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Exploring recent developments in novel technologies and AI integration for plant-based protein functionality: A review

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ABSTRACT

The increasing demand for plant-based proteins faces challenges due to their inherent functional limitations. To meet eco-friendly standards, several "green" and innovative processing technologies like high-pressure processing (HPP), pulse electric field (PEF), precision fermentation, 3D extrusion, and ultrasonic technology are gaining attention for protein functionality. Modifying protein structure through these technologies unlocks unique possibilities for functional food design. Understanding the mechanisms and advancements of these technologies is crucial for targeted functional improvements, opening new pathways for exploration. This review explores recent advances in HPP, PEF, precision fermentation, 3D extrusion, and ultrasonic technology for enhancing plant protein functionality, detailing their positive impacts. The role of Artificial Intelligence (AI) in discovering health-enhancing molecules in functional food ingredients is examined. Real-time monitoring and software development for precise protein control are key tools for leveraging these technologies effectively. Moreover, the need for further research in digitalization technologies to advance healthier and sustainable food choices was highlighted. Thus, the review offers invaluable insights for food researchers and scientists, providing a roadmap to advance the development of healthier, innovative, and sustainable food choices, aligning with evolving consumer preferences and eco-friendly standards.

1. Introduction

The rising desire for creative and nutritious food options, and in light of the surging prevalence of lifestyle-related diseases, has significantly driven the emergence of a new market for plant-based foods. This has as a result led to a shift towards plant-derived proteins. Proteins are pivotal in achieving the desired texture and structure of foods. Additionally, they contribute to enhancing the nutritional quality and functionality of food products [1–3]. Functionality refers to the non-nutritional characteristics of proteins that impact the physical and chemical attributes of the food system. Protein functionality involves an intricate interaction among the protein's conformation, structure, composition, and physicochemical properties in the presence of other non-protein components and the matrix environment [4]. Proteins exhibit various functional properties in food, including sensory attributes, hydration, surface characteristics, and texture-related properties. These properties play crucial roles in food formulation, influencing characteristics like gelation, grittiness, extrudability, foamability, surface hydrophobicity, emulsification, oil and water holding capacity, and solubility [2,3].

Plant proteins hold great promise as a sustainable alternative to animal-derived proteins because of their environmental advantages, health benefits, and reduced ecological impact. Examples of plant-based protein sources include cereals (rice, wheat, and corn), as well as pulses (peas, mung beans, chickpeas, lentils, and lupins), leaves (jackfruit, water hyacinth, pumpkin, amaranth, mulberry, and moringa), and oilseeds (soybeans, canola, and sunflowers) [5–7]. Plant proteins naturally exhibit limited and rigid functionality due to their tightly packed nature and inactive structures. This inert nature hinders their use in a wider range of food applications. Additionally, they require extensive processing, significantly impacting the environment [8–10]. For instance, legume proteins, like soy and pea, often have a 'beany' taste, which is considered unpleasant and poses a significant challenge for plant-based products like plant-based meat analogs (PBMA) [11]. The nutritional digestibility and mineral solubility in legume and cereal products are

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also limited without protein modification [12]. Likewise, pea protein isolate is a promising ingredient due to its high nutritional value, low allergenicity, and excellent foaming and emulsifying properties. However, its limited gelling ability needs to be addressed for wider use in new formulations [13].

Recent methods for enhancing protein functionality included physical modifications (thermal treatment, freeze-thawing, and hot-melt extrusion) and chemical alterations (glycosylation, phosphorylation, pH adjustments, and deamidation) [4,14]. However, these conventional methods, especially chemical modification, raised concerns about potential adverse health effects due to growing consumer demand for 'clean label' products, and practical challenges in scaling up due to their toxic nature [3]. Additionally, the substantial energy input required by heat treatments and hot-melt extrusion can hinder cost-effectiveness in achieving desired protein characteristics [15,16].

These limitations can be overcome by adopting cutting-edge non-thermal and non-chemical methods such as high-pressure processing (HPP), pulse electric field (PEF), precision fermentation, 3D extrusion, and ultrasonic technology. Fig. 1 illustrates the use of these methods as green approaches for enhancing the characteristics of plant proteins while minimally affecting their sensory and structural characteristics. HPP and PEF are non-thermal, minimal processing techniques that induce protein denaturation and gelation, resulting in enhanced textural properties [1,3,17]. Precision fermentation of plant proteins has emerged as a promising avenue for producing recombinant proteins with improved functionality. Researchers have used ester compounds generated during precision fermentation with specific yeast co-cultures to address the issue of off-flavors in plant proteins [17,18].

Moreover, the rise of digital food marketing has led to a heightened interest in using extrusion-based 3D printing for creating nutritionally customized and geometrically intricate food products [19]. Recent advancements in artificial intelligence and machine learning algorithms have significantly expedited the functionalization of ingredients, including optimizing formulations, predicting consumer preferences, and promoting the development of innovative plant-based ingredients. These processing methods induce changes in protein structures, which are common yet intricate. Comprehending their mechanism offers potential for targeted functional improvements during food processing, thereby opening new avenues for exploration. Consequently, the primary objective of this review is to explore the recent developments in five promising green processing technologies: HPP, PEF, precision fermentation, 3D extrusion, and ultrasonic technology. The exploration into the mechanisms by which these technologies modify protein structure and function, unlocking their potential for tailoring plant proteins to specific food applications was emphasized. The review discusses how these technologies positively impact various functional properties, including texture, solubility, water holding capacity, and emulsification were discussed. Furthermore, the review explores the potential of AI in characterizing health-enhancing molecules within functional food ingredients, paving the way for the development of targeted interventions for individual and public health needs. Recognizing the limitations of each technology and the need for further research in digitalization and Industry 4.0 solutions, the review highlighted the significant implications of these advancements for developing innovative, sustainable, and healthier plant-based food options, aligning with evolving consumer preferences and environmentally conscious standards.

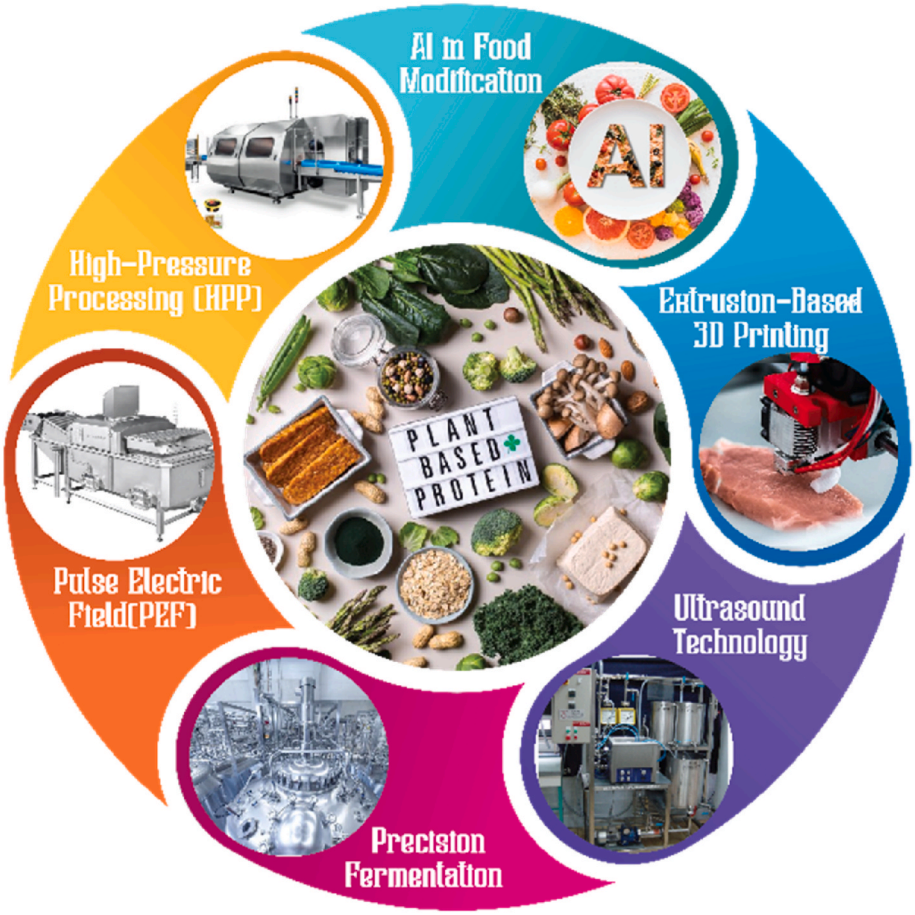


Fig. 1. Novel technologies for plant-based protein functionalization.

2. Novel processing techniques for plant proteins functionality

Innovative non-thermal and non-chemical processes significantly transform the functionality of plant-based proteins, key to creating innovative plant-based foods. Technologies such as high-pressure processing (HPP), pulse electric field (PEF), precision fermentation, ultrasound, 3D printing, and Artificial Intelligence (AI) have shown immense promise. HPP utilizes high pressures to alter protein structure, enhancing solubility and textural properties, while PEF influences protein interactions, improving solubility, foaming, and retention capacities. Precision fermentation engineers microorganisms to produce functional ingredients mimicking traditional proteins, offering potential for innovative plant-based food products. Ultrasound modifies proteins by enhancing solubility and reducing particle size through disruption of interactions. 3D printing influences food texture and flavor perception such as creating intricate shapes or mimicking meat textures, while AI characterizes bioactive ingredients for specific health needs. This section provides a comprehensive understanding of the mechanism and impacts of the novel processing techniques, outlining their significant roles in enhancing various plant-based proteins for functional food design. Various structural and functional properties related to plant proteins were discussed.

2.1. High pressure processing (HPP)

High-pressure processing (HPP), also referred to as high hydrostatic pressure (HHP) or high isostatic pressure (HIP), is an innovative non-thermal technology that uses controlled temperature and time conditions to apply hydrostatic pressures up to 1000 MPa to a food product. HPP can be used at temperatures ranging from below 0 °C to above 100 °C to mitigate adiabatic heat effects. This pressure treatment alters the volume of the food material, resulting in improved texture [20–22]. HPP modifies protein molecules by rupturing, unfolding, denaturing, and aggregating, enhancing their textural properties (see Fig. 2). The protein modification process in HPP follows key principles that dictate how foods behave under pressure. Le Chatelier's principle describes the inverse relationship between pressure and volume, where increased pressure leads to a reduction in volume. The principle of microscopic ordering reveals how temperature and pressure affect molecular structure and chemical reactions. Specifically, at constant temperature, higher pressure increases the ordering degree of molecules. Furthermore, the isostatic principle ensures that pressure and its effects are uniformly and rapidly applied throughout the entire food product, regardless of its size, shape, or composition [23].

HPP has shown great potential for altering food structures, particularly in macromolecules like proteins, through pressure-induced denaturation. This process modifies protein functionality, enhancing attributes such as solubility, water retention, emulsification, foaming, and gel formation. HPP selectively targets non-covalent bonds (e.g., hydrogen, ionic, and hydrophobic), leaving covalent bonds intact, making it a valuable tool for tailoring protein properties. It increases surface hydrophobicity, leading to denaturation, aggregation, and gelation [24,25]. At pressures above 200 MPa, protein denaturation, and aggregation significantly alter the secondary and tertiary structures of plant proteins. HPP also enhances the functionality and digestibility of cereals and legumes while deactivating antinutritional factors on a laboratory scale [26–28]. Under specific conditions, HPP-induced modifications can result in protein unfolding, aggregation, and the formation of a three-dimensional network [20,29]. For instance, exposing pea protein concentrates to 350 MPa for 15 min led to increased denaturation, aggregation, and network formation due to changes in protein tertiary and quaternary conformations [30]. Furthermore, applying high pressure (600 MPa, 4 min, 5 °C) to pea, lentil, and faba bean proteins increased their surface hydrophobicity and water-holding capacity. These changes influenced their ability to emulsify and foam, although outcomes varied depending on the protein type and treatment. Notably, lentil and pea protein isolates treated at 300 MPa for 15 min and 600 MPa for 5 min, respectively, showed enhanced proteolytic activity with greater peptide production, indicating improved gastric digestion compared to autoclaving [1,31].

High-pressure homogenization (HPH), also known as ultra-high-pressure homogenization (UHPH), is gaining popularity in food processing for its ability to enhance the functional properties of plant proteins [21,23,32]. HPH results in a uniform particle size distribution and improves the functionality of plant proteins. Smaller particle size, achieved through HPH, increases solubility and improves emulsifying and foaming properties, as seen with hazelnut and lentil proteins treated under 100 MPa pressure [33]. Furthermore, HPH also induces structural changes in proteins, such as increased α-helix and β-turns and reduced β-sheets in faba bean protein at around 207 MPa. HPH also impacts the secondary structure of faba bean and kidney bean proteins by specifically affecting hydrogen bonds [34].

A study on sweet potato protein gels induced by HPP revealed a strong correlation between rheological properties and system pH. Gels created under 400 MPa pressure at different pH levels (9.0, 6.0, and 3.0) showed promise for novel food ingredients, performing best at higher pH values [29]. Further research has highlighted the positive influence of HPP pre-treatment on the rheological behavior of heat-induced cowpea protein and wheat gluten gels [35,36]. Chao et al. [37] showed that HPP treatment at pH 3.0 enhances emulsion formation and foaming capacity in pea proteins. However, the impact of HPP on other functional properties like emulsion formation and foaming can vary, with improvements, reductions, or no changes observed. This variability depends on factors like the protein type, solution conditions, and processing parameters, including the applied pressure. Therefore, interpreting results must be considered on a case-by-case basis. To comprehensively understand how these proteins behave under HPP, it is essential to further study the interaction of these proteins with surfactants and their adsorption behavior to achieve the desired functionality, such as emulsifying and foaming properties for specific applications [1,3,20,21].

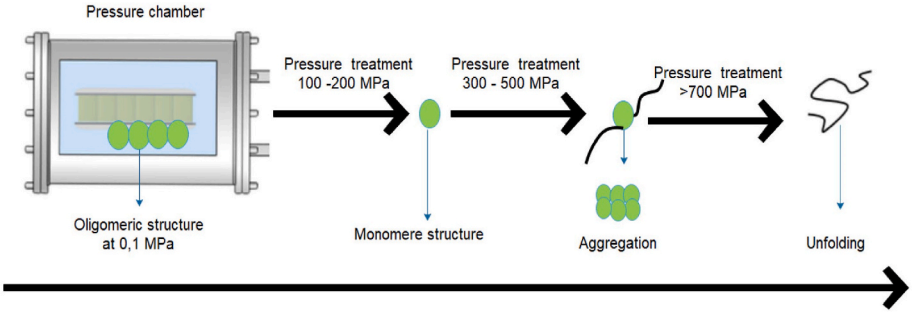


Fig. 2. Protein functionality using HPP [3].

2.2. Pulse electric field (PEF)

Pulse electric field (PEF) technology is a short-duration electrical treatment, typically lasting from 10^-4 to 10^-2 s, applying electric pulses from 100 to 300 V/cm to 0.1–80 kV/cm. During PEF treatment, the electric field interact with proteins' polar groups, absorbing energy and generating free radicals. These free radicals influence interactions within protein molecules, including hydrophobic and electrostatic interactions, disulfide bridges, hydrogen bonds, salt bridges, and van der Waals forces to form a stabilized protein system (Fig. 3). Additionally, PEF treatments can alter the apparent charge of proteins by modifying their ionic interactions [3,7,21]. PEF creates a strong electrical field across cell membranes, making it easier to extract proteins. Moreover, PEF induces changes in secondary and tertiary protein structures while disrupting non-covalent bonds, enhancing protein functionality [38]. PEF technology can either cause severe cell damage or induce sublethal stress through temporary permeabilization of cell membranes and the electrophoretic movement of charged substances between cellular compartments. This makes PEF a valuable tool for selectively recovering valuable compounds without compromising the treated material, simplifying subsequent separation and purification processes.

Moderate intensity pulsed electric field (MIPEF) treatment of rice and pea samples revealed that gluten, which contains highly reactive sulfhydryl groups, exhibited significant improvements in solubility, foaming capacity, and water and oil holding capacity when subjected to 20,000 pulses. Notably, at pH 6, gluten's water and oil-holding capacity increased, while at pH 5, its solubility nearly doubled [38]. These findings underscore MIPEF's potential to shape protein structures and enhance their functionality. Applying a PEF treatment with an intensity exceeding 35 kV/cm to soy protein isolate (SPI) induced substantial changes in amino acid side chains, anti-parallel β-sheets, β-turns, and β-sheets within SPI's secondary structure. This suggests that PEF treatment could be a novel processing method for SPI, accompanied by the partial polarization of certain bonds and complete denaturation of β-conglycinin and glycinin [39], with potential applications in protein nanotubes. PEF treatment of almond milk impacted its physical, chemical, and physicochemical properties by reducing particle size and enhancing emulsion stability, preventing separation compared to untreated samples [40]. The impact of PEF on functional properties depends on protein type. Low electric strengths (<10 kV/cm) have minimal effects on proteins. Parameters like pulse shape, pulse duration, treatment chamber type, and electric field strength significantly influence the effects of PEF on protein functionality. Further research on applying nanosecond PEF treatment to food proteins' structure and techno-functional properties is recommended. Additionally, PEF technology holds promise as an emulsification technique for producing stable food-based emulsions.

2.3. Precision fermentation

Fermentation is emerging as a highly effective technology for enhancing the functional qualities of the newest generation of plant-based products. Three main fermentation techniques commonly used for plant-based products are precision fermentation, traditional, and biomass fermentation. Among these, precision fermentation (PF) stands out as a prominent trend in the fourth industrial revolution of the food industry [41]. In precision fermentation, synthetic biology methods are employed to program microorganisms, turning them into cell factories that produce functional ingredients for the food sector (Fig. 4). The selection of the recombinant host microorganism and the engineering of specific strains have the potential to design microbes capable of expressing and producing the desired molecules in sufficient quantities. This involves using suitable fermentation conditions to maximize

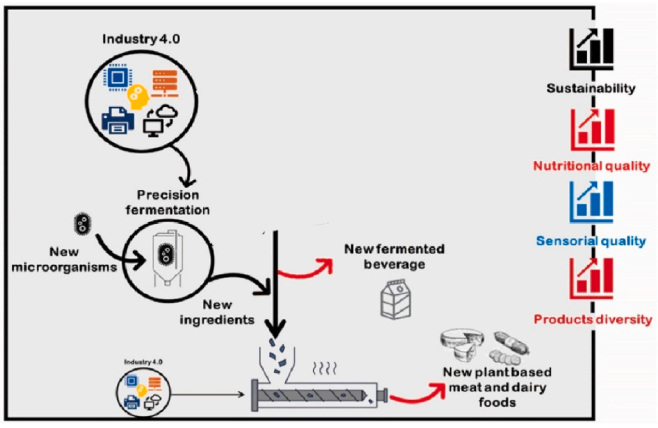


Fig. 4. Precision Fermentation for plant-based products [48].

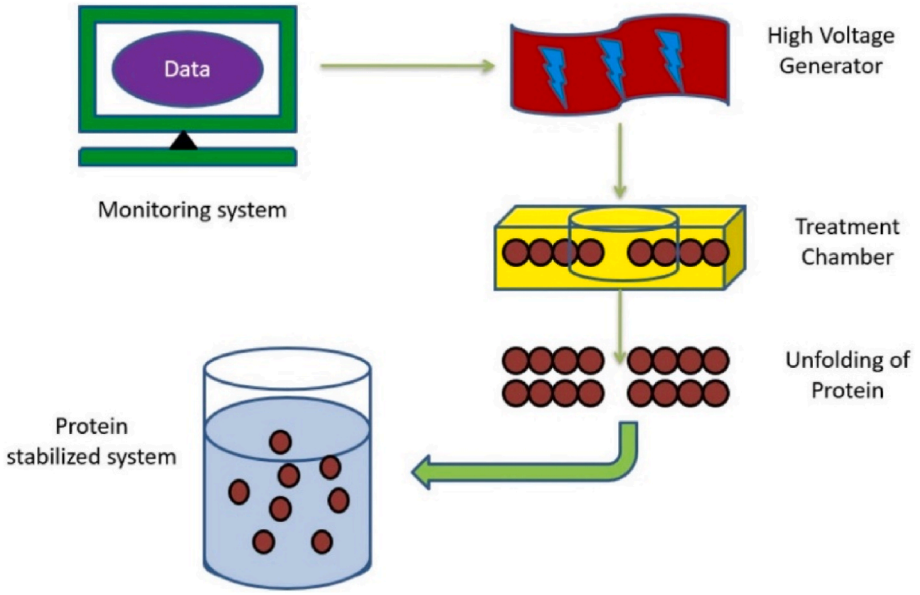


Fig. 3. Protein functionality using PEF technology [3].

production efficiency. Microbial hosts are preferred due to their ease of genetic manipulation and compatibility with standardized fermentation equipment. Regarding food applications, microorganisms that are generally regarded as safe (GRAS) or non-harmful are preferred. The engineering of specific strains often involves utilizing benign bacteria (e.g., Bacillus spp.), yeasts (e.g., Saccharomyces cerevisiae, Pichia pastoris, or Komagaetella phaffii), or filamentous fungi (e.g., Trichoderma spp., notably popular strains like T. reesei) [42–44].

Precision fermentation (PF) is a promising technique for producing target proteins that closely resemble those derived from traditional agriculture. PF offers plant-based meat and dairy manufacturers more opportunities to create products that mimic the experience of traditional meat and dairy. For instance, engineered yeast *Pichia pastoris* has been used to produce soy leghemoglobin, giving plant-based burgers the flavor and color of animal meat [45]. Safety concerns have been raised about genetically edited ingredients. However, a recent literature analysis suggests that foods containing recombinant soy leghemoglobin are unlikely to pose unacceptable risks of allergenicity or toxicity to consumers [46]. Hemami™, another yeast-derived heme protein, imparts an umami flavor and a meaty aroma, potentially enhancing the sensory experience of plant-based products. PF can also be used to create fats with molecular structures similar to animal-derived counterparts [47]. For example, Melt & Marble has developed a precision fermentation-derived beef fat alternative using yeasts [48].

Additionally, significant amounts of vitamin B12 are produced through the co-fermentation of Propionibacterium freudenreichii and Lactobacillus brevis in wheat bran [49,50]. This vitamin can fortify plant-based meat products since it is naturally absent in plant-based sources and exclusively found in animal products. Innovation in this field stems from using new species, or strains, genetic engineering, and synthetic biology techniques to enhance product yield. This can be achieved by improving factors like expression, secretion, substrate conversion, and product titer. Enzymes derived from precision fermentation can address functional limitations in plant proteins, making them more versatile. Exploring natural microbial diversity offers significant potential for developing efficient microbial cell factories for novel and safe fermented foods. Recent advanced genetic analysis tools and synthetic biology help uncover these possibilities, enabling the development of products tailored to meet specific criteria. Digitalization offers further opportunities to optimize the production of high-value ingredients such as enzymes, fats, proteins, and vitamins. Innovative technologies like 3D printing can serve as innovative solutions for shaping and texturizing products after fermentation, allowing the replication of the structure and texture of traditional products. This integrated approach enhances product development and quality [47,48].

2.4. Ultrasound technology

Ultrasound (US) processing, also known as acoustic cavitation, employs high-intensity, low-frequency sound waves ranging typically from 20 to 100 kHz [51]. This technology relies on cavitation, where air bubbles form within a liquid, expand, and ultimately implode [52]. US induces high shear forces and enhances solubility by subjecting cellular structures to stress, and deformation. The collapse of bubbles can create microscopic channels, which facilitate mass transfer within the solution (as depicted in Fig. 5). Widely recognized as an eco-friendly method, ultrasound is extensively used for cell disruption and obtaining bioactive components [3,53]. The cavitation's effects, such as increased temperature, turbulence, and mixing, enhance extraction efficiency [54]. As a result, US can modify proteins, improving their solubility, modifying hydrogen bonds, enhancing protein recovery, reducing extraction time, and mitigating protein aggregation. It can alter the secondary structure and partially denature the tertiary and quaternary protein structures with minimal impact on the primary structure [55]. Cavitation-induced micro-jets on the protein surface result in micro-jetting and particle breakdown, facilitating solvent permeation into the food matrix.

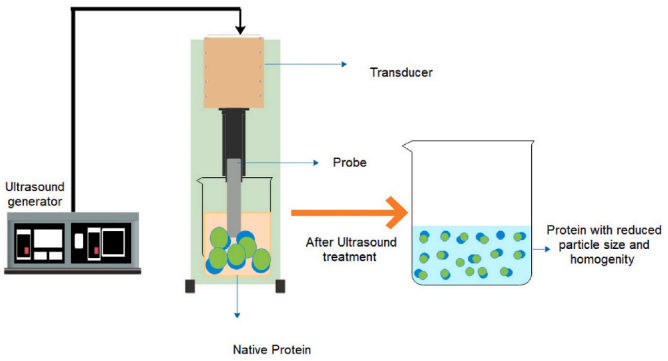


Fig. 5. Protein functionality using ultrasound technology [3].

Additionally, they can alter protein allergen conformation and reactivity [56].

A study examining walnut protein isolate revealed that exposure to higher power levels (600 W for 15 min) led to a transformation of its secondary structure, changing α-helix to β-sheet, β-turns, and random coil, as observed through circular dichroism spectroscopy [57]. The longer sonication duration at high intensity potentially disrupts specific hydrogen bonds, resulting in structural modifications. High ultrasonic power significantly reduced particle size due to intense agitation and collisions. For instance, sonication of pea protein isolates at 90% amplitude for 30 min resulted in smaller broken particles and a broader size distribution, which in turn improves solubility by reducing protein aggregate size by disrupting non-covalent interactions [58]. Similar effects were observed in soy protein isolate solutions, where sonication at 95% amplitude [59] and 600 W for 15 min reduced the particle size distribution [57]. This reduction in protein aggregates results from disrupted non-covalent interactions, such as hydrophobic, electrostatic, and hydrogen forces. Ultrasound technology, as a novel approach, has the potential to impact the structure and functional characteristics of meat alternatives while appealing to environmental sustainability. High-intensity ultrasound is a rapid, cost-effective technology used for modifying the structural and functional properties of globular proteins [58]. It has also been used for extracting valuable proteins from food industry by-products, such as olive kernels [60] and soybean okara [61].

2.5. Extrusion-based 3D printing

Three-dimensional (3D) food printing, also known as additive food assembly, is an evolving technology that structures food from digital designs. It uses computer-aided design software to control the layer-by-layer construction of 3D objects, affecting the texture of the printed food [62,63]. This technology offers several advantages, such as design freedom, customization, minimal waste, complex structure fabrication, and rapid prototyping. 3D printing allows the modification of geometric designs and spatial distributions of ingredients to alter the sensorial properties of foods [64]. Research shows that 3D printing can create larger pores in cereal cubes than traditional methods, affecting their hardness, chewiness, and cohesiveness after baking. Altering infill patterns and densities during printing can vary the texture of printed foods, as observed in the development of potato snacks. The oil content of the potato snacks reduced under controlled conditions of 3D printings. Merging instrumental analysis with sensory tests can provide further understanding into how alterations in food structure affect its functional properties [65]. Flavor modifications using 3D printing involve spatially distributing ingredients to change sweetness, saltiness, or fullness perception. Changing the layer thickness in printed chocolate showed bite-to-bite differences in sweetness, influencing liking. Salt distribution strategies during the 3D printing of starch snacks affected saltiness perception and offered the potential for salt reduction. 3D layering different lemon mousse formulations resulted in sweet and sour

variations, catering to specific consumer preferences. Furthermore, additive manufacturing with dynamic properties like 4D printing techniques have been explored for controlled flavor release and color changes in printed buckwheat snacks upon microwave heating. While existing sensory studies demonstrate the impact of 3D food printing on texture and flavor perceptions, understanding its influence on consumer preferences remains challenging due to the lack of long-term research [63].

2.6. Artificial intelligence in functional food ingredients

Artificial intelligence (AI) is significantly broadening the range of functional food ingredients (FFIs) by systematically exploring and defining safe, effective bioactive ingredients. This technology radically transforms the characterization of ingredient molecules, enabling an unprecedented understanding of the food and natural product space. The expanded pool of bioactives results in the design of targeted ingredients to address health needs facilitated by AI-driven large-scale characterization [66]. AI has successfully identified novel anti-inflammatory bioactive peptides to combat chronic low-grade inflammation. Using deep learning models and diverse data, Asian rice was revealed as containing these peptides. A rice-derived hydrolysate, designated as rice Natural Peptide Network (NPN), was designed as a new functional ingredient with immunomodulatory potential [67]. Furthermore, AI helps characterize known ingredients or plant sources in terms of their bioactive components and targeted functionalities. For instance, AI identified constituent peptides in a Vicia faba hydrolysate, previously known for exhibiting anti-atrophic activity in vivo. These predicted peptides showed positive effects in vitro, increasing protein synthesis and reducing inflammation, highlighting the crucial role of AI in discovering and characterizing peptide-based FFIs [68,69]. While, there is sparse literature on how AI characterizes plant ingredients which requires further investigation for effective design of functional ingredients.

3. Future prospects and conclusion

Today's dietary preferences are favoring sustainable, plant-based protein alternatives, prompting food researchers and the industry to focus on advancing food processing technologies. High-pressure processing offers notable enhancements to plant proteins, such as improved functional properties and increased digestibility, while reducing allergenicity and anti-nutritional factors. Other emerging techniques like PEF and US show potential in positively altering protein properties. Employing PEF enables the recover of valuable compounds from food sources and waste, minimizing resource depletion. Ultrasound, besides its benefits in protein extraction and bioactive compound recovery, enhances sensory perception by restructuring proteins through acoustic cavitation. Precision fermentation holds promise in elevating the quality of plant-based foods to match animal products, yet encounters hurdles in consumer perception, scalability, and ethical concerns. Consumers are hesitant to accept products derived from precision fermentation due to concerns about genetic modification and potential health risks. Closing the gap between consumers and this innovative technology through increased awareness is essential. Collaboration across the food industry is necessary to overcome these challenges. Future efforts should focus on comprehensive sensory evaluations for consumer understanding, investigating the digestibility of fermented products, and exploring the impact on gut microbiota. Also, a lack of understanding is available regarding the adaptation of microorganisms in a bioreactor and the relationship between the ecology and evolution of the process. Forecasting the outcomes of microorganism adaptation when transitioning from a lab to a larger scale remains uncertain, necessitating a better grasp of cell physiology and environmental interactions in larger-scale bioreactors.

3D food printing technology presents opportunities for diverse functionalities and personalized nutrition. It can produce custom soft foods tailored for older people, addressing issues like vitamin D deficiency. The technology not only tackles nutritional gaps but also replicates color, flavor, and texture in the eating experience. By adjusting filling patterns and material percentages, the internal structure can be varied to create novel foods with different microstructures and textures. The future lies in 4D printing, enabling products with automatic flavor changes. Smart materials used in 3D printing can transform instantly in response to specific stimuli, generating new structures with varied shapes, colors, or flavors. These transformable materials will spark great interest in printed food and drive the commercialization of 3D food printing technology. Identifying or developing functional ingredients that can respond to environmental stimuli (such as temperature, pH, or moisture) to achieve the desired transformation poses a challenge. While some materials have shown potential for shape-changing abilities, finding materials that are safe, cost-effective, and suitable for food applications is crucial. Ingredients such as edible insects have shown potential, however, further research on their ability to undergo controlled transformations is required. Moreover, ensuring these materials meet food safety standards is a major concern.

As technology integrates further into healthcare, and with the rising significance of functional food ingredients (FFIs), we're approaching a new era in nutrition technology. AI presents a powerful tool for the efficient discovery and characterization of health-enhancing molecules in FFIs. These interventions aim to meet individual and public health needs, contributing to a safer and more sustainable food system. By utilizing AI in the discovery and development of FFIs, we can significantly improve the safety and cost-effectiveness of food solutions for better human and animal health in the coming decades. In conclusion, these technologies have proven to modify protein structure, offering unique opportunities for functional food design. However, further development is necessary for the industrial implementation of these methods beyond laboratory scales. More research exploring digitalization and Industry 4.0 technologies can also pave the way for healthier and sustainable food options. Moving ahead, real-time monitoring and software development for precise protein structural control is essential for leveraging these technologies to improve protein functionality.

CRediT authorship contribution statement

Sodiq Oladimeji Alasi: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Mayowa Saheed Sanusi:** Writing – review & editing. **Musiliu Olushola Sunmonu:** Writing – review & editing. **Michael Mayokun Odewole:** Writing – review & editing. **Abiola Lydia Adepoju:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Data availability

No data was used for the research described in the article.

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