



## Research

## Diversified Food Supply System—Review

# Innovative Food Processing Technologies Promoting Efficient Utilization of Nutrients in Staple Food Crops



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## ABSTRACT

With the rapid growth of the global population and the increasing demand for healthier diets, improving the nutrient utilization efficiency of staple food crops has become a critical scientific and industrial challenge, prompting innovation in food processing technologies. This review introduces first the common nutritional challenges in the processing of staple food crops, followed by the comprehensive examination of research aiming to enhance the nutritional quality of staple food crop-based foods through innovative processing technologies, including microwave (MW), pulsed electric field (PEF), ultrasound, modern fermentation technology, and enzyme technology. Additionally, soybean processing is used as an example to underscore the importance of integrating innovative processing technologies for optimizing nutrient utilization in staple food crops. Although these innovative processing technologies have demonstrated a significant potential to improve nutrient utilization efficiency and enhance the overall nutritional profile of staple food crop-based food products, their current limitations must be acknowledged and addressed in future research. Fortunately, advancements in science and technology will facilitate progress in food processing, enabling both the improvement of existing techniques as well as the development of entirely novel methodologies. This work aims to enhance the understanding of food practitioners on the way processing technologies may optimize nutrient utilization, thereby fostering innovation in food processing research and synergistic multi-technological strategies, ultimately providing valuable references to address global food security challenges.

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## 1. Introduction

Grains, legumes, and tubers are fundamental staple food crops that form the core of the human diet, providing essential macronutrients such as carbohydrates, fats, and proteins, thereby directly contributing to human health and well-being [1]. Throughout history, societies have consistently advanced food

processing technologies to maximize the nutritional benefits and healthiness of staple food crops [2]. Unfortunately, conventional food processing methods often result in substantial nutrient losses, low utilization efficiency, the generation of potentially harmful substances, and suboptimal sensory properties in the final staple food crop-based products [3]. This has created a growing need for innovative food processing technologies to overcome these limitations and meet the evolving consumer preferences [4–6].

Innovative processing technologies can be broadly categorized into three types: physical, chemical, and bioprocessing [3,7,8].

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Physical methods, such as high-pressure, ultrasound, and pulsed electric field (PEF) processing, use non-thermal energies to extract bioactive compounds, improve nutrient bioavailability, and modulate texture without harmful chemicals, resulting in safer, cleaner and greener offerings [4–6]. Chemical processing employs food-grade reagents, antioxidants, and antimicrobials to boost the functionality, digestibility, and safety of staple food crop-based products, meeting consumer demands for nutritious and safe options [9,10]. Bioprocessing leverages microorganisms and enzymes to enhance flavor, texture, and nutritional profiles, aligning with the growing preferences of consumers for lightly or unprocessed, natural, and sustainable foods [11,12]. The judicious integration and implementation of these diverse processing technologies enable the development of staple food crop-based products with enhanced nutritional value, improved quality characteristics, and greater consumer appeal, ultimately contributing to better health outcomes and environmental sustainability [13].

From the perspective of food processing, improving nutrient utilization, reducing losses, and increasing functional benefits are effective strategies for addressing the global food crisis and meeting human health needs [14]. However, the successful implementation of these strategies depends on innovations in food processing technology [2]. Therefore, it is essential to systematically analyze the limitations of traditional processing technologies regarding nutrient utilization in staple food crops and further understand the principles of innovative processing technologies to promote the efficient utilization and improvement of their nutritional value. As shown in Fig. 1 [15,16], this work will first analyze the common nutritional problems encountered with the processing of various staple food crops including grains, legumes, and tubers. Subsequently, innovative food processing technologies with the potential to significantly address these problems—such as non-thermal processing, natural deep eutectic solvents (NADESS), fermentation, and enzyme processing—will be reviewed, outlining their development status and current limitations. Finally, future directions for food processing technology, based on the latest scientific and technological progress as well as the current needs of the food industry, will be discussed.

## 2. Main nutritional challenges in staple food crop processing

Nutritional challenges posed by consumers' consumption of grains, legumes, and tubers arise from nutrient imbalances and antinutritional factors [17]. For instance, grain husks contain beneficial nutrients like vitamins and minerals alongside antinutritional factors such as phytic acid. Mechanical processing, like grinding and refining, often removes husks, resulting in refined grains that provide energy but lack a comprehensive nutritional value, potentially contributing to dietary imbalances and chronic diseases [18]. In contrast, whole grain consumption is consistently linked to health benefits, with many countries' dietary guidelines advocating their increased consumption [18–20]. However, improving the texture, sensory quality, and functional characteristics of whole-grain products remains a challenge [21].

While using whole grains reduces nutrient losses, the presence of antinutritional factors is still a concern. Legumes such as beans, lentils, and peas, contain lectins and protease inhibitors that can hinder digestion and nutrient absorption [22,23]. Lectins may damage the gut lining, while protease inhibitors reduce protein digestibility. Tubers, like potatoes, cassava, and yams, staples in many regions, are also not exempt of concerns; for instance, cassava will produce cyanide if not properly processed [24]. Similarly, potatoes can accumulate glycoalkaloids, toxic compounds whose presence increases when exposed to light, posing health risks if consumed in large amounts. Consequently, research focuses on

developing sustainable technologies to reduce the presence of antinutritional factors while preserving the nutritional value of foods.

Recent advancements in processing staple food crops have centered on two primary areas: whole grains and extracted staple food crop ingredients. For whole grains, the goal is to enhance their nutritional value, improve their sensory qualities, and address the challenges associated with their incorporation into food products. One major challenge is the less appealing texture and sensory profile of whole grains compared to their refined alternatives. Optimized milling processes have been developed to retain more bran and germ, enhancing the texture of whole grain flour. Additionally, fermentation and enzymatic treatments have been employed to improve the taste, texture, and digestibility of whole grain products, making them more palatable. Research is also investigating the functional properties of whole grains, particularly their potential to reduce the risk of chronic diseases. Technological advancements aim to retain and enhance these health benefits through minimal processing to preserve bioactive compounds such as dietary fiber, polyphenols, and flavonoids.

In addition to whole grains, recent advancements have explored the extraction and utilization of ingredients from staple food crops or their by-products, including starch, protein, dietary fiber, oil, and bioactive compounds [25–27]. These ingredients can be formulated into value-added products, improving their nutritional profiles, as well as enhancing the sustainability of the food sector by reducing the amount of waste materials generated. For instance, starch can be processed to become indigestible by humans but available for targeted colonic fermentation that produces beneficial short-chain fatty acids supporting immunity, intestinal health, and microbiota balance [28–30]. Plant oils extracted from crops such as rapeseed, soybeans, and peanuts have complex compositions of fatty acids, vitamins, polyphenols, and other bioactive compounds enhancing their sensory qualities. Current efforts in oil processing focus on leveraging new technologies to enhance extraction efficiency, preserve or augment nutritional value, and improve flavor. However, the utilization of abundant proteins in staple food crop residues after starch or oil extraction can pose some challenges, as certain phytochemicals may diminish nutritional value or lead to undesirable sensory properties [31]. Innovative processing technologies to obtain high-quality proteins are attracting significant attention. Additionally, staple food crop-derived dietary fibers and bioactive compounds are incorporated into foods to enhance gut health and develop functional products with specific health benefits.

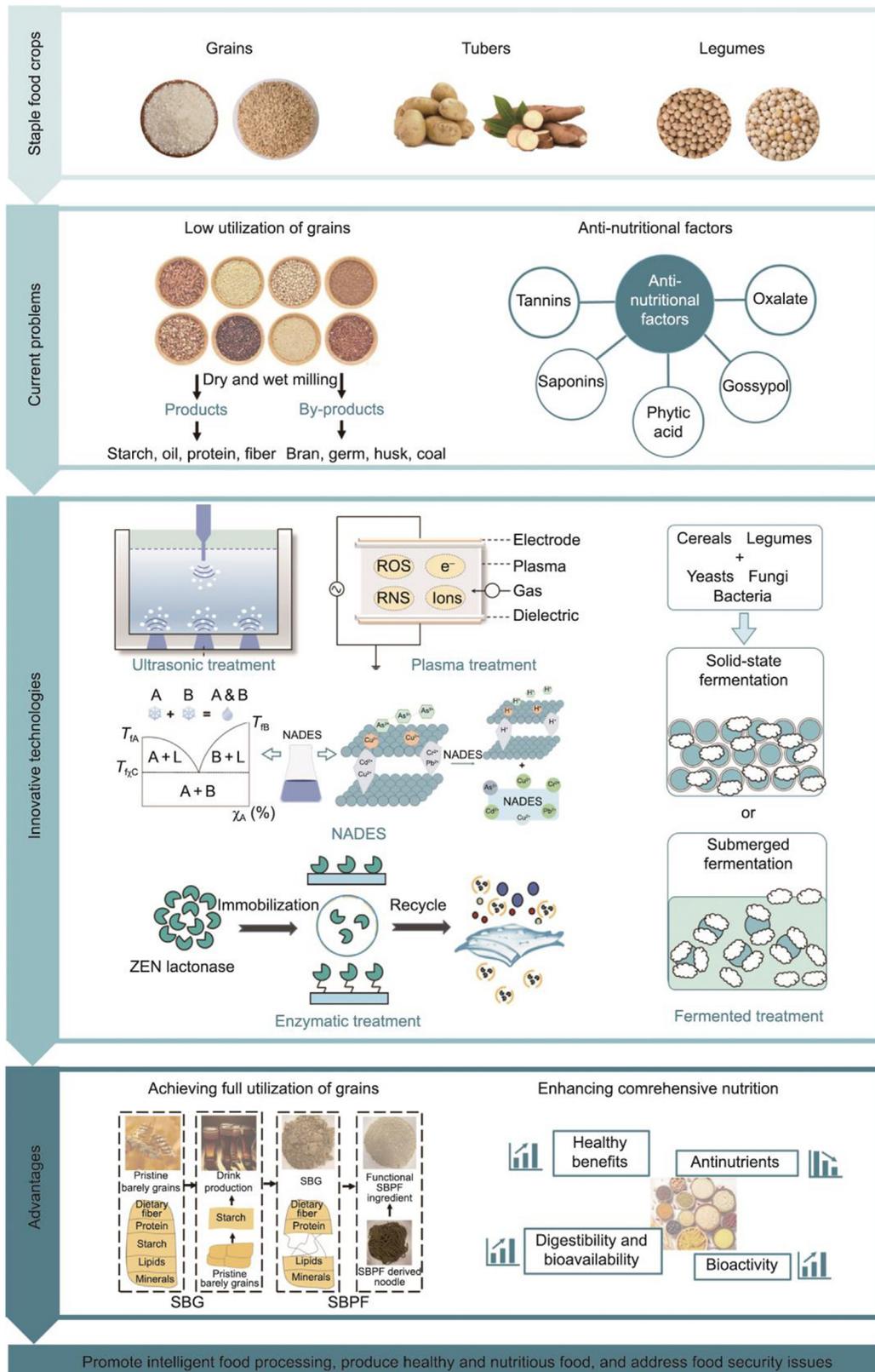
In conclusion, addressing the nutritional challenges of grains, legumes, and tubers is essential for improving dietary health and preventing chronic diseases. While whole grains offer significant benefits, their use in food products is often limited by their texture and antinutritional factors. Recent advancements in processing technologies aim to enhance the nutritional value and palatability of whole grains while facilitating the extraction of beneficial ingredients from staple crops. These innovations create value-added products that reduce waste and improve nutrition, contributing to more sustainable food systems. The following sections will detail how these technologies effectively tackle these challenges.

## 3. Efficient utilization of nutritional components through innovative food processing technologies

### 3.1. Innovative physical processing technologies

#### 3.1.1. Dielectric heating technologies in staple food crop processing

Dielectric heating raises the temperature of electrically insulating materials by exposing them to a high-frequency



**Fig. 1.** Innovative food processing technologies promoting the full utilization of staple food crops' nutrients and enhancing the nutrition provided by staple food crop-based foods. The innovative food processing technologies shown in the figure include ultrasound technology, cold plasma technology, natural deep eutectic solvents (NADES) technology, enzyme technology, and fermentation technology. NADES part reproduced with permission under the Creative Commons Attribution (CC BY) license from Ref. [15]. Achieving full utilization of grains part reproduced with permission under the Creative Commons Attribution (CC BY) license from Ref. [16]. ZEN: zearalenone; SBG: spent barley grain; SBPF: spent barley protein and fiber; ROS: reactive oxygen species; RNS: reactive nitrogen species. The definition of all the abbreviations in the figure could be found in the cited references.

electromagnetic field. Unlike conventional conduction-based methods, which rely on a temperature gradient, dielectric heating generates heat internally, minimizing temperature variations between external and internal layers—a common issue in conventional thermal processes [32,33]. This technique employs two regions of the electromagnetic spectrum: radio frequency (RF), spanning from 10 kHz to 300 MHz, and microwave (MW), ranging from 300 MHz to 300 GHz. These high-frequency fields enable rapid heating of insulating materials.

Novel heating methods in food processing must ensure consumer safety and acceptance while retaining nutritional integrity. Studies indicate that MW treatment outperforms conventional methods, enhancing food quality—such as structure, texture, and color—while retaining more nutrients, including vitamins and bioactive compounds [34–38]. Moreover, MW techniques boost production efficiency by reducing treatment time and energy consumption [39–41]. The application of a 915 MHz industrial MW, noted for its superior penetration power compared to 2.45 GHz MW, has been tested for rice drying. This technology significantly shortens drying time compared to traditional heated-air dryers [35], achieving a 67% head rice yield in one-pass drying at an energy input of 450 kJ·kg<sup>-1</sup> and a bed thickness of 5 cm, outperforming conventional methods that yield only 58%. The potential gains for the global rice processing sector from this technology are tremendous, with data from Arkansas estimating additional revenue of 15 million USD just for that United States [42,43]. It also helps reduce energy costs, prevent rice breakage, minimize nutritional degradation, and improve rice quality, making a breakthrough in rice drying technologies [36,42,44]. Additionally, MW processing effectively reduces anti-nutritional factors, such as phytic acid and trypsin inhibitors, in grains, thus enhancing food quality and safety. Beyond rice drying, MW processing also improves the extraction efficiency of essential oils with strong antioxidant properties and is widely used to recover valuable compounds from food processing waste [45,46].

In contrast, RF energy penetrates deeper into samples, making it suitable for processing large size and bulk materials. As technology progresses, RF heating is emerging as a potential non-chemical method for insect control in grains, possibly replacing chemical fumigation [47,48]. This approach can reduce grain losses during storage and transportation, ensuring more grains available for consumption, thus enhancing overall grain utilization [49,50]. The differences in dielectric properties between pest insects and grains allow for selective heating under RF conditions. The higher loss factor in insects, particularly those with higher moisture content, enables RF heating to reach lethal temperatures for insects while keeping grain temperatures relatively low [51]. This capability is advantageous for developing effective RF disinfestation treatments that control pests without compromising grain quality [52].

While MW and RF heating provide benefits like rapid heating, minimal nutritional losses, and high controllability, they still face challenges, particularly uneven heating. Factors, such as the size, shape, and dielectric property heterogeneity of raw material can lead to uneven electromagnetic wave distribution, affecting temperature uniformity. Future research should integrate insights from food science, physics, and materials science to better understand how polar components in food materials behave in electromagnetic fields, particularly their absorption and conversion of electromagnetic energy into heat, in order to meet the demand for comprehensive nutrition utilization in food processing.

### 3.1.2. Electric field technologies in staple food crop processing

Electric field technologies, including PEF and cold plasma, are novel non-thermal processing techniques gaining considerable attention for their advantages over conventional ones. Electric field energy is used to induce physical or chemical changes in grains at

the molecular level without requiring high temperatures, thus preserving the nutritional value and quality of the food product.

PEF, particularly promising for maintaining product quality and for its energy efficiency in food processing [53–55], features a system that includes a high-voltage pulse power supply, treatment chamber, and control systems. Square wave and bipolar pulses are preferred for sustained intensity and cell membrane permeability, respectively. PEF has been shown to modify starches by transforming them from crystalline to non-crystalline states, with intensified effects at higher field strengths due to the disruption of hydrogen bonds and double helices [53,56–59]. However, excessive PEF can cause significant damage to starch granules, altering their morphology [60,61]. Additionally, PEF enhances the germination rate (10%) and seedling rate (28%) while decreasing the endogenous microflora and improving grain storage. Despite its potential, the use of PEF implies that foods are able to withstand high electric fields and requires significant equipment costs, necessitating efforts to reduce power consumption and ensure consistent field strength for commercial viability.

Cold plasma technology offers a sustainable alternative by minimizing the need for chemical additives. It ionizes gases with electric fields to generate chemically active substances that interact with food components, thereby altering nutritional quality in grains like pearl millet, guar seed, horse gram, yam, and rice [62–67]. This method effectively utilizes available food raw materials, making various foods more digestible and compatible with human nutritional needs. In terms of starch utilization, plasma treatment enhances enzymatic accessibility and promotes digestion by etching surfaces and depolymerizing starch molecules in legume flours [68]. It also improves *in vitro* protein digestibility in legume flours by decreasing anti-nutritional components and altering protein conformation [66,67]. Notably, plasma treatment can mitigate excessive anti-nutritional factors like tannins, phytic acid, and saponins in legumes and grains and enhancing minerals absorption [62,66,69,70]. Additionally, it can modify total phenol and flavonoid content by either releasing bound phenols or degrading them [66,67,69,70]. Plasma treatment may also be used for nutrient fortification, elevating the content of rice in iron and ascorbic acid to 862.93 and 1398.27 mg per 100 g, respectively, improving their bioavailability with the formation of acidic functional groups on the rice surface [63]. Additionally, it can remedy methionine deficiencies in kidney and adzuki beans by 37.5% and 50%, respectively, while altering the amino acid composition of yam and rice flours [62,68,71]. Despite the promising enhancements in functional and nutritional properties through plasma treatment, further research is essential to clarify the impacts of reactive species and assess their long-term effects.

### 3.1.3. Mechanical technologies in staple food crop processing

Mechanical technologies like high pressure processing (HPP) and ultrasound have revolutionized food processing by offering efficient, non-thermal treatment options. These technologies utilize extreme pressures or mechanical waves to alter the microstructure and physicochemical properties of food materials under relatively mild conditions [72]. HPP utilizes water or other fluids as a medium to distribute pressure uniformly across the food matrix, while ultrasound enhances mass transfer through acoustic cavitation caused by sound waves. Both technologies result in shorter processing times and lower temperature conditions, making them advantageous over traditional methods [73,74].

Traditional heat treatment often alters the structure of macromolecules and degrades small molecules in foods. In contrast, HPP is a commercialized non-thermal technology that subjects foods, in sealed containers, to pressures ranging from 100 to 600 MPa at room temperature, allowing for the processing of foods in various sizes and packaging forms [73]. This method causes

minimal damage to the nutritional and sensory qualities of grains compared to thermal methods, effectively preserving color, aroma, taste, and nutritional content. For instance, HPP can induce starch gelatinization in rice, improving texture, nutritional value, and quality attributes [75]. It can also facilitate the transfer of nutrients, such as thiamine, from the rice outer layers to its endosperm [76]. In Japan, HPP has been applied to enhance ready-to-eat steamed rice by modifying proteins and starches [77] and increasing  $\gamma$ -aminobutyric acid (GABA) levels in brown rice [78]. HPP offers numerous advantages for processing legumes and whole grains, enhancing efficiency and sensory attributes while eliminating anti-nutritional factors and maximizing nutritional and functional benefits [79–81]. For instance, lentils, peas, and faba beans exhibit higher gel strength and increased foaming capacity after HPP treatment. Additionally, reduced hardness and chewiness of chickpea and rice were observed due to protein aggregation during HPP processing. However, HPP faces challenges such as the need for robust packaging, handling issues for low-density materials, and compliance with safety regulations.

Like HPP, ultrasound technology is a non-thermal treatment that alters the physicochemical properties of grains using mechanical waves. Low-intensity, high-frequency ultrasound is employed for non-destructive analysis, while high-intensity, low-frequency ultrasound is utilized in food processing [82]. The cavitation effect of ultrasound disrupts plant cell walls, alters protein conformation to expose hydrolysis sites, and regulates enzyme activity, promoting the hydrolysis of protein into more digestible peptides [83–85]. Ultrasound also accelerates solvent penetration through cell walls, enhancing the release and extraction efficiency of bioactive compounds from grains such as quinoa, corn cob, rice bran, peanut, lupin, and sweet potatoes [83,86–89]. Additionally, ultrasound-mediated hydration has improved functional properties of finger millet by reducing phytates and tannins by 73% and 71%, respectively [90]. It has also served as a pretreatment to significantly increase nutrient absorption in fortified rice by 140% for vitamin B5 and by 1982-fold for folate [91,92]. High-intensity ultrasound has been recommended for increasing phenolic phytonutrient levels in tofu whey [93]. While ultrasound technology plays an important role in efficient nutrition utilization, further research is needed to elucidate the detailed mechanisms of its effects on nutrients, enzymes, and microorganisms, as well as the influencing factors of cavitation intensity and quantitative methods of measuring cavitation activity.

As shown in Fig. 2, the advantages of novel physical processing technologies primarily lie in the maximizing nutrient retention, reducing antinutritional factors, fortifying nutrients, and regulating the digestive outcomes of grains during processing. This is particularly significant to address global challenges such as climate change, land scarcity, population growth, and rising nutritional demands. These technologies, characterized by high efficiency, clean production, and environmental sustainability, align with the growing trend of sustainable development in the food sector. By leveraging these advanced physical processing technologies, food processing can be refined to minimize resource wastage and ensure the retention of nutrients in food products, thereby meeting consumers' growing demand sustainable healthy and nutritious foods.

### 3.2. Innovative chemical processing technologies

#### 3.2.1. Treating by-products with NADES to enhance the utilization of nutrients

Food processing faces challenges to improve the utilization of nutrients in staple food crops. Extracting vegetable oil from rapeseed (*Brassica napus* L.) and starch from peas (*Pisum sativum* L.) enriches the protein content of residues. However, antinutrients

and phytochemicals may undermine their nutritional quality and sensory properties, causing off-tastes, off-flavors, and off-colors [94,95]. The perception of grain proteins, especially from rapeseed, as inferior to animal proteins limits their use [96]. Conventional aqueous methods struggle to remove these compounds, resulting in their co-solubilization and co-precipitation with proteins. While organic solvents can retain insoluble proteins, they raise toxicity concerns, and even food-grade ethanol can denature proteins [97]. The alternative method, dry fractionation, relies on grinding and particle separation without water or chemicals, with the resulting pea protein concentrate still having undesirable sensory properties and requiring further extraction [98].

To overcome these limitations and maximize the potential of staple food crop-based foods, chemical processing technologies have been explored, particularly the use of NADES, by the food industry. These solvents, formed by combining hydrogen bond acceptors and donors derived from natural sources, have garnered significant attention due to their effectiveness in extracting low molecular weight phytochemicals from various plant materials [99,100]. The unique solvation properties of NADES enable selective extraction of target compounds, potentially allowing for the recovery of both the phytochemicals and the protein- and fiber-rich residues [101]. However, challenges persist regarding the separation of extracted materials, achieving complete sedimentation of particles due to the viscosity of certain NADES, and understanding the effects of water content on the stability of dispersed proteins. Additionally, the recovery and reuse of the NADES, along with the efficient extraction and purification of the phytochemicals, require further research and development [101–104]. Addressing these technical and operational challenges is crucial for the successful implementation of NADES-based extraction processes in the context of staple food crop protein refining and the advancement of staple food crop-based food products.

#### 3.2.2. Introducing natural preservatives as components to achieve chemical preservation

Food spoilage during storage is a major concern, as moisture and nutrients foster microbial growth and toxin production, leading to declines in quality, nutritional value, and food safety [105]. Preservatives are used to inhibit microbial growth and enhance food quality. Although synthetic preservatives extend shelf-life significantly, consumer concerns have led the shift towards natural alternatives from plants, animals, and microbes [105,106]. Natural preservatives like essential oils [107], polyphenols, lysozymes, lactoferrin, chitosan, and antimicrobials [105,106] have gained industry attention.

Baked goods, especially bread, are susceptible to microbial spoilage during storage [107]. Essential oils have emerged as promising natural preservatives through various methods: ① incorporation into packaging, ② encapsulation for controlled release, and ③ direct inclusion [107–109]. For instance, lemongrass essential oil, when encapsulated in cassava starch fibers, extended, by inhibiting spoilage microorganisms such as *Penicillium crustosum* and *Aspergillus flavus*, the bread shelf-life from 5 to 10 d [110]. Carvacrol loaded into potato soluble starch nanofibers also showed anti-spoilage benefits [111], and orange essential oil-enriched oleogel extended shelf-life by at least 5 d while also improving bread texture [112]. Furthermore, nanoencapsulated oregano and thyme essential oils demonstrated strong resilience against mold and yeast in bread, extending shelf-life by 21 d [113]. Although the unpleasant odor associated with many essential oils remains a challenge [107], *Rosmarinus officinalis* L. essential oils have been found to improve both aroma and safety in bread [114].

Antimicrobial peptides also offer potent resistance against bacteria, fungi, and molds [105]. Derived through enzymatic hydrolysis and fermentation [115], they inhibit microbial growth

and extend shelf-life. For instance, faba bean flour fermented with *Levilactobacillus brevis* AM7 produced antibacterial peptides [116], while surplus bread fermented with *Lactobacillus brevis* AM7 demonstrated antifungal properties [117]. Palm kernel cake, fermented with *Lactobacillus casei* ATCC334, yielded bioactive peptides that extended bread shelf-life by 10 d [118]. Enzyme technology has also been employed to generate antimicrobial peptides from proteins. For instance, lactopeptidase hydrolyzed wheat gluten, producing peptides that delayed fungal growth in bread (e.g., *Aspergillus niger* and *Penicillium* sp.) for up to 3 d at 0.3 g·kg<sup>-1</sup> [9]. Similarly, enzymatic hydrolysis of pea, lentil, and faba bean flours yielded an extract rich in antimicrobial peptides that inhibited fungi growth, extending bread shelf life by up to 14 d without affecting sensory properties [119]. Hydrolyzed goat whey with trypsin also enhanced antifungal activity, reducing fungal presence and mycotoxins, thus extending bread shelf-life [120].

Despite these benefits, antimicrobial peptides face challenges such as hygroscopicity, bitterness, and instability. Encapsulation systems, such as spray-drying with maltodextrin and whey protein concentrate, have improved the stability and sensory properties of alcalase-hydrolyzed oleaster-seed peptides, enhancing texture properties and masking bitterness in bread [121].

### 3.2.3. Introducing natural antioxidants as components to inhibit food oxidation

Food oxidation during storage can be effectively delayed by incorporating natural antioxidants, such as polyphenols,

flavonoids, and vitamins derived from food-grade raw materials, thereby replacing synthetic additives to enhance functionality [106,122]. Although complex purification processes are sometimes required, simple treatments—such as crushing or water extraction—can yield antioxidant-rich mixtures suitable for direct food applications.

Vegetable powders, including carrot, spinach, and beetroot, mixed with ground rice and thermoplastically extruded, impart natural color and enhance the mineral, protein, lipid, fiber, phenolic, and antioxidant content in breakfast cereals. However, the high fiber content affects the physical structure by reducing swelling, hardness, and paste viscosity. Overall, these vegetable powders serve as beneficial additives that improve the nutritional and functional value of breakfast cereals [10]. Additionally, partial substitution of common wheat flour with cereal coffee in pasta production resulted in reduced brightness, heightened redness, shorter cooking time, and higher cooking losses, while affecting favorably aroma, flavor, and color, and reducing stickiness at elevated levels. Pasta enriched with cereal coffee, with an optimal addition of up to 4 g per 100 g of wheat flour, exhibited a greater total phenolic content and antioxidant capacity [123]. Although potentially having negative impacts on texture and overall food perception, murici (*Byrsonima verbascifolia*), rich in fiber, lipids, carotenoids, and antioxidants, has been used in the production of cereal bars, for all the benefits it conferred [124]. Similarly, spirulina and orange blossom essential oils were incorporated into gluten-free, sugar-free cereal bars, resulting in

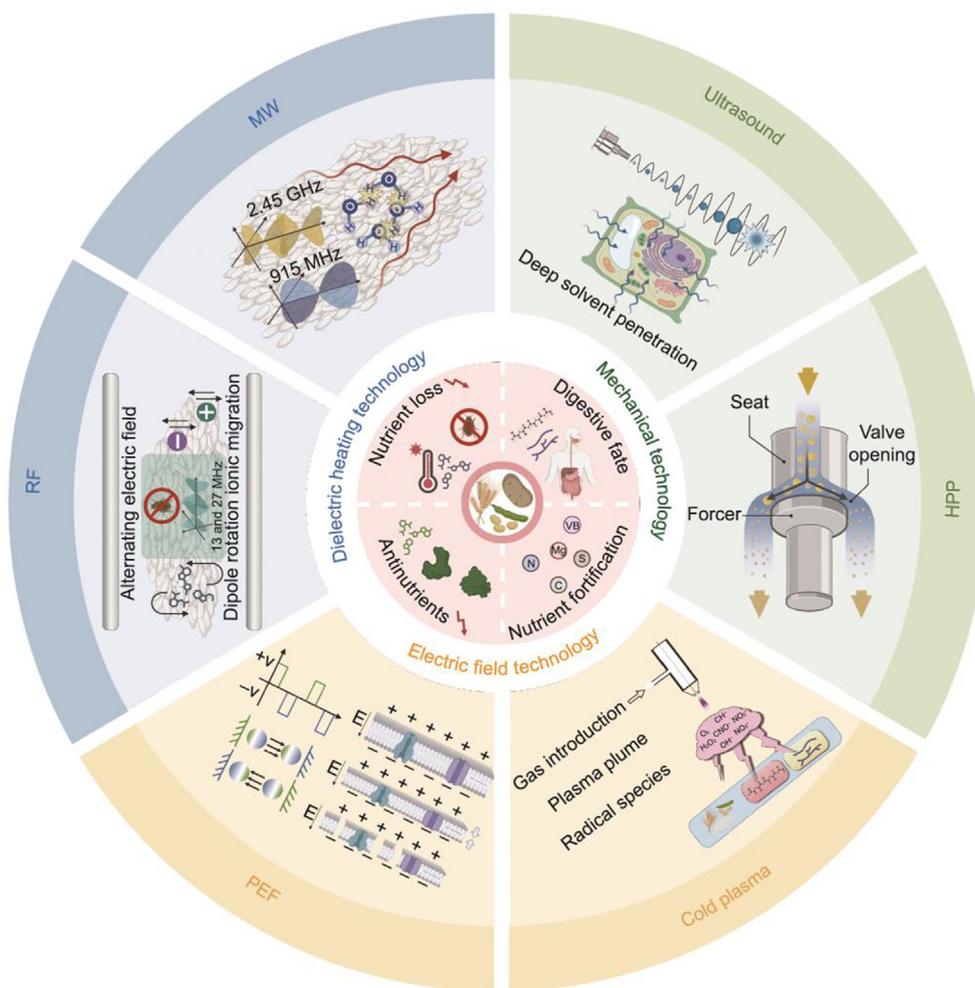


Fig. 2. Schematic diagram of the relationships between physical technologies and nutritional characteristics related to staple food crops. Created with BioRender. v: voltage; E: electric field; VB: vitamin B.

higher sensory scores and significantly enhanced nutritional and energy values [125]. Tea extracts, rich in flavanols and gallic acid derivatives—including catechins and epicatechins—are potent natural antioxidants. Incorporating tea extracts, like Assam tea at 0.3 mg·g<sup>-1</sup>, into cereal foods not only boosts the antioxidant capacity but also enhances the food functionality. The use of 0.5% Assam tea extract in rice bran breakfast cereal production significantly increased total phenolic content and antioxidant capacity, while also improving sensory properties and consumer acceptance [126].

Traditional food processing methods, such as sugaring, salting, smoking, and the use of additives, pose potential health risks. Recently, innovative chemical processing techniques, including NADES and the incorporation of natural preservatives and antioxidants, have garnered significant attention. As illustrated in Fig. 3, NADES can be utilized for extracting and separating by-products from staple food crops during processing to obtain alternative proteins [99,127]. Plant-derived essential oils and protein-derived peptides have demonstrated efficacy in preserving baked goods, minimizing the loss of nutritional components from raw staple food crops, and maximizing their utilization [111,119]. Moreover, utilizing powders or extracts from food raw materials or by-products abundant in natural antioxidants, such as polyphenols and flavonoids, as ingredients in commercial staple food crop-based foods can enhance both the antioxidant capacity and functionality of foods, while simultaneously boosting their nutritional value [124].

### 3.3. Innovative bioprocessing technologies

#### 3.3.1. Modern fermentation technology

Fermentation has long been a crucial method in food processing. Microorganisms, including bacteria, yeasts, and fungi, convert carbohydrates into acids, gases, or alcohol, facilitating energy production under anaerobic conditions. This biochemical process enhances food quality, digestibility, and nutritional value [128]. With advancements in biotechnology, numerous sophisticated fermentation methods have emerged. This part focuses on three significant advancements: the selection of specific bacterial strains for fermentation, the application of synthetic biology, and the optimization of reaction environments, all of which have led to a multitude of novel applications [129–131].

Recent research has made significant strides in utilizing natural microbes for fermentation, with ongoing efforts aimed at enhancing their efficiency. Shi et al. [132] employed lactic acid fermentation with *Lactobacillus plantarum* to eliminate grassy off-flavors from pea protein isolates, thereby enhancing aroma and increasing customer acceptance. Byanju et al. [133] demonstrated that fermentation involving *Lactobacillus plantarum* and *Pediococcus acidilactici* significantly reduces anti-nutritional factors in legumes, particularly lowering total phenolic content. Budhwar et al. [134] proposed that the combination of germination and probiotic fermentation will optimize nutrient utilization in cereals and millets. Beyond the use of single bacterial strains, the use of mixed bacterial cultures has also demonstrated some value. Chen et al. [135]

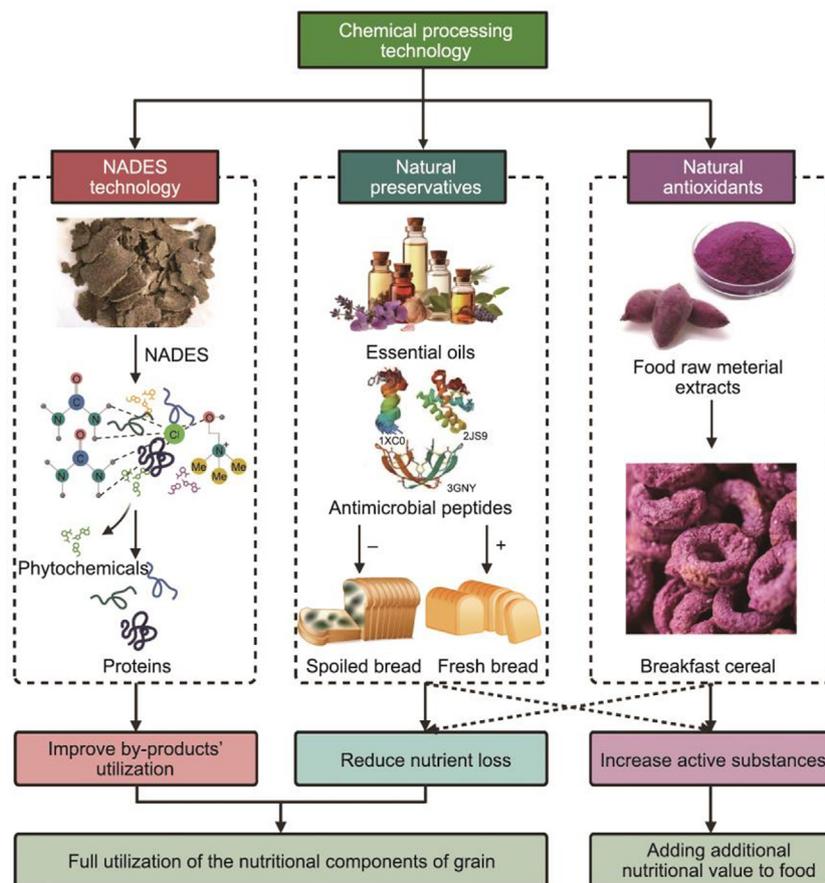


Fig. 3. Application of chemical technologies in staple food crop processing. Increasing the nutritional value of staple food crop-based food by improving by-product utilization, reducing nutrient losses, and increasing the presence of active substances. Created with BioRender.

applied a mixed starter culture of *Rhizopus arrhizus*, *Saccharomyces cerevisiae*, *Pichia kudriavzevii*, and *Lacticaseibacillus rhamnosus* to effectively enhance the fermentation process and improve the quality of highland barley yellow wine.

The advancement of synthetic biology facilitates the development of more potent microbes with enhanced specificity and multifunctionality for application in fermentation systems. Gene modification of lactic acid bacteria using innovative technologies, such as clustered regularly interspaced short palindromic repeats (CRISPR)-CRISPR associated protein 9 (Cas9), has demonstrated increased phytase expression during fermentation [136]. Through gene editing, engineered bacteria can be optimized for specific fermentation purposes. Lee et al. [137] applied Cas9 gene editing to *Saccharomyces cerevisiae*; by deleting the *RGT2* and *SNF3* genes, they enhanced carbon dioxide production during bread fermentation. Additionally, overexpressing *ASP3* while deleting *URE2* resulted in reduced acrylamide formation in potato chips and increased savory amino acid levels in rice wine, illustrating the potential of gene editing in fermentation processes. Lang et al. [138] utilized CRISPR-Cas9 to disrupt the *ECM33* gene in *EC1118*, which increased fermentation efficiency by 20% in nitrogen-limited defined media and by 13% in nitrogen-sufficient media, both under continuous shaking conditions. Improvements in fermentation performance through gene editing have also been documented with *Aspergillus oryzae* [139], *Saccharomyces cerevisiae* AGY001 [140], *Aspergillus niger* [141], and other species [142].

Mutagenesis has also been applied in fermentation. Takahashi et al. [143] developed a mutant strain of sake yeast, K901C8, derived from Kyokai No. 901. This strain produces elevated levels of ethyl caprylate, imparting a distinctive pineapple- and apricot-like flavor to sake. The mutant yeast has potential application for the production of premium sake, enhancing both quality and consumer acceptance. A comparative study [144] on bioprospecting and synthetic biology in beverage fermentation indicates that both techniques have achieved significant advancements. The interaction between these two methodologies may play a crucial role in the design of future fermentation schemes.

Improved control over the fermentation process has provided deeper insights into the mechanisms involved and increased the ability to regulate key variables. Ye et al. [145] utilized gas chromatography-olfactometry and odor activity value analysis to identify the primary aroma components in Millet Huangjiu during fermentation. Chai et al. [136] employed single-factor experiments and response surface methodology to optimize the fermentation of bean dregs and soybean meal, resulting in higher efficiency and improved fermentation quality. Wu et al. [146] optimized fermentation time and added potato pulp to enhance its control during steamed bread production. Their findings indicated that alterations to these factors would modify the bread's volatile compounds and texture.

Multiple advanced sensors have been employed for the intelligent monitoring of fermentation processes. For instance, Greulich et al. [147] utilized fourier transform infrared spectroscopy to monitor the fermentation of oats and peas, facilitating a precise control of the pH. Lin et al. [148] implemented a mixed fermentation involving lactic acid bacteria and *Neurospora crassa*, combined with MW treatment, to significantly enhance the functional properties and structural characteristics of soybean soluble polysaccharides. Wang et al. [149] employed a CRISPR/Cas12-based nucleic acid assay to monitor *Bacillus amyloliquefaciens* at the species level during Daqu fermentation. This approach facilitates improved control of key microorganisms that influence flavor, ultimately improving the quality of fermented foods.

### 3.3.2. Modern enzyme technology

Fermentation harnesses natural microbial processes and emphasizes the crucial role of enzymes in breaking down complex molecules, thereby driving advancements in enzyme technology. Enzymes such as amylases and proteases enhance dough properties and broaden gluten applications in breadmaking [150,151]. Enzyme-assisted modification of plant protein has been shown to enhance textures in plant-based foods through processes including extraction, hydrolysis, and cross-linking [152]. Additionally, enzyme technology is employed to reduce allergenicity in foods by degrading allergenic proteins into non-allergenic forms, thereby rendering products safer for individuals with food allergies [153,154].

In addition to isolating and selecting natural enzymes, the design of artificial enzymes has advanced through computer-aided methods, allowing precise modifications to enhance enzyme activity, stability, specificity, and selectivity [146]. Directed evolution, which simulates natural evolutionary processes, has demonstrated significant potential in expanding enzyme diversity and functionality. This approach customizes enzymes to function under new reaction conditions, optimizes their catalytic activity for different substrates, and enables them to catalyze novel chemical reactions [155]. As biotechnology advances, innovative enzyme solutions are emerging, propelling advancements in food science and improving nutrient utilization across diverse applications.

In industrial applications, enzymes encounter challenges related to recovery and recycling [156], leading to increased costs. To optimize enzyme reusability and adaptability to various operational environments, enzyme immobilization has been extensively studied. When compared to free enzymes, immobilization typically enhances pH and thermal stability, as well as activity [157]. For example, the immobilization of soybean urease, isolated from mature seeds, onto alginate and chitosan improved its physicochemical properties, maintaining stability at 75 °C and enabling reuse up to 14 times with only a 20% reduction in the original activity [158]. Similarly, protease-resistant  $\alpha$ -galactosidase from *Oudemansiella radicata*, immobilized on sodium alginate and chitosan, exhibited higher efficiency and stability. It completely hydrolyzed within 3 h raffinose family oligosaccharides in soymilk at 50 °C, rendering it highly effective and reusable in industrial environments [159]. Additionally, nano co-immobilization of  $\alpha$ -amylase and maltogenic amylase using nano-magnetic combined cross-linked enzyme aggregates (NM-Combi-CLEAs) significantly improved thermostability and reusability, retaining 80.4% of activity after ten cycles and showing a 1.5-fold increase in thermostability at 95 °C [160].

In recent years, innovations in fermentation and enzyme technologies have significantly enhanced the nutritional utilization, processing efficiency, and product quality of staple food crops. Fig. 4 illustrates the innovative applications of these technologies in the processing of staple food crops. These advancements have played a crucial role in increasing the nutritional value and production efficiency of staple food crops, rendering processing more sustainable and environmentally friendly, while also improving the health benefits of food products.

### 3.4. Multi-technologies collaboration

The use of a single technology often fails to achieve optimal results, even with optimized processing conditions. To address this, an increasing amount of research has focused on the collaborative use of multiple processing technologies. This integrated approach aims to obtain desirable processing effects, such as ideal texture and full bioavailability of nutrients [161].

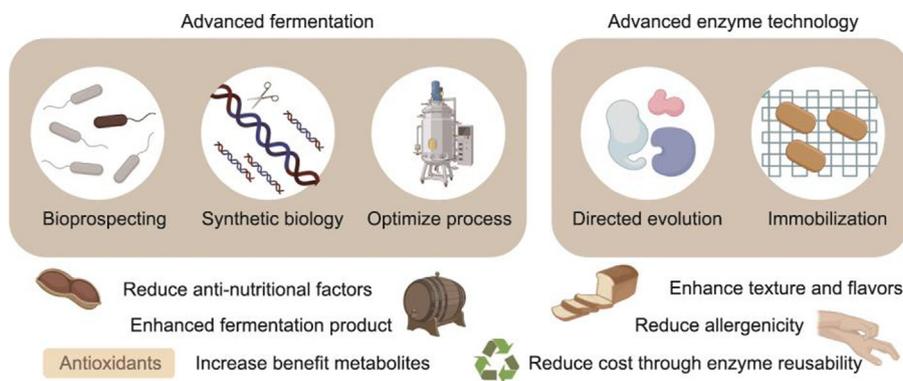


Fig. 4. Application of biotechnologies in the processing of staple food crops.

### 3.4.1. MW-based co-processing technologies

MW technology is extensively utilized in food processing for its energy efficiency, deep penetration, and ability to heat food materials effectively. However, despite its better uniformity compared to direct heating, MW heating alone can lead to uneven heating. To overcome this limitation, MW processing is often combined with other technologies, such as ultrasonic processing, hot air drying, and high-pressure cooking [13,162]. In the context of processing tubers such as potatoes, sweet potatoes, and yams, it has been empirically demonstrated that integrating ultrasonic and MW in vacuum frying significantly reduces oil absorption in potato chips by 20% to 40%. Additionally, the frying process is shortened by 20% to 28%, resulting in reduced energy consumption. Moreover, the visual appearance, texture, and microstructure of fried products are improved [13,162–166].

The combination of ultrasonic and MW drying technologies has been shown to accelerate drying times (by about 20%), increase energy efficiency, and preserve or even enhance the nutritional, such as free amino acid content, and flavor profiles of staple food crop-based foods [167–171]. Sequential application of ultrasonic pretreatment followed by MW drying positively impacts the physicochemical properties of various staple food crops, including rice, potatoes, and kidney beans, by improving color, structure, total phenolic contents, texture, and rehydration ability [167–171]. Additionally, pulse-spouted MW vacuum drying has been found to improve the organoleptic quality of edamame, preserving its crisp texture and color while maintaining its nutrient and antioxidant content. Notably, the ascorbic acid content of the soya bean product processed with this method is 2.7 times higher than that of products dried with hot air, while total phenolic and chlorophyll content increased by approximately 12% and 20%, respectively [172].

In rice processing, combining MW and hot air increased gelatinization, reduced crystallinity, and produced instant rice that cooks quickly (in just 2 min) under vacuum conditions [173], leading to lighter weight and longer shelf life [174]. The integration of moist heat and MW treatment in quinoa flour processing also altered its composition, increasing dietary fiber, amylose, and resistant starch content, which resulted in a lower estimated glycemic index and greater health benefits [175].

MW technology has also been applied in combination with other techniques to utilize staple food crop by-products and extract active ingredients. For instance, Wang et al. [176] combined ultrafine grinding with high-pressure, MW, or high-temperature cooking to process bean dregs, significantly enhancing their quality by increasing soluble dietary fiber content (increased by 91.52% when compared to hot air drying), creating a honeycomb porous structure, decreasing anti-nutritional factors (decreased by 30% when compared to hot air drying), and enhanc-

ing processing properties, thus broadening their applications. Moreover, MW pretreatment of wheat gluten protein before enzymatic hydrolysis has been shown to alter its structure, reduce allergenicity (with a nearly ten-fold reduction in immunoreactive epitopes with R5-competitive enzyme linked immunosorbent assay (ELISA)), accelerate hydrolysis, and improve the biological activity of the resulting hydrolysate, including free-radical scavenging and metal-ion chelating activity [177].

### 3.4.2. Ultrasonic-based co-processing technologies

The combination of ultrasonic method with other technologies has been widely used to improve the nutritional value of staple food crops. For instance, the addition of GABA and ultrasonic treatment significantly increased free flavonoid levels by 28.1% to 31.5% and free polyphenol levels by 71.1% to 73.2%, thereby improving the antioxidant capacity of sprouted mung beans. Additionally, the glycemic index of mung bean starch was reduced by approximately 17% [178–180]. Moreover, brown glutinous rice treated with low-frequency ultrasonic and calcium chloride stress during the pre-germination stage exhibited improved germination and an up to 12% increase in total polyphenols. This treatment also significantly increased GABA and metabolite levels including pyruvic acid (up to 3.29-fold), glycerol (1.32-fold), glutamate (7.63-fold), glucose (4.88-fold), and other metabolites, thereby improving its nutritional content [181].

The use of multi-frequency ultrasonic pretreatment combined with infrared drying has been effective in sweet potato processing, reducing drying time, increasing phytochemical content, and enhancing antioxidant activity in the final product. At 60 °C infrared drying, sweet potato pretreated with ultrasound at a frequency of 40 kHz exhibited increased levels of  $\beta$ -carotene (by 42.2%), polyphenols (by 136.4%), and flavonoids (by 145.0%) [182]. While ultrasonic treatment with infrared drying accelerated the drying process and reduced moisture content, it did not lead to a significant increase in bioactive ingredients content, maintaining consistency with untreated samples [183]. Additionally, combining ultrasonic with PEF has been shown to enhance the quality and safety of fried potato chips, reducing acrylamide content by 66% and lipid levels by 24.7% [184].

### 3.4.3. Fermentation-based co-processing technologies

Fermentation is an important technology in staple food crop processing that enhances nutritional quality when combined with other methods such as cereal or legume sprouting. The fermentation of germinated corn seeds with microorganisms significantly increased the levels of protein, vitamin E, total phenolics, vitamin B1, and GABA, while also doubling antioxidant activity and generating volatile compounds that impart a sweet, corny, and creamy flavor [185]. The use of sprouted germinated quinoa for yogurt

fermentation led to a notable increase in total phenolic and flavonoid content by 30.9% and 11.9%, respectively, resulting in enhanced antioxidant capacity [186]. The combination of sprouting and sourdough fermentation in whole grain produced cereals rich in dopamine (27 mg·kg<sup>-1</sup>) and L-3,4-dihydroxyphenylalanine (50 mg·kg<sup>-1</sup>), attributed to the conversion of tyrosine released during sprouting by microorganisms. This process also increased GABA levels (up to 674 mg·kg<sup>-1</sup>) and helped regulate histamine and phenylethylamine levels [187,188]. Concurrent fermentation of germination and solid-state fermentation considerably improved the nutritional profile of brown finger millet flour, enhancing protein, fiber, minerals, resistant starch, flavonoids, phenolics, antioxidants, and amino acids, while reducing antinutritional factors such as phytic acid and oxalate by up to 59.57% and 72.09%, respectively. Additionally, this process enhanced water absorption and protein solubility, and slightly altered gelatinization and thermal properties [189]. Lactic acid fermentation and grain germination were found to impact microorganisms and metabolomics of rye dough, with germination affecting the types of microorganisms present, resulting in increased levels of terpenoids, phenolic compounds, and both protein and non-protein amino acids in the dough [190].

Enzyme technology, similar to the hydrolysis of polysaccharides and proteins during germination, is increasingly integrated with fermentation for staple food crop processing, active ingredient extraction, and by-product utilization. Synergistic fermentation using multiple enzymes, including cellulase, xylanase, esterase,  $\alpha$ -amylase, and protease, has been shown to significantly increase extractable phenolics and antioxidant properties in spelt seeds, especially trans-ferulic acid contents, which increased by 8263% [191]. The use of multiple bacterial strains, including *Bacillus subtilis*, *Saccharomyces cerevisiae*, *Lactobacillus plantarum*, and *Lactobacillus rhamnosus*, in conjunction with proteases to ferment soybean dregs and meal resulted in more than a fivefold enhancement in peptide, free amino acid, and organic acid content. The addition of protease significantly boosted total protease activity, stimulated microbial growth, enhanced amylase secretion, and reduced sugar metabolism, thereby lowering pH, improving fermentation efficiency, and enhancing the quality of fermented products [192]. Solid-state fermenting of corn gluten-wheat bran mixture has been found to enhance the contents of crude protein, ash, small peptides, free amino acids, total phenol, and lactic acid [193]. Furthermore, the combination of fermentation with dynamic high-pressure micro-fluidization resulted in a higher soluble dietary fiber content in soybean residue while reducing the insoluble-to-soluble ratio [194].

#### 3.4.4. Enzyme-based co-processing technologies

Enzyme technologies can also be combined with other processing methods in staple food crop-based food production. Enzymatic extrusion (2%  $\alpha$ -amylase) of oat flour improved water solubility from 5.99% to 43.63%, resulting in a 11-fold increase in reducing sugar content. This process caused gelatinization and reduced crystallinity, lowering viscosity and increasing fluidity in oat milk, which enhanced both its stability and sensory appeal [195]. Using a double-enzyme approach (thermostable  $\alpha$ -amylase and pullulanase) during rice flour annealing increased resistant starch content from 5.00% to 16.56%, thus reducing digestibility. Incorporating single pullulanase improved hydration properties, impacting starch and protein structures, thermal properties, water solubility, and swelling characteristics [196].

Enzyme technology is extensively applied to manage indigestible raw materials or create functional hydrolysates, often integrated with other technologies to improve efficiency and applicability. Kong et al. [197] demonstrated a significant increase in water-soluble dietary fiber content (e.g., water-extractable ara-

binoxylan from 0.31 to 3.03 g per 100 g) in rye bran through a co-modification method involving extrusion and enzymatic hydrolysis (using cellulase, xylanase, high-temperature  $\alpha$ -amylase, and acid protease). This method also enhanced water-holding capacity, oil-holding capacity, and cholesterol adsorption capacity by 100%, 71%, and 133%, respectively, promoting the growth of beneficial bacteria and demonstrating strong prebiotic potential.

A combined approach of high hydrostatic pressure, temperature, and enzymatic hydrolysis was used to create fiber-rich ingredients from oat and wheat by-products. Enzymatic hydrolysis conducted before and after high hydrostatic pressure treatment increased  $\beta$ -glucan release, reduced phytic acid, and enhanced total phenolic content. Optimal conditions, such as wheat bran hydrolysis at 60 or 70 °C before high hydrostatic pressure treatment, and oat hull hydrolysis at 70 °C after treatment, significantly improved the nutritional value of the end products. Notably, the extraction of  $\beta$ -glucan increased 19 and 21 times in wheat bran and oat hull, respectively [198].

#### 4. Integration of innovative food processing technologies: Enabling the upgrading of the staple food crops industry value chain from farm to fork

In the modern food processing landscape, ensuring the safety and quality of raw material sources is critical. This imperative serves as the fundamental foundation for guaranteeing overall food quality, safety, and healthiness, as well as a prerequisite for the smooth operation of food manufacturing processes. To further enhance the safety of food raw materials, the concept of the “non-stop processing” has been introduced. This novel approach aims to achieve a seamless production line during the harvesting, storage, and handling of food raw materials, minimizing potential contamination and loss, thereby providing significant support for bolstering food security.

Through the application of innovative processing techniques, a wide array of novel and nutritious food products can be derived from raw material sources. For instance, as shown in Fig. 5, soybeans, an important source of plant-based oils and proteins, are commonly transformed into a diverse range of products, including tofu, soy milk, natto, soybean oil, soy sauce, and miso, which are widely integrated into our daily diets. However, the presence of anti-nutritional factors and undesirable beany flavors in soybeans can potentially affect protein absorption and trigger allergic reactions. To address these challenges, strategic processing interventions are employed, such as high-temperature steaming to inactivate the anti-nutritional factors in soy milk production, thereby improving protein bioavailability and reducing the likelihood of allergic responses. Similarly, in the extraction of soybean oil, a combination of cold and hot extrusion techniques is utilized to ensure the comprehensive recovery of the oil while preserving its nutritional content and sensory properties. Furthermore, in the production of miso, novel enzyme blending technologies are employed to impart more unique and appealing flavor profiles, enhancing the product's market competitiveness.

In the modern food industry, advanced technological methods are widely adopted to enhance the nutritional properties of raw materials and optimize the efficiency of resource utilization. For instance, through precision processing and comprehensive monitoring, every stage of the food processing workflow can be closely regulated to meet stringent safety and quality standards. This will not only elevate product quality but also enables the effective and comprehensive utilization of every component within the raw materials, thereby reducing waste.

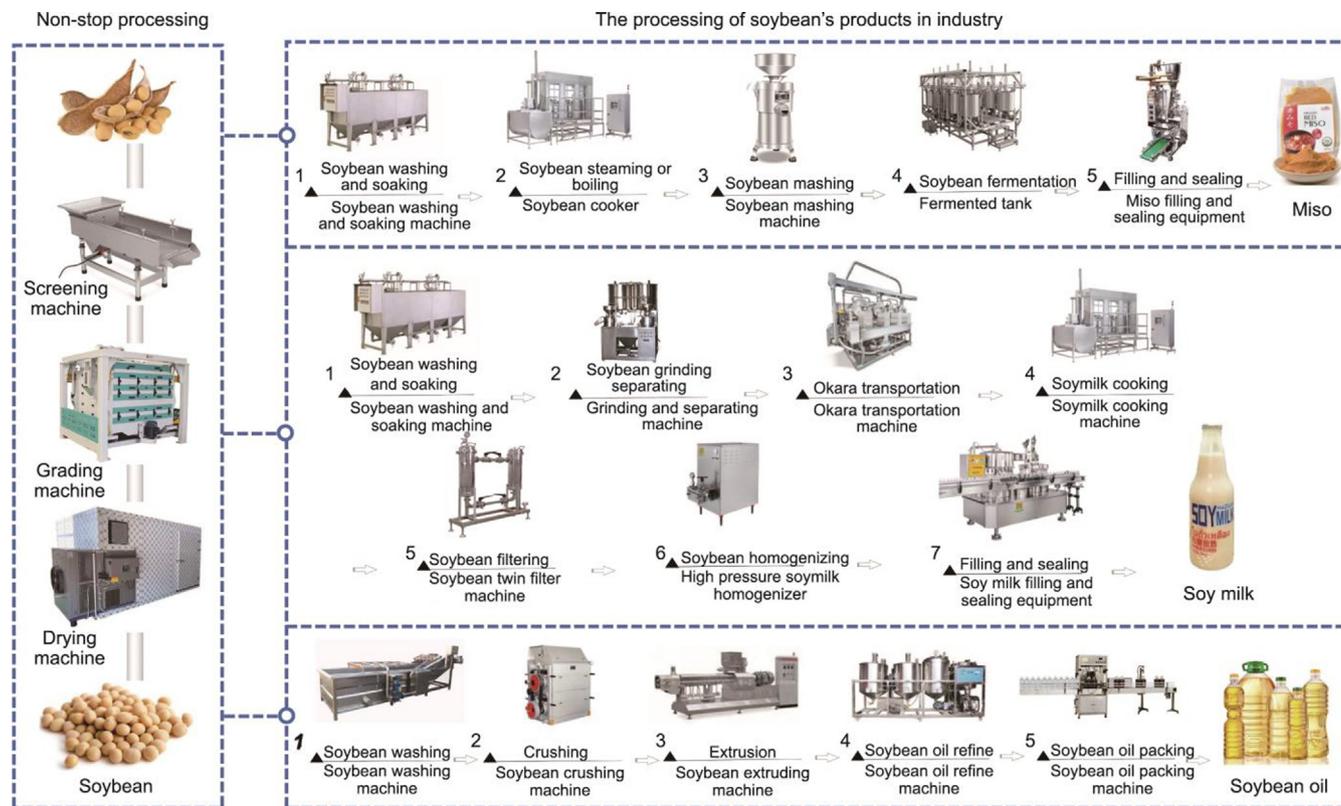


Fig. 5. The concept of “non-stop processing” and multi-technology integration upgrades the soybean industry value chain, ensuring nutritional quality from soybeans to soybean products.

In conclusion, with the continuous advancements in food processing technologies, the control over the safety and quality of raw materials is becoming increasingly stringent. Through the implementation of the “non-stop processing” concept and the strategic deployment of various cutting-edge processing technologies, the food industry can produce a wider range of high-quality, safe, and nutritious food products while achieving comprehensive and efficient resource utilization, thereby making positive contributions to food security and nutritional health.

5. Prospects

With the rapid advancements in artificial intelligence and automation technologies, the global modern food processing industry is transitioning from the traditional mechanized production system to a more refined and intelligent approach. In recent years, the food processing industry has progressed from the rough mechanized mode to the stages of automatic control, program control, batch processing, and rapidly moved towards the era of intelligent control, enabling on-demand design and personalized product processing. The application of automation technologies, such as advanced robotics, machine learning, and artificial intelligence, has not only optimized processing operations and reduced resource waste, but also significantly improved the quality of the final products. The introduction of the Internet of Things and big data analysis to achieve real-time monitoring and fine management of processing, ensures product quality and safety while using artificial intelligence algorithms will optimize the production process and improve efficiency and resource utilization. In the future, the food processing industry will be committed to using the most advanced technological means to ensure the maximum retention of nutrients, meeting consumers’ needs for high-quality, healthy

foods. Through continuous innovations, the development of functional products will have a brighter future. An efficient, intelligent, and sustainable food processing industry will not only bring more nutritious choices to consumers but also play an important role in healthy eating and sustainable development around the world. This development direction not only meets the needs of modern society for health and environmental protection, but also lays a solid foundation for the long-term sustainable development of the food industry.

6. Conclusions

Staple food crops constitute the most fundamental food sources for human sustenance, and optimized staple food crops processing is a crucial strategy for addressing the global food crisis. Currently, staple food crops processed using traditional food processing technologies encounter challenges such as incomplete nutritional utilization and limited nutritional value of the derived products. Consequently, research has increasingly concentrated on comprehensive staple food crops’ nutrient utilization and the nutritional enhancement of staple food crop-based foods through the development of whole grain products and the processing and utilization of staple food crop by-products. The advancement of science and technology, in conjunction with evolving human needs, has jointly driven a new wave of transformations in the field of food processing. Innovative physical processing technologies, including electric heating, electric field, and mechanical methods, as well as chemical processing technologies represented by NADES and natural additives, and bioprocessing technologies such as modern fermentation and enzyme technologies, have demonstrated significant potential in improving staple food crops’ nutrient utilization, enhancing the comprehensive nutritional profile of staple food crop-based foods,

and overcoming the limitations of traditional food processing. However, these emerging technologies also pose inherent challenges, including high energy consumption, equipment costs, and limited commercial viability, which will require further research and development. Fortunately, advancements in technologies such as artificial intelligence, big data, and the Internet of Things are poised to shape the future trajectory of food processing. Continuous innovation in food processing technology is crucial to further improve nutritional quality and enhance product functionalities, which will be a pivotal step towards addressing the global food crisis.

### CRedit authorship contribution statement

**Yi Yuan:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Xinyao Wei:** Writing – original draft, Visualization, Software, Investigation, Conceptualization. **Yuhong Mao:** Writing – original draft, Visualization, Software, Investigation, Conceptualization. **Yuxue Zheng:** Writing – original draft, Visualization, Software, Investigation. **Ni He:** Writing – original draft, Visualization, Software, Investigation. **Yuan Guo:** Writing – original draft, Visualization, Software, Investigation. **Ming Wu:** Writing – original draft, Visualization, Software, Investigation. **Joseph Dimpler:** Writing – review & editing, Writing – original draft. **Bing Li:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Xu Chen:** Writing – review & editing, Validation, Formal analysis. **Xixi Cai:** Writing – review & editing, Validation, Formal analysis. **Jianping Wu:** Writing – review & editing, Validation. **Yongqi Tian:** Writing – review & editing. **Sihan Xie:** Writing – original draft. **Jeyamkondan Subbiah:** Writing – review & editing. **Shaoyun Wang:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### References

- [1] Ruan S, Wang L, Li Y, Li P, Ren Y, Gao R, et al. Staple food and health: a comparative study of physiology and gut microbiota of mice fed with potato and traditional staple foods (corn, wheat and rice). *Food Funct* 2021;12(3):1232–40.
- [2] Priyadarshini A, Rajauria G, O'Donnell CP, Tiwari BK. Emerging food processing technologies and factors impacting their industrial adoption. *Crit Rev Food Sci Nutr* 2019;59(19):3082–101.
- [3] Zhou C, Okonkwo CE, Inyinbor AA, Yagoub AEA, Olaniran AF. Ultrasound, infrared and its assisted technology, a promising tool in physical food processing: a review of recent developments. *Crit Rev Food Sci Nutr* 2023;63(11):1587–611.
- [4] Singla M, Sit N. Application of ultrasound in combination with other technologies in food processing: a review. *Ultrason Sonochem* 2021;73:105506.
- [5] Arshad RN, Abdul-Malek Z, Roobab U, Munir MA, Naderipour A, Qureshi MI, et al. Pulsed electric field: a potential alternative towards a sustainable food processing. *Trends Food Sci Technol* 2021;111:43–54.

- [6] Lazou AE. Food extrusion: an advanced process for innovation and novel product development. *Crit Rev Food Sci Nutr* 2024;64(14):4532–60.
- [7] Sharif Swallah M, Bondzie-Quaye P, Wang H, Shao CS, Hua P, Alrasheed Bashir M, et al. Potentialities of *Ganoderma lucidum* extracts as functional ingredients in food formulation. *Food Res Int* 2023;172:113161.
- [8] Fan J, Qu G, Wang D, Chen J, Du G, Fang F. Synergistic fermentation with functional microorganisms improves safety and quality of traditional Chinese fermented foods. *Foods* 2023;12(15):2892.
- [9] Freitas DC, Zambelli RA, Ramos MV, Oliveira JPB, Souza PFN, Santos GBM, et al. Latex peptidases produce peptides capable of delaying fungal growth in bread. *Food Chem* 2022;373:131410.
- [10] Guilherme Sebastião V, Batista D, Rebellato AP, Alves Macedo J, Steel CJ. Sustainable production of naturally colored extruded breakfast cereals from blends of broken rice and vegetable flours. *Food Res Int* 2023;172:113078.
- [11] Nedele AK, Gross S, Rigling M, Zhang Y. Reduction of green off-flavor compounds: comparison of key odorants during fermentation of soy drink with *Lycoperdon pyriforme*. *Food Chem* 2021;334:127591.
- [12] Zhang Q, Zhao Y, Yao Y, Wu N, Chen S, Xu L, et al. Characteristics of hen egg white lysozyme, strategies to break through antibacterial limitation, and its application in food preservation: a review. *Food Res Int* 2024;181:114114.
- [13] Li M, Zhou C, Wang B, Zeng S, Mu R, Li G, et al. Research progress and application of ultrasonic- and microwave-assisted food processing technology. *Compr Rev Food Sci Food Saf* 2023;22(5):3707–31.
- [14] Knorr D, Augustin MA. Food processing needs, advantages and misconceptions. *Trends Food Sci Technol* 2021;108:103–10.
- [15] Wu K, Ren J, Wang Q, Nuerjiang M, Xia X, Bian C. Research progress on the preparation and action mechanism of natural deep eutectic solvents and their application in food. *Foods* 2022;11(21):3528.
- [16] Shi P, Ng Yuen Kai R, Vijayan P, Lim SL, Bhaskaran K. Valorization of spent barley grains: isolation of protein and fibers for starch-free noodles and its effect on glycemic response in healthy individuals. *Front Sustain Food Syst* 2023;7:1146614.
- [17] Samtiya M, Aluko RE, Dhewa T. Plant food anti-nutritional factors and their reduction strategies: an overview. *Food Prod Process Nutr* 2020;2(1):6.
- [18] Mathews R, Chu Y. The effect of whole-grain oats, oat bran, and isolated beta-glucan on indices of satiety and short-term energy intake. *Food Rev Int* 2023;40(4):1196–216.
- [19] Allai FM, Azad Z, Gul K, Dar BN. Wholegrains: a review on the amino acid profile, mineral content, physicochemical, bioactive composition and health benefits. *Int J Food Sci Technol* 2021;57(4):1849–65.
- [20] Niu M, Hou GG. Increasing whole grain consumption in China: processing and sensory challenges. *Cereal Foods World* 2020;65(5):0058.
- [21] Bressiani J, Oro T, Da Silva PML, Montenegro FM, Bertolin TE, Gutkoski LC, et al. Influence of milling whole wheat grains and particle size on thermo-mechanical properties of flour using Mixolab. *Czech J Food Sci* 2019;37(4):276–84.
- [22] Călinoiu LF, Vodnar DC. Whole grains and phenolic acids: a review on bioactivity, functionality, health benefits and bioavailability. *Nutrients* 2018;10(11):1615.
- [23] Mir SA, Dar BN, Shah MA, Sofi SA, Hamdani AM, Oliveira CAF, et al. Application of new technologies in decontamination of mycotoxins in cereal grains: challenges, and perspectives. *Food Chem Toxicol* 2021;148:111976.
- [24] Saini R, Kaur S, Aggarwal P, Dhiman A, Suthar P. Conventional and emerging innovative processing technologies for quality processing of potato and potato-based products: a review. *Food Control* 2023;153:109933.
- [25] Nosworthy MG. Enhancing pulse protein quality through processing and genetic tools. *Cereal Foods World* 2020;65(2):0015.
- [26] Rao V, Poonia A. Protein characteristics, amino acid profile, health benefits and methods of extraction and isolation of proteins from some pseudocereals—a review. *Food Prod Process Nutr* 2023;5(1):37.
- [27] Li M, Niu M. New technologies in cereal processing and their impact on the physical properties of cereal foods. *Foods* 2023;12(21):4008.
- [28] Yang Z, Zhang Y, Wu Y, Ouyang J. Factors influencing the starch digestibility of starchy foods: a review. *Food Chem* 2023;406:135009.
- [29] Sudlapa P, Suwannaporn P. Dual complexation using heat moisture treatment and pre-gelatinization to enhance starch–phenolic complex and control digestibility. *Food Hydrocoll* 2023;136:108280.
- [30] Gebre BA, Zhang C, Li Z, Sui Z, Corke H. Impact of starch chain length distributions on physicochemical properties and digestibility of starches. *Food Chem* 2024;435:137641.
- [31] Nartea A, Kuhalskaya A, Fanesi B, Orhotohwo OL, Susek K, Rocchetti L, et al. Legume byproducts as ingredients for food applications: preparation, nutrition, bioactivity, and techno-functional properties. *Compr Rev Food Sci Food Saf* 2023;22(3):1953–85.
- [32] Birla SL, Wang S, Tang J, Hallman G. Improving heating uniformity of fresh fruit in radio frequency treatments for pest control. *Postharvest Biol Technol* 2004;33(2):205–17.
- [33] Huang Z, Marra F, Subbiah J, Wang S. Computer simulation for improving radio frequency (RF) heating uniformity of food products: a review. *Crit Rev Food Sci Nutr* 2018;58(6):1033–57.
- [34] Ekezie FGC, Sun DW, Han Z, Cheng JH. Microwave-assisted food processing technologies for enhancing product quality and process efficiency: a review of recent developments. *Trends Food Sci Technol* 2017;67:58–69.
- [35] Le TQ, Jittanit W. Optimization of operating process parameters for instant brown rice production with microwave-followed by convective hot air drying. *J Stored Prod Res* 2015;61:1–8.

- [36] Olatunde GA, Atungulu GG. Milling behavior and microstructure of rice dried using microwave set at 915 MHz frequency. *J Cereal Sci* 2018;80:167–73.
- [37] Verma DK, Tripathy S, Srivastav PP. Microwave heating in rice and its influence on quality and techno-functional parameters of rice compositional components. *J Food Compos Anal* 2024;128:106030.
- [38] Sale AJH. A review of microwave for food processing. *J Food Technol* 1976;11:319–29.
- [39] Wu X, Zhao W, Wang X, Bai Z, Ma L. A novel variable power microwave (VPM) drying technology for lowering energy consumption and improving the in vitro protein digestibility of black soldier fly larvae. *Innov Food Sci Emerg Technol* 2023;89:103470.
- [40] Kusuma HS, Lantip GIA, Mutiara X, Lestari FW, Jaya DEC, Illiyanasafa N, et al. Experimental investigation in the drying process of moringa leaves using microwave drying: drying kinetics, energy consumption, and CO<sub>2</sub> emission. *Appl Food Res* 2024;4(1):100401.
- [41] Chen BL, Lin GS, Amani M, Yan WM. Microwave-assisted freeze drying of pineapple: kinetic, product quality, and energy consumption. *Case Stud Therm Eng* 2023;41:102682.
- [42] Smith DL, Atungulu GG. Impact of drying deep beds of rice with microwave set at 915 MHz frequency on the rice milling yields. *Innov Food Sci Emerg Technol* 2018;45:220–7.
- [43] Olatunde GA, Atungulu GG, Smith DL. One-pass drying of rough rice with an industrial 915 MHz microwave dryer: quality and energy use consideration. *Biosyst Eng* 2017;155:33–43.
- [44] Ouma F, Kaushik L, Sreenivasula B, Abass O, Atungulu GG. High power microwave treatment impacts on microbes in rough rice. *Rice Sci* 2024;31(2):139–41.
- [45] Xu L, Zhu C, Liu T, Karrar E, Ouyang Y, Li D. Effect of microwave heating on lipid composition, chemical properties and antioxidant activity of oils from *Trichosanthes kirilowii* seed. *Food Res Int* 2022;159:111643.
- [46] Li H, Xu J, Nyambura SM, Wang J, Li C, Zhu X, et al. Food waste pyrolysis by traditional heating and microwave heating: a review. *Fuel* 2022;324:124574.
- [47] Shrestha B, Baik OD. Radio frequency selective heating of stored-grain insects at 27.12 MHz: a feasibility study. *Biosyst Eng* 2013;114(3):195–204.
- [48] Hou L, Wu Y, Kou X, Li R, Wang S. Developing high-temperature-short-time radio frequency disinfestation treatments in coix seeds: insect mortality, product quality and energy consumption. *Biosyst Eng* 2022;215:262–70.
- [49] Song X, Ma B, Kou X, Li R, Wang S. Developing radio frequency heating treatments to control insects in mung beans. *J Stored Prod Res* 2020;88:101651.
- [50] Liu Q, Qu Y, Liu J, Wang S. Effects of radio frequency heating on mortality of lesser grain borer, quality and storage stability of packaged milled rice. *Lebensm Wiss Technol* 2021;140:110813.
- [51] Macana R, Moirangthem TT, Baik OD. Mortality and thermal death kinetics of rusty grain beetle in stored wheat using a pilot-scale 50-Ω radio frequency (RF) heating system. *Crop Prot* 2021;150:105794.
- [52] Cui M, Sun W, Xia L, Wang Z, Cao Y, Wu Y. Effect of radio frequency heating on the mortality of *Rhizopertha dominica* (F.) and its impact on grain quality. *J Stored Prod Res* 2020;89:101695.
- [53] Niu D, Zeng XA, Ren EF, Xu FY, Li J, Wang MS, et al. Review of the application of pulsed electric fields (PEF) technology for food processing in China. *Food Res Int* 2020;137:109715.
- [54] Naliyadhara N, Kumar A, Girisa SB, Daimary UD, Hegde M, Kunnumakkara AB. Pulsed electric field (PEF): avant-garde extraction escalation technology in food industry. *Trends Food Sci Technol* 2022;122:238–55.
- [55] Martínez JM, Abad V, Quilez J, Raso J, Cebrían G, Alvarez-Lanzarote I. Pulsed electric fields (PEF) applications in the inactivation of parasites in food. *Trends Food Sci Technol* 2023;138:470–9.
- [56] Chen BR, Xiao Y, Ali M, Xu FY, Li J, Wang R, et al. Improving resistant starch content of cassava starch by pulsed electric field-assisted esterification. *Int J Biol Macromol* 2024;276:133272.
- [57] Han Z, Zeng XA, Yu SJ, Zhang BS, Chen XD. Effects of pulsed electric fields (PEF) treatment on physicochemical properties of potato starch. *Innov Food Sci Emerg Technol* 2009;10(4):481–5.
- [58] Gagneten M, Cáceres SG, Rodríguez Osuna IA, Olaiz NM, Schebor C, Leiva GE. Modification of cassava starch by acetylation and pulsed electric field technology: analysis of physical and functional properties. *Innov Food Sci Emerg Technol* 2023;85:103344.
- [59] Chen BR, Teng YX, Wang LH, Xu FY, Li Y, Wen QH, et al. Pulsed electric field-assisted esterification improves the freeze-thaw stability of corn starch gel by changing its molecular structure. *Int J Biol Macromol* 2023;231:123085.
- [60] Han Z, Zeng X, Zhang B, Yu S. Effects of pulsed electric fields (PEF) treatment on the properties of corn starch. *J Food Eng* 2009;93(3):318–23.
- [61] Almeida RLJ, Santos NC, Muniz CES, da Silva ER, de Almeida SR, Ribeiro CAC, et al. Red rice starch modification-combination of the non-thermal method with a pulsed electric field (PEF) and enzymatic method using  $\alpha$ -amylase. *Int J Biol Macromol* 2023;253:127030.
- [62] Yang XD, Ju SY, Liu MJ, Feng JX, Du MR, Zhuang J, et al. Effect of cold atmospheric surface microdischarge plasma on the inactivation of fusarium moniliforme and physicochemical properties of Chinese yam flour. *Food Bioprocess Technol* 2024;17(4):1072–85.
- [63] Akasapu K, Ojah N, Gupta AK, Choudhury AJ, Mishra P. An innovative approach for iron fortification of rice using cold plasma. *Food Res Int* 2020;136:109599.
- [64] Han Y, Cheng JH, Sun DW. Activities and conformation changes of food enzymes induced by cold plasma: a review. *Crit Rev Food Sci Nutr* 2019;59(5):794–811.
- [65] Liao X, Liu D, Xiang Q, Ahn J, Chen S, Ye X, et al. Inactivation mechanisms of non-thermal plasma on microbes: a review. *Food Control* 2017;75:83–91.
- [66] Kheto A, Mallik A, Sehwari R, Gul K, Routray W. Atmospheric cold plasma induced nutritional & anti-nutritional, molecular modifications and *in-vitro* protein digestibility of guar seed (*Cyamopsis tetragonoloba* L.) flour. *Food Res Int* 2023;168:112790.
- [67] Patra A, Prasath VA, Shende AS, Thakur R, Deep B, Madhumathi G, et al. Effect of pin-to-plate atmospheric cold plasma on technological and nutritional functionality of horse gram (*Macrotyloma uniflorum*) flour. *J Food Process Eng* 2024;47(3):e14571.
- [68] Wu YM, Feng XW, Zhu YY, Li SY, Hu YC, Yao Y, et al. The effect of atmospheric dielectric barrier discharge cold plasma treatment on the nutritional and physicochemical characteristics of various legumes. *Foods* 2023;12(17):3260.
- [69] Jaddu S, Sahoo S, Sonkar S, Alzahrani K, Dwivedi M, Misra NN, et al. Cold plasma treatment of little millet flour: impact on bioactives, antinutritional factors and functional properties. *Plant Foods Hum Nutr* 2024;79(2):503–10.
- [70] Sarkar A, Niranjana T, Patel G, Kheto A, Tiwari BK, Dwivedi M. Impact of cold plasma treatment on nutritional, antinutritional, functional, thermal, rheological, and structural properties of pearl millet flour. *J Food Process Eng* 2023;46(5):e14317.
- [71] Pal P, Kaur P, Singh N, Kaur A, Misra NN, Tiwari BK, et al. Effect of nonthermal plasma on physico-chemical, amino acid composition, pasting and protein characteristics of short and long grain rice flour. *Food Res Int* 2016;81:50–7.
- [72] Rostamabadi H, Nowacka M, Colussi R, Frasson SF, Demirkenen I, Mert B, et al. Impact of emerging non-thermal processing technologies on major food macromolecules: starch, protein, and lipid. *Trends Food Sci Technol* 2023;141:104208.
- [73] Barbhuiya RI, Singha P, Singh SK. A comprehensive review on impact of non-thermal processing on the structural changes of food components. *Food Res Int* 2021;149:110647.
- [74] Gokul Nath K, Pandiselvam R, Sunil CK. High-pressure processing: effect on textural properties of food—a review. *J Food Eng* 2023;351:111521.
- [75] Carpentieri S, Larrea-Wachtendorff D, Barbosa-Canovas GV, Ferrari G. *In vitro* digestibility of rice and tapioca starch-based hydrogels produced by high-pressure processing (HPP). *Innov Food Sci Emerg Technol* 2024;93:103646.
- [76] Balakrishna AK, Farid M. Enrichment of rice with natural thiamine using high-pressure processing (HPP). *J Food Eng* 2020;283:110040.
- [77] Huang HW, Wu SJ, Lu JK, Shyu YT, Wang CY. Current status and future trends of high-pressure processing in food industry. *Food Control* 2017;72:1–8.
- [78] Wang H, Zhu S, Ramaswamy HS, Hu F, Yu Y. Effect of high pressure processing on rancidity of brown rice during storage. *Lebensm Wiss Technol* 2018;93:405–11.
- [79] Leite TS, de Jesus ALT, Schmieles M, Tribst AAL, Cristianini M. High pressure processing (HPP) of pea starch: effect on the gelatinization properties. *Lebensm Wiss Technol* 2017;76:361–9.
- [80] Balakrishna AK, Auckaili A, Farid M. Effect of high pressure impregnation on micronutrient transfer in rice. *Food Chem* 2021;362:130244.
- [81] Larrea-Wachtendorff D, Nobile GD, Ferrari G. Effects of processing conditions and glycerol concentration on rheological and texture properties of starch-based hydrogels produced by high pressure processing (HPP). *Int J Biol Macromol* 2020;159:590–7.
- [82] Zheng L, Regenstein JM, Teng F, Li Y. Tofu products: a review of their raw materials, processing conditions, and packaging. *Compr Rev Food Sci Food Saf* 2020;19(6):3683–714.
- [83] Phongthai S, Homthawornchoo W, Rawdkuen S. Preparation, properties and application of rice bran protein: a review. *Int Food Res J* 2017;24(1):25–34.
- [84] Yu ZL, Zeng WC, Zhang WH, Liao XP, Shi B. Effect of ultrasound on the activity and conformation of  $\alpha$ -amylase, papain and pepsin. *Ultrason Sonochem* 2014;21(3):930–6.
- [85] Ozuna C, Paniagua-Martínez I, Castaño-Tostado E, Ozimek L, Amaya-Llano SL. Innovative applications of high-intensity ultrasound in the development of functional food ingredients: production of protein hydrolysates and bioactive peptides. *Food Res Int* 2015;77:685–96.
- [86] Hu YC, Zhang JM, Zou L, Fu CM, Li P, Zhao G. Chemical characterization, antioxidant, immune-regulating and anticancer activities of a novel bioactive polysaccharide from *Chenopodium quinoa* seeds. *Int J Biol Macromol* 2017;99:622–9.
- [87] Ochoa-Rivas A, Nava-Valdez Y, Serna-Saldivar SO, Chuck-Hernández C. Microwave and ultrasound to enhance protein extraction from peanut flour under alkaline conditions: effects in yield and functional properties of protein isolates. *Food Bioprocess Technol* 2017;10(3):543–55.
- [88] Aguilar-Acosta LA, Serna-Saldivar SO, Rodríguez-Rodríguez J, Escalante-Aburto A, Chuck-Hernández C. Effect of ultrasound application on protein yield and fate of alkaloids during lupin alkaline extraction process. *Biomolecules* 2020;10(2):292.
- [89] Habinshuti I, Mu TH, Zhang M. Ultrasound microwave-assisted enzymatic production and characterisation of antioxidant peptides from sweet potato protein. *Ultrason Sonochem* 2020;69:105262.
- [90] Dubey A, Tripathy PP. Ultrasound-mediated hydration of finger millet: effects on antinutrients, techno-functional and bioactive properties, with evaluation of ANN-PSO and RSM optimization methods. *Food Chem* 2024;435:137516.

- [91] Bonto AP, Camacho KSI, Camacho DH. Increased vitamin B5 uptake capacity of ultrasonic treated milled rice: a new method for rice fortification. *Lebensm Wiss Technol* 2018;95:32–9.
- [92] Tiozon RN, Camacho DH, Bonto AP, Oyong GG, Sreenivasulu N. Efficient fortification of folic acid in rice through ultrasonic treatment and absorption. *Food Chem* 2021;335:127629.
- [93] Ali F, Tian KM, Wang ZX. Modern techniques efficacy on tofu processing: a review. *Trends Food Sci Technol* 2021;116:766–85.
- [94] Chmielewska A, Kozłowska M, Rachwał D, Wnukowski P, Amarowicz R, Nebesny E, et al. Canola/rapeseed protein—nutritional value, functionality and food application: a review. *Crit Rev Food Sci Nutr* 2021;61(22):3836–56.
- [95] Asen ND, Aluko RE, Martynenko A, Utioh A, Bhowmik P. Yellow field pea protein (*Pisum sativum* L.): extraction technologies, functionalities, and applications. *Foods* 2023;12(21):3978.
- [96] Hald C, Dawid C, Tresselt R, Hofmann T. Kaempferol 3-O-(2''-O-Sinapoyl-β-sophoroside) causes the undesired bitter taste of canola/rapeseed protein isolates. *J Agric Food Chem* 2019;67(1):372–8.
- [97] Jia W, Kyriakopoulou K, Roelofs B, Ndiaye M, Vincken JP, Keppler JK, et al. Removal of phenolic compounds from de-oiled sunflower kernels by aqueous ethanol washing. *Food Chem* 2021;362:130204.
- [98] Pulivarthi MK, Buenavista RM, Bangar SP, Li Y, Pordesimo LO, Bean SR, et al. Dry fractionation process operations in the production of protein concentrates: a review. *Compr Rev Food Sci Food Saf* 2023;22(6):4670–97.
- [99] Bajkacz S, Adamek J. Evaluation of new natural deep eutectic solvents for the extraction of isoflavones from soy products. *Talanta* 2017;168:329–35.
- [100] Tong X, Yang J, Zhao Y, Wan H, He Y, Zhang L, et al. Greener extraction process and enhanced *in vivo* bioavailability of bioactive components from *Carthamus tinctorius* L. by natural deep eutectic solvents. *Food Chem* 2021;348:129090.
- [101] Cvjetko Bubalo M, Curko N, Tomasevic M, Kovacevic Ganic K, Radojic RI. Green extraction of grape skin phenolics by using deep eutectic solvents. *Food Chem* 2016;200:159–66.
- [102] Bakirtzi C, Triantafyllidou K, Makris DP. Novel lactic acid-based natural deep eutectic solvents: efficiency in the ultrasound-assisted extraction of antioxidant polyphenols from common native Greek medicinal plants. *J Appl Res Med Aromat Plants* 2016;3(3):120–7.
- [103] Duan L, Dou LL, Guo L, Li P, Liu EH. Comprehensive evaluation of deep eutectic solvents in extraction of bioactive natural products. *ACS Sustain Chem Eng* 2016;4(4):2405–11.
- [104] Farooq MQ, Abbasi NM, Anderson JL. Deep eutectic solvents in separations: methods of preparation, polarity, and applications in extractions and capillary electrochromatography. *J Chromatogr A* 2020;1633:461613.
- [105] El-Saber Batiha G, Hussein DE, Algammal AM, George TT, Jeandet P, Al-Snafi AE, et al. Application of natural antimicrobials in food preservation: recent views. *Food Control* 2021;126:108066.
- [106] Novais C, Molina AK, Abreu RMV, Santo-Buelga C, Ferreira ICFR, Pereira C, et al. Natural food colorants and preservatives: a review, a demand, and a challenge. *J Agric Food Chem* 2022;70(9):2789–805.
- [107] Gavahian M, Chu YH, Lorenzo JM, Mousavi Khaneghah A, Barba FJ. Essential oils as natural preservatives for bakery products: understanding the mechanisms of action, recent findings, and applications. *Crit Rev Food Sci Nutr* 2020;60(2):310–21.
- [108] Ju J, Xie Y, Yu H, Guo Y, Cheng Y, Qian H, et al. A novel method to prolong bread shelf life: sachets containing essential oils components. *Lebensm Wiss Technol* 2020;131:109744.
- [109] Khazani B, Almasi H, Mohtarami F, Amjadi S. Incorporation of *Artemisia* essential oil loaded chitosomes in salep based film for use in toast bread packaging: new generation of active films. *Food Packag Shelf Life* 2024;43:101305.
- [110] Cruz EPD, Pires JB, Santos FND, Fonseca LM, Radünz M, Dal Magro J, et al. Encapsulation of lemongrass essential oil into cassava starch fibers for application as antifungal agents in bread. *Food Hydrocoll* 2023;145:109105.
- [111] Fonseca LM, Souza EJD, Radünz M, Gandra EA, Zavarze ER, Dias ARG, et al. Suitability of starch/carvacrol nanofibers as biopreservatives for minimizing the fungal spoilage of bread. *Carbohydr Polym* 2021;252:117166.
- [112] da Silva FT, dos Santos FN, Fonseca LM, de Souza EJD, dos Santos Hackbart HC, da Silva KG, et al. Oleogels based on germinated and non-germinated wheat starches and orange essential oil: application as a hydrogenated vegetable fat replacement in bread. *Int J Biol Macromol* 2023;253:126610.
- [113] Gonçalves da Rosa C, Zapelini de Melo AP, Sganzerla WG, Machado MH, Nunes MR, de Oliveira V, et al. Application *in situ* of zein nanocapsules loaded with *Origanum vulgare* Linneus and *Thymus vulgaris* as a preservative in bread. *Food Hydrocoll* 2020;99:105339.
- [114] Kessler JC, Vieira V, Martins IM, Manrique YA, Ferreira P, Calhelha RC, et al. Chemical and organoleptic properties of bread enriched with *Rosmarinus officinalis* L.: the potential of natural extracts obtained through green extraction methodologies as food ingredients. *Food Chem* 2022;384:132514.
- [115] Ulug SK, Jahandideh F, Wu J. Novel technologies for the production of bioactive peptides. *Trends Food Sci Technol* 2021;108:27–39.
- [116] Verni M, Wang Y, Clement H, Koirala P, Rizzello CG, Coda R. Antifungal peptides from faba bean flour fermented by *Levilactobacillus brevis* AM7 improve the shelf-life of composite faba-wheat bread. *Int J Food Microbiol* 2023;407:110403.
- [117] Nionelli L, Wang Y, Pontonio E, Immonen M, Rizzello CG, Maina HN, et al. Antifungal effect of bioprocessed surplus bread as ingredient for bread-making: identification of active compounds and impact on shelf-life. *Food Control* 2020;118:107437.
- [118] Mohamad Asri N, Muhialdin BJ, Zarei M, Saari N. Low molecular weight peptides generated from palm kernel cake via solid state lacto-fermentation extend the shelf life of bread. *Lebensm Wiss Technol* 2020;134:110206.
- [119] Rizzello CG, Verni M, Bordignon S, Gramaglia V, Gobetti M. Hydrolysate from a mixture of legume flours with antifungal activity as an ingredient for prolonging the shelf-life of wheat bread. *Food Microbiol* 2017;64:72–82.
- [120] Luz C, Izzo L, Ritieni A, Mañes J, Meca G. Antifungal and antimycotoxigenic activity of hydrolyzed goat whey on *Penicillium* spp.: an application as biopreservation agent in pita bread. *Lebensm Wiss Technol* 2020;118:108717.
- [121] Sarabandi K, Karami Z, Akbarbaglu Z, Duangmal K, Jafari SM. Spray-drying stabilization of oleaster-seed bioactive peptides within biopolymers: pan-bread formulation and bitterness-masking. *Food Biosci* 2024;58:103837.
- [122] Dziki D, Różyło R, Gawlik-Dziki U, Świeca M. Current trends in the enhancement of antioxidant activity of wheat bread by the addition of plant materials rich in phenolic compounds. *Trends Food Sci Technol* 2014;40(1):48–61.
- [123] Biernacka B, Dziki D, Gawlik-Dziki U, Różyło R. Common wheat pasta enriched with cereal coffee: quality and physical and functional properties. *Lebensm Wiss Technol* 2021;139:110516.
- [124] de Barros VG, Ribeiro Sanches MA, Barcia MT, Rodrigues D, Pertuzatti PB, Murici (*Byrsonima verbascifolia*): a high bioactive potential fruit for application in cereal bars. *Lebensm Wiss Technol* 2022;160:113279.
- [125] Souiy Z, Zakhama N, Cheraief I, Hammami M. Nutritional, physical, microbial, and sensory characteristics of gluten- and sugar-free cereal bar enriched with spirulina and flavored with neroli essential oil. *Lebensm Wiss Technol* 2022;169:113955.
- [126] Utama-ang N, Phawatwiangnak K, Naruenartwongsakul S, Samakradhamrongthai R. Antioxidative effect of Assam Tea (*Camellia sinensis* Var. *Assamica*) extract on rice bran oil and its application in breakfast cereal. *Food Chem* 2017;221:1733–40.
- [127] Grudniewska A, de Melo EM, Chan A, Gnińska R, Boratyński F, Matharu AS. Enhanced protein extraction from oilseed cakes using glycerol–choline chloride deep eutectic solvents: a biorefinery approach. *ACS Sustain Chem Eng* 2018;6(11):15791–800.
- [128] Çabuk B, Nosworthy MG, Stone AK, Korber DR, Tanaka T, House JD, et al. Effect of fermentation on the protein digestibility and levels of non-nutritive compounds of pea protein concentrate. *Food Technol Biotechnol* 2018;56(2):257–64.
- [129] Kaleda A, Talvistu K, Tamm M, Viirma M, Rosend J, Tanilas K, et al. Impact of fermentation and phytase treatment of pea-oat protein blend on physicochemical, sensory, and nutritional properties of extruded meat analogs. *Foods* 2020;9(8):1059.
- [130] Al-Ansi W, Mushtaq BS, Mahdi AA, Al-Maqtari QA, Al-Adeeb A, Ahmed A, et al. Molecular structure, morphological, and physicochemical properties of highlands barley starch as affected by natural fermentation. *Food Chem* 2021;356:129665.
- [131] Balli D, Bellumori M, Pucci L, Gabriele M, Longo V, Paoli P, et al. Does fermentation really increase the phenolic content in cereals? A study on millet. *Foods* 2020;9(3):303.
- [132] Shi Y, Singh A, Kitts DD, Pratap-Singh A. Lactic acid fermentation: a novel approach to eliminate unpleasant aroma in pea protein isolates. *Lebensm Wiss Technol* 2021;150:111927.
- [133] Byanju B, Hojilla-Evangelista MP, Lamsal BP. Fermentation performance and nutritional assessment of physically processed lentil and green pea flour. *J Sci Food Agric* 2021;101(14):5792–806.
- [134] Budhwar S, Sethi K, Chakraborty M. Efficacy of germination and probiotic fermentation on underutilized cereal and millet grains. *Food Prod Process Nutr* 2020;2(1):12.
- [135] Chen X, Song C, Zhao J, Xiong Z, Peng L, Zou L, et al. Effect of a new fermentation strain combination on the fermentation process and quality of highland barley yellow wine. *Foods* 2024;13(14):2193.
- [136] Chai KF, Ng KR, Samarasinghe M, Chen WN. Precision fermentation to advance fungal food fermentations. *Curr Opin Food Sci* 2022;47:100881.
- [137] Lee YG, Kim BY, Bae JM, Wang Y, Jin YS. Genome-edited *Saccharomyces cerevisiae* strains for improving quality, safety, and flavor of fermented foods. *Food Microbiol* 2022;104:103971.
- [138] Lang TA, Walker ME, Jiranek V. Disruption of ECM33 in diploid wine yeast EC1118: cell morphology and aggregation and their influence on fermentation performance. *FEMS Yeast Res* 2021;21(5):foab044.
- [139] Li Q, Lu J, Zhang G, Zhou J, Li J, Du G, et al. CRISPR/Cas9-mediated multiplexed genome editing in *Aspergillus oryzae*. *J Fungi* 2023;9(1):109.
- [140] De Mélo AHF, Nunes AL, Carvalho PH, da Silva MF, Teixeira GS, Goldbeck R. Evaluation of *Saccharomyces cerevisiae* modified via CRISPR/Cas9 as a cellulosic platform microorganism in simultaneously saccharification and fermentation processes. *Bioprocess Biosyst Eng* 2023;46(8):1111–9.
- [141] Korja V. CRISPR/Cas9-based engineering of *Aspergillus niger* for the improved fermentation of pectin-rich materials [dissertation]. Kampusareena: Tampere University of technology; 2018.
- [142] Van Wyk N, Kroukamp H, Espinosa MI, von Wallbrunn C, Wendland J, Pretorius IS. Blending wine yeast phenotypes with the aid of CRISPR DNA editing technologies. *Int J Food Microbiol* 2020;324:108615.
- [143] Takahashi T, Ohara Y, Sueno K. Breeding of a sake yeast mutant with enhanced ethyl caproate productivity in sake brewing using rice milled at a high polishing ratio. *J Biosci Bioeng* 2017;123(6):707–13.

- [144] Alperstein L, Gardner JM, Sundstrom JF, Sumbly KM, Jiranek V. Yeast bioprospecting versus synthetic biology—which is better for innovative beverage fermentation? *Appl Microbiol Biotechnol* 2020;104(5):1939–53.
- [145] Ye Y, Wang L, Zhan P, Tian H, Liu J. Characterization of the aroma compounds of Millet Huangjiu at different fermentation stages. *Food Chem* 2022;366:130691.
- [146] Wu L, Qin L, Nie Y, Xu Y, Zhao YL. Computer-aided understanding and engineering of enzymatic selectivity. *Biotechnol Adv* 2022;54:107793.
- [147] Greulich O, Duedahl-Olesen L, Mikkelsen MS, Smedsgaard J, Bang-Berthelsen CH. Fourier transform infrared spectroscopy tracking of fermentation of oat and pea bases for yoghurt-type products. *Fermentation* 2024;10(4):189.
- [148] Lin D, Long X, Xiao L, Wu Z, Chen H, Zhang Q, et al. Study on the functional properties and structural characteristics of soybean soluble polysaccharides by mixed bacteria fermentation and microwave treatment. *Int J Biol Macromol* 2020;157:561–8.
- [149] Wang Y, Xia X, Wu M, Sun Q, Zhang W, Qiu Y, et al. Species-level monitoring of key bacteria in fermentation processes using single-nucleotide resolved nucleic acid assays based on CRISPR/Cas12. *J Agric Food Chem* 2023;71(35):13147–55.
- [150] Gu M, Hong T, Ma Y, Xi J, Zhao Q, Xu D, et al. Effects of a commercial peptidase on rheology, microstructure, gluten properties of wheat dough and bread quality. *Lebensm Wiss Technol* 2022;160:113266.
- [151] Pourmohammadi K, Abedi E. Hydrolytic enzymes and their directly and indirectly effects on gluten and dough properties: an extensive review. *Food Sci Nutr* 2021;9(7):3988–4006.
- [152] Gouseti O, Larsen ME, Amin A, Bakalis S, Petersen IL, Lametsch R, et al. Applications of enzyme technology to enhance transition to plant proteins: a review. *Foods* 2023;12(13):2518.
- [153] Pang L, Liu M, Li X, Guo L, Man C, Yang X, et al. Effect of enzymatic hydrolysis combined with processing on allergenicity of food allergens. *Trends Food Sci Technol* 2024;143:104248.
- [154] Zhou E, Li Q, Zhu D, Chen G, Wu L. Characterization of physicochemical and immunogenic properties of allergenic proteins altered by food processing: a review. *Food Sci Hum Wellness* 2024;13(3):1135–51.
- [155] Deckers M, Deforce D, Fraiture MA, Roosens NHC. Genetically modified micro-organisms for industrial food enzyme production: an overview. *Foods* 2020;9(3):326.
- [156] Chalella Mazzocato M, Jacquier JC. Recent advances and perspectives on food-grade immobilisation systems for enzymes. *Foods* 2024;13(13):2127.
- [157] Bié J, Sepodes B, Fernandes PCB, Ribeiro MHL. Enzyme immobilization and co-immobilization: main framework, advances and some applications. *Processes* 2022;10(3):494.
- [158] Kumar S, Dwevedi A, Kayastha AM. Immobilization of soybean (*Glycine max*) urease on alginate and chitosan beads showing improved stability: analytical applications. *J Mol Catal, B Enzym* 2009;58(1–4):138–45.
- [159] Geng X, Lei J, Bau T, Guo D, Chang M, Feng C, et al. Purification, characterization, and immobilization of a novel protease-resistant  $\alpha$ -galactosidase from *Oudemansiella radicata* and its application in degradation of raffinose family oligosaccharides from soy milk. *Foods* 2022;11(19):3091.
- [160] Torabizadeh H, Montazeri E. Nano co-immobilization of  $\alpha$ -amylase and maltogenic amylase by nanomagnetic combi-cross-linked enzyme aggregates method for maltose production from corn starch. *Carbohydr Res* 2020;488:107904.
- [161] Tsevdou M, Dimopoulos G, Gogou E, Dermesonlouglou E, Taoukis P. Nonthermal processing technologies: synergies and new applications in food engineering. In: Režek Jambak A, editor. *Nonthermal processing in agri-food-bio sciences: sustainability and future goals*. Cham: Springer International Publishing; 2022. p. 311–4.
- [162] Zhou S, Chen W, Fan K. Recent advances in combined ultrasound and microwave treatment for improving food processing efficiency and quality: a review. *Food Biosci* 2024;58:103683.
- [163] Su Y, Zhang M, Zhang W, Liu C, Adhikari B. Ultrasonic microwave-assisted vacuum frying technique as a novel frying method for potato chips at low frying temperature. *Food Bioprod Process* 2018;108:95–104.
- [164] Chitrakar B, Zhang M, Fan D. The synergistic effect of ultrasound and microwave on the physical, chemical, textural, and microstructural properties of vacuum fried Chinese yam (*Dioscorea polystachya*). *J Food Process Preserv* 2019;43(9):e14073.
- [165] Qiu L, Zhang M, Wang Y, Bhandari B. Effects of ultrasound pretreatments on the quality of fried sweet potato (*Ipomea batatas*) chips during microwave-assisted vacuum frying. *J Food Process Eng* 2018;41(8):e12879.
- [166] Su Y, Zhang M, Adhikari B, Mujumdar AS, Zhang W. Improving the energy efficiency and the quality of fried products using a novel vacuum frying assisted by combined ultrasound and microwave technology. *Innov Food Sci Emerg Technol* 2018;50:148–59.
- [167] Zhang P, Li B, Hu Z, Zhang Q, Zhu Y, Hao W. Effects of ultrasonic and microwave treatment on color, quality and drying characteristics of rice. *J Cereal Sci* 2024;116:103856.
- [168] Dehghannya J, Kadkhodaei S, Heshmati MK, Ghanbarzadeh B. Ultrasound-assisted intensification of a hybrid intermittent microwave–hot air drying process of potato: quality aspects and energy consumption. *Ultrasonics* 2019;96:104–22.
- [169] Lagnika C, Huang J, Jiang N, Li D, Liu C, Song J, et al. Ultrasound-assisted osmotic process on quality of microwave vacuum drying sweet potato. *Dry Technol* 2018;36(11):1367–79.
- [170] Li M, Wang B, Lv W, Zhao D. Effect of ultrasound pretreatment on the drying kinetics and characteristics of pregelatinized kidney beans based on microwave-assisted drying. *Food Chem* 2022;397:133806.
- [171] Cheng X, Wang S, Shahid Iqbal M, Pan L, Hong L. Effect of ultrasound-assisted osmotic dehydration on the drying kinetics, water state, and physicochemical properties of microwave vacuum-dried potato slices. *Ultrason Sonochem* 2023;99:106557.
- [172] An N, Sun W, Li B, Wang Y, Shang N, Lv W, et al. Effect of different drying techniques on drying kinetics, nutritional components, antioxidant capacity, physical properties and microstructure of edamame. *Food Chem* 2022;373:131412.
- [173] Agrawal S, Raigar RK, Mishra HN. Effect of combined microwave, hot air, and vacuum treatments on cooking characteristics of rice. *J Food Process Eng* 2019;42(4):e13038.
- [174] Okeyo AA, Luthra K, Vazquez AR, Atungulu GG. Quality characteristic of instant rice produced using microwave-assisted hot air drying. *Cereal Chem* 2024;101(3):641–53.
- [175] Dong J, Huang L, Chen W, Zhu Y, Dun B, Shen R. Effect of heat-moisture treatments on digestibility and physicochemical property of whole quinoa flour. *Foods* 2021;10(12):3042.
- [176] Wang F, Zeng J, Gao H, Sukmanov V. Effects of different physical technology on compositions and characteristics of bean dregs. *Innov Food Sci Emerg Technol* 2021;73:102789.
- [177] Gazikalović I, Mijalković J, Šekuljica N, Jakovetić Tanasković S, Đukić Vuković A, Mojić L, et al. Synergistic effect of enzyme hydrolysis and microwave reactor pretreatment as an efficient procedure for gluten content reduction. *Foods* 2021;10(9):2214.
- [178] Wang L, Li X, Gao F, Liu Y, Lang S, Wang C. Effects of pretreatment with a combination of ultrasound and  $\gamma$ -aminobutyric acid on polyphenol metabolites and metabolic pathways in mung bean sprouts. *Front Nutr* 2023;9:1081351.
- [179] Wang L, Li X, Gao F, Liu Y, Lang S, Wang C, et al. Effect of ultrasound combined with exogenous GABA treatment on polyphenolic metabolites and antioxidant activity of mung bean during germination. *Ultrason Sonochem* 2023;94:106311.
- [180] Lang S, Gao F, Li X, Sui C, Wang F, Wang L, et al. Effect of exogenous GABA combined with ultrasound treatment on the physicochemical and functional properties of sprouted mung bean starch. *Int J Food Sci Technol* 2023;58(5):2380–90.
- [181] Wu Y, He S, Pan T, Miao X, Xiang J, Ye Y, et al. Enhancement of  $\gamma$ -aminobutyric acid and relevant metabolites in brown glutinous rice (*Oryza sativa* L.) through salt stress and low-frequency ultrasound treatments at pre-germination stage. *Food Chem* 2023;410:135362.
- [182] Rashid MT, Ma H, Jatoi MA, Wali A, El-Mesery HS, Ali Z, et al. Effect of infrared drying with multifrequency ultrasound pretreatments on the stability of phytochemical properties, antioxidant potential, and textural quality of dried sweet potatoes. *J Food Biochem* 2019;43(4):e12809.
- [183] Tayyab Rashid M, Liu K, Ahmed Jatoi M, Safdar B, Lv D, Wei D. Developing ultrasound-assisted hot-air and infrared drying technology for sweet potatoes. *Ultrason Sonochem* 2022;86:106047.
- [184] Ostermeier R, Hill K, Dingis A, Töpfl S, Jäger H. Influence of pulsed electric field (PEF) and ultrasound treatment on the frying behavior and quality of potato chips. *Innov Food Sci Emerg Technol* 2021;67:102553.
- [185] Hiran P, Kerdchoechuen O, Laohakunjit N. Combined effects of fermentation and germination on nutritional compositions, functional properties and volatiles of maize seeds. *J Cereal Sci* 2016;71:207–16.
- [186] Joy Ujiroghene O, Liu L, Zhang S, Lu J, Zhang C, Lv J, et al. Antioxidant capacity of germinated quinoa-based yoghurt and concomitant effect of sprouting on its functional properties. *Lebensm Wiss Technol* 2019;116:108592.
- [187] Canlı M, Çelik EE, Kocadağlı T, Kanmaz EÖ, Gökmen V. Formation of bioactive tyrosine derivatives during sprouting and fermenting of selected whole grains. *J Agric Food Chem* 2021;69(42):12517–26.
- [188] Çelik EE, Canlı M, Kocadağlı T, Özkaynak Kanmaz E, Gökmen V. Formation of Histamine, phenylethylamine and  $\gamma$ -aminobutyric acid during sprouting and fermenting of selected wholegrains. *Food Res Int* 2023;173:113447.
- [189] Azeez SO, Chinma CE, Bassey SO, Eze UR, Makinde AF, Sakariyah AA, et al. Impact of germination alone or in combination with solid-state fermentation on the physicochemical, antioxidant, *in vitro* digestibility, functional and thermal properties of brown finger millet flours. *Lebensm Wiss Technol* 2022;154:112734.
- [190] Mancino W, Carnevali P, Terzi V, Pérez PG, Zhang L, Giuberti G, et al. Hierarchical effects of lactic fermentation and grain germination on the microbial and metabolomic profile of rye doughs. *Foods* 2023;12(5):998.
- [191] Mencin M, Jamnik P, Mikulič Petkovšek M, Veberič R, Terpinč P. Enzymatic treatments of raw, germinated and fermented spelt (*Triticum Spelta* L.) seeds improve the accessibility and antioxidant activity of their phenolics. *Lebensm Wiss Technol* 2022;169:114046.
- [192] Heng X, Chen H, Lu C, Feng T, Li K, Gao E. Study on synergistic fermentation of bean dregs and soybean meal by multiple strains and proteases. *Lebensm Wiss Technol* 2022;154:112626.
- [193] Jiang X, Liu X, Xu H, Sun Y, Zhang Y, Wang Y. Improvement of the nutritional, antioxidant and bioavailability properties of corn gluten–wheat bran mixture fermented with lactic acid bacteria and acid protease. *Lebensm Wiss Technol* 2021;144:111161.

- [194] Tu Z, Chen L, Wang H, Ruan C, Zhang L, Kou Y. Effect of fermentation and dynamic high pressure microfluidization on dietary fibre of soybean residue. *J Food Sci Technol* 2014;51(11):3285–92.
- [195] Ren X, Yang Y, Liu Q, Wang Y, Jin Z, Jiao A. Effects of enzymatic extrusion on the structure and physicochemical properties of oat flour and its application in oat milk production. *Int J Food Sci Technol* 2023;58(9):4638–51.
- [196] Gong X, Li J, Liu Z, Xu X, Wang A, Nie M, et al. New insights into influence of green composite modification on the structure, digestive, and physicochemical properties of rice flour. *Lebensm Wiss Technol* 2023;189:115491.
- [197] Kong C, Duan C, Zhang S, Liu R, Sun Y, Zhou S. Effects of co-modification by extrusion and enzymatic hydrolysis on physicochemical properties of black wheat bran and its prebiotic potential. *Foods* 2023;12(12):2367.
- [198] Jiménez-Pulido JJ, Rico D, De Luis D, Martín-Diana AB. combined strategy using high hydrostatic pressure, temperature and enzymatic hydrolysis for development of fibre-rich ingredients from oat and wheat by-products. *Foods* 2024;13(3):378.