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Artificial Intelligence in Food Innovation: A Critical Review of Emerging Ingredients and New Product Development

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ABSTRACT
Global population growth, climate change, and evolving consumer demands are reshaping the food industry and intensifying the need for innovation. This review explores recent advancements in food innovation, with a particular focus on the transformative role of Artificial Intelligence (AI) in emerging ingredients and new product development. A systematic analysis of 123 publications published between 2020 and 2025 was conducted to evaluate how AI and sustainable ingredient sourcing are transforming the global food system. The review highlights how unconventional ingredients such as plants, insects, fungi, microalgae, seaweeds, and agro-waste derivatives are valued for their nutritional density rich in proteins, fibres, antioxidants, and essential fatty acids as well as their techno-functional properties like emulsification, gelation, and water retention. Modern processing methods including high pressure processing, pulsed electric field, ultrasound, and 3D printing proved to be potential processes for developing new food products. AI-driven technologies such as machine learning, deep learning, computer vision, IoT, and robotic are accelerating ingredient discovery, optimising formulation, and improving transparency across food value chains. They enable efficient screening of bioactive compounds, predictive modelling of sensory and nutritional properties, and real-time monitoring of safety risks. By shifting product development from conventional trial-and-error approaches to data-driven systems, AI enhances resource efficiency, reduces development time, and supports sustainability goals. Although challenges remain in large-scale and consumer acceptance, AI-enabled systems demonstrate strong potential to shorten development timelines and enhance resilience. Therefore, AI-integrated approaches could be positioned as critical enablers in advancing sustainable ingredient transformation and new food product development.

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INTRODUCTION

With the global population projected to surpass 9.7 billion by 2050 (Habib *et al*., 2025), global food systems currently face pressing challenges, including population growth, climate change, and resource scarcity (Galanakis, 2024). These challenges result in the shift of consumer expectations towards nutritionally rich foods (Habib *et al*., 2025). Therefore, innovation has become a necessity rather than a luxury in the food industry (Galanakis, 2024). Food innovation is a deliberate and dynamic process involving the development of novel or significantly improved food products, ingredients, systems, and processing methods aimed at enhancing productivity, promoting sustainability, and meeting evolving consumer demands (McClements *et al*., 2021).

A central aspect of this innovation lies in the transformation of food ingredients. Traditionally, the conventional food ingredients are valued for technological functions like preservation. However, new food or modern ingredients are now expected to offer health benefits, meet sustainability criteria, and come from traceable and ethical sources (Lisboa *et al*., 2024). This has driven interest in clean-label products and functional compounds such as antioxidants, dietary fibres, and healthy fats, reducing reliance on synthetic additives (Rabadán *et al*., 2021). Moreover, the increase in demand for eco-friendly ingredient solutions is being driven by climate change and environmental concerns (Ukhurebor and Aidonojie, 2021). Currently, the interests in plant proteins, microalgae, insects, and useful microorganisms reflect the search for alternative, nutritional, ecofriendly, and functional food sources (Grossmann and Weiss, 2021).

At the industrial level, the development of new food is directly linked to consumers' perspectives (Taneja *et al.,* 2023). Additionally, new food product development considers economic (prices and profit or loss), social (availability and health), and environmental (waste and carbon emissions) reasons (Garcia-Garcia *et al.,* 2021). These make new food product development complex because it involves diverse phases and inputs. For sustainability reasons, plant-based materials such as legumes, seeds, and nuts are being blended with food by-products to create formulations that match or surpass animal proteins in texture, nutrition, and functionality. These innovations embrace circular economy principles through the valorisation of food waste materials like banana peel flour, aquafaba, spent grain flour, and pineapple peel (Tachie *et al*., 2023). Innovating these new food products also involves prototyping, conducting numerous tests, less cost efficient and time-consuming. Moreover, the complex nature (chemical structures) of food makes it difficult to properly optimise the processing and predict the nutritional, functional, and other beneficial attributes. Therefore, it is necessary to consider processes that can accurately predict food attributes and optimise ingredient combinations and processing (Muthukumar *et al.,* 2021).

Artificial Intelligence (AI) has therefore emerged as a powerful enabler of innovating new food. AI systems are increasingly being employed to accelerate ingredient screening, optimise formulation design, improve processing efficiency, and enhance the monitoring of food quality and safety. For instance, AI technologies were used to develop sport drinks derived from rice proteins, suggest diet plans based on consumer's preference, and soft drinks with different flavour selection options (Taneja *et al.,* 2023). Additionally, AI technology (machine learning) was used to predict product nutritional composition (Davies *et al.,* 2021), organoleptic attribute (Charoenkwan *et al.,* 2021), and shelf life (Gomez Romero *et al.,* 2023). Technologies such as smart sensors, Internet of Things (IoT) platforms, cloud computing, and optical biosensors are now being used to improve transparency and traceability within the food supply chain (Bhatlawande *et al*., 2024). These tools support the early detection of pathogens, contamination risk assessment, and fraud prevention across the value chain.

Several recent reviews have examined the intersections of artificial intelligence and food systems from complementary angles. These reviews include surveys of AI applications across food supply chains and quality control (Ikram *et al.*, 2024), broad overviews of AI's transformative potential in food science and industry (Zatsu *et al*., 2024), and analyses focused on accelerating ingredient discovery and democratizing food research and development with AI (Kuhl, 2025). However, there is limited information on review comprising the application of artificial intelligence in relation to emerging ingredients and development of new food products. Therefore, this review examines the role of artificial intelligence in ingredient discovery, product development, and safety prediction, highlighting its potential to create resilient, nutritious, and sustainable food systems.

Conceptual Framework

This review employed a systematic conceptual framework integrating Artificial Intelligence (AI), emerging food ingredients, and innovative processing technologies as interconnected components shaping modern food innovation. Figure 1 shows the conceptual framework adopted in this review. The framework was developed through a systematic analysis of 250 peer-reviewed publications published between 2020 and 2025, focusing on how AI supports ingredient discovery, new product development, and sustainability across the global food system.

The process began with a structured breakdown of the research topic into key thematic areas, including emerging food ingredients and their nutritional, functional, and technological characteristics; advanced and sustainable food processing methods that enhance product quality, safety, and sensory properties; and the application of AI in ingredient innovation, formulation optimisation, and product development. These thematic areas served as a guide for data retrieval, organisation, and synthesis throughout the study.

Relevant literature was obtained from multiple academic databases, including Web of Science, Google Scholar, Springer, and ScienceDirect. Search keywords such as "Artificial Intelligence in Food Innovation," "Machine Learning in Food Processing," "AI in Ingredient Discovery," and "Smart Food Systems" were employed to identify relevant publications. The search was restricted to peer-reviewed journal articles, conference proceedings, and academic reports published between 2020 and 2025 to ensure both regency and methodological credibility. Articles written in English were included, while duplicates, non-peer-reviewed works, and studies lacking methodological clarity were excluded.

A total of 250 articles were initially retrieved across the identified databases. These were screened by title, abstract, and methodological detail to assess quality and relevance. After applying the inclusion and exclusion criteria, 123 articles were selected, cited, and referenced in this review, while 127 were excluded.

The selected articles were organised according to the study outlines, covering areas such as AI-driven ingredient discovery, intelligent formulation design, precision processing, nutritional optimisation, sustainability enhancement, and consumer acceptance modelling. The findings were synthesised thematically to provide a comprehensive understanding of AI applications in emerging food ingredients and new product development.

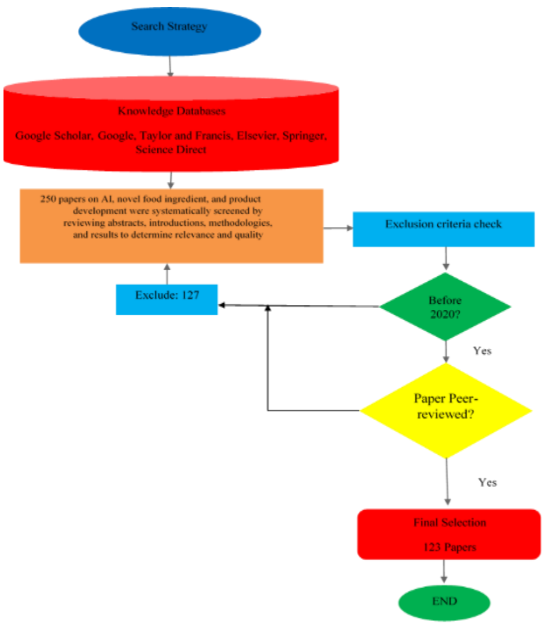

Figure 1: Approach to Paper Refinement and Selection Flowchart

Recent Developments in Food Ingredients

In recent times, food ingredient technology has restructured the terrain of the food industry, due to consumer focus on health, sustainability, and foods functional properties (Galanakis, 2024). The sector is witnessing a surge in the recognition and integration of novel ingredients offering superior nutritional, sensory, and functional qualities. These novel ingredients are sourced from plants, microbes, algae, and even by-products. In the industry, these ingredients are processed with advanced techniques to maintain or enhance their bioactivity, safety, and overall quality (Lee *et al*., 2024).

Alternative Plant and Insect-Based Proteins

A significant development is the use of plant-based protein ingredients, especially those derived from legumes such as peas, lentils, chickpeas, and mung beans (Nadeeshani *et al.,* 2022). These proteins are gaining traction as alternatives to animal-derived proteins because of their relatively high protein content, reduced environmental footprint, and desirable functional traits like emulsification, gelation, and water retention. Processing methods such as dry fractionation, wet extraction, and ultrasound assisted techniques are commonly utilised to produce protein concentrates and isolates (Mondor and Hernández-Álvarez, 2022). Pea protein isolates are often produced via wet extraction (isoelectric precipitation method) or enhanced through ultrasound-assisted technology contains approximately 80 to 85% protein. The extracted protein could be used as a valuable ingredient in meat analogues, protein bars, and plant-based dairy substitutes (Shanthakumar *et al.,* 2022). Additionally, there has been growing interest in the use of plant seed flour as functional ingredients in cereal-based products. Roobab and Maqsood (2024) investigated the inclusion of flaxseed, pumpkin seed, and chia seed flours in noodle formulations. Typically, these seeds were processed into nutrient-rich flours via milling and drying. The authors found out that the ingredients increased dietary fibre, protein, and essential fatty acid content, while also altering texture and cooking characteristics.

Edible insect-based ingredients such as cricket powder, mealworm powder, *Cirina butyrospermi* powder, and edible winged termites are gaining recognition as sustainable food innovations. These ingredients are typically processed via sun-drying, and oven-drying, followed by milling. Alternatively, non-thermal methods like ultrasound, boiling, and extrusion are also used for the ingredient processing (Sanusi *et al*., 2024; Sanusi *et al*., 2025). These powders are rich in protein (45-70% dry matter), essential fatty acids, and micronutrients such as zinc, iron, and vitamin B12. In terms of usefulness, cricket powder enhances bread protein without reducing sensory quality (Gantner *et al*., 2024); *Cirina butyrospermi* improves rice pasta and protein digestibility under ultrasound treatment (Sanusi *et al*., 2024; Sanusi *et al*., 2025) while winged termites (*Macrotermes spp.*) have been reported to provide valuable proteins, fats, and minerals (Cheseto *et al*., 2024) and hold economic development in insect farming. Therefore, insect-based ingredients are potentially applicable in sustainable food development due to their nutritional and technological attributes.

Microbial Proteins

Microalgae proteins have emerged as a focus, valued for their comprehensive amino acid profiles, sustainability, and versatility. Mosibo *et al.* (2024) noted that proteins from microalgae like *spirulina* and *chlorella* are usually extracted through mechanical disruption and enzymatic hydrolysis, which preserve their bioactivity. Due to their emulsifying and water holding capabilities, these proteins are suitable for meat substitutes, baked goods, and beverages.

Fungal biomass (*Rhizomucor pusillus*) is emerging as a sustainable and protein-rich food ingredient (Elhalis, 2025). It is cultivated via submerged or solid-state fermentation on agro-industrial substrates (Matei *et al*., 2021). After harvesting the biomass, it is heat-treated to deactivate enzymes, and dried. In some cases, enzymatic digestion is applied to enhance nutritional value. *Rhizomucor pusillus* is a good source of fungal protein, fibre (particularly chitin), and minerals. It contains B-vitamins and has moderate fat content. This fungal biomass is explored as a sustainable protein ingredient in meat substitutes, protein blends, and health supplements. It is also considered for flavour enhancing compounds and enzyme production in food processing (Elhalis, 2025).

Functional Bioactives and Polysaccharides

Fucoidans are sulfated polysaccharides derived mainly from brown seaweeds such as *Fucus vesiculosus* and *Laminaria* species (Usov *et al*., 2022). Enzyme-assisted extraction and acid hydrolysis are the common methods used for their extraction, with enzyme-assisted methods showing improved yields and preservation of bioactivity (Streimikyte *et al.,* 2022). Fucoidans contain complex polysaccharides that function as antioxidants and anti-inflammatory agents and neuroprotectants (Wang *et al.,* 2021). Fucoidans are used in functional beverages and supplements because of their gelling and emulsifying properties and their potential to lower blood sugar and cholesterol levels which could expand their use in therapeutic food applications.

Emerging developments in dietary fibre applications have highlighted sources such as β-glucans (from oats and barley), inulin (from chicory root), and polysaccharides (alginates and carrageenan's) from seaweed (Ahmad *et al.,* 2025). These dietary fibres are processed with enzymatic hydrolysis or aqueous extraction to increase solubility and functional properties. These fibres are known for their cholesterol reduction, glycemic control, and gut microbiota regulation, facilitating their need in bakery products, dairy substitutes, and sugar reduction formulations (Singla *et al*., 2024).

Butterfly pea flower, known for its brilliant blue hue, is more than just a natural colourant. The dried flowers are typically milled into powdered, and steeped to extract natural pigments (anthocyanins) (Barani *et al*., 2022). Minimal processing retains the flower's colour, aroma, and bioactive content. Butterfly pea flowers are valued for their rich anthocyanin content, especially ternatins and contain flavonoids, phenolics, and moderate amounts of carbohydrates and fibre. Consuming beverages, desserts, and noodles containing butterfly pea flower extract, offers antioxidant and anti-inflammatory benefits (Jeyaraj *et al*., 2021).

Upcycled Ingredients

Upcycled ingredients are obtained from food by-products that otherwise would be discarded, such as banana peel flour, aquafaba (the liquid from cooked chickpeas), okara (soy pulp), along with fruit pomace (Benvenutti *et al*., 2025). Processing these by-products through drying, milling, and enzymatic treatment could positively influence their functional qualities. Dietary fibre and polyphenols with proteins along with resistant starches improve upcycled ingredients (Idrishi *et al*., 2022). These nutritional elements improve gut health plus contribute to safety. Aquafaba has natural emulsifying and foaming capabilities, while banana peel flour is high with antioxidants and dietary fibre, making them sustainable alternatives to egg whites in bakery products. Okara (rich in insoluble fibre) and soy protein are valuable in alternative meat development (Basha, 2023). Sayem *et al*. (2024) also demonstrated the viability of upcycling fruit and vegetable waste to provide dietary fibre for fortification in biscuit, resulting in improved nutritional composition and product quality. Food waste can be reduced or eliminated by recycling, hence aligning with sustainability goals and supporting a circular economy.

Rapeseed has become a staple in the global food industry, especially known for the edible oil (canola) it produces (Jia *et al*., 2021). Rapeseed is rich in unsaturated fats, especially oleic and linoleic acids, and provides quality protein, fibre, and minerals. With its light taste and heart-healthy profile, rapeseed oil is used in kitchens worldwide. Rapeseed undergoes careful oil extraction, typically using cold-press or solvent-based methods (Rani *et al*., 2021). Beyond oil, its protein-rich byproducts are gaining attention as plant-based food ingredients. Rapeseed cake or meal obtained after oil extraction, is also a source of bioactive compounds like glucosinolates and polyphenols (Petraru and Amariei, 2024). It shows potential in developing plant-based proteins and functional foods due to its techno-functional properties and nutritional value (Mustakova *et al*., 2025). Therefore, it can be used in the production of protein-fortified food products (Jia *et al*., 2021), meat alternatives, bakery items, and animal feed.

Therefore, these new developments in food industries sustain commitment to aligning product innovation with global health, sustainability, and consumer preference objectives. The integration of novel ingredients and advanced processing technologies continues to enhance stability, nutritional quality and a diverse consumer appeal array of food products. Table 1 shows the recent developments in food ingredients, their sources, processing, nutritional compositions, applications and references.

Table 1: Recent Developments in Food Ingredients, Their Sources, Processing, Nutritional Composition, Applications and References

Ingredient	Source	Processing Methods	Nutritional Composition	Applications	Reference
Plant-Based Proteins	Legumes (peas, lentils, chickpeas, mung beans), dry fractionation, wet extraction,	Dry fractionation, wet extraction, ultrasound-assisted processing.	80 to 85% protein (e.g., pea isolate), good emulsification, gelation, and water retention.	Meat analogues, protein bars, plant-based dairy products	(Mondor and Hernández-Álvarez*,* 2022; Nadeeshani *et al.*, 2022; Shanthakumar *et al.*, 2022)
Edible insects	House crickets, mealworms, *Cirina butyrospermi*, winged termites	Freeze or oven-drying, milling, ultrasound, boiling, extrusion	45–70% protein (dry matter), essential fatty acids, zinc, iron, vitamin B12	Cricket powder: bread fortification; *Cirina butyrospermi*: rice pasta and protein digestibility; Termites: proteins, fats, minerals, insect farming	Cheseto *et al*., 2024; Gantner *et al*., 2024; Sanusi *et al*., 2024; Sanusi *et al*., 2025
Plant Seed Flours	Flaxseed, pumpkin seed, chia	Milling, drying	High in protein, dietary fibre, essential fatty acids	Cereal-based products, noodles	Roobab and Maqsood, 2024
Rapeseed and Byproducts	Rapeseed (canola)	Cold-press or solvent extraction; fermentation or enzymatic treatment of cake/meal to reduce antinutrients	Unsaturated fats (oleic, linoleic acids), quality protein, fibre, minerals, bioactives (glucosinolates, polyphenols)	Edible oil, protein-fortified foods, meat alternatives, bakery items, animal feed	Jia *et al*., 2021; Petraru and Amariei 2024; Mustakova *et al*., 2025
Butterfly Pea Flower	Clitoria ternatea flowers	Drying, powdering, steeping, fermentation, encapsulation	Anthocyanins (ternatins), flavonoids, phenolics, carbohydrates, fibre	Natural colourant in beverages, desserts, noodles; antioxidant and anti-inflammatory uses; pH-sensitive smart packaging	Jeyaraj *et al*., 2021; Barani *et al.,* 2022
Fucoidans	Brown and seaweeds	Hot water extraction, enzyme-assisted extraction	Polysaccharides, antioxidants, neuroprotective compounds	Functional foods (beverages, dairy, nutraceuticals), emulsifiers, edible films, active packaging (antioxidant and antimicrobial properties)	Wang *et al*., 2021; Streimikyte *et al*., 2022; Usov *et al*., 2022
Upcycled Ingredients	Banana peel flour, aquafaba, okara	Drying, milling, concentration, enzymatic treatment.	Dietary fibre, protein, antioxidants	Bakery, dairy, snack products; food waste reduction	Idrishi *et al*., 2022; Benvenutti *et al*., 2025

Ingredient	Source	Processing Methods	Nutritional Composition	Applications	Reference
Fungal Biomass (*Rhizomucor pusillus*)	*Rhizomucor pusillus* grown on agro-industrial substrates	Submerged or solid-state fermentation; harvesting; heat treatment; drying; optional enzymatic digestion	Fungal protein, fibre (chitin), B-vitamins, minerals, moderate fat content	Meat substitutes, protein blends, health supplements, flavour enhancers, enzyme production	Matei *et al*., 2021; Elhalis, 2025
Dietary Fibres	Oats, barley (β-glucans), chicory (inulin), seaweed (alginate, carrageenan), fruit and vegetable waste	Enzymatic hydrolysis, aqueous extraction, Maillard conjugation, upcycling	Soluble fibre, antioxidant activity, cholesterol-lowering, gut health benefits	Functional bakery items, dairy alternatives, fibre-enriched snacks	Sayem *et al*., 2024; Singla *et al*., 2024; Ahmad *et al*., 2025
Microalgae proteins	Spirulina, Chlorella	Mechanical disruption, enzymatic hydrolysis	Complete amino acid profile, high protein	Meat substitutes, baked goods, beverages	Mosibo *et al*., 2024

Novel Production Processes for Ingredients and Product Development

Novel production processes are revolutionising the food industry by addressing the limitations of conventional methods such as prolonged cooking, solvent-based extraction, and uncontrolled thermal treatments, which often compromise nutritional value, functionality, and sustainability. Advanced techniques including high-pressure processing (HPP), pulsed electric fields (PEF), ultrasound, 3D food printing, cold plasma, precision fermentation and enzymatic hydrolysis are enabling the efficient use of diverse food ingredients such as plant proteins, insect-based powders, plant seed flours, dietary fibres, mushrooms, and microbial algae.

High-Pressure Processing (HPP)

High-pressure processing is a modern non-thermal food preservation technology that applies elevated hydrostatic pressure (100 to 600 MPa), at low temperatures between 5 and 20°C. This method is designed to effectively inactivate harmful microorganisms and enzymes responsible for food spoilage, thereby enhancing food safety and extending shelf life without the need for heat (Luo *et al*., 2025). Non-thermal processing, such as HPP, is increasingly relevant in functional food development due to its ability to preserve the nutritional quality and bioavailability of sensitive ingredients like omega-3 fatty acids by avoiding high temperatures (Yuan *et al*., 2024, Luo *et al*., 2025). In functional snack development, HPP was applied in the development of *Nannochloropsis sp* (NSP) cocoa balls, enriched with omega-3 fatty acids (Luo *et al*., 2025). The uniform distribution of omega-3 fatty acids achieved under HPP minimised the formation of oxidative hotspots, enhancing the oxidative stability of the product, prolonging shelf life, maintaining original texture, sensory appeal and offering better financial returns for industrial production (Saravana *et al*., 2023; Luo *et al*., 2025). HPP can maintain and preserve the natural antioxidants present in cocoa powder, which act as natural antioxidants by donating electrons to free radicals, thereby stabilising them and preventing the oxidation of omega-fatty acids (Fadda *et al*., 2022; Luo *et al*., 2025). HPP's ability to preserve nutritional quality and extend shelf life can offset higher initial equipment costs through increased consumer acceptance and willingness to pay a premium (Lohita and Srijaya, 2024; Luo *et al*., 2025).

Pulsed Electric Field

Pulsed Electric Field (PEF) is a method for treating food products at short, high-intensity electrical pulses, thereby enhancing quality retention of food. PEF pretreatment enhances the extraction of valuable bioactive compounds and helps maintain quality characteristics of fruit and vegetables, including colour, phytochemical, antioxidant capacity, proteins, volatile compounds, and sensory attributes (Jadhav *et al*., 2021; Burak, 2024; Rashvand *et al*., 2025). For fruits like oranges, kiwifruits, and tomatoes, PEF treatment creates microscopic pores in the skin, which weakens its structural integrity (Koch *et al.,* 2022; Shorstkii *et al*., 2022; Giancaterino and Jaeger, 2023). For example, oranges, PEF treatment led to less albedo (the white spongy layer), making them easier to peel (Koch *et al*., 2022; Giancaterino and Jaeger, 2023). In food waste valorisation, PEF disrupts cellular structures to facilitate the extraction of bioactive compounds such as antioxidants, phenolics, vitamins, and essential oils from fruits and vegetable waste, enhancing both the efficiency and quality of extraction compared to conventional methods (Chatzimitakos *et al*., 2023). This method helps minimise weight loss and reduces chemical consumption and environmental pollution, making it a more sustainable option.

Ultrasound Technology

Ultrasound (US), or ultra-sonication, is gaining popularity as a sustainable non-thermal technology which involves using high-frequency sound waves, typically around 20 kHz, to treat foods (Tahir *et al*., 2023). This technology treats food by causing the disruption of cell walls, and DNA, thereby causing microbial inactivation and enzyme denaturation (Bagheri and Abbaszadeh, 2020). US facilitates the extraction of various bioactive components like ascorbic acid, carotenoids, and phenolic compounds, as well as macronutrients (Pathania and Dubey, 2025). The development of functional kiwifruit juice is highlighted as an advanced product concept utilising ultrasound technology

(Satpal *et al*., 2021). US enhances breaking down of the cellular matrix of the kiwifruit, which in turn facilitates the release of beneficial intracellular compounds, and bioactive accessibility (Pathania and Dubey, 2025). In the work of Sanusi *et al.* (2025), ultrasound treatment of *Cirina butyrospermi* powder resulted in the reduced moisture content, slightly reduced grittiness, and enhanced protein content. Another research conducted by Sanusi *et al.* (2025) indicated that cashew apple juice treated with ultrasound enhanced its overall aroma. However, ultrasound is a promising processing technique for creating a versatile and enriched food ingredient.

Precision Fermentation

Precision fermentation is an advanced biotechnology that employs genetically engineered microorganisms such as yeast and fungi to produce highly specific proteins, fats, enzymes, vitamins, and other bioactives with consistency and scalability (Alasi *et al*., 2024). It utilising synthetic biology methods to program microbes which are used as cell factories, enables the production of alternative animal-free proteins, including caseins, whey proteins, egg replacers, and recombinant non-animal heme proteins (Augustin *et al*., 2024). These ingredients are used to enhance the functional attributes, such as providing colour and flavour to meat analogues, in plant-based analogue food products, thereby supporting more sustainable food production methods through reduced reliance on land, lower greenhouse emissions, and less water use compared to traditional agriculture (Augustin *et al*., 2024). Precision fermentation offers the structural integrity and molecular building blocks required to replicate the texture, flavour, and appearance of traditional animal products when combined with technologies like 3D printing (Ajayeoba and Ijabadeniyi, 2025). By engineering microorganisms such as *Escherichia coli*, *Saccharomyces cerevisiae*, and *Pichia pastoris*, precision fermentation creates proteins, fats, and enzymes with nutritional and structural qualities comparable to their animal-derived counterparts, offering opportunities for sustainable food innovation (Knychala *et al.*, 2024). Similarly, yeast-derived fats with molecular structures resembling animal lipids, such as the beef fat alternative developed by melting and marble, contribute to recreating the sensory and nutritional experience of animal products (Boukid *et al*., 2023). Engineered microbial pathways allow the production of essential vitamins, enzymes, and bioactive molecules with functional health benefits. Furthermore, vitamin B12 can be produced through microbial co-fermentation, addressing a critical gap in plant-based diets (Singh and Kumar, 2025). Technology also supports allergen-free alternatives, with recombinant dairy proteins produced in fungi or yeast offering safe options for lactose-intolerant or milk allergic consumers. By tailoring macronutrient content, precision fermentation expands the scope of personalized nutrition and sustainable protein alternatives (Alasi *et al.,* 2024).

Three-Dimensional Food Printing

Three-dimensional (3D) food printing is an innovative additive manufacturing process recognised for its potential to revolutionize food choices and consumption. This technology requires formalised food inks, often composed of structured ingredients, allowing foods to be manufactured layer-by-layer while controlling the food's precise nutrient content, amount, and taste (Neamah and Tandio, 2024). This versatility supports the creation of innovative products such as Spirulina cookies (Mosibo *et al*., 2024). Controlled addition of vitamins, phytochemicals, antioxidants, and probiotics have been achieved in printed foods, with studies demonstrating stability of vitamin D in starch blends, antioxidant retention in fruit-based smoothies, and probiotic viability in mashed potato matrices (Jayan and Wani, 2025). More recently, encapsulation strategies have been developed through 3D printing to enhance the stability and bio accessibility of compounds such as lutein and anthocyanins (Ahmadzadeh *et al.,* 2025). 3D printing also reshapes physical properties by enabling precise control of porosity, geometry, and weight through adjustable infill patterns. This facilitates not only novel structures but also 4D printing applications, where foods change shape, colour, or flavour in response to stimuli such as pH, moisture, or temperature, thereby extending design possibilities (Qin *et al.,* 2025). Textural qualities are likely the most visually obvious result of 3D printing; by adjusting infill density, printing parameters, and the usage of hydrocolloids, hardness, chewiness, and cohesiveness can be adjusted (Pereira *et al*., 2021). Applications include bite-to-bite sweetness variation in chocolate, reduced oil content in potato snacks, and soft foods designed for elderly individuals with dysphagia. Importantly, recent studies show that extrusion-based printing of nixtamalised corn and chickpea pastes produces distinct textural outcomes depending on post-printing cooking, with steam-cooked products yielding greater hardness and structural stability (Rodríguez-Herrera *et al.,* 2024).

Cold Plasma

Cold Plasma (CP) treatment is a non-thermal processing technology utilising partially ionized gas composed of free radicals, energised ions, atoms, and reactive species, for food microbial safety, shelf-life extension, and structural modifications (Fernandes and Rodrigues, 2024). It promotes sustainable food innovation, reduces carbon footprint, and supports eco-friendly processing with zero residue discharge (Eazhumalai *et al*., 2025). Oat protein treated with CP at 230 V for 15 minutes, improved the gelation properties, viscosity, visco-elastic moduli, and stability. This made the oat protein a promising ingredient for improving the textural attributes of plant-based patties and aiding in the development of high quality, meat-like plant-based foods without chemical additives (Eazhumalai *et al*., 2025).

Enzymatic Hydrolysis

Enzymatic hydrolysis is the most common method for generating food-derived bioactive peptides, particularly those with hypocholesterolemic activity. Enzymatic hydrolysis uses proteolytic enzymes to break proteins from sources such as soy, pea, and milk into low molecular weight peptides with enhanced absorption and therapeutic benefits, including hypocholesterolemic activity through bile acid sequestration and HMG-CoA reductase inhibition, making it an eco-friendly alternative to chemical hydrolysis (Li *et al*., 2024). Process optimisation and enzyme engineering have further improved efficiency, scalability, and cost-effectiveness, enabling incorporation of bioactive peptides into nutraceuticals, functional dairy alternatives, and fortified foods for cardiovascular health management (Murtaza *et al*., 2022). Product applications already demonstrated include antioxidant rich drinks, insect-based energy bars, protein fibre fortified biscuits, and functional dairy alternatives, highlighting the role of these processes in advancing sustainable and health-oriented food innovation (Gantner *et al*., 2024). For example, the enzymatic treatment of soy protein isolate increases its nitrogen solubility index and Protein Digestibility-Corrected Amino Acid Score (PDCAAS), rendering it more suitable for human consumption (Wei *et al.,* 2025). In dairy applications, hydrolysed proteins increase thermal stability and pH tolerance, making them compatible with Ultra High Temperature (UHT) processing and acidic beverages (de Souza *et al*., 2024).

Maillard Conjugation

Maillard conjugation, a non-enzymatic browning reaction between reducing sugars and amino groups of proteins or amino acids, is widely utilized in food processing to improve both sensory and functional properties. While often associated with flavour and colour enhancement, this reaction also yields biofunctional benefits when applied under controlled conditions (Wei *et al.,* 2025). Proximate composition remains largely stable in terms of total protein or carbohydrate content; however, the reaction alters protein structure and potentially affects its digestibility. Depending on the processing conditions, it can either enhance or reduce protein availability. For instance, mild Maillard conjugation improves protein solubility and can mask bitter flavours, increasing palatability and consumer acceptability, especially in plant-based protein formulations (Wei *et al.,* 2025). For example, conjugates of whey protein isolate and dextran improve foaming capacity and foam stability. This enhances applications in bakery and aerated dairy products, where consistent air incorporation and retention are key (Wei *et al*., 2025). Maillard conjugated proteins include improved solubility across wide pH ranges, increased thermal stability, and reduced phase separation. These characteristics make such conjugates suitable for applications in acidic beverages, infant formulas, and thermally processed foods (Wei *et al.*, 2025).

Nanotechnology

Nanotechnology in food processing refers to the manipulation and application of materials at the nanometer scale (1–100 nm) to improve food structure, nutrient delivery, and preservation which encompasses nanoemulsions, nanocapsules, solid lipid nanoparticles, and polymer-based nanocarriers (Sahoo *et al.,* 2021; Biswas *et al.,* 2022). Although nanotechnology does not directly affect the total macronutrient composition, it drastically enhances the functional availability and retention of key nutrients. Nanoscale encapsulation of lipophilic nutrients such as omega-3 fatty acids, coenzyme Q10, and fat-soluble vitamins improves their solubility and absorption in aqueous food systems (Gorantla *et al.,* 2022). Nanocarriers shield bioactives from degradation due to heat, pH, and enzymatic activity. For example, curcumin-loaded nanoparticles improve antioxidant stability and enable targeted intestinal delivery. Other encapsulated ingredients like lycopene, catechins, and probiotics have shown increased shelf life and efficacy in vivo (Oleandro *et al.,* 2024; Peng *et al.,* 2024). In terms of texture, nanoemulsions contribute to improved mouthfeel, creaminess, and product consistency. Their uniform droplet size enhances stability and dispersibility in dressings, sauces, and beverages. Solid lipid nanoparticles also contribute to desirable rheological properties and delayed melting behavior in confectionery (Aliabbasi *et al.,* 2024). Nanotechnology is also involved in sensory enhancement, as encapsulated ingredients can hide bitter tastes or odours. Applications exist for functional beverages, fortified dairy, and dietary supplements. Despite regulatory and safety concerns, nanotechnology is an emerging field in food ingredient technology with precise solutions to personalised nutrition and improved functional performance (Zhang *et al*., 2025). Table 2 shows the summary of novel production processes for food ingredients and product development.

Table 2: Influence of Novel Food Processing Technologies on the Nutritional Profile of Food Materials

Novel Technology	Food Material Studied	Proximate Composition	Bioactive Constituents	Physical Properties	Textural Properties	References
High-Pressure Processing (HPP)	Nannochloropsis sp.-cocoa balls	Preserved omega-3 fatty acids; reduced oxidation losses; nutrient-rich functional snacks	Retained polyphenols (cocoa flavonoids); enhanced dispersion of omega-3 due to cell wall disruption	Improved oxidative stability, uniform oil dispersion; extended shelf-life	Maintained firmness and sensory quality; superior consumer preference	Fadda *et al.,* 2022; Saravana *et al.,* 2023; Lohita and Srijaya, 2024; Luo *et al.,* 2025
Pulsed Electric Field (PEF)	Juices (fruit and vegetable); fresh-cut produce; sweet persimmon	Maintains intrinsic parameters (TSS, TA, pH); possible increase in TSS due to carbohydrate release	Preserves phenolics, flavonoids, anthocyanins; enhances nutraceutical value	Maintains colour, reduces browning; improved extraction of bioactives from waste	Preserves textural quality in persimmon; delays softening in apples	Jadhav *et al*., 2021; Nowosad *et al*., 2021; Chatzimitakos *et al*., 2023 Li *et al.*, 2023; Burak, 2024; Lin *et al.,* 2024; Pizarro-Oteíza *et al*., 2025 Yudhister *et al.,* 2025
Ultrasound	*Cirina butyrospermi* powder; fruit juices	Increased protein (23.5%), ash, carbohydrate; reduced moisture; enhanced mineral retention (Fe, Ca, Zn)	Improved extraction of bioactive compounds; retention of heat-labile vitamins	Reduced viscosity; enhanced cell permeability; increased mineral retention	Smoother texture; reduced grittiness; improved aroma, taste, and appearance	Nonglait *et al.,* 2022; Sanusi *et al.,* 2024; Pathania and Dubey, 2025

Novel Technology	Food Material Studied	Proximate Composition	Bioactive Constituents	Physical Properties	Textural Properties	References
Precision Fermentation	Engineered microbes producing proteins, fats, enzymes	Production of high-quality proteins (casein, whey, ovalbumin); yeast-derived fats mimic animal lipids	Enhanced production of vitamins (B12), omega-3s, lactoferrin, and peptides with health benefits	Consistent structural properties (micelle formation, emulsification, solubility); scalable production	Authentic cheese texture, meltability, juiciness in plant-based meats; enhanced elasticity via enzymes	Boukid *et al*., 2023; Yu *et al*., 2023; Alasi *et al.,* 2024; Augustin *et al*., 2024; Knychala *et al*., 2024; Syamala *et al*., 2024; Ajayeoba and Ijabadeniyi, 2025; Singh and Kumar 2025
3D Food Printing	Printed snacks (algae, insects, grains, fruit purées)	Customizable protein, fibre enrichment; reduction of fat/sugar; improved dietary quality	Controlled inclusion of vitamins, antioxidants, probiotics; encapsulation improves stability	Designed porosity, geometry, weight; 4D stimuli-responsive structures	Tailored hardness, chewiness, softness; suitable for elderly-friendly foods	Pereira *et al*., 2021; Alasi *et al.,* 2024; Rodríguez-Herrera *et al*., 2024; Ahmadzadeh *et al*., 2025; Jayan and Wani, 2025; Prithviraj *et al*., 2025; Qin *et al*., 2025; Sohel *et al*., 2025
Cold Plasma	Cereal/legume proteins; fresh-cut produce; edamame	Enhances protein solubility, digestibility; improved nutrient recovery	Preserves vitamin C, phenolics, antioxidant activity; reduces enzymatic browning	Alters surface permeability; maintains integrity while improving microbial safety	Maintains or improves firmness, cohesiveness; improved softness in edamame	Chen *et al.,* 2024; Lin *et al.*, 2024; Rodríguez-Herrera *et al.,* 2024; Li *et al*., 2024; de Souza *et al*., 2024; Li *et al.,* 2025; Yuan *et al*., 2025
Enzymatic Hydrolysis	Soy protein, whey, fish proteins	Improves protein solubility and digestibility; nitrogen availability enhanced	Releases bioactive peptides with antioxidative, antimicrobial, antihypertensive effects	Improves foaming, emulsification, solubility, and thermal stability	Enhances water-holding capacity, smoothness; softer textures beneficial for elderly/nutrition	Wei *et al*., 2025
Maillard Conjugation	Protein-sugar conjugates (whey, dextran)	Alters protein digestibility; enhances solubility under mild conditions	Produces MRPs (antioxidant, antimicrobial, antihypertensive); risk of harmful AGEs if uncontrolled	Improves protein solubility, emulsification, pH stability	Enhances gelling, viscosity, and foam stability for bakery/dairy	Wei *et al.*, 2025
Nanotechnology	Nutrient delivery systems (omega-3, curcumin, probiotics)	No major effect on macronutrient totals; enhances nutrient availability	Protects bioactives from degradation; improved antioxidant stability, targeted release	Improves clarity, stability, oxidation resistance, optical properties	Enhances mouthfeel, creaminess, dispersibility; delayed melting in confectionery	Sahoo *et al*., 2021; Biswas *et al*., 2022; Gorantla *et al*., 2022; Aliabbasi *et al*., 2024; Oleandro *et al*., 2024; Peng *et al*., 2024;

Artificial Intelligence in Food Systems

Artificial intelligence (AI) is the replication of human intelligence in machines, enabling them to perform tasks such as learning, reasoning, problem solving, perception, language comprehension, planning, and creativity capabilities that would traditionally require human cognition (Olusola-Ilori and Afolaranmi, 2024; Bidyalakshmi *et al.,* 2025). At its core, AI operates on data, algorithms, and programming, requiring vast amounts of input data to function effectively and accurately. It leverages interdisciplinary knowledge spanning computer science, mathematics, psychology, linguistics, biology, engineering, and statistics, while its algorithms continually learn and adapt based on data patterns, though errors in data can result in inaccurate outcomes (Bidyalakshmi *et al.*, 2025).

AI is best understood as an evolving ecosystem of computational methods and technologies, with core elements including Machine Learning (ML), Deep Learning (DL), natural language processing, Computer Vision (CV), robotics, IoT, and Expert Systems (ES). Machine learning develops statistical models and algorithms that allow systems to learn and adapt without explicit programming, while computer vision equips machines with the ability to process and interpret visual information through techniques such as object recognition, pattern detection, and image segmentation (Olusola-Ilori and Afolaranmi, 2024; Pennells *et al.,* 2025). Although some of these methods have existed for decades, breakthroughs in computational power, algorithmic sophistication, and big data availability have enabled AI to achieve greater precision, scalability, and simultaneous task performance (Bidyalakshmi *et al.,* 2025). Beyond general applications, AI plays a transformative role in specific fields such as food science, where it has advanced from early uses of computational modeling, neural networks, hyperspectral imaging, and computer vision to modern integrated ML-driven approaches (Pennells *et al.,* 2025). It also serves as a powerful tool in the systematic exploration and characterisation of bioactive molecules, significantly expanding the discovery of functional food ingredients and reshaping understanding of plant-based protein functionality and health enhancing compounds (Alasi *et al*., 2024).

The role of AI in modern food systems is profoundly transformative, spanning the entire "farm to fork" continuum and reshaping industries by enhancing efficiency, quality, safety, and sustainability (Din *et al*., 2025). In agriculture, AI supports precision farming and the fourth agricultural revolution by improving crop yields, optimising sowing and harvesting schedules, managing resources like water, fertilizers, and pesticides, and reducing environmental impact through data driven decision making. Machine learning, computer vision, drones, robotics, and IoT-based systems enable real time farm monitoring, early disease and pest detection, intelligent application of farm chemicals, irrigation management, grading and sorting of produce, and livestock monitoring, all of which increase productivity, sustainability, and profitability (Olusola-Ilori and Afolaranmi, 2024). Predictive analytics provide yield forecasts, while robotics diminish reliance on manual labor, ensuring safer and more efficient agricultural practices. AI further streamlines supply chains, enhances traceability, and improves food safety and market access, directly contributing to food security, climate targets, and poverty reduction, particularly in developing nations (Olusola-Ilori and Afolaranmi, 2024). Its convergence with advanced sensory technologies like electronic noses, electronic tongues, and near infrared spectroscopy has strengthened quality control and food safety standards (Bidyalakshmi *et al.,* 2025). Beyond agriculture, AI improves process monitoring, control, and optimisation during food production, automating adjustments, predicting outcomes, and enabling predictive maintenance to minimise downtime (Bidyalakshmi *et al.,* 2025; Pennells *et al.*, 2025). AI powered quality control enhances grading, sorting, packaging, and sensory evaluation, with platforms like Gastrograph AI and NotCo's Giuseppe refining product development and consumer preference modeling (Pennells *et al.,* 2025). These developments collectively foster smarter, safer, and more sustainable food systems by optimising decision making, reducing waste, and ensuring transparency across supply chains. While AI spans the food value chain, its role in ingredient discovery and product development revolutionises the food systems.

AI is vital for advancing functional food ingredients (FFIs) and plant-based proteins, where it expedites ingredient functionalisation, optimises formulations, predicts consumer preferences, and supports targeted health interventions. AI facilitates large-scale molecular characterisation and discovery of bioactive compounds, such as novel anti-inflammatory peptides from rice or functional peptides from *Vicia faba* hydrolysate, which support protein synthesis and reduce inflammation (Alasi *et al*., 2024).

Machine Learning in Ingredient Discovery and Optimisation

Machine Learning (ML), a core branch of artificial intelligence (AI), represents an advanced technological approach designed to emulate human-like intelligence by enabling algorithms to learn from vast datasets without explicit programming, thereby facilitating intelligent decision making and managing the "big data" generated by modern technologies (Machireddy, 2024; Bidyalakshmi *et al*., 2025). Within the food system, ML serves as a transformative force that aligns with Industry 4.0 principles automation, robotics, AI, and the Internet of Things (IoT) to improve efficiency, enhance product quantity and quality, minimise waste, and streamline processes across pre-harvest to post-harvest stages (Machireddy, 2024; Bidyalakshmi *et al.,* 2025). ML encompasses several algorithmic approaches suited for different tasks. Supervised learning uses labeled data to improve model accuracy through methods such as neural networks, Support Vector Machines (SVM), logistic regression, random forests, and decision trees. Deep Learning (DL), a subset of ML, learns hierarchical representations of features through techniques such as Convolutional Neural Networks (CNNs) (Bidyalakshmi *et al*., 2025; Kehinde *et al*., 2025).

The applications of ML span the entire food value chain. In agriculture, ML contributes to crop management, boosting raw material quality and yield (Machireddy, 2024). In sorting and grading, ML has expanded capabilities beyond basic quality checks, with random forest models classifying fruits autonomously, and SVMs historically applied to classify biscuits by colour with over 96% accuracy or group pizzas by topping distribution with 96.67% accuracy (Machireddy, 2024; Bidyalakshmi *et al*., 2025). Sensor-based optical sorting systems, such as those used by TOMRA Sorting Food, integrate ML to reduce costs, improve yields, and ensure high quality outputs (Bidyalakshmi *et al.*, 2025). In cleaning processes, multi-sensor AI systems combined with ultrasonic measurements have achieved predictive accuracies of close to 100% in monitoring fouling in food-processing pipes (Machireddy, 2024; Bidyalakshmi *et al*., 2025).

ML also plays a central role in product development, where predictive algorithms model consumer preferences, forecast responses to new flavours, and provide personalised food suggestions tailored to demographic groups. In supply chain management, AI-driven ML networks minimise waste, reduce errors, optimise deliveries, and enhance sustainable financial streams (Machireddy, 2024; Bidyalakshmi *et al*., 2025). For demand forecasting, ML models such as regression, neural networks, LSTMs, and ARIMA analyse historical sales, market trends, weather, and holidays to optimise inventory and avoid stockouts or overstocking. In food safety, ML and DL models analyze variables like chemical composition, humidity, and temperature to detect contamination risks, while CNNs and RNN-based models monitor real time production lines, identifying defects or foreign objects to prevent unsafe products from reaching consumers (Machireddy, 2024).

Beyond industrial use, ML impacts restaurants and consumer experiences through applications in menu optimisation, pricing strategies, personalised nutrition recommendations, and smart kitchen appliances equipped with sensors and predictive analytics. ML-driven food platforms also aid in waste reduction by improving meal planning and inventory management, ensuring ingredient optimisation, and offering real-time recipe recommendations (Machireddy, 2024).

Deep Learning in Food

Deep learning, a subset of machine learning characterised by its use of neural networks with multiple layers, has shown significant utility in food systems. Its capacity to process large-scale, unstructured data such as images, spectra, and sensor outputs makes it especially suited for predicting food quality and modelling ingredient interactions (Lun *et al*., 2025). According to Choi *et al*. (2024), deep learning has been successfully applied in predicting food composition and allergenicity, thereby aiding in the design of safer and healthier food products. In the context of ingredient discovery, convolutional neural networks (CNNs) and recurrent neural networks (RNNs) are increasingly being employed to model protein folding, enzymatic hydrolysis pathways, and bioactive peptide release.

Deep learning can optimise AI-driven protein functionality prediction, particularly for plant-based proteins (Alasi *et al.,* (2024). Similarly, Cui *et al.* (2025) demonstrated the use of deep learning models to enhance sensory quality predictions, bridging the gap between consumer expectations and formulation outcomes. These applications show that deep learning enables not only accurate ingredient screening but also informed decision making in product development.

Computer Vision in Food Systems

Computer Vision, another core AI technology, has transformed quality control and process optimisation into food innovation. By analysing visual data from cameras and sensors, computer vision systems can detect defects, classify products, and monitor structural changes in real-time, ensuring consistency and safety in manufacturing. Shi *et al.* (2021) reported that computer vision techniques have been widely used in detecting texture, colour, and surface morphology in foods, which are critical parameters for consumer acceptance. Unlike traditional quality control methods, which can be destructive and time consuming, computer vision allows for non-invasive, rapid, and scalable analysis (Wang *et al*., 2025).

In novel ingredient development, computer vision also supports the evaluation of microstructural changes during processing. For example, technology can monitor the textural evolution of plant-based protein gels during extrusion, helping researchers understand and fine tune processing conditions for optimal product quality (Choi *et al.*, 2024). When combined with deep learning, computer vision systems can move beyond simple classification to predictive analytics, such as anticipating spoilage or microbial contamination based on subtle visual cues (Altemimi *et al.,* 2025). These advancements make computer vision an essential tool for bridging laboratory research and industrial-scale application in food systems.

Internet of Things (IoT)

The Internet of Things (IoT) is fundamentally reshaping modern food systems and driving significant innovation across the entire food value chain, from initial production to consumer consumption (Duguma and Bai, 2025). This transformation is crucial for sustainably meeting the increasing global food demand, which is projected to require a substantial increase in agricultural production. In agriculture, IoT is redefining traditional farming by transforming it into a dynamic, data driven, and sustainable system (Duguma and Bai, 2025). It integrates interconnected sensors, devices, and data analytics to facilitate precision agriculture, optimise resource use, and enable predictive decision making. Specific applications include automated irrigation, monitoring soil and crops, tracking livestock health, and preventing diseases, which collectively help farmers optimise resource usage and boost productivity (Duguma and Bai, 2025). For example, IoT-enabled precision irrigation systems have demonstrated the potential to significantly reduce water consumption while simultaneously improving crop yields (Duguma and Bai, 2025). IoT mechanisms also support real time crop planning and harvesting, animal tracking and control, accurate data analysis, smart farming, and drought monitoring, all of which contribute to enhanced efficiency and reduced resource wastage (Duguma and Bai, 2025).

IoT significantly enhances food processing and supply chain management. It enables real-time monitoring and control of various operations through integrated sensors, providing critical data for precise decision-making in areas like pest control, irrigation, and fertilization (Duguma and Bai, 2025). IoT applications, combined with Machine Learning (ML) and Artificial Intelligence (AI), provide actionable insights for real time control and strategic planning. The economic impact is substantial, with IoT-driven advancements projected to contribute significant value to global food production without requiring additional labor or resource inputs (Duguma and Bai, 2025). IoT also converges with other cutting-edge technologies to foster further innovation in the food system (Dakhia *et al*., 2025; Duguma and Bai, 2025):

The integration of AI with IoT facilitates intelligent decision making and advanced analytics for food safety, quality control, and shelf-life predictions (Dakhia *et al*., 2025). This synergy is vital for applications such as smart greenhouses and autonomous machinery (Duguma and Bai, 2025). AI models analyse vast datasets, including those from IoT sensors and satellite imagery, to optimise yields, detect pests, and control diseases in primary production (Akkem *et al*., 2023). Generative AI further enhances capabilities by processing real-time IoT data to identify patterns, detect anomalies, predict spoilage, and create personalised nutrition plans (Sai *et al*., 2025). When integrated with IoT, blockchain offers end-to-end visibility, real-time monitoring, and immutable record keeping for food products. This addresses concerns about food fraud, enhances traceability, and supports sustainability throughout the supply chain (Duguma and Bai, 2025). This combination ensures transparency, security, and integrity in food supply chains.

Robotics integrated with computer-based sensors from IoT, advances precision agriculture, greenhouse farming, and field management by automating tasks such as planting, harvesting, and environmental monitoring (Duguma and Bai, 2025). Drones revolutionise agriculture by enabling precision agriculture, improving data collection, enhancing crop management, and ensuring safety through applications like plant health monitoring and precision spraying (Duguma and Bai, 2025).

Edge Computing processes data locally on IoT devices, reducing latency and enabling faster decision making for critical applications such as food spoilage detection, logistics optimisation, and precision irrigation (Dakhia *et al.,* 2025). Smart Packaging and intelligent packaging solutions, often incorporating IoT sensors, enhance the monitoring, preservation, and safety of food products. They can predict shelf life, detect spoilage gases, and integrate anti-counterfeiting features (Dakhia *et al.,* 2025). Digital Twins technology promises to revolutionise food production by enabling real-time simulations of manufacturing and processing workflows, predicting inefficiencies, and optimising resource utilisation (Dakhia *et al.,* 2025).

IoT also underpins the development of smart appliances for food consumption and storage, such as IoT-enabled ovens and refrigerators, which can be remotely controlled and personalised (Dakhia *et al.*, 2025). The overarching goal of these technological advancements is to create resilient, resource-efficient, and sustainable agricultural systems capable of meeting the demands for global food security in the future (Duguma and Bai, 2025).

Robotics

Robotics, significantly enhanced by Deep Learning (DL), is fundamentally transforming the modern food system and driving substantial innovation across all stages, from primary production to processing, packaging, and supply chain management. This technological evolution is ushering in an era of Agriculture, aiming for smarter, more efficient, and ecologically conscious food systems (Balaska *et al.,* 2023).

In primary production, AI-driven robotic systems are optimising yields and crop monitoring through the analysis of extensive datasets including soil conditions, weather patterns, and crop health, providing real time insights for farmers (Akkem *et al.*, 2023). Drones and autonomous robots, equipped with Machine Learning (ML) and computer vision, detect diseases, nutrient deficiencies, and pests early, enabling targeted interventions and reducing broad chemical applications (Mittal *et al*., 2024). Automated harvesting by AI-powered robotic harvesters with advanced vision systems selectively pick ripe crops, reducing manual labour, waste, and damage, and improving agricultural output (Ji *et al*., 2023). AI also optimises resource management, such as precision irrigation for water conservation and precision spraying to reduce pesticide use, contributing to increased yields and environmental sustainability (Umutoni and Samadi, 2024).

Within food processing, AI-powered robotic systems automate tasks like sorting, cleaning, cutting, cooking, and packaging, thereby enhancing workflow efficiency, ensuring high sanitation, and improving product quality (Harry, 2025). Quality control and safety are bolstered as robotics with AI vision sort food by various attributes, and ML models detect bacteria, toxins, and foreign particles with superior speed and accuracy compared to traditional methods (Idhalama and Makori, 2024). For food preservation and packaging, intelligent packaging solutions embed sensors and data processors to monitor food conditions, allowing AI algorithms to predict remaining shelf life, which aids in accurate stock rotation and significantly reduces food waste (Shehzad, 2025). These solutions further contribute to sustainability by optimising resource use and supporting environmentally conscious packaging material selection.

In supply chain optimisation, predictive analytics, driven by advanced statistical algorithms and ML, analyse sales, market trends, and consumer behavior to provide accurate demand forecasts, minimising overproduction and waste while improving supply chain responsiveness (Rodriguez *et al.,* 2024). Traceability and transparency are greatly enhanced by the integration of AI with blockchain technology, creating an immutable record of food products from farm to table, safeguarding data integrity, facilitating recalls, and combatting food fraud (Harry, 2025). The benefits of integrating robotics and AI across the food industry are numerous, including increased productivity, higher crop yields, reduced operational costs (labour, water, fertilizers, pesticides), minimised food waste and spoilage, and improved food safety and quality control (Barthwal *et al.,* 2024; Ta *et al.,* 2024).These technologies also significantly contribute to environmental sustainability by lowering greenhouse gas emissions, conserving soil fertility, and promoting biodiversity (Ta *et al*., 2024).

However, the widespread implementation of AI and robotics faces several challenges. These include high initial costs, particularly for smallholder farmers, and a lack of technical expertise and adequate infrastructure, especially in developing regions (Wang *et al*., 2025). Ethical and regulatory concerns arise regarding algorithmic bias, data privacy, transparency, and the potential for workforce displacement due to automation (Barthwal *et al.,* 2024; Harry, 2025).

Despite these hurdles, future prospects for AI and robotics in the food industry are highly promising. Continued advancements are expected in low-cost, modular, and crop-specific robots, especially for smallholder farmers (Obeng-Ofori *et al.*, 2025). Emerging innovations such as AI-powered vertical farming, autonomous food delivery systems, customised nutrition counselling, Swarm robotics, and the potential of quantum computing to drastically accelerate AI training are anticipated to further transform the sector (Geda and Tang, 2025). The focus will also be on AI-human collaboration to ensure that technological advancements benefit the workforce rather than causing displacement (Harry, 2025).

Advantages and Risks of Artificial Intelligence in Food Innovation

Artificial intelligence (AI) is rapidly transforming the food sector by enabling innovations in production, processing, safety, quality assurance, ingredient discovery, and consumer personalisation. Its advantages lie in its ability to manage complex datasets, optimise production systems, and deliver tailored food solutions, while the risks are mainly associated with ethical, regulatory, and technical limitations (Dakhia *et al*., 2025). One of the major advantages of AI in food is its ability to enhance food safety and quality assurance. AI-based systems, such as hyperspectral imaging, electronic tongues, and predictive algorithms, can detect microbial contamination, adulteration, and chemical residues at levels beyond conventional techniques (Hwang *et al.*, 2025). This contributes to early detection of pathogens, reducing foodborne illnesses, and increasing consumer trust. Also, AI algorithms integrated with Internet of Things (IoT) sensors and big data platforms can forecast shelf life and predict spoilage patterns, thereby minimising food waste and improving distribution efficiency (Shehzad, 2025).

AI also drives automation and efficiency in food manufacturing and supply chain systems. Machine learning models are applied to optimise resource use, reduce energy consumption, and ensure equipment reliability through predictive maintenance (Song *et al.*, 2025). This not only reduces costs but also supports sustainable practices in line with climate and environmental goals. Additionally, AI-powered robotics improve consistency in food processing,

reducing human error and enabling real-time adjustments during production (Zatsu *et al*., 2024).
Another key advantage is the role of AI in product innovation and personalised nutrition. By processing consumer data, AI can recommend individualised diets and support the formulation of functional foods that cater to health needs such as diabetes management, weight control, or allergen-free alternatives (Wang *et al.,* 2023). This personalisation enhances consumer engagement and addresses public health challenges by aligning food products with specific nutritional requirements. At the same time, AI supports traceability through block chain and advanced data analytics, ensuring that food authenticity and provenance can be verified across global supply chains (Song *et al*., 2025).
AI integration into food systems also enhances ingredient discovery and functionality studies. According to Alasi *et al.* (2024), the incorporation of deep learning algorithms enables optimisation of plant-based protein formulations by identifying molecular interactions that would otherwise require lengthy and costly experimental trials. Similarly, computer vision technologies provide significant improvements in real-time quality control. For example, hyperspectral imaging combined with machine learning allows precise detection of defects, adulteration, and contamination in raw materials and processed products, thus improving safety and reducing food waste (Kang *et al*., 2022). With AI-powered screening tools, bioactive compounds such as peptides, polysaccharides, and micronutrients can be identified faster, supporting the development of functional foods that align with consumer health demands. Deep learning models integrated with high-throughput screening reduce research and development timeframes and lower costs, providing a competitive advantage for the food industry (Wang *et al.*, 2025).
However, the application of AI in food innovation also carries significant risks. One of the most pressing concerns is data dependency and bias. AI models require vast amounts of high-quality data to function effectively, but in practice, datasets may be incomplete, biased, or poorly standardised, leading to inaccurate predictions and inequities in food system decision-making (Song *et al., 2*025). For instance, models trained on limited regional datasets may not generalise well to diverse global food systems, undermining their effectiveness in addressing safety or nutritional challenges. This lack of interpretability poses problems for regulators tasked with ensuring food safety and fairness in consumer markets. Moreover, ethical concerns arise when AI is used in consumer profiling and targeted marketing, which can manipulate food choices and potentially exacerbate health inequalities (British Standard Institution, 2024).
Socio-economic risks must also be considered. While AI enhances automation and efficiency, it risks displacing workers in processing plants and quality inspection roles (Zatsu *et al.,* 2024). Without investment in workforce retraining and digital skill development, AI adoption could intensify unemployment and inequality in regions dependent on food industry labour. Additionally, the heavy reliance on computational power and digital infrastructure increases the cost of implementation and may widen the gap between resource rich industries and small-to medium sized enterprises. Furthermore, cybersecurity vulnerabilities present another layer of risk. As AI-driven platforms collect and transmit sensitive data across food supply chains, they become targets for cyberattacks that can disrupt production or compromise food safety information (British Standards Institution, 2024).

Future Prospects
As the global food industry evolves, the demand for innovative and sustainable solutions is more pressing than ever. Future ingredient innovation lies in developing multi-source hybrids that combine plant, fungal, algal, and insect proteins or bioactives through green technologies, creating multifunctional blends with superior nutrition, texture, and sustainability. Though underexplored, these strategies could unlock next-generation functional foods that meet health, sensory, and circular economy goals. Hybrid processing systems that combine novel technologies such as pulsed electric fields with enzymatic hydrolysis or cold plasma with precision fermentation offer significant potential for improving nutrient bioavailability, functionality, and scalability. Therefore, looking ahead, digital transformation would play a central role in advancing these developments. AI-guided ingredient exchange platforms could map underutilised bioresources and match them with industry needs, while smart bioreactors and sustainability scoring engines could support customised ingredient production and smarter product development. Emerging prospects also include advanced AI tools capable of predicting nutrient transitions throughout a product's lifecycle, reinforcement-learning systems designed to optimise texture development, and AI-driven platforms for modelling bioactive interactions within food matrices. Additionally, gut-on-chip digital twins may support virtual digestion trials, while integrated quantum-AI risk prediction systems could anticipate contamination events and supply-chain disruptions, shifting food systems from reactive detection toward proactive prevention.

CONCLUSION
Recent advancements in food ingredient technology are driving innovation in the food industry, emphasising sustainability, health, and functionality. Novel ingredients sourced from plants, fungi, algae, insects, and upcycled by-products, are presently recognised as nutrient-rich and sustainable alternatives, which could potentially address insecurity, environmental, and nutritional challenges. These ingredients support health and sustainability by providing proteins, bioactives, fibres, and functional components. Artificial intelligence stands as an important enhancer of food innovations by applying tools such as machine learning, deep learning, computer vision, and internet-of-things. AI is transforming the global food system by driving efficiency, sustainability, and innovation across agriculture, processing and product development. Through machine learning and other advanced tools, AI accelerates functional ingredient discovery, optimises formulations, and supports personalised, health-focused solutions. These advancements position AI as a key enabler of a smarter, more resilient, and consumer-driven food ecosystem. AI is revolutionising plant-based, alternative, and algae-based proteins by optimising cultivation, processing, and formulation through machine learning, deep learning, and digital twins. These innovations enable precise protein engineering, bioactive discovery, recipe optimisation and sustainable, consumer-focused product development.

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