

# Emerging Technologies for Sustainable Food Innovation: Integrating Processing, Powder Engineering, Digitalisation, Circularity, and Sustainable Packaging

Nutsuda Sumonsiri\* and Ishak Ruzaina

School of Health and Life Sciences, Teesside University, Middlesbrough TS1 3BX, United Kingdom

\*Corresponding Author, E-mail: nutsudasumonsiri@gmail.com DOI: 10.14416/JASET.KMUTNB.2026.02.001

**Received** 14 July 2026; **Revised** 20 August 2026; **Accepted** 28 August 2026

## ABSTRACT

The food sector is under increasing pressure to improve productivity and food security while reducing resource consumption, food loss, waste, and environmental impacts. Emerging technologies are providing new approaches to address these challenges, but their contribution to sustainability depends on their technical performance, economic feasibility, and integration within the wider food system. This review examines recent advances in sustainable food innovation, focusing on five complementary areas: advanced food processing, powder engineering, circular food systems, digital transformation, and sustainable packaging. Technologies including high-pressure processing, pulsed electric fields, cold plasma, ultrasound, electrostatic powder coating, artificial intelligence, food-waste valorisation, and biodegradable and active packaging are discussed in relation to their effects on processing efficiency, resource use, product quality, and waste reduction. The review also considers the main barriers to wider adoption, including scale-up, investment costs, regulatory requirements, process integration, data availability, and variability in raw materials and processing conditions. Particular attention is given to the need for life cycle, techno-economic, and social assessment to determine whether improvements at individual processing stages translate into benefits at the food-system level. Future research should focus on integrating complementary technologies, developing data-driven and resource-efficient manufacturing systems, and improving the commercial viability of circular and sustainable solutions. Such an integrated approach can help move promising technologies from laboratory research towards practical applications that support more resilient, efficient, and sustainable food systems.

**KEYWORDS:** Sustainable food innovation, Emerging technologies, Food processing, Powder engineering, Circular economy

## 1. INTRODUCTION

The global food system is facing unprecedented challenges in ensuring food security while minimising environmental impacts and meeting evolving consumer expectations. Global food systems currently account for approximately one-third of anthropogenic greenhouse gas emissions, utilise around 70% of global freshwater withdrawals, and occupy nearly half of the world's habitable land, highlighting the substantial environmental footprint associated with food production (Cerutti et al., 2023; Knorr & Augustin, 2025; Wisser et al., 2024). Rapid population growth, urbanisation, climate change, diminishing natural resources, and increasing pressure on agricultural production have intensified the need for innovative approaches to food production and processing. According to the United Nations, the global population is projected to reach approximately 9.7 billion by 2050, increasing global food demand by an estimated 50–60% compared with current production levels (Hussain et al., 2025; Oluwole et al., 2023). Meeting this demand while reducing environmental impacts represents one of the greatest challenges facing modern food systems. Consequently, sustainability has become a central objective throughout the food supply chain, encompassing agricultural production, food manufacturing, distribution, consumption, and waste management.

In recent years, sustainable food innovation has emerged as an important response to these pressures. It extends beyond the development of new food products to consider how foods are sourced, processed, packaged, distributed, consumed, and ultimately disposed of. The aim is to use resources more efficiently, reduce environmental impacts, maintain nutritional and sensory quality, and minimise food loss. At the

same time, manufacturers are responding to growing interest in healthier foods, clean-label products, minimally processed ingredients, and more environmentally responsible production practices. These expectations are increasingly influencing product development and processing decisions across the food sector (Balasubramaniam et al., 2023).

Emerging technologies are central to this transition. Developments in food processing, materials science, biotechnology, digitalisation, and engineering are giving manufacturers new ways to improve process efficiency without compromising food quality. Technologies such as high-pressure processing, pulsed electric fields, cold plasma, ultrasound, ohmic heating, and microwave-assisted processing provide alternatives to conventional thermal treatments, with potential benefits for microbial safety, product quality, processing time, and energy use (Srivastava & Sit, 2025). At the same time, artificial intelligence (AI), machine learning, digital twins, and smart sensing are being used to monitor processes, support quality control, and improve resource management (Ding et al., 2023).

Alongside advances in processing technologies, innovations in powder engineering have gained increasing attention owing to their broad applications across the food industry. Powder-based ingredients are widely utilised in snack seasonings, dairy products, beverages, nutritional supplements, and functional food formulations, where particle characteristics and adhesion behaviour significantly influence manufacturing efficiency, product quality, and ingredient utilisation. Emerging technologies such as electrostatic powder coating provide promising approaches to improving powder transfer efficiency, enhancing seasoning adhesion, reducing ingredient losses, and facilitating the development of

healthier food products with lower salt and fat contents (Sumonsiri & Barringer, 2024). Such innovations demonstrate how engineering solutions can simultaneously improve product performance and contribute to more sustainable manufacturing practices through reduced material waste and improved process efficiency.

Another important pillar of sustainable food innovation is the transition towards circular food systems. Approximately one-third of food produced globally is lost or wasted throughout the supply chain, representing substantial losses of resources, energy, and economic value (Heydari, 2024). Consequently, increasing emphasis has been placed on the valorisation of agricultural by-products and food processing residues into high-value ingredients, bioactive compounds, functional food ingredients, biodegradable packaging materials, and renewable biomaterials. Emerging extraction technologies, biorefinery approaches, and novel biomaterial engineering have expanded opportunities to transform food waste streams into valuable resources, thereby supporting circular economy principles and reducing environmental burdens (Panda et al, 2024).

Sustainable food innovation also extends beyond food production to encompass packaging and distribution systems. Growing concerns regarding plastic pollution and carbon emissions have accelerated research into biodegradable polymers, edible coatings, active packaging, intelligent packaging, and bio-based composite materials (Murugesan & Li, 2026). These innovations aim not only to reduce dependence on petroleum-based plastics but also to improve food preservation, minimise spoilage, and extend product shelf life. The integration of sustainable packaging with advanced food processing technologies represents

an increasingly important strategy for reducing the overall environmental impact of food systems.

Despite remarkable technological progress, several challenges continue to limit the widespread adoption of emerging technologies within the food industry. High capital investment, technological complexity, regulatory approval processes, scalability, consumer acceptance, and integration into existing manufacturing systems remain significant barriers. Furthermore, evaluating sustainability requires a systems-level perspective that considers environmental, economic, and social dimensions throughout the entire food value chain (Alamandi, 2025). Future innovations must therefore balance technological feasibility with commercial viability, regulatory compliance, and societal expectations to achieve meaningful and lasting impacts.

This review critically examines recent advances in emerging technologies that are driving sustainable food innovation, with particular emphasis on novel food processing technologies, powder engineering, circular food systems through food waste valorisation, digital transformation, and sustainable packaging. In addition to discussing current applications and sustainability benefits, the review highlights existing challenges, knowledge gaps, and future research directions. By integrating perspectives from food engineering, material science, and sustainable manufacturing, this review aims to provide a comprehensive overview of how emerging technologies can contribute to the development of resilient, resource-efficient, and environmentally sustainable food systems.

## **2. SUSTAINABLE FOOD INNOVATION**

### ***2.1 Concept and Drivers of Sustainable Food Innovation***

Sustainability is now an important consideration in the development of food products and manufacturing processes. Conventional food production has traditionally placed strong emphasis on productivity, yield, and economic return, while environmental pressures and resource constraints have broadened the criteria used to judge innovation (Galanakis, 2024). The food and beverage sector is also energy intensive, accounting for approximately 30% of industrial energy consumption in many developed economies (Corigliano et al., 2025). Improving the efficiency of food processing therefore offers a practical route to reducing environmental impacts. Sustainable food innovation encompasses not only new products, but also changes in processing, packaging, distribution, and consumption that can improve environmental performance while remaining economically viable and socially beneficial.

The concept of sustainable food innovation is closely aligned with the three pillars of sustainability—environmental protection, economic prosperity, and social responsibility. Environmentally, food innovation seeks to reduce greenhouse gas emissions, conserve water and energy resources, minimise food loss and waste, and decrease reliance on non-renewable materials. Economically, innovations should improve production efficiency, enhance resource utilisation, and generate value throughout the food supply chain. Socially, sustainable innovation aims to improve food security, nutrition, consumer health, and equitable access to safe and affordable foods (Çakmakçı et al., 2023). Consequently, successful food innovation requires balancing these interconnected dimensions rather than optimising a single objective.

Several global initiatives have accelerated the transition towards sustainable food systems. The

United Nations Sustainable Development Goals (SDGs), particularly Zero Hunger (SDG 2), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), and Life Below Water (SDG 14), have provided strategic frameworks that encourage governments, industries, and researchers to develop sustainable solutions throughout the food value chain (Jacob-John et al., 2021). Simultaneously, increasing corporate commitments towards carbon neutrality and circular economy principles have further stimulated investment in innovative food technologies and sustainable manufacturing practices.

Consumer expectations are another important driver of food innovation. There is growing interest in foods that are nutritious, minimally processed, clean-label, and produced with greater consideration for environmental impacts (Balasubramaniam et al., 2023). This has contributed to increased interest in plant-based foods, functional ingredients, sustainable packaging, and processing technologies that use resources more efficiently (Golshany et al., 2026). Sustainability is therefore becoming increasingly relevant to product development and market positioning, rather than being treated solely as an environmental consideration.

## ***2.2 Pillars of Sustainable Food Innovation***

Sustainable food innovation encompasses multiple interconnected domains throughout the food system. These domains extend beyond product formulation and include technological innovations that improve efficiency, reduce environmental impacts, and enhance resource utilisation across the entire food value chain.

The first pillar is sustainable food processing, which focuses on improving manufacturing efficiency while maintaining food safety and nutritional

quality. Conventional thermal processing often requires substantial energy inputs and may negatively affect heat-sensitive nutrients and sensory characteristics (Srivastava & Sit, 2025). Consequently, considerable research has been directed towards developing alternative processing technologies that reduce energy consumption while preserving product quality.

The second pillar involves sustainable ingredients and product development. This includes reformulation strategies to reduce salt, sugar, and saturated fat without compromising sensory quality (Onyeaka et al., 2023), as well as the incorporation of functional ingredients derived from sustainable sources (Teixé-Roig et al., 2023). Advances in ingredient functionality and powder engineering have enabled the development of healthier food products with improved ingredient utilisation and reduced manufacturing losses.

A third pillar is the transition towards circular food systems, where agricultural by-products and food processing residues are viewed as valuable resources rather than waste. Valorisation strategies convert these materials into functional food ingredients, nutraceuticals, biodegradable packaging materials, animal feeds, and bio-based chemicals (Boudalia et al., 2026). Such approaches simultaneously reduce waste generation and create new economic opportunities while supporting circular economy principles.

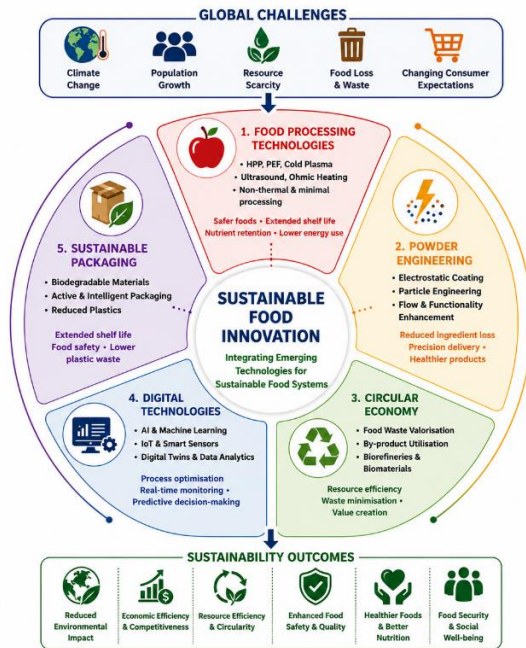
Another increasingly important pillar is digital transformation, encompassing artificial intelligence, machine learning, big data analytics, Internet of Things (IoT) technologies, and digital twins. These technologies facilitate real-time process monitoring, predictive maintenance, quality optimisation, supply chain transparency, and precision manufacturing, thereby improving both productivity and sustainability (Rahmani et al., 2024).

Finally, sustainable packaging innovation has become essential for reducing environmental impacts associated with food preservation and distribution. Research efforts increasingly focus on biodegradable polymers, edible coatings, bio-based composites, active packaging, and intelligent packaging systems capable of extending shelf life while reducing reliance on conventional petroleum-based plastics (Dutta & Sit, 2024).

These areas are closely connected in practice. For example, a more efficient processing method may reduce energy use, but its overall sustainability will also depend on ingredient utilisation, packaging, waste management, and the resources required elsewhere in the supply chain. Similarly, digital process optimisation can support better control of processing and powder application, while packaging and by-product valorisation can help reduce losses after production. Considering these interactions is therefore important when evaluating the overall contribution of emerging technologies to sustainable food systems.

### ***2.3 Measuring Sustainability in Food Innovation***

The sustainability of food innovations cannot be assessed solely based on technological performance or product quality. Comprehensive evaluation requires consideration of environmental, economic, and social impacts throughout the product life cycle (Marques et al., 2025). Consequently, life cycle assessment (LCA) has become one of the most widely adopted methodologies for quantifying environmental impacts associated with food production, including greenhouse gas emissions, energy consumption, water use, land use, and waste generation. For example, LCA enables quantification of greenhouse gas emissions (kg CO<sub>2</sub>-equivalent), energy demand (MJ), water footprint (m<sup>3</sup>), land use (m<sup>2</sup>), and waste generation across the entire food life cycle (D'Agaro



**Figure 1** Integrated framework illustrating how emerging technologies collectively advance sustainable food innovation.

et al., 2021), providing a comprehensive basis for comparing emerging technologies.

Environmental performance is only one part of the assessment. Techno-economic analysis (TEA) can be used to examine capital investment, operating costs, productivity, and scalability, while social considerations include food safety, nutritional quality, consumer acceptance, affordability, and ethical issues (Vickram et al., 2025; Biesbroek et al., 2023). Considering these factors together can reveal trade-offs that may not be apparent when a technology is assessed on processing performance alone. A process that uses less energy, for example, may still be unattractive if its capital cost is prohibitive or if it requires substantial changes to existing production infrastructure.

Despite substantial progress, evaluating sustainability remains challenging due to the complexity of food systems and the trade-offs that often exist between different sustainability dimensions. Technologies that reduce energy consumption may require high capital investment,

while biodegradable packaging materials may present limitations in barrier performance or shelf-life extension (Panou & Karabagias, 2023). Similarly, highly efficient processing technologies may face regulatory hurdles or consumer scepticism, particularly when they involve novel manufacturing methods. These considerations highlight the importance of adopting holistic and systems-based approaches when designing and implementing sustainable food innovations.

Collectively, these five technological domains provide a comprehensive framework for advancing sustainable food innovation by integrating engineering, digitalisation, circular resource management, and environmentally responsible packaging to improve food quality, manufacturing efficiency, and sustainability outcomes. The relationships between these technological pillars and their contributions to sustainable food systems are illustrated in Figure 1.

### 3. EMERGING TECHNOLOGIES IN SUSTAINABLE FOOD INNOVATION

Technological development is changing how food products are processed, formulated, monitored, and packaged. Recent advances in food engineering, materials science, biotechnology, and digital technologies have created alternatives to conventional processes and provided new opportunities to improve efficiency and reduce resource use (Alam et al., 2025). The technologies discussed in this section differ considerably in their maturity and applications, but they share a common objective: to improve food production while addressing one or more environmental, economic, or social sustainability concerns (Gavahian, 2024).

### 3.1 Novel Food Processing Technologies

Food processing plays a fundamental role in ensuring food safety, extending shelf life, and improving product functionality. However, conventional thermal processing methods often involve prolonged heating, leading to high energy consumption and undesirable changes in nutritional value, flavour, texture, and colour (Srivastava & Sit, 2025). Consequently, considerable research has focused on developing non-thermal and advanced thermal technologies capable of maintaining food quality while improving process sustainability.

Among these technologies, high-pressure processing (HPP) has become one of the most commercially established non-thermal preservation methods. HPP applies hydrostatic pressures typically ranging from 300 to 600 MPa to inactivate microorganisms and certain enzymes without requiring high temperatures (Abera, 2019). Because pressure is transmitted uniformly throughout the food matrix, products retain their nutritional quality, fresh flavour, colour, and texture more effectively than conventionally heat-treated foods. HPP has been widely adopted for fruit juices, ready-to-eat meats, seafood, dairy products, and fresh produce, contributing to reduced food spoilage and extended shelf life (Nema et al., 2022).

Another promising technology is pulsed electric field (PEF) processing, which utilises short high-voltage electrical pulses to permeabilise microbial and cellular membranes (Gao et al., 2026). Besides microbial inactivation, PEF enhances mass transfer processes, improving extraction efficiency, drying performance, and juice yield while reducing processing time and energy consumption. Studies have demonstrated improvements in juice extraction yields by approximately 35–40%, while drying (or extraction) times may be reduced by 60–80% compared with conventional processing

methods, depending on the food matrix and the target compounds (Chatzimitakos et al., 2023). Its ability to preserve heat-sensitive nutrients has attracted increasing interest in fruit and vegetable processing.

Cold plasma technology has emerged as an environmentally friendly approach for surface decontamination (Katsigiannis et al., 2022). Reactive oxygen and nitrogen species generated within plasma effectively inactivate microorganisms while requiring minimal water and chemical inputs. Cold plasma has shown considerable potential for fresh produce, grains, packaging materials, and food contact surfaces. Microbial reductions of approximately 1.5 to 3.5 log CFU have been reported for various fresh-produce applications without the use of chemical disinfectants (Pignata et al., 2017). Although industrial implementation remains limited by equipment design and regulatory considerations, the technology offers significant opportunities for sustainable sanitation.

Other innovative technologies, including ultrasound, ohmic heating, and microwave-assisted processing, have also demonstrated considerable sustainability advantages. Ultrasound enhances extraction, emulsification, drying, and freezing processes through acoustic cavitation, reducing processing times and improving energy efficiency. Ultrasound-assisted extraction has been shown to reduce extraction times by up to 90% while decreasing solvent consumption by between 25% and 50%, depending on the food matrix and target compounds (Linares & Rojas, 2022). Ohmic heating enables rapid and uniform volumetric heating by passing electrical currents directly through food materials, thereby reducing thermal gradients and improving product quality (Javed et al., 2025). Microwave-assisted processing provides rapid internal heating that shortens cooking and drying

times while lowering overall energy consumption compared with conventional heating methods (Ekezie et al., 2017).

Despite these advantages, several challenges continue to hinder widespread industrial adoption. High capital investment, equipment standardisation, process validation, and regulatory approval remain significant barriers (Alamandi, 2025), particularly for small- and medium-sized enterprises. Furthermore, optimisation of processing parameters for different food matrices requires continued research to maximise sustainability benefits while maintaining food quality and consumer acceptance.

### ***3.2 Powder Engineering and Electrostatic Coating Technologies***

Powder ingredients are widely used throughout the food industry, from seasonings and flavourings to milk powders, beverage mixes, nutritional supplements, spices, and bakery premixes. Their behaviour during handling and application depends on properties such as particle size, morphology, density, moisture content, surface characteristics, and electrostatic charge (Sumonsiri & Barringer, 2024). These properties affect flowability, segregation, adhesion, dust generation, and ultimately the amount of ingredient that reaches the intended product surface. Powder engineering therefore provides an important means of improving material utilisation and process consistency.

One of the major challenges associated with powder application is poor adhesion efficiency. Conventional seasoning systems often rely on mechanical tumbling, where a considerable proportion of powder fails to adhere to the product surface and is subsequently lost during processing (Sumonsiri & Barringer, 2024). Such losses increase

raw material consumption, cleaning requirements, and production costs while generating unnecessary food waste.

Electrostatic powder coating (EPC) has emerged as a promising technology for improving powder deposition efficiency. By electrically charging powder particles and applying an opposite charge or grounded surface to the food product, electrostatic attraction enhances particle adhesion and promotes more uniform coating distribution (Barringer & Sumonsiri, 2015). Compared with conventional seasoning methods, EPC can substantially improve transfer efficiency, reduce overspray losses, and achieve desired flavour intensity using smaller quantities of seasoning. Electrostatic coating, influenced by powder characteristics, processing parameters, and surface properties of the product, has been shown to enhance powder transfer efficiency by roughly 20–50%, thereby minimising ingredient loss and improving overall coating performance (Sumonsiri & Barringer, 2024).

Beyond improving manufacturing efficiency, electrostatic coating offers several sustainability advantages. Enhanced particle adhesion reduces ingredient losses, minimises airborne powder emissions, and lowers cleaning requirements, thereby improving both material utilisation and workplace hygiene (Likitwattanasade & Barringer, 2015). More precise powder deposition also supports product reformulation by enabling targeted delivery of salt, sugar, flavourings, and functional ingredients while maintaining desirable sensory attributes. Consequently, electrostatic coating not only improves process efficiency but also contributes to healthier product development and more sustainable manufacturing practices (Sumonsiri et al., 2020; Sumonsiri & Barringer, 2024).

Recent developments in particle engineering have further expanded the capabilities of electrostatic coating. Optimisation of particle size distribution, particle morphology, moisture content, and surface charge characteristics can significantly improve powder flowability and deposition behaviour (Suhag et al., 2024). The integration of electrostatic coating with computational modelling, image analysis, and machine learning offers additional opportunities for process optimisation and quality prediction (Dávalos-Saucedo et al., 2026).

Although electrostatic coating has demonstrated considerable promise, several technical challenges remain. Product geometry, surface roughness, humidity, powder composition, and environmental conditions all influence electrostatic charging behaviour and coating efficiency. Furthermore, scale-up from laboratory systems to industrial production requires robust process control strategies to ensure consistent product quality (Song et al., 2025). Continued interdisciplinary research combining food engineering, materials science, and process automation will be essential for maximising the commercial potential of this technology.

### ***3.3 Circular Food Systems and Food Waste Valorisation***

The transition from linear production models towards circular food systems represents a fundamental shift in sustainable food innovation. Rather than treating food processing residues as waste, circular approaches seek to recover valuable components and reintroduce them into the food value chain (Rizwan et al., 2025). This strategy not only reduces environmental impacts but also generates additional economic value from underutilised resources.

Numerous agricultural by-products, including fruit peels, vegetable residues, cereal bran, brewer's spent grain, coffee grounds, seafood shells, and seaweed biomass, contain valuable dietary fibre, proteins, bioactive compounds, pigments, antioxidants, and polysaccharides (Boruah & Ray, 2024). Globally, fruit and vegetable processing alone generates approximately 25–30% by-product biomass (Ray et al., 2025), much of which remains underutilised despite containing valuable dietary fibre, proteins, polyphenols, pigments, and other bioactive compounds. Advances in extraction technologies—including ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, and enzyme-assisted extraction—have significantly improved the recovery of these high-value compounds while reducing solvent usage and energy consumption (Díaz-de-Cerio & Trigueros, 2025).

Recovered materials can be incorporated into functional foods, nutraceuticals, natural preservatives, biodegradable packaging materials, and biomaterials, supporting both product innovation and waste reduction (Hossain et al., 2026). For example, seaweed-derived polysaccharides have attracted increasing attention for the development of biodegradable films and edible coatings, while seafood processing by-products provide valuable sources of chitosan, collagen, and bioactive peptides with applications in food preservation and packaging (Sousa et al., 2025).

Despite substantial progress, the successful implementation of circular food systems requires overcoming technical, regulatory, and economic barriers. Variability in raw material composition, collection logistics, consumer acceptance, and standardisation of extraction processes continue to limit large-scale commercialisation (Ligarda-Samanez et al., 2025). Future research should

therefore focus on integrated biorefinery approaches capable of maximising resource recovery while maintaining economic feasibility.

### ***3.4 Digital Technologies and Smart Food Manufacturing***

Digitalisation is rapidly transforming food manufacturing by enabling data-driven decision-making and intelligent process optimisation. The integration of artificial intelligence (AI), machine learning (ML), Internet of Things (IoT) devices, cloud computing, digital twins, and advanced sensing technologies has facilitated the emergence of smart food factories capable of continuously monitoring production processes in real time (Ding et al., 2023). Machine learning algorithms can analyse large datasets generated during food manufacturing to predict product quality, optimise process parameters, detect equipment faults, and minimise production variability (Ding et al., 2023). Recent studies have reported prediction accuracies exceeding 90–95% for quality classification, shelf-life prediction, and process optimisation using machine learning algorithms (Melikoglu, 2026). AI-assisted product formulation further enables the rapid identification of ingredient combinations that satisfy nutritional, sensory, economic, and sustainability objectives simultaneously (Datta et al., 2026).

Digital twins—virtual representations of physical manufacturing systems—offer new opportunities for process simulation, optimisation, and predictive maintenance without disrupting industrial production (Corradini et al., 2024). Combined with IoT-enabled sensors, these technologies improve traceability, resource management, and energy efficiency while supporting more responsive manufacturing systems. Nevertheless, widespread adoption remains constrained by data integration challenges, cybersecurity concerns, infrastructure

investment, and workforce training requirements (Iranshahi et al., 2025). Establishing standardised digital platforms and improving interoperability between manufacturing systems will be essential for fully realising the sustainability benefits of Industry 4.0 technologies.

### ***3.5 Sustainable Packaging Technologies***

Packaging plays a critical role in maintaining food quality, reducing spoilage, and ensuring safe distribution throughout increasingly complex food supply chains. However, conventional petroleum-based plastics have raised significant environmental concerns due to their persistence in ecosystems and contribution to global plastic pollution (Yin & Woo, 2024). Consequently, considerable research has focused on developing sustainable alternatives that combine environmental benefits with effective food protection.

Bio-based polymers derived from renewable resources, including starch, cellulose, proteins, chitosan, alginate, and seaweed polysaccharides, have shown considerable potential as biodegradable packaging materials (Gamage et al., 2024). Recent advances have also enabled the development of active packaging, capable of releasing antimicrobial or antioxidant compounds, and intelligent packaging, incorporating sensors that monitor freshness, temperature, or gas composition throughout storage and distribution (Mkhari et al., 2025). Although biodegradable materials continue to improve, challenges relating to mechanical performance, moisture sensitivity, industrial scalability, regulatory compliance, and end-of-life management remain significant (Murugesan & Li, 2026). Future developments should focus on designing packaging systems that balance functionality, environmental performance, and economic viability while integrating seamlessly with emerging food processing and circular

**Table 1** Comparison of emerging technologies supporting sustainable food innovation.

| Technology                   | Sustainability contribution   | Major Challenge      |
|------------------------------|-------------------------------|----------------------|
| HPP                          | Longer shelf life             | High investment      |
| PEF                          | Higher extraction efficiency  | Mainly liquids       |
| Cold plasma                  | Chemical-free decontamination | Regulatory approval  |
| Ultrasound                   | Faster extraction             | Scale-up             |
| Electrostatic powder coating | Reduced ingredient loss       | Humidity sensitivity |
| AI                           | Process optimisation          | Data quality         |
| Packaging                    | Reduced plastic waste         | Barrier properties   |

manufacturing technologies. Although each technological domain offers distinct advantages, their greatest potential lies in their integration across the food value chain, as illustrated conceptually in Figure 1.

Although each emerging technology offers distinct advantages for improving sustainability, their levels of technological maturity, industrial application, and implementation challenges vary considerably. A comparative summary of the principal technologies, their sustainability contributions, representative food applications, and current limitations is presented in Table 1, highlighting both their potential and the barriers to wider industrial adoption.

#### 4. CHALLENGES IN IMPLEMENTING EMERGING TECHNOLOGIES FOR SUSTAINABLE FOOD INNOVATION

Despite significant advances in emerging technologies, their widespread adoption within the food industry remains constrained by several scientific, technological, economic, and societal challenges. While many technologies have demonstrated promising results at laboratory and pilot scales, translating these innovations into commercially viable solutions requires overcoming

numerous barriers related to scalability, investment, regulatory compliance, consumer acceptance, and systems integration. Addressing these challenges is essential to fully realise the potential of emerging technologies in supporting sustainable food systems.

##### 4.1 Technological and Scale-Up Challenges

One of the primary challenges associated with emerging food technologies is the successful transition from laboratory-scale research to industrial-scale implementation (Šuput et al., 2026). Many technologies demonstrate excellent performance under controlled experimental conditions but encounter significant limitations when applied to commercial manufacturing environments. Differences in production capacity, equipment design, product variability, and process stability often result in reduced efficiency and increased operational complexity during scale-up. For example, the effectiveness of non-thermal technologies such as pulsed electric field processing, cold plasma, and ultrasound is highly dependent on product characteristics, including composition, moisture content, electrical conductivity, and structural properties (Yuan et al., 2026). Similarly, electrostatic powder coating performance is influenced by particle size distribution, surface morphology, electrostatic charge density, ambient humidity, and product geometry (Sumonsiri & Barringer, 2024). Maintaining consistent process performance under continuously changing industrial conditions therefore requires robust process control systems and extensive optimisation.

Another challenge involves the limited availability of standardised equipment and operating protocols. Many emerging technologies continue to rely on customised laboratory-scale systems that differ substantially from commercial production

equipment (Martínez-Monteagudo et al., 2017). The absence of harmonised operating standards makes direct comparison between studies difficult and slows industrial adoption. Future research should therefore place greater emphasis on technology validation under realistic manufacturing conditions and the development of standardised methodologies that facilitate industrial implementation.

#### ***4.2 Economic and Industrial Adoption***

Although emerging technologies often provide long-term sustainability benefits, their adoption is frequently constrained by economic considerations. Advanced processing equipment, automation systems, and digital manufacturing platforms typically require substantial capital investment, which may be difficult to justify, particularly for small- and medium-sized enterprises (SMEs) (Ndiata et al., 2025). Additional costs associated with equipment maintenance, staff training, process validation, and infrastructure upgrades further increase implementation barriers. The economic benefits of sustainable technologies are not always immediately apparent. While technologies such as high-pressure processing or electrostatic coating may reduce ingredient losses, improve product quality, or extend shelf life, the financial return on investment often depends on production scale, product value, and operational efficiency. Consequently, comprehensive techno-economic analyses should accompany technological development to evaluate commercial feasibility alongside environmental performance.

Industrial adoption is also influenced by compatibility with existing production systems. Many food manufacturers operate established processing lines designed around conventional technologies, making the integration of new

equipment technically challenging and economically disruptive (Galanakis, 2024). Modular technologies capable of being incorporated into existing manufacturing infrastructure may therefore facilitate more rapid industrial uptake than technologies requiring complete production line redesign.

#### ***4.3 Regulatory and Consumer Acceptance***

The successful commercialisation of emerging food technologies depends not only on technical performance but also on regulatory approval and consumer acceptance (Lisboa et al., 2024). Food safety authorities require comprehensive scientific evidence demonstrating that novel technologies consistently produce safe foods without compromising nutritional quality or generating unintended chemical or microbiological risks. Obtaining regulatory approval can therefore be both time-consuming and resource-intensive, particularly for technologies involving new processing mechanisms or packaging materials.

Consumer perception represents an equally important determinant of market success. Although sustainability has become an increasingly influential purchasing criterion, consumers may remain hesitant to accept foods produced using unfamiliar technologies. Terms such as cold plasma, nanotechnology, or artificial intelligence may generate uncertainty despite the scientific evidence supporting their safety and benefits. Transparent communication, effective risk assessment, and public education will therefore play essential roles in improving consumer confidence and encouraging acceptance of innovative food technologies (Meijer, et al., 2021). Furthermore, sustainability claims must be supported by robust scientific evidence. Consumers increasingly expect food manufacturers to demonstrate measurable environmental benefits rather than relying on broad or

**Table 2** Key research challenges and future directions for sustainable food innovation.

| Area                      | Current challenge     | Future direction              |
|---------------------------|-----------------------|-------------------------------|
| <b>Food processing</b>    | Scale-up              | Integrated processing         |
| <b>Powder engineering</b> | Process variability   | AI-assisted coating           |
| <b>Circular economy</b>   | Feedstock variability | Biorefineries                 |
| <b>Digitalisation</b>     | Data integration      | Digital twins                 |
| <b>Packaging</b>          | Barrier properties    | Smart biodegradable materials |

unsubstantiated marketing claims. Consequently, life cycle assessment (LCA), environmental product declarations, and transparent sustainability reporting are becoming increasingly important components of technology commercialisation.

#### ***4.4 Towards Integrated and Systems-Based Food Innovation***

Most emerging technologies are developed to address a particular processing or manufacturing problem. Their contribution to sustainability, however, depends on what happens before and after that individual process. For example, combining advanced processing with digital monitoring, precision powder engineering, by-product valorisation, and sustainable packaging could reduce losses at several stages of the food value chain rather than improving only one operation (Ligarda-Samanez et al., 2025). This broader perspective also calls for collaboration between food scientists, engineers, materials scientists, data specialists, economists, policymakers, and industry. Such collaboration is needed to ensure that improvements in technical performance are compatible with cost, regulation, environmental performance, and practical manufacturing requirements.

Sustainability assessments should likewise consider more than the individual manufacturing operation. Raw material sourcing, transport, packaging,

consumer use, and end-of-life treatment can all influence the overall environmental performance of a food product. Assessing these stages together can help identify where a technological improvement delivers a genuine system-level benefit and where it may simply shift an environmental burden from one stage of the supply chain to another.

### **5. FUTURE PERSPECTIVES**

The next stage of sustainable food innovation will depend less on developing individual technologies and more on how well they can be combined and implemented. Progress has already been made in advanced processing, powder engineering, digital manufacturing, circular resource use, and sustainable packaging, but these developments are often considered separately. Future research should therefore examine how complementary technologies can work together to improve production efficiency and product quality while reducing environmental impacts and maintaining economic viability (Galanakis, 2024).

The AI and machine learning are likely to have a growing role across the food value chain. Current applications include process optimisation, quality prediction, equipment monitoring, and decision support, with the potential to reduce production variability and improve the use of energy and raw materials (Yang et al., 2025). As sensor networks and Internet of Things (IoT) systems become more widely connected, digital twins could allow manufacturers to test process changes and predict production outcomes before making changes to the physical system (Corradini et al., 2024; Rahmani et al., 2024). The main challenge will be moving these applications beyond isolated demonstrations towards reliable systems that can operate with real

industrial data and existing manufacturing infrastructure.

Precision food engineering offers another route to improving the efficiency of ingredient use and product formulation. Controlling ingredient functionality, processing conditions, and product structure at smaller length scales can help tailor nutritional, sensory, and functional properties to specific applications (Hailu et al., 2026). In this context, electrostatic coating could support more controlled deposition of flavours, micronutrients, and other functional ingredients while reducing losses during application (Sumonsiri & Barringer, 2024). Further work is needed to establish how such precision approaches can be incorporated into commercial reformulation strategies, particularly where reductions in salt, sugar, or fat must be achieved without compromising consumer acceptance.

Food by-products are likely to become increasingly important feedstocks as manufacturers look for ways to recover more value from existing resources. Residues from agricultural and food-processing operations can be processed into ingredients, bioactive compounds, biomaterials, and packaging components, but the economic case depends on the consistency, availability, and cost of the feedstock as well as the efficiency of the recovery process (Ligarda-Samanez et al., 2025). Future work should therefore move towards integrated biorefinery systems that can recover several products from the same biomass stream rather than relying on a single high-value compound.

Packaging development will also need to keep pace with changes in food processing and product formulation. Biodegradable materials are increasingly being combined with active and intelligent functions, such as antimicrobial agents,

freshness indicators, gas sensors, and digital traceability (Mkhari et al., 2025). These systems could provide benefits beyond replacing conventional plastics by helping to monitor product condition and reduce spoilage. However, their practical value will depend on achieving adequate barrier and mechanical properties, compatibility with food-processing conditions, regulatory approval, and appropriate end-of-life options (Murugesan & Li, 2026).

Future studies should also assess technologies at the food-system level rather than focusing only on individual processing steps. Life cycle assessment (LCA), techno-economic analysis (TEA), and social life cycle assessment (S-LCA) can be combined to examine environmental impacts, economic feasibility, and social consequences across the life cycle (Engel-Cox et al., 2022). This is particularly important when technologies involve trade-offs—for example, when a process reduces energy consumption but requires more expensive equipment, or when a biodegradable packaging material performs well environmentally but provides a shorter shelf life.

Technology development alone will not be sufficient to bring these innovations into routine industrial use. Researchers need to work with manufacturers, regulators, policymakers, and other stakeholders to address practical issues such as process validation, regulatory requirements, workforce skills, investment, and consumer communication. Early collaboration between these groups could also help identify commercial and regulatory constraints before technologies reach the later stages of development, improving the prospects for successful scale-up.

Taken together, these developments point towards a food manufacturing sector in which processing, formulation, digital monitoring, resource recovery,

and packaging are considered as connected parts of the same system. The challenge is to determine which combinations of technologies provide meaningful benefits under real production conditions, rather than assuming that adding more technology will automatically improve sustainability. Research that combines technical performance with life cycle, economic, and social assessment will be particularly valuable in guiding these decisions. The main research priorities identified from this perspective are summarised in Table 2.

## 6. CONCLUSIONS

Food production is under increasing pressure to improve efficiency and resilience while reducing its environmental footprint. The technologies discussed in this review show that these objectives can be approached through changes in processing, ingredient application, resource recovery, digital manufacturing, and packaging. Their sustainability benefits, however, depend on how they are designed, implemented, and assessed within the wider food system.

The review shows that emerging technologies can address different points along the food value chain. Advanced processing can improve preservation and processing efficiency; powder engineering can increase the precision of ingredient application; valorisation can turn processing residues into useful products; digital tools can support process monitoring and optimisation; and new packaging materials can help maintain quality while reducing reliance on conventional plastics. Considered together, these approaches offer greater potential for sustainable food production than any single technology considered in isolation.

The main barriers are no longer limited to technical performance. Cost, scale-up, regulatory requirements, compatibility with existing manufacturing systems, and consumer acceptance can all determine whether a promising laboratory technology succeeds commercially. Addressing these issues will require closer interaction between researchers, manufacturers, regulators, and policymakers, together with sustainability assessments that capture environmental, economic, and social outcomes rather than relying on a single performance indicator.

The long-term contribution of emerging technologies will depend on their successful integration across the food value chain. Advances in food engineering, digital technologies, biotechnology, materials science, and circular resource management can provide the building blocks for more resilient and resource-efficient food systems, but their benefits must be demonstrated under realistic technical, economic, and environmental conditions. Continued collaboration across academia, industry, and policy will be essential to move promising technologies from research into practice and to ensure that innovation contributes to the production of safe, nutritious, affordable, and environmentally responsible foods.

## REFERENCES

- Abera, G. (2019). Review on high-pressure processing of foods. *Cogent Food & Agriculture*, 5(1), 1568725. <https://doi.org/10.1080/23311932.2019.1568725>
- Alamandi, M. (2025). Sustainable innovation management: balancing economic growth and environmental responsibility. *Sustainability*, 17(10), 4362. <https://doi.org/10.3390/su17104362>
- Alam, M.W., Kumar, J.V., & Awad, M., et al. (2025). Emerging trends in food process engineering: integrating sensing technologies for health, sustainability, and consumer preferences. *Journal of Food Process Engineering*, 48, e70035. <https://doi.org/10.1111/jfpe.70035>
- Balasubramaniam, V. M., Lee, J., & Serventi, L. (2023). Understanding new foods: Development of next generation of food processing, packaging, and ingredients technologies for clean label foods.

- In L. Serventi (Ed.), *Sustainable Food Innovation*. pp. 157-167. Cham: Springer International Publishing. [https://doi.org/10.1007/978-3-031-12358-0\\_12](https://doi.org/10.1007/978-3-031-12358-0_12)
- Barringer, S. A., & Sumonsiri, N. (2015). Electrostatic coating technologies for food processing. *Annual Review of Food Science and Technology*, 6(1), 157-169. <https://doi.org/10.1146/annurev-food-022814-015526>
- Biesbroek, S., Kok, F. J., & Tufford, A. R., et al. (2023). Toward healthy and sustainable diets for the 21<sup>st</sup> century: Importance of sociocultural and economic considerations. *Proceedings of the National Academy of Sciences*, 120(26), e2219272120. <https://doi.org/10.1073/pnas.2219272120>
- Boruah, B., & Ray, S. (2024). Current progress in the valorization of food industrial by-products for the development of functional food products. *Food Science and Applied Biotechnology*, 7(2), 289-317. <https://doi.org/10.30721/fsab2024.v7.i2.349>
- Boudalia, S., Symeon, G. K., & Dots, V., et al. (2026). The valorization of agrifood byproducts and waste to advance the sustainable development goals: current state and new perspectives. *Sustainability*, 18(5), 2165. <https://doi.org/10.3390/su18052165>
- Çakmakçı, R., Salık, M. A., & Çakmakçı, S. (2023). Assessment and Principles of Environmentally Sustainable Food and Agriculture Systems. *Agriculture*, 13(5), 1073. <https://doi.org/10.3390/agriculture13051073>
- Cerutti, N., Lamb, W. F., & Crippa, M., et al. (2023). Food system emissions: a review of trends, drivers, and policy approaches, 1990–2018. *Environmental Research Letters*, 18(7), 074030. <https://doi.org/10.1088/1748-9326/acddfd>
- Chatzimitakos, T., Athanasiadis, V., & Kalompatsios, D., et al. (2023). Pulsed electric field applications for the extraction of bioactive compounds from food waste and by-products: a critical review. *Biomass*, 3(4), 367-401. <https://doi.org/10.3390/biomass3040022>
- Corigliano, O., Morrone, P., & Algieri, A. (2025). Navigating the challenges of sustainability in the food processing chain: insights into energy interventions to reduce footprint. *Energies*, 18(2), 296. <https://doi.org/10.3390/en18020296>
- Corradini, M. G., Homez-Jara, A. K., & Chen, C. (2024). Virtualization and digital twins of the food supply chain for enhanced food safety. *Advances in Food and Nutrition Research*, 111, 71-91. <https://doi.org/10.1016/bs.afnr.2024.06.001>
- Datta, B., Buehler, M. J., & Chow, Y., et al. (2026). Artificial intelligence for food innovation. *Nature Food*, 7, 644–654. <https://doi.org/10.1038/s43016-026-01380-7>
- Dávalos-Saucedo, C. A., Rossi-Márquez, G., & Rodríguez-Miranda, S., et al. (2026). Precision edible coating engineering: deposition physics, image metrology and a roadmap toward digital-twin-ready edible surface interfaces. *Coatings*, 16(7), 812. <https://doi.org/10.3390/coatings16070812>
- Díaz-de-Cerio, E., & Trigueros, E. (2025). Evaluating the sustainability of emerging extraction technologies for valorization of food waste: microwave, ultrasound, enzyme-assisted, and supercritical fluid extraction. *Agriculture; Basel*, 15(19), 2100. <https://doi.org/10.3390/agriculture15192100>
- Ding, H., Tian, J., & Yu, W., et al. (2023). The Application of Artificial Intelligence and Big Data in the Food Industry. *Foods*, 12(24), 4511. <https://doi.org/10.3390/foods12244511>
- Dutta, D., & Sit, N. (2024). A comprehensive review on types and properties of biopolymers as sustainable bio-based alternatives for packaging. *Food Biomacromolecules*, 1, 58-87. <https://doi.org/10.1002/fob2.12019>
- D'Agaro, E., Rosa, F. & Akentieva, N.P. (2021). New technology tools and life cycle analysis (LCA) applied to a sustainable livestock production. *The EuroBiotech Journal*, 5(3), 130-141. <https://doi.org/10.2478/ebtj-2021-0022>
- Ekezie, F. G. C., Sun, D. W., & Han, Z., et al. (2017). Microwave-assisted food processing technologies for enhancing product quality and process efficiency: A review of recent developments. *Trends in Food Science & Technology*, 67, 58-69. <https://doi.org/10.1016/j.tifs.2017.05.014>
- Engel-Cox, J. A., Wikoff, H. M., & Reese, S. B. (2022). Techno-economic, environmental, and social measurement of clean energy technology supply chains. *Journal of Advanced Manufacturing and Processing*, 4(3), e10131. <https://doi.org/10.1002/amp2.10131>
- Galanakis, C. M. (2024). The future of food. *Foods*, 13(4), 506. <https://doi.org/10.3390/foods13040506>
- Game, A., Thiviya, P., & Liyanapathirana, A., et al. (2024). Polysaccharide-based bioplastics: eco-friendly and sustainable solutions for packaging. *Journal of Composites Science*, 8(10), 413. <https://doi.org/10.3390/jcs8100413>
- Gao, X., Wang, Z., & Sun, G., et al. (2026). Pulsed electric field (PEF) technology for preserving fruits and vegetables: Applications, benefits, and comparisons. *Food Reviews International*, 42(2), 540-565. <https://doi.org/10.1080/87559129.2025.2489754>
- Gavahian, M. (2024). Opinion on the prospects of emerging food processing technologies to achieve sustainability in the industry by reduced energy consumption, waste reduction and valorisation, and improved food nutrition. *International Journal of Food Science and Technology*, 59(11), 8135-8140. <https://doi.org/10.1111/ijfs.17525>
- Golshany, H., Bakry, I. A., & Seddiek, A. S., et al. (2026). Synergistic design of sustainable plant-based foods: The emerging role of protein-polysaccharide interactions for next-generation food structures. *Journal of Carbohydrate Chemistry*, 45(1–3), 25–73. <https://doi.org/10.1080/07328303.2026.2631809>
- Hailu, G. G., Kumar, A., & Khan, I., et al. (2026). Unlocking the potential of precision food processing: industrial, biotechnological, and nutritional perspectives. *Comprehensive Reviews in Food Science and Food Safety*, 25(3), e70490. <https://doi.org/10.1111/1541-4337.70490>
- Heydari, M. (2024). Cultivating sustainable global food supply chains: A multifaceted approach to mitigating food loss and waste for climate resilience. *Journal of Cleaner Production*, 442, 141037. <https://doi.org/10.1016/j.jclepro.2024.141037>
- Hossain, M. S., Wazed, M. A., & Preya, M. S. A., et al. (2026). A Comprehensive review of biotechnological innovations in valorization of food waste: enhancing nutritional, techno-functional properties, and process optimization for sustainable

- product development. *Food Frontiers*, 7(2), e70194. <https://doi.org/10.1002/fft2.70194>
- Hussain, M., Abdullah, M., & Ashraf, M. N., et al. (2025). *World food hunger in 2050 and nano solutions: probabilities and prospects based on plant based food*. In H. Tombuloglu, G. Tombuloglu & K.R. Hakeem, et al. (Eds.), *Nanomaterials for Enhanced Plant-Based Food Production*, 11-21. Academic Press. <https://doi.org/10.1016/B978-0-443-23688-4.00010-5>
- Iranshahi, K., Brun, J., & Arnold, T., et al. (2025). Digital twins: Recent advances and future directions in engineering fields. *Intelligent Systems with Applications*, 26, 200516. <https://doi.org/10.1016/j.iswa.2025.200516>
- Jacob-John, J., D'Souza, C., & Marjoribanks, T., et al. (2021). Synergistic Interactions of SDGs in Food Supply Chains: A Review of Responsible Consumption and Production. *Sustainability*, 13(16), 8809. <https://doi.org/10.3390/su13168809>
- Javed, T., Oluwale-Ojo, O., & Zhang, H., et al. (2025). System design, modelling, energy analysis, and industrial applications of ohmic heating technology. *Food and Bioprocess Technology*, 18(3), 2195-2217. <https://doi.org/10.1007/s11947-024-03568-w>
- Katsigiannis, A. S., Bayliss, D. L., & Walsh, J. L. (2022). Cold plasma for the disinfection of industrial food-contact surfaces: An overview of current status and opportunities. *Comprehensive Reviews in Food Science and Food Safety*, 21(2), 1086-1124. <https://doi.org/10.1111/1541-4337.12885>
- Knorr, D., & Augustin, M. A. (2025). Towards resilient food systems: interactions with indigenous knowledge. *Trends in Food Science & Technology*, 156, 104875. <https://doi.org/10.1016/j.tifs.2025.104875>
- Ligarda-Samanez, C. A., Huamán-Carrión, M. L., & Calsina-Ponce, W. C., et al. (2025). Technological innovations and circular economy in the valorization of agri-food by-products: advances, challenges and perspectives. *Foods*, 14(11), 1950. <https://doi.org/10.3390/foods14111950>
- Likitwattanasade, T., & Barringer, S. A. (2015). The influence of particle size on separation and dustiness in powder mixtures during nonelectrostatic and electrostatic coating. *Journal of Electrostatics*, 77, 44-50. <https://doi.org/10.1016/j.elstat.2015.07.001>
- Linares, G., & Rojas, M. L. (2022). Ultrasound-assisted extraction of natural pigments from food processing by-products: a review. *Frontiers in Nutrition*, 9, 891462. <https://doi.org/10.3389/fnut.2022.891462>
- Lisboa, H. M., Pasquali, M. B., & Dos Anjos, A. I., et al. (2024). Innovative and sustainable food preservation techniques: enhancing food quality, safety, and environmental sustainability. *Sustainability*, 16(18), 8223. <https://doi.org/10.3390/su16188223>
- Martinez-Monteagudo, S. I., Yan, B., & Balasubramaniam, V. M. (2017). Engineering process characterization of high-pressure homogenization—from laboratory to industrial scale. *Food Engineering Reviews*, 9(3), 143-169. <https://doi.org/10.1007/s12393-016-9151-5>
- Marques, C., Güneş, S., & Vilela, A., et al. (2025). Life-cycle assessment in agri-food systems and the wine industry—a circular economy perspective. *Foods*, 14(9), 1553. <https://doi.org/10.3390/foods14091553>
- Meijer, G. W., Lähteenmäki, L., & Stadler, R. H., et al. (2021). Issues surrounding consumer trust and acceptance of existing and emerging food processing technologies. *Critical Reviews in Food Science and Nutrition*, 61(1), 97-115. <https://doi.org/10.1080/10408398.2020.1718597>
- Melikoglu, M. (2026). Artificial intelligence and deep learning in food shelf life management: A global review. *Food and Humanity*, 6, 101089. <https://doi.org/10.1016/j.foohum.2026.101089>
- Mkhari, T., Adeyemi, J. O., & Fawole, O. A. (2025). Recent advances in the fabrication of intelligent packaging for food preservation: a review. *Processes*, 13(2), 539. <https://doi.org/10.3390/pr13020539>
- Murugesan, A., & Li, H. (2026). Toward sustainable food packaging: Innovations in biodegradable materials, smart technologies, and AI integration. *Comprehensive Reviews in Food Science and Food Safety*, 25(1), e70397. <https://doi.org/10.1111/1541-4337.70397>
- Ndiata, F. K., Masood, T., & Mehnen, J. (2025). Enabling digital transformation in food manufacturing small and medium enterprises: key drivers, barriers and strategic frameworks. *Journal of Innovative Digital Transformation*, 2(3), 233-251. <https://doi.org/10.1108/JIDT-02-2025-0008>
- Nema, P. K., Sehwat, R., & Ravichandran, C., et al. (2022). Inactivating food microbes by high-pressure processing and combined nonthermal and thermal treatment: A review. *Journal of Food Quality*, 2022(1), 5797843. <https://doi.org/10.1155/2022/5797843>
- Oluwale, O., Ibadapo, O., & Arowosola, T., et al. (2023). Sustainable transformation agenda for enhanced global food and nutrition security: a narrative review. *Frontiers in Nutrition*, 10, 1226538. <https://doi.org/10.3389/fnut.2023.1226538>
- Onyeaka, H., Nwaiwu, O., & Obileke, K., et al. (2023). Global nutritional challenges of reformulated food: A review. *Food Science & Nutrition*, 11, 2483-2499. <https://doi.org/10.1002/fsn3.3286>
- Panda, J., Mishra, A. K., & Mohanta, Y. K., et al. (2024). Exploring biopolymer for food and pharmaceuticals application in the circular bioeconomy: An agro-food waste-to-wealth approach. *Waste and Biomass Valorization*, 15(10), 5607-5637. <https://doi.org/10.1007/s12649-024-02452-0>
- Panou, A., & Karabagias, I. K. (2023). Biodegradable packaging materials for foods preservation: sources, advantages, limitations, and future perspectives. *Coatings*, 13(7), 1176. <https://doi.org/10.3390/coatings13071176>
- Pignata, C., D'angelo, D., & Fea, E., et al. (2017). A review on microbiological decontamination of fresh produce with nonthermal plasma. *Journal of Applied Microbiology*, 122(6), 1438-1455. <https://doi.org/10.1111/jam.13412>
- Rahmani, R., Jesus, C., & Lopes, S. I. (2024). Implementations of digital transformation and digital twins: exploring the factory of the future. *Processes*, 12(4), 787. <https://doi.org/10.3390/pr12040787>
- Rizwan, D., Kirmani, S. B. R., & Masoodi, F. A. (2025). Circular Economy in the Food Systems: A Review. *Environmental Quality Management*, 34(4), e70096. <https://doi.org/10.1002/tqem.70096>
- Ray, R. C., Behera, S. S., & Awogbemi, O., et al. (2025). Beyond enzymes and organic acids, solid-state fermentation as an alternative for valorizing fruits and vegetable wastes into novel bio-products

- in a circular economy: A critical review. *AIMS Microbiology*, 11(2), 462. <https://doi.org/10.3934/microbiol.2025021>
- Song, Y., Yuan, Y., & Zhu, J. (2025). A review on applications of fine particles integrated with fluidization technologies. *The Canadian Journal of Chemical Engineering*, 103(4), 1474-1493. <https://doi.org/10.1002/cjce.25260>
- Sousa, G., Ferreira-Dias, S., & Tecelão, C., et al. (2025). Potential of marine biomolecules: Advances in extraction and applications of proteins, polysaccharides, and antioxidant compounds. *Foods*, 14(15), 2555. <https://doi.org/10.3390/foods14152555>
- Srivastava, P. K., & Sit, N. (2025). A review on fruit and vegetable processing using traditional and novel methods. *Future Postharvest and Food*, 2(1), 4-26. <https://doi.org/10.1002/fpf2.12046>
- Suhag, R., Kellil, A., & Razem, M. (2024). Factors influencing food powder flowability. *Powders*, 3(1), 65-76. <https://doi.org/10.3390/powders3010006>
- Sumonsiri, N., Akkaraekthalin, P., & Rungsardthong, V. (2020). Effect of electrode voltage for NaCl coating on baked potato chips in continuous electrostatic coating system. *International Journal of Agricultural and Biological Engineering*, 13(3), 213-216. <https://dx.doi.org/10.25165/j.ijabe.20201303.5152>
- Sumonsiri, N., & Barringer, S. A. (2024). Coating foods with powders. In B. Bhandari, N. Bansal, & M. Zhang, et al. (Eds.), *Handbook of Food Powders*. pp. 495-506. Woodhead Publishing. <https://doi.org/10.1016/B978-0-323-98820-9.00019-3>
- Šuput, D., Kurek, M., & Stupar, A. (2026). Industrial Scaling and Commercialization of Biopolymer-Based Food Packaging: Processing, Performance, Regulatory and Sustainability Challenges. *Coatings*, 16(8), 894. <https://doi.org/10.3390/coatings16080894>
- Teixé-Roig, J., Oms-Oliu, G., & Odriozola-Serrano, I., et al. (2023). Emulsion-based delivery systems to enhance the functionality of bioactive compounds: towards the use of ingredients from natural, *Sustainable Sources*. *Foods*, 12(7), 1502. <https://doi.org/10.3390/foods12071502>
- Vickram, S., Infant, S.S., & Balamurugan, B.S., et al. (2025). Techno-economic and life cycle analysis of biorefineries: assessing sustainability and scalability in the bioeconomy. *Environmental Quality Management*, 34, e70077. <https://doi.org/10.1002/tqem.70077>
- Wisser, D., Grogan, D. S., & Lanzoni, L., et al. (2024). Water use in livestock agri-food systems and its contribution to local water scarcity: a spatially distributed global analysis. *Water*, 16(12), 1681. <https://doi.org/10.3390/w16121681>
- Yang, H., Jiao, W., & Zouyi, L., et al. (2025). Artificial intelligence in the food industry: innovations and applications. *Discover Artificial Intelligence*, 5(1), 60. <https://doi.org/10.1007/s44163-025-00296-8>
- Yin, Y., & Woo, M. W. (2024). Transitioning of petroleum-based plastic food packaging to sustainable bio-based alternatives. *Sustainable Food Technology*, 2(3), 548-566. <https://doi.org/10.1039/d4fb00028e>
- Yuan, X., Fang, Y., Diao, Y., Wu, B., Wen, X., Nag, A., & Liang, Y. (2026). Non-Thermal Processing Technologies in Food Industries. *Foods*, 15(10), 1677. <https://doi.org/10.3390/foods15101677>