9. Sustainability and Life Cycle Assessment**

282 Transitioning from linear to circular models involves converting agri-food waste into
283 bioplastics—such as starch, cellulose, pectin, and proteins—that are renewable,
284 biodegradable, and suitable for packaging. Life cycle assessments demonstrate significant
285 reductions in carbon footprint and plastic waste when using bio-based materials (Fig. 7, 8).
286 Smart packaging technologies, including sensors and indicators, enable real-time
287 monitoring, reduce food waste, and improve resource efficiency aligned with SDGs 12, 13,
288 2, and 15 (Molina-Besch et al., 2019; Pavón Losada et al., 2025).

289 **10. Regulatory and Safety Considerations**

290 Food contact materials (FCMs) are regulated in the EU under Regulation (EC) No.
291 1935/2004 and in the US by the FDA, with rigorous migration and toxicological assessments.
292 Encapsulation, nanomaterials, and bioactive compounds require safety validation,
293 standardization, and consumer transparency to ensure acceptance.

294 **11. Challenges and Limitations**

295 **Major challenges include:**

296 **Raw Material Variability:** Inconsistent composition due to crop, region, and processing
297 factors.

298 **Bioactive Stability:** Sensitivity to environmental factors during processing and storage.

299 **Scale-Up:** Transitioning from lab to industry demands infrastructure and process
300 optimization.

301 **Regulatory Hurdles:** Harmonizing standards for nanomaterials and bio-based
302 components.

303 **Consumer Acceptance:** Education on safety and benefits is essential.

304 **12. Future Perspectives**

305 The integration of AI, IoT, and big data will enable predictive, adaptive, and autonomous
306 smart packaging systems. Development of cost-effective, scalable sensors, and
307 comprehensive regulatory frameworks will accelerate commercialization. Consumer
308 engagement and transparency will be vital for market success, promoting sustainable, safe,
309 and intelligent packaging solutions aligned with global SDGs.

310 **Novelty and Impact Statement**

311 This review offers a pioneering synthesis of interdisciplinary research on converting
312 agri-food by-products into sustainable, bioactive, and smart packaging materials. It aligns
313 circular economy principles with advanced technologies—nanotechnology, AI, IoT, and
314 biosensors—driving innovations that enhance package functionality, food safety, and
315 environmental sustainability. The findings pave the way for safer, eco-friendly packaging
316 solutions that support global sustainability agendas and revolutionize food and
317 pharmaceutical systems.

318 **Alignment with UN Sustainable Development Goals (SDGs)**

319 This work advances SDGs 12 (Responsible Consumption and Production), 13
320 (Climate Action), 2 (Zero Hunger), and 15 (Life on Land) by promoting waste valorization,
321 reducing dependency on fossil plastics, extending shelf life, and minimizing environmental
322 pollution.

323 **13. Conclusion**

324 This review underscores the transformative potential of agri-food by-products as
325 sustainable resources for next-generation smart packaging. Valorization of residues such
326 as peels, husks, seeds, and processing by-products yields functional materials—bioactives,
327 biopolymers, nanomaterials—that enhance food safety, extend shelf life, and support a
328 circular economy. Advanced fabrication techniques, nanotechnology, and digital tools have
329 significantly improved performance and monitoring capabilities.

330 Industrial applications across sectors—meat, seafood, dairy, produce—demonstrate
331 active and intelligent packaging's effectiveness in inhibiting microbial growth, preventing lipid
332 oxidation, and providing visual freshness indicators. These innovations reduce food waste,
333 environmental pollution, and reliance on plastics, aligning with sustainability goals.

334 Life cycle assessments confirm substantial environmental benefits, including reduced
335 carbon emissions and plastic waste. Future research must address raw material variability,
336 bioactive stability, scalability, regulatory frameworks, and consumer acceptance. Integrating
337 AI, IoT, and multifunctional bio-based materials will further accelerate commercialization.

338 Harnessing agri-food by-products for smart packaging offers a promising pathway
339 toward environmentally responsible, safe, and efficient food systems, fostering sustainable
340 industrial practices and global food security.

341 **Abbreviations**

342 ADI: acceptable daily intake

343 AFSC: agriculture and food supply chain

344 AI: artificial intelligence

345 BNC: bacterial nanocellulose

346 CNCs: cellulose nanocrystals

347 CNFs: cellulose nanofibrils

348 EE: Encapsulation efficiency

349 EFSA: European Food Safety Authority

350 EO: Essential oil

351 EU: European Union

352 FCMs: Food contact materials

353 FDA: Food and Drug Administration

354 IoT: Internet of Things

355 LCA: life cycle assessment

356 NIAS: non-intentionally added substances

357 OMW: Olive mill wastewater

358 PE: polyethylene

359 PET: polyethylene terephthalate

360 PP: polypropylene

361 RFID:

362 SDGs: sustainable development goals

363 SMLs specific migration limits

364 TDI: tolerable daily intake

365 TTI: time–temperature indicator

366 UN: United Nations

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373 The authors confirm that the data supporting the findings of this study are available within
374 the article.

375 **Clinical trial number**

376 Not applicable.

377 **Declarations**

378 **Ethics approval and consent to participate**

379 Not applicable.

380 **Consent for publication**

381 Not applicable.

382 **Competing interests**

383 The authors declare that they have no competing interests.

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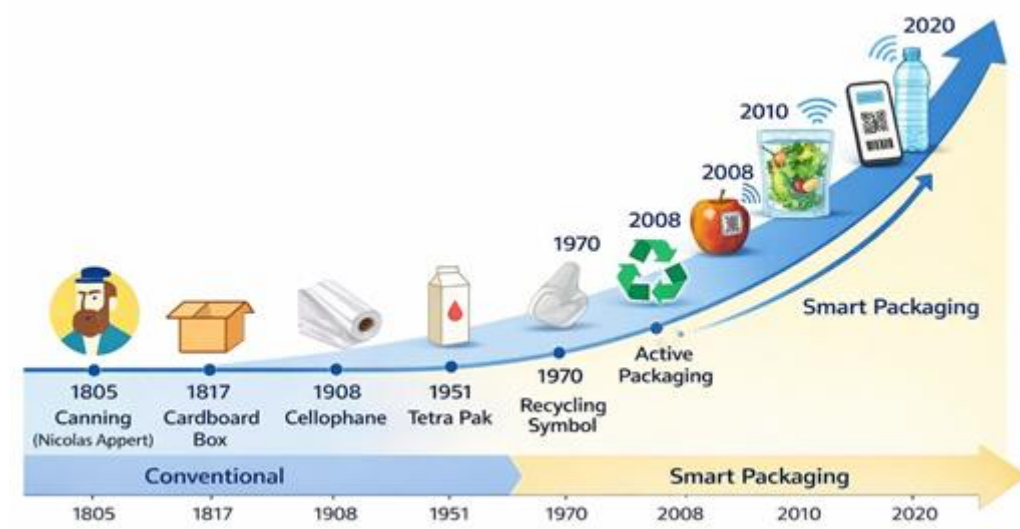
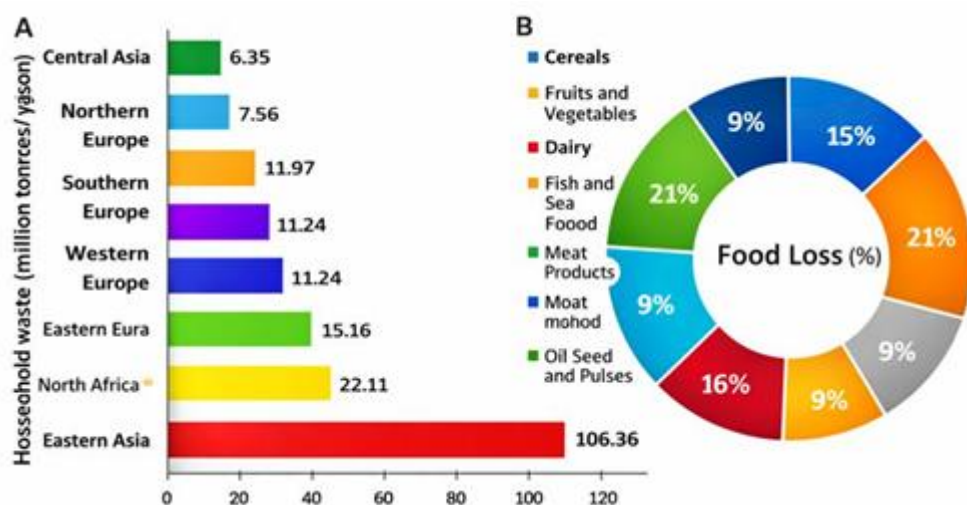
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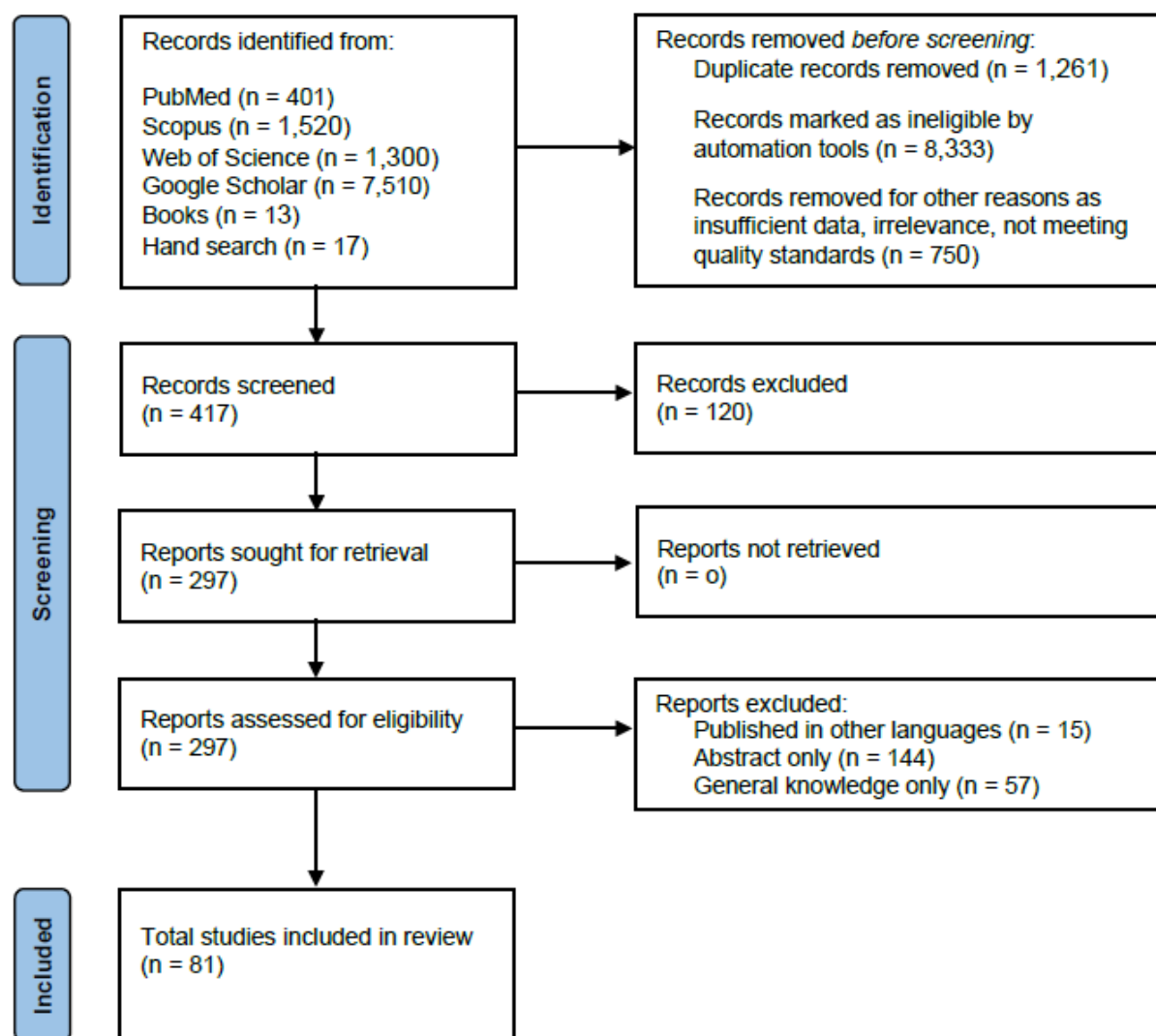
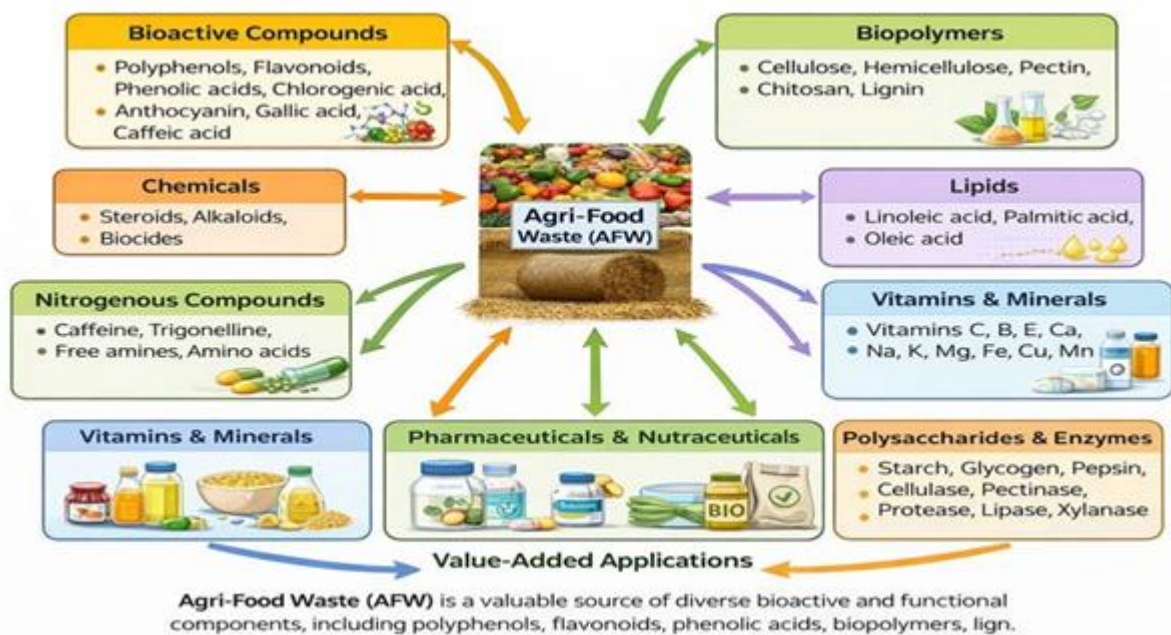


Fig. 3 PRISMA flow diagram including searches of databases and registers (2010-2026)

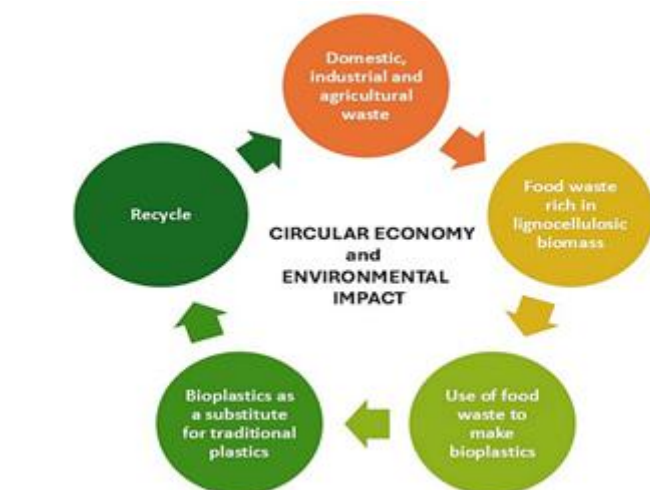




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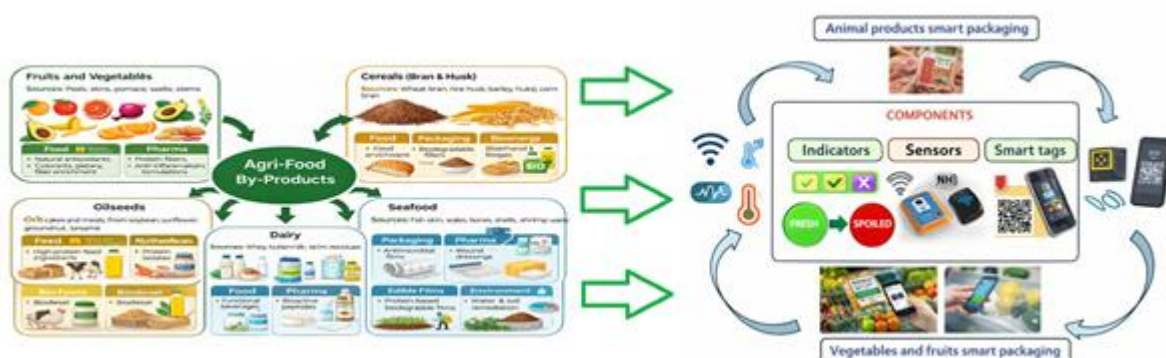
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