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Recent Advances in Heat-Induced Wheat Protein Modifications

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ABSTRACT

Wheat protein plays a crucial role in food processing, valued for its distinctive viscoelastic properties. Heating, a fundamental step in food production, profoundly affects the structure and functionality of wheat protein. These changes, driven by temperature variations and physical interactions, are key determinants of product quality. This paper explores the mechanisms behind gluten network and gel formation in wheat protein, focusing on how different heat induction methods—such as wet heating, superheated steam, extrusion, and microwave treatments—alter its structure and functionality. Furthermore, it examines the interactions between wheat protein and other components, including polysaccharides, water, and sodium ions, within heat-induced processing systems. These interactions and their impact on product quality and application are analyzed in detail. The study aims to provide theoretical insights that can enhance the quality and utility of wheat protein in food processing.

1. Introduction

Protein is an essential nutrient for the human body, and ensuring adequate intake of high-protein foods is crucial for overall health. High-protein foods are typically divided into two categories: animal protein and plant protein. Animal protein includes milk, livestock meat, poultry meat, eggs, fish, and shrimp, while plant protein mainly consists of legumes, such as soybeans, green beans, and black beans, as well as dried fruits like sesame, melon seeds, walnuts, almonds, and pine nuts (Alves & Tavares, 2019). In high-protein cereal products, protein is the most direct factor influencing microbial spoilage, as well as the flavor, taste, and freshness of food. Changes in protein and its colloidal structure led to fundamental alterations in functional properties such as water retention and emulsification, which are also key reasons why fresh food cannot be preserved at room temperature. Wheat protein is a critical raw material in food processing, particularly in meat processing, dairy products, and baking (Ortolan & Steel, 2017). The different components, structures, and functional properties of wheat protein significantly affect the quality of wheat protein and its processed products, with wheat gluten playing a central role among them (Johansson et al., 2013; Ma et al., 2019). Wheat gluten consists mainly of gliadin and glutenin, which provide gluten with its viscoelasticity and ductility. These properties arise from the interaction of covalent and non-covalent bonds between the two proteins, which maintain the gluten network structure. Thus, gluten not only serves as a nutritional supplement in food but also acts as an auxiliary agent, stabilizer, and dough strengthener during food processing (Johansson et al., 2013). Heating is an essential step in the processing of wheat protein products. During heating, wheat proteins release a variety of chemical groups that form new chemical bonds, causing cross-linking between protein components. This results in the production of new surface properties and protein aggregates (Zhang, Zhao et al., 2022). Under different heating conditions and other physical effects, the structural composition, molecular size, and processing properties of wheat protein change, which subsequently affects the quality of wheat protein products (Ma et al., 2019). In recent years, there has been growing attention to other functional properties of wheat protein. For instance, components in the food thermal processing system, such as polysaccharides, water, and salt ions, also influence the structural conformation, cross-linking degree, and state of wheat protein. These factors significantly affect the processing properties of food (Han et al., 2021). Thus far, few literature reviews have specifically addressed the physical modifications of wheat gluten proteins, with existing work primarily focusing on techniques such as high-pressure processing, ultrasound, and irradiation (Abedi & Pourmohammadi, 2021). However, these reviews do not provide a comprehensive analysis of the structural and functional changes induced by thermal treatments. In contrast, the present review offers an in-depth examination of recent advances in heat-induced modifications of wheat proteins, emphasizing the effects of various thermal processing methods on protein structure, functionality, and the quality of wheat-based products. Additionally, it

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explores the interactions between wheat proteins and other food components such as polysaccharides, water, and salt ions under thermal conditions. By systematically reviewing the structural transformations and functional implications of heat treatments, this work aims to provide theoretical support for enhancing the application of wheat proteins in thermal food processing.

2. Structure and functional properties of wheat protein

Wheat gluten consists primarily of gliadin and glutenin proteins that form unique viscoelastic networks when hydrated. Gliadins (α, β, γ, ω-types) contribute viscosity through their monomeric, disulfide-stabilized structures, while glutenins form polymeric networks via intermolecular disulfide bonds between high- and low-molecular-weight subunits (Shewry, 2023; Shewry et al., 2002). This β-sheet-rich structure enables the aggregation properties critical for dough functionality (Johansson et al., 2013). As shown in Figure 1, wheat protein exhibits unique network structure characteristics. During hydration and mixing, glutenin forms an ordered fibrous macromolecular polymer through intermolecular disulfide bonds, creating the network skeleton, while gliadin forms spherical structures through intrachain disulfide bonds, hydrogen bonds and hydrophobic interactions, cross-linking within the glutenin skeleton to form a stable viscoelastic network (Ortolan & Steel, 2017). This network gives wheat protein products their characteristic shape and texture. High-quality networks improve product quality by increasing bread volume, enhancing noodle gluten strength, reducing cooking loss, and improving extruded product texture (Bruneel et al., 2010; Gao et al., 2018; Zang et al., 2022). Unlike globular plant proteins like soy and pea protein that form viscous solutions through hydrogen bonds and hydrophobic interactions, wheat protein has low solubility due to its hydrophobic groups, resulting in weak gel properties that limit its applications (Zhang, Jia, et al., 2023). Heating can open the gluten network, promoting protein-protein and protein-water interactions that strengthen cross-linking during cooling to form a dense three-dimensional gel network (Alves & Tavares, 2019). After cooling, a dense three-dimensional gel network is formed (Alves & Tavares, 2019), as shown in Figure 1. Therefore, wheat protein forms a loose gluten network after hydration, and a denser gel network after heating and cooling. The appropriate addition of exogenous substances can promote the formation of the gel network. The research conducted by Guo et al. (2023) discovered that small amounts of NaCl and $CaCl_2$ (0.001–0.002 g/mL) had a significant impact on improving the storage modulus (G') and textural properties of a composite protein gel produced from mung bean protein and wheat gluten. In their study, Abedi et al. (2018) showed that acetylated proteins demonstrated a notably higher water-holding capacity in gels when compared to native proteins. In addition, $CaCl_2$ was more efficient than NaCl in increasing the water retention and firmness of both untreated and modified proteins. The acetylated glutenin exhibited a greater level of hardness compared to gliadin and gluten, mostly because of its higher degree of acetylation. The findings of the study conducted by Zhang, Zhao, et al. (2022) indicated that a combination of soy protein concentrates and wheat gluten in equal proportions resulted in the most favorable fibrous structures. However, extrudates produced exclusively from soy protein concentrates or wheat gluten did not have well-defined fibrous structures.

3. Effects of different heat treatments on wheat protein structure, functional properties and processed product quality

Heat treatment is crucial in wheat protein processing, significantly influencing its structure and functional properties. Different heat treatment methods affect disulfide bonds, free thiol groups, molecular weight, secondary structure, rheological properties, and water-holding capacity, all of which ultimately impact product quality. Appropriate temperature and heating time enhance wheat protein's viscoelasticity and texture by promoting protein unfolding and aggregation, forming a tighter network. Conversely, excessive heat causes depolymerization and weakens the protein structure, reducing product quality. High-pressure methods, like extrusion, improve solubility and water-holding capacity by creating a more robust protein network. To optimize wheat protein's functionality, precise control of thermal induction conditions, such as temperature and time, is essential. Scientific experimentation helps determine the best conditions to enhance wheat protein's suitability for food processing, nutritional value, and safety. In food thermal processing, there are four types of thermal induction based on heating temperature and method, as shown in Table 1.

3.1. Wet heating treatment

3.1.1. Protein structure

Wet heating treatment, often conducted in water baths at controlled temperatures, significantly influences the structural configuration and functional characteristics of wheat proteins. As temperature escalates, typically within the range of 25–100 °C, various protein transformations occur, including unfolding, aggregation, and denaturation. Each of these alterations depends on the inherent thermal stability of the specific protein fractions present in wheat, namely glutenins, gliadins, and other soluble proteins (Xu & Kuang, 2024). As shown in Figure 2, at 45 °C, wheat protein polymers unfold and expose hydrophobic groups, causing hydrophobic interactions to reach 10 μmol/g, which is an increase of 21.95% compared to the unheated state. However, the sulfhydryl groups (SH) on the protein subunits are not fully exposed. At temperatures 60 °C, the concentration of free SH in wheat protein falls by 6.25%, and the

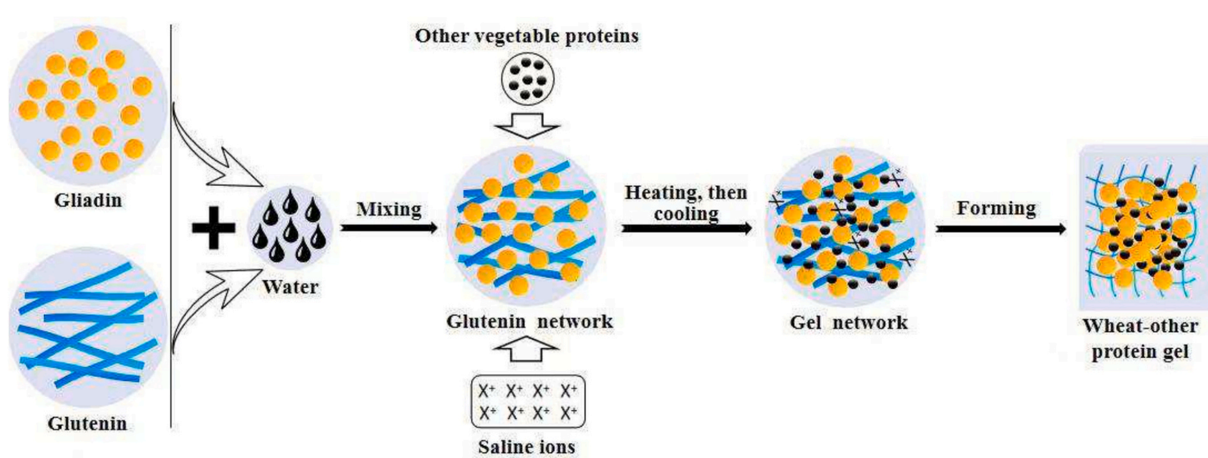

Figure 1. The mechanism of formation for the wheat protein network and gel.

Table 1
Comparison of heat treatment methods and their impact on wheat protein structure and functional properties

Heat Treatment Method	Conditions	Effects	Applications	References
Wet heating	25 °C–95 °C	Gliadin had high denaturation temperature and hindered thermal reaction progress. Heating caused structural changes and reduced SH in proteins.	Insights for cooking, processing, and storage of gluten proteins. Understanding thermal stability and protein interactions for food industry applications.	(Xu & Kuang, 2024)
	45 °C, 65 °C and 95 °C for 30 min, 60 min, 90 min, and 120 min	Hydrogen bond breakage induces conformational transitions in gluten polypeptides. Strengthened hydrophobic interactions significantly contribute to fibrillation of gluten polypeptides.	Formation of self-assembled fibrillation in wheat gluten polypeptide. Influence of different bonding changes on fibril morphology.	(Liu et al., 2023a)
	175 ± 1 °C for 5, 10, 15 and 20 min	Protein denaturation degree reached ~77% after 20 min at 175°C. Stabilization process affected foaming stability and protein solubility at pH 2 and pH.	Stabilizing wheat germ for food and cosmetic formulations. Evaluating protein fraction properties for industrial food products.	(Meriles et al., 2019)
	25 to 100°C for 20 min	Heat-induced changes in gluten proteins' structure and antigenic properties. Reduction of antigenic properties in thermally denatured proteins.	Foodstuffs like bakery products, sausages, ice creams. Excipient in some drugs.	(Stănciuc et al., 2018)
	50–90 °C for 3 hours	Heat treatment causes gluten aggregates, decreasing protein solubility and dough strength. Rheological data show starch aggregates and modified gluten-starch interactions.	Industrial heat treatment processes for inactivating microorganisms or enzymes. Understanding changes in wheat flour due to heat treatment.	(Mann et al., 2013)
Superheated steam treatment (SST)	165 °C and 190 °C for 1 min, 2 min, 3 min, 4 min, and 5 min	SST improved dough elasticity and stable gluten network formation. SST enhanced emulsifying properties and foaming ability of proteins.	Modification of soft wheat protein for improving cake quality. SST of wheat grain for protein modification.	(Liu et al., 2023b)
	130 °C, 150 °C and 170 °C for 1 min or 4 min	SST weakened water-gluten interaction during hydration. SST enhanced thermal stability and weakened viscoelastic characteristics of gluten.	Understanding improvement of wheat flour quality. Weakened viscoelastic characteristics due to weakened hydrated gluten network.	(Ma et al., 2023b)
	130 °C, 150 °C and 170 °C for 1 min or 4 min	Enhanced thermal stability and improved viscoelastic properties of wheat gluten. Changes in secondary structure and increased protein aggregation observed.	Food industry applications. Potential for improving food texture and quality.	(Ma et al., 2022)
	130 °C, 150 °C and 170 °C for 1 min or 4 min	Changes in molecular rearrangement and polymerization behavior of gluten observed. Wheat flour SST induced significant alterations in gluten properties.	Changes in gluten structure. Polymerization behavior of gluten.	(Ma et al., 2021b)
Extrusion treatment	Extrusion temperature 130–150 °C; screw speed 260–300 rpm	Structural change in wheat germ protein. Functional improvement of wheat germ protein.	Functional improvement of wheat germ protein. Structural change promoted by extrusion	(Gao et al., 2023)
	Extrusion temperature 80–140 °C; screw speed 40–80 rpm	High molecular weight glutenin subunits increased, low molecular weight subunits decreased during extrusion. Specific β-sheet structures of gluten increased forming a tight network.	Improvement and regulation of extrusion quality during gluten extrusion process. Formation of a homogeneous and denser gluten network.	(Jia et al., 2020)
	Extrusion temperature 130, 150, and 170 °C; screw speed 250 rpm	Protein yield decreased under non-reducing extraction conditions after extrusion. Reduced sugar content decreased in all double-screw extruded samples.	Protein modification during extrusion affects celiac gluten toxicity. Maillard reaction may contribute to protein modification during extrusion.	(Wu et al., 2022)
	Extrusion temperature 100 and 180 °C; screw speed 100 and 400 rpm	Extrusion impacts protein quality through denaturation, Maillard reaction, and oxidation. Bioavailability of lysine, methionine, and cysteine can be compromised.	Freeze drying applications. Meat and pet food freeze drying profiles.	(Bosch, 2022)
	Extrusion temperature 130 and 155 °C; screw speed 210 rpm	Improved fibrous structures in proteins from various sources. High-moisture extruding with transglutaminase modifications enhanced protein functionality.	Improving protein fibrous structures from different sources. Using transglutaminase modifications through high-moisture extruding techniques	(Zhang et al., 2023a)
Microwave treatment	Microwave power 1–5 KW; microwave treatment time 20 seconds	Microwave treatment decreased microorganisms and PPO activity significantly. Microwave changed gluten protein microstructures and inhibited fresh noodles darkening.	Microwave treatment for wheat kernels to improve flour quality. Enhancing fresh wet noodles' shelf life and textural properties	(Zhang et al., 2024)
	Microwave power 700 W; microwave treatment time 0, 30, 60, 90,120, 150 and 180 seconds	Microwave treatment reduced protease activity in sprouted wheat significantly. Dough properties and gluten quality improved after microwave treatment.	Microwave treatment effects on protease activity, dough properties, protein quality. Protein polymerization, gluten cross-linking, B/C-LMW-GS involvement after treatment	(Wang et al., 2024)
	Microwave power 300 W to 600 W; microwave treatment time 30 seconds to 3 min	Microwave treatment decreased solubility of proteins but improved thermal stability.	Microwave treatments on wheat gluten protein and whey protein. Effects on functional and structural properties of proteins studied.	(Mastani et al., 2024)
	Microwave power 200 W to 800 W; microwave treatment time 1 to 5 min	Microwave treatment reduced gluten content by about 2.5-fold. Microwave pretreatment accelerated enzymatic hydrolysis, enhancing protein properties.	Reduced allergenicity and conserved techno-functional features for food application. Enhanced antioxidant and functional properties of protein hydrolysates.	(Gazikalović et al., 2021)

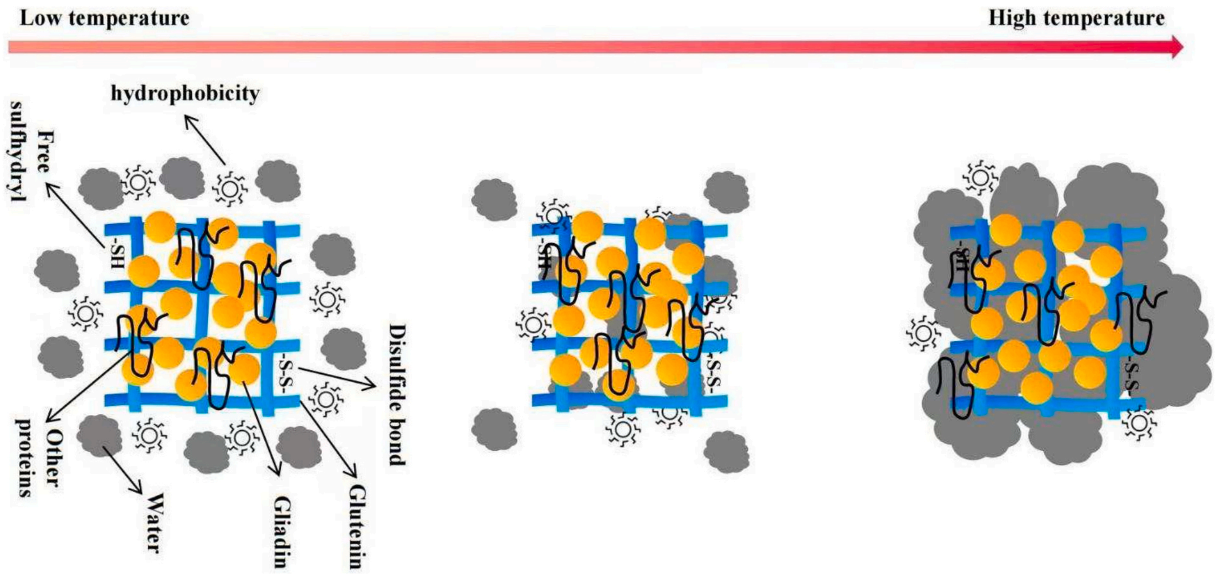

Figure 2. illustrates the mechanism by which temperature influences the conformation of wheat protein.

wheat gluten molecules undergo crosslinking processes (Wang, Luo, et al., 2017). This indicates that below 60 °C, hydrophobic groups play a major role in forming aggregates through hydrophobic interactions. At this temperature, non-covalent bonds such as hydrogen bonds in wheat protein are disrupted, and the proportion of random coils increases, leading to reduced elastic extensibility, elasticity, and hardness behavior of gluten (Han et al., 2021). Increasing temperature led to a decrease in the solubility of gluten proteins, indicating the formation of aggregates. While the glutenin polymers exhibited enhanced aggregation, particularly at elevated temperatures. The solubility of gliadin proteins exhibited a minor decline as the temperature increased, resulting in a reduced number of cross-links and less aggregation, as evidenced by the SE-HPLC profiles and the reduction in SDS-extractable protein content (Luo et al., 2016). Ma, Xie, et al. (2021) observed that the content of β-sheets increases with the extension of heat treatment at 100°C, reaching 35.95% and 33.21% by the end of the 30-minute heating process. In contrast, the mass fraction of α-helix structures decreases over time. After 30 minutes of heating, the β-turn content decreases from 26.92% and 28.12% (unheated) to 19.67% and 17.63%. The mass proportions of the random coil structures in gliadin and glutenin increase from 21.80% and 21.56% to 29.78% and 29.76%, respectively, after 30 minutes of heat treatment. This suggests that the α-helix and β-turn structures are transformed into β-sheets and random coils during the heating process. It is possible that this metamorphosis is the result of the hydrogen bonds between adjacent peptide bonds in the protein molecules being broken during the heating process. The hydrogen bonds that stabilize the α-helix structure are disrupted, resulting in the unwinding of the helix and a reduction in the mass fraction of α-helix structures. The protein structure becomes more disordered, and the mass fraction of random coil structures increases as a result of the unfolding of a portion of the α-helix structure. Intermolecular interactions result in the conversion of an additional portion of the α-helix structure to β-sheet structures. The mass fraction of β-sheet structures increases as a result of the fact that β-sheets are typically found in the pleated regions of proteins. Moreover, the impact of heat treatment on the solvent retention capacity (SRC) profiles of wheat flour has been documented, indicating that different heat treatments can lead to varying degrees of polymerization and extraction of glutenin and gliadin proteins. Specifically, higher temperatures tend to decrease the extractability of gliadins more significantly than that of glutenins, suggesting that heat-induced polymerization primarily affects glutenin subunits (Steertegem et al., 2013). This alteration in protein composition can have profound implications for the baking quality of wheat flour, as the balance between gliadin and glutenin is essential for optimal dough performance (Delcour et al., 2012).

3.1.2. Functional properties

Heat-induced treatment significantly affects the emulsification properties of wheat proteins, primarily through structural modifications and changes in physicochemical properties. Wheat gluten proteins, when subjected to heat, undergo a transition from α-helical structures to random coil and β-turn structures, which can influence their emulsifying properties by altering surface hydrophobicity and solubility (Xu & Kuang, 2024). The reduction in SH and the formation of disulfide bonds during heating contribute to protein aggregation, enhancing emulsion stability by forming a more compact protein network (Xu & Kuang, 2024). This is consistent with findings in other protein systems, where heat treatment improves emulsifying properties due to increased surface hydrophobicity, a critical factor in protein functionality (Voutsinas et al., 1983). In the case of wheat gluten, heat treatment combined with enzymatic hydrolysis improves emulsifying activity and stability, although excessive hydrolysis can negatively affect foam capacity and water-holding capacity (Elmalimadi et al., 2017). Additionally, the synergistic effect of heat and enzymatic treatment enhances the antioxidant properties of wheat gluten hydrolysates, making them more suitable for functional food applications (Elmalimadi et al., 2017). The optimal temperature range for preserving emulsification properties appears to be between 60°C and 90°C. A process developed for preparing wheat gluten with high emulsifying performance involves heating to this range (Du, 2006). Temperatures above 80°C led to increased viscosity and decreased protein extractability in gluten-water suspensions, indicative of protein polymerization (Lagrain et al., 2005). Moreover, SRC profiles of wheat flour show that heat treatments at 80°C and 100°C increase water retention capacity, associated with protein cross-linking that could influence emulsification properties (Steertegem et al., 2013). Heat-induced treatment also enhances the gelation properties of wheat proteins through manipulation of protein interactions and structural modifications. Gelation is significantly influenced by the ratio of glutenin to gliadin and the presence of calcium ions. A higher gliadin content improves gel strength and water-holding capacity, while calcium ions promote cross-linking and enhance the gel network by increasing disulfide and hydrogen bonds and β-sheet content (Qu et al., 2024). The incorporation of egg white protein (EWP) into wheat gluten improves gel strength by enhancing protein-protein interactions, reducing surface hydrophobicity, and increasing β-sheet content. EWP facilitates cross-linking with gluten subunits via disulfide bonds and hydrophobic interactions, strengthening the gel network (Cui et al., 2025). Furthermore, the addition of sodium chloride to wheat gluten dispersions under heat treatment enhances gel strength by exposing and rearranging active sites (Zheng et al., 2017a). Molecular changes during heating, such as transition to β-sheet structures and formation of high-molecular-weight protein polymers, further improve the textural characteristics of wheat protein gels (Yang et al., 2021).

3.1.3. Product quality

Optimal heat treatment conditions for improving the quality of wheat protein processing products such as noodles, pasta, and dough involve a careful balance of temperature, time, and moisture content, often supplemented with additional ingredients like salt or grape peels flour (GPF). Heat treatment at temperatures ranging from 80°C to 100°C for 30 minutes has been shown to enhance the quality of fresh noodles by reducing microbial counts and stabilizing pH, while also improving texture and color (Hong et al., 2021). For pasta, a heat moisture treatment (HMT) at 64.35°C for 3 hours with 26.65% moisture content, combined with 4.94% GPF, optimizes the product by increasing polyphenolics, dietary fiber, and resistant starch contents, while maintaining desirable dough rheology and pasta texture (Iuga & Mironeasa, 2021). Similarly, another study recommends a slightly higher temperature of 87.56°C for 3 hours with 26.01% moisture and 4.81% GPF to achieve maximum functional and nutritional values with minimal negative impact on pasta quality (Iuga et al., 2021). For dough, heat treatment at 98°C with a 2% salt concentration has been found to control the quality effectively by increasing bound water content and reducing SDS-soluble protein aggregation, which enhances the hardness and chewiness of cooked noodles (Zhang et al., 2020). Additionally, heat treatment of wheat flour at 60°C to 100°C can modify the starch and protein structures, leading to improved viscoelastic properties and reduced cooking loss in pasta and noodles (Iuga et al., 2021; Li et al., 2022). The stability of gluten proteins, particularly gliadin, during heat treatment is crucial as it impedes glutenin aggregation and enhances the overall thermal stability of the gluten network, which is beneficial for the texture and storage of gluten-based products (Xu & Kuang, 2024). Furthermore, the interaction between wheat proteins and starch during thermal processing is crucial for the overall quality of wheat-based products. Rooyen et al. (2022) highlighted that thermal treatments can enhance the interactions between starch and gluten, which are essential for the texture and structure of bread and other baked goods. These interactions are influenced by the degree of heat applied, which can either promote or hinder the formation of a stable protein-starch network (van Rooyen et al., 2022). The Maillard reaction, which occurs during thermal processing, also plays a significant role in modifying the quality of wheat protein products. This reaction not only affects flavor and color but also influences the nutritional profile of the final product. The formation of Maillard reaction products can lead to the development of new flavors and aromas, which are often desirable in baked goods (Liu et al., 2022). However, excessive thermal treatment can lead to the formation of undesirable compounds that may negatively impact the nutritional quality of wheat products.

3.2. Superheated steam treatment (SST)

3.2.1. Protein structure

The application of SST to wheat proteins has garnered attention due to its potential to enhance the structural and functional properties of wheat-based products. SST operates at temperatures above the boiling point of water, allowing for effective heat transfer and moisture removal without the adverse effects associated with wet heating treatments. This method has been shown to significantly impact the physicochemical properties of wheat proteins, particularly in terms of their structure, digestibility, and functional characteristics. The treatment of wheat proteins with superheated steam has been shown to significantly influence their molecular structure, secondary structure, and cross-linking properties. This process involves exposing wheat flour or grains to steam at temperatures above the boiling point, which facilitates various biochemical and structural transformations in the proteins, particularly glutenins and gliadins, which are essential for the quality of wheat-based products. SST leads to the denaturation of wheat proteins, which alters their molecular structure. According to Liu, Li, Guan, et al. (2023), the application of SS treatment enhances the polymerization of gluten proteins, resulting in larger protein aggregates that improve the elasticity and strength of dough. The denaturation process is crucial as it allows for the formation of new protein-protein interactions, which can enhance the overall texture and structural integrity of baked goods. In terms of secondary structure, SST has been shown to influence the arrangement of protein secondary structures, such as α-helices and β-sheets. reported that steaming does not alter the crude protein content but can affect the functional properties of proteins, indicating that structural changes occur without a loss in protein quantity (Bak et al., 2023). This suggests that the treatment may lead to a reorganization of the protein structure, enhancing its functional capabilities. Additionally, the study highlighted that the heat from superheated steam can lead to significant changes in protein denaturation, which is essential for the development of desirable textures in high-fiber bread (Elawad & Yang, 2017). The cross-linking properties of wheat proteins are also significantly affected by SST. The heat-induced changes promote the formation of disulfide bonds and other cross-links between protein molecules, which can enhance the mechanical properties of the dough. This is crucial for the development of a cohesive and elastic dough structure, as noted by Liu, Li, Guan, et al. (2023), who emphasized that the increased cross-linking contributes to improved gas retention and stability during baking. Furthermore, the oxidative stability of the proteins is enhanced due to the oxygen-free environment created during SS treatment, which minimizes oxidative degradation (Jia et al., 2021). This characteristic is particularly beneficial for maintaining the quality and nutritional value of wheat proteins during processing.

3.2.2. Functional properties

SST significantly influences the emulsification properties of wheat proteins by modifying their structural and functional characteristics. It induces protein aggregation, particularly in gliadin and glutenin, which initially enhances gluten network stability and improves emulsifying properties when applied for short durations (1–3 minutes) at 165–190 °C (Liu, Li, Guan, et al., 2023). These improvements are attributed to increased protein solubility and altered molecular weight distribution, enhancing their ability to stabilize emulsions (Liu et al., 2023b). However, prolonged SS exposure leads to excessive aggregation, decreasing solubility and foaming ability and ultimately deteriorating the quality of products such as cakes (Liu et al., 2023b). Thermal stability improvements are reflected by increased degradation temperatures and enthalpy values, as shown by differential scanning calorimetry (DSC), where the enthalpy of wheat gluten increased from 2.35 J/g to 2.76 J/g after treatment at 150 °C for 4 minutes (Ma, Sang, et al., 2023). Compared to SST, other protein modification techniques like phosphorylation and deamidation enhance solubility and emulsifying capacity by introducing charged groups that promote electrostatic repulsion and reduce emulsion droplet size (Hu et al., 2022; Ma, Liu, et al., 2023). Besides protein functionality, SST modifies the physicochemical properties of wheat flour, increasing swelling power, viscosity, and gelatinization temperature, while reducing gelatinization enthalpy (Ma, Zhang, et al., 2021; Liu et al., 2023). Moreover, SST weakens water–gluten interactions during hydration, altering the gluten network's viscoelasticity (Ma et al., 2023b). SST can also enhance the mechanical strength of protein gels; for example, in gluten–carrageenan systems, it prevents undesirable gel weakening and excessive aggregation during high-temperature processing (Zhu et al., 2024). Furthermore, it promotes the formation of a compact, cross-linked protein network, strengthening wheat gluten gels (Zheng et al., 2017b).

3.2.3. Product quality

SST promotes the aggregation of gliadin and glutenin, which strengthens the gluten network, improving dough elasticity and cake quality (Liu et al., 2023b). When applied under optimal conditions, SST can enhance the emulsifying capacity and foaming ability of wheat proteins, which are critical for the texture and volume of baked goods (Liu et al., 2023b; Mahroug et al., 2020). SST reduces the density and viscosity of cake batter, facilitating better air incorporation. This leads to cakes with higher volume, better texture, and reduced hardness (Ma, Xu, & Xu, 2023). Additionally, SST-treated wheat flour has lower moisture and starch damage content, brighter color, and enhanced viscosities, desirable traits for various flour products (Hu et al., 2017). While SST can improve gluten network formation, excessive treatment can lead to severe protein aggregation, reducing critical properties such as foaming and emulsifying capacity (Liu et al., 2023b). SST-induced protein denaturation and starch gelatinization can negatively affect the rheological properties of dough, altering dough handling and baking characteristics (Liu et al., 2019). The denaturation of gluten proteins under high temperatures weakens their interaction with water, which can impair hydration and gluten network formation, essential for maintaining the quality of baked goods (Ma et al., 2023b). SST can enhance the quality of wheat protein products by improving their physicochemical properties. For instance, it reduces lipid oxidation and prevents the generation of harmful compounds while improving protein functionality and starch gelatinization (Fang et al., 2023). SST improves the eating quality of weak-gluten wheat, making it particularly suitable for high-quality crisp biscuits by reducing hardness and enhancing crispness (Hu et al., 2017). Despite the challenges, SST presents a promising technique for enhancing the quality and safety of wheat protein processing products, offering numerous advantages over traditional thermal processing methods. SST offers significant potential for improving the quality of wheat protein processing products, but it requires careful optimization to avoid negative effects. Understanding and controlling the parameters of SST are crucial for maximizing its benefits and ensuring the consistent quality of wheat-based products.

3.3. Extrusion treatment

3.3.1. Protein structure

Extrusion treatment plays a significant role in modifying the structure of wheat proteins, impacting their functional properties and potential applications. As shown in Figure 3, wheat protein undergoes approximately four major conformational changes during extrusion, including molecular chain unfolding, association, aggregation and cross-linking, and potential degradation. As the extrusion temperature increases, hydrogen bonds in wheat protein break, protein chains gradually unfold, exposing hydrophobic amino acids. Gliadin and glutenin undergo molecular rearrangement and cross-linking, forming fibrous structures. At an extrusion temperature of 90°C, gliadin and glutenin subunits begin to undergo polymerization reactions through disulfide bond formation; at 120 °C, molecular cross-linking occurs through thiol-disulfide exchange reactions (Pietsch et al., 2019). The process of extrusion, particularly at high temperatures and screw speeds, induces protein cross-linking through intermolecular disulfide bonds, as evidenced by the increased number of free-SH-groups and reduced intensity of low-molecular-weight proteins in SDS-PAGE analysis (Wu et al., 2022). This cross-linking is particularly pronounced at higher temperatures and screw speeds, contributing to a denser and more homogeneous gluten network. Additionally, extrusion treatment has been shown to increase the degree of hydrolysis and protein recovery during enzymatic hydrolysis, suggesting that the conformational changes and structural rearrangements of wheat gluten enhance the catalytic efficiency of proteases (Cui et al., 2011). Fourier transform infrared spectroscopy (FTIR) analysis reveals that extrusion alters the secondary structure of wheat proteins, leading to changes in molecular weight distribution and amino acid composition, which are critical for improving enzymatic hydrolysis efficiency (Cui et al., 2011). The structural changes induced by extrusion are also evident in the increased β-turns and random coil structures, indicating a more disordered and flexible molecular conformation (Dai et al., 2023). The process also impacts the molecular weight distribution of proteins, with high molecular weight glutenin subunits increasing and low molecular weight subunits decreasing, indicating a shift towards a more polymerized state (Jia et al., 2020). These modifications are influenced by extrusion parameters such as moisture content, barrel temperature, and screw configuration, which determine the extent of mechanical energy input and subsequent protein transformations. Li et al. (2020) found that as the extrusion temperature increases, protein-protein interactions increase, promoting stable orientation and cross-linked structures with better texturization. However, at excessively high extrusion temperatures, the extrudate becomes loose and shapeless, which is unfavorable for fiber structure formation. Therefore, controlling the temperature at different stages during extrusion affects the structure and functional properties of wheat protein, determining the quality of wheat protein extruded products. Moreover, there is little research on the impact of extrusion on the structure of various components (gliadin, glutenin) in wheat protein. The specific roles of glutenin and gliadin during extrusion remain unclear and need further investigation.

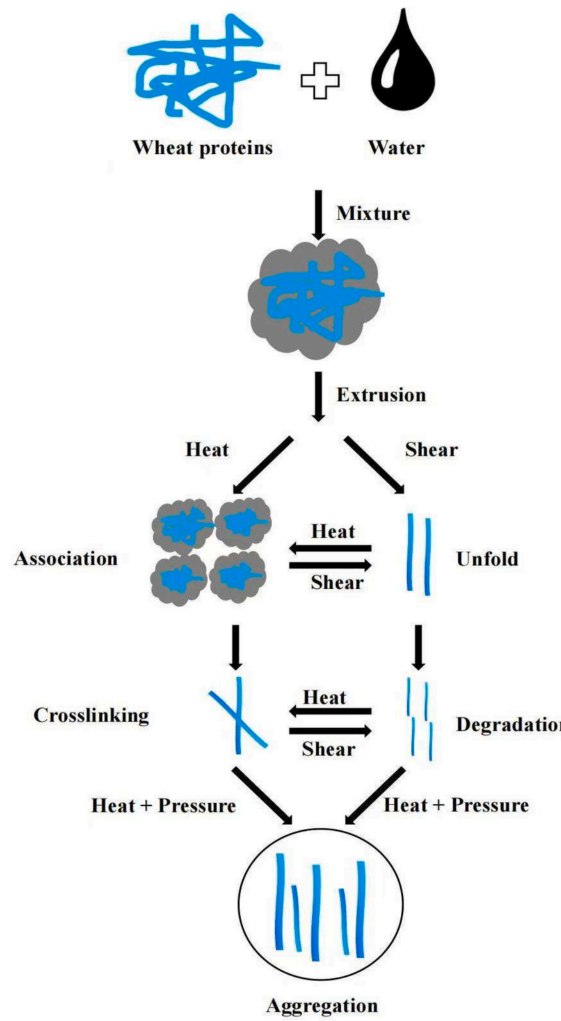

Figure 3. Conformational changes of wheat protein during extrusion processing

3.3.2. Functional properties

Extrusion treatment significantly impacts the functional properties of wheat proteins, including gel-forming ability, rheology, solubility, and water-holding capacity. The process of extrusion modifies the structural and rheological properties of wheat proteins by inducing protein cross-linking through intermolecular disulfide bonds, particularly at high temperatures and screw speeds, which enhances the stability and polymerization of the gluten network (Li et al., 2023; Wu et al., 2022). This cross-linking results in a more stable and polymerized gluten network, as evidenced by the conversion of β-turns into β-sheets, which improves the dough's elasticity and stability (Li et al., 2023). The extrusion process also affects the solubility of wheat proteins. For instance, extruded wheat flour proteins exhibit decreased solubility under non-reducing conditions due to the formation of disulfide bonds, although their solubility can be maintained under reducing conditions (Wu et al., 2022). Additionally, extrusion enhances the water-holding capacity of wheat proteins, as seen in studies where extruded wheat bran showed improved hydration and swelling power, leading to better water retention in the dough matrix (Li et al., 2023). The rheological properties of wheat proteins are also altered by extrusion, with farinographic data indicating increased dough stability and viscoelastic data showing improved elasticity, characterized by higher elastic moduli and lower loss tangent values (Li et al., 2023). Furthermore, the extrusion process can lead to the formation of a denser and more homogeneous gluten network, which is crucial for the gel-forming ability of wheat proteins. This is supported by the increase in high molecular weight glutenin subunits and the formation of a tight gluten network observed under high extrusion temperatures and screw speeds (Jia et al., 2020). The extrusion conditions, such as temperature, screw speed, and moisture content, play a critical role in determining these functional properties. For example, higher extrusion temperatures and appropriate moisture levels can enhance the water-holding capacity and emulsion stability of extruded proteins, as seen in studies on rice protein, which can be extrapolated to wheat proteins (Gao et al., 2022). The effect of extrusion treatment on the functional properties of wheat proteins has been a subject of extensive research, leading to some contradictory findings. These contradictions arise from variations in extrusion conditions, such as temperature, moisture content, and the specific formulations used. Extrusion is known to induce significant structural changes in proteins, but the nature of these changes can vary. For instance, it was reported that increasing the extrusion temperature from 130 °C to 170 °C resulted in a smoother texture of texturized soybean protein/wheat gluten composites, suggesting that higher temperatures may not favor the formation of organized structures (Wu et al., 2019a). Conversely, it was indicated that certain wheat proteins can maintain their structural integrity under high-shear conditions during extrusion, which implies that not all proteins are negatively affected by high temperatures (Kowalski et al., 2015). This discrepancy highlights the complexity of protein behavior under different extrusion conditions. Kaur (2023) noted that the extrusion process leads to the partial breakdown of starch granules and proteins, which can enhance water absorption and improve the binding properties of extruded whole wheat flour in pasta preparation. However, Wu et al. (2022) found that extrusion can also lead to a reduction in crude protein values due to the volatilization of nitrogenous compounds, suggesting that while some functional properties may improve, others, such as protein content, may diminish. This presents a contradiction where the functional enhancement of water absorption may come at the cost of reduced protein availability. The aggregation of proteins during extrusion is another area of contradiction. Gao et al. (2023) reported that the extensive disulfide-mediated cross-linking during extrusion increases the molecular weight of wheat proteins, leading to decreased solubility. In contrast, Wittek et al. (2021) suggested that the extrusion process can lead to significant increases in viscosity due to protein aggregation, indicating that the proteins may still retain some functional properties despite changes in solubility. This contradiction raises questions about the balance between protein aggregation and functional performance.

3.3.3. Product quality

Extrusion heat-induction significantly impacts the quality of texturized wheat protein (TWP) products by altering their physical, chemical, and functional properties. The process involves high-temperature, short-time cooking, which minimizes nutrient loss and enhances the digestibility and availability of proteins by inactivating antinutritional factors and promoting Maillard reactions (Martinchik & Sharikov, 2015). The extrusion parameters, such as temperature, screw speed, and moisture content, play crucial roles in determining the final product's quality. For instance, higher extrusion temperatures and screw speeds can lead to increased protein cross-linking through intermolecular disulfide bonds, enhancing the structural integrity of the extrudates (Wu et al., 2022). The addition of wheat gluten to texturized soybean protein (TSP) composites during extrusion increases resistance to creep and unrecoverable deformation, indicating improved mechanical properties (Wu et al., 2019a). Moreover, the inclusion of mixed oils, such as soybean, peanut, and sunflower seed oils, during extrusion can reduce the texturization degree of gluten protein, resulting in a flocculent oil surface that improves the appearance and eating quality of the product. The use of twin-screw extrusion systems allows for precise control over the extrusion conditions, leading to the production of TWP with high fibrosis degree, rehydration rate, and water holding capacity, while maintaining desirable textural properties such as hardness, elasticity, and chewiness. Additionally, the extrusion process can modify the protein structure, as evidenced by the decreased yield of proteins under non-reducing conditions and the absence of lysinoalanine, indicating that non-disulfide bonds do not form under typical extrusion conditions (Wu et al., 2019a; Wu et al., 2022). The incorporation of texturizing agents and the optimization of screw-thread sets can further enhance the fiber effects and overall quality of TWP products (Zhang, Yu, et al., 2023). The extrusion response parameters, such as die pressure, torque, and specific mechanical energy, are positively correlated with several physical properties, including texture and water holding capacity, making them reliable indicators of TWP quality (Singh et al., 2024). According to Wang, Li, et al. (2017), the twin-screw extrusion treatment enhances the in vitro protein digestibility (IVPD) values of extruded wheat gluten/starch products, indicating improved protein structure flexibility and increased exposure of enzyme cleavage sites. This aligns with findings from Cui et al. (2011), who noted that extrusion treatment causes marked changes in the secondary structure of wheat gluten, primarily due to the combined effects of heat and pressure during the extrusion process. These structural modifications are crucial as they can enhance the functional properties of the proteins, such as solubility and emulsification capacity. In addition to structural changes, it was found that the extrusion process leads to partial breakdown of starch granules and the degradation of larger protein molecules, which improves water absorption and binding in extruded products like pasta (Kaur, 2023). This is particularly important for the development of high-quality pasta, as improved water absorption facilitates better dough formation and cooking characteristics. Nutritionally, extrusion treatment can influence the digestibility and bioavailability of proteins in wheat products. noted that protein denaturation during extrusion exposes previously hidden amino acid residues, making them more available for enzymatic reactions (Oladiran & Emmambux, 2016). However, they also reported a decrease in IVPD due to the maillard reaction, which can occur between free amino acids and reducing sugars during the extrusion process (Oladiran & Emmambux, 2016). This highlights a dual effect of extrusion on protein quality, where some nutritional benefits may be offset by the formation of non-digestible complexes. Moreover, the extrusion process can enhance the functional properties of dietary fibers present in wheat. emphasized that extrusion cooking can modify the dietary fiber content and improve the water solubility index of wheat bran extrudates, making them more functional in food applications (Rashid et al., 2015). This is particularly relevant for developing high-fiber products that meet consumer demand for healthier options.

3.4. Microwave treatment

3.4.1. Protein structure

Microwave heating significantly impacts the structural properties of wheat proteins, particularly influencing their molecular and secondary structures. This technique modifies wheat proteins through several mechanisms that lead to protein denaturation, unfolding, and alteration of structural characteristics. The primary mechanism by which microwave heating affects wheat proteins involves electromagnetic radiation causing polar molecules to oscillate. This oscillation generates heat, leading to the disruption of various types of bonds that maintain the protein's native structure, including ionic, hydrogen, and disulfide bonds (Mattioni et al., 2024; Orenday-Ortiz & Morris, 2018). As these bonds are disrupted, the protein molecules undergo unfolding, causing significant changes in their conformation. Specifically, microwave treatment has been documented to reduce the content of secondary structures such as β-sheets while simultaneously increasing the proportion of α-helices and β-turns (Qin et al., 2016). Additionally, microwave treatment at specific power levels and temperatures can significantly change the secondary structure and conformation of gluten proteins, as confirmed by FTIR analysis, with the most pronounced effects observed at 200 W and 100 °C (Gazikalović et al., 2021). This treatment not only reduces gluten content but also accelerates enzymatic hydrolysis, enhancing the functional properties of the resulting protein hydrolysates (Gazikalović et al., 2021). Microwave treatment alters wheat gluten protein (WGP) by affecting hydroxyl stretching intensity, surface hydrophobicity, and the content of free sulfhydryl groups and disulfide bonds. This results in the breaking of disulfide bonds and their conversion into sulfhydryl groups, leading to a disruption of the compact structure of WGP, making it more incompact (Zhang et al., 2011). It also promotes the formation of intermolecular and intramolecular cross-linking in gluten, resulting in increased aggregation and structural changes, such as the promotion of α-helix and β-turn formations under high power inputs (Xiang et al., 2020). Furthermore, microwave treatment can lead to a shift towards more compact protein conformations by intensifying intramolecular electrostatic interactions and hydrogen bonds, although it primarily affects tertiary rather than secondary structures (Broz et al., 2024). Research has indicated that different gluten protein fractions, including gliadin and glutenin, respond variably to microwave treatment. Interaction studies suggest that while both fractions can form a network, their responses to thermal and microwave treatments differ significantly (Wang et al., 2024; Xu & Kuang, 2024). For instance, heat-induced polymerization of gliadins is influenced by the heating conditions, indicating that glutenin-gliadin interactions are enhanced under microwave conditions (Lagrain et al., 2011). Overall, microwave treatment induces significant structural modifications in wheat proteins, affecting their functional and nutritional properties.

3.4.2. Functional properties

Microwave treatment of wheat proteins results in significant alterations in their functional properties compared to untreated proteins. The solubility of wheat gluten proteins generally decreases with increased microwave treatment time, although the highest solubility is observed at lower power levels, such as 50% power (Yalcin et al., 2008). This decrease in solubility is attributed to protein polymerization, likely due to intermolecular disulfide bond cross-linking, which is more pronounced in glutenin subunits (Wang et al., 2024). Despite the reduction in solubility, microwave treatment enhances other functional properties such as emulsifying and foaming capacities. For instance, the emulsifying stability of microwave-treated gluten is slightly higher than that of untreated samples, and foam stability increases with treatment time, particularly at higher power levels (Yalcin et al., 2008). Treatment durations less than or equal to 20 seconds at 700 W have minimal adverse effects on gluten properties, suggesting that shorter treatment times can preserve functional integrity for applications like steamed bread (Qu et al., 2017). Moreover, combining microwave and ultrasound treatments has been shown to enhance emulsification by promoting peptide content and preserving bioactive properties, indicating that a synergistic approach might be beneficial (Aamir et al., 2023). However, prolonged exposure, especially at high power levels, can lead to protein denaturation and structural changes, such as increased surface hydrophobicity and disruption of secondary bonds, which negatively impact emulsification (Zhang et al., 2011). Therefore, a short treatment duration, ideally around 20 seconds at moderate power levels, seems optimal for preserving wheat protein emulsification while minimizing structural damage. Microwave treatment significantly influences the gelation temperature and strength of wheat protein-based gels by altering the protein's structural and functional properties. It can enhance gel strength by promoting protein denaturation and unfolding, facilitating the formation of a more ordered network, as evidenced by increased ζ-potential values and changes in secondary structure elements such as α-helices and β-sheets (Qin et al., 2016; Tan et al., 2024). Additionally, microwave pretreatment can accelerate enzymatic reactions, such as those involving microbial transglutaminase, leading to improved gelation properties through enhanced covalent bonding and disulfide bond formation (Qin et al., 2016). However, the extent of these effects varies with microwave power and duration, with higher energy levels generally resulting in firmer gels due to increased protein denaturation and water evaporation (Pure et al., 2021). Despite these changes, microwave heating tends to favor non-covalent interactions over covalent cross-linking, producing firmer gels compared to those made by conventional heating (Rombouts et al., 2020). Furthermore, the interaction of microwave energy with water molecules plays a crucial role in transmitting energy to proteins, thereby influencing structural changes and gelation behavior (Jiao et al., 2022). Additionally, microwave treatment can improve the water and oil holding capacities, as well as the swelling power of wheat proteins, which are crucial for their functional performance in food products (Ashraf et al., 2012; Kamble et al., 2020).

3.4.3. Product quality

Microwave treatment significantly impacts the nutritional content and quality of wheat protein processing products, primarily through alterations in protein structure and functionality. Studies have shown that microwave treatment can reduce protease activity in sprouted wheat, leading to improved dough properties and gluten quality due to protease inactivation and heat-induced gluten cross-linking (Wang et al., 2024). However, microwave heating can decrease wet gluten content while increasing the gluten index and falling number, indicating improved baking quality despite reduced gluten content (Kaasová et al., 2005). Additionally, microwave treatment enhances the solubility of wheat germ isolated proteins, maintaining high functional quality without the need for additives (Liu et al., 2014). Microwave treatment has also been explored in the context of meat products, particularly in enhancing the binding properties of wheat proteins in meat analogs. The study by Qin et al. (2016) indicated that microwave pretreatment of wheat gluten improved its gelation properties, which can be beneficial for creating meat substitutes with desirable textures. This enhancement in binding and gelation can lead to improved mouthfeel and overall quality in meat products that incorporate wheat proteins. Optimal conditions for microwave treatment involve a careful balance of power, duration, and temperature to achieve desired functional and storage outcomes. Short treatments, such as 20 seconds at 700 W, can enhance the quality of wheat products like steamed bread by maintaining gluten integrity and improving texture, while longer treatments ($\geq$30 seconds) at higher temperatures ($\geq$68°C) are more suitable for products requiring less gluten, such as biscuits (Qu et al., 2017). For whole-wheat flour, microwave treatment for 90 seconds significantly extends the shelf life of fresh noodles by inhibiting microbial growth and reducing polyphenol oxidase activity, while also enhancing dough stability and resistance to extension (Li et al., 2017). In the context of wheat germ, microwave processing at controlled temperatures (below 120°C) inactivates enzymes and microorganisms, preventing rancidity and maintaining nutritional quality (Guo, 2016). Treatment at specific power levels (e.g., 200 W at 100°C) can also reduce gluten content and allergenicity while preserving functional properties, which is beneficial for producing gluten hydrolysates with enhanced antioxidant activity (Gazikalović et al., 2021). The interaction of microwave energy with water molecules plays a crucial role, as it facilitates energy transfer and affects protein structure and functionality (Jiao et al., 2022). Nutritionally, microwave-treated wheat germ retains high protein, fat, and mineral content, with notable increases in crude fiber and vitamin E compared to other treatments (Youssef et al., 2009).

4. Effect of other components on the structure, functional properties, and quality of heat-induced wheat protein processing products

In heat-induced wheat protein products, the addition of ingredients such as polysaccharides, water, and salt ions significantly affect the structure and properties of wheat proteins, resulting in various changes in the quality of processed products. Polysaccharides, in particular, play a crucial role in enhancing water retention and improving the visco-elastic properties of dough, which are essential for achieving desirable baking qualities. Water availability is another critical factor that influences the quality of wheat protein products. Sufficient hydration helps maintain dough rheology and enhances baking performance, while insufficient hydration can lead to poor product quality. Salt ions, such as sodium, can impact protein solubility and the formation of the gluten network, both of which are crucial for dough properties.

4.1. Interaction between wheat protein and polysaccharides and its impact on product processing quality

The incorporation of polysaccharides into heat-induced wheat protein processing products significantly influences their structural, functional, and quality attributes. Polysaccharides, particularly non-starch polysaccharides such as arabinoxylans and β-glucans, play a crucial role in modifying the rheological properties of dough and the overall quality of baked goods. For instance, arabinoxylans, which are abundant in wheat flour, enhance dough stability and gas retention, leading to improved bread volume and texture (Xu et al., 2023). The structural characteristics of these polysaccharides, such as their ability to form gels and interact with proteins, are pivotal in determining the final product quality. The effects of polysaccharides extend beyond mere structural changes; they also influence the functional properties of wheat proteins during processing. For example, the addition of polysaccharides like sodium alginate and xanthan gum during high-moisture extrusion cooking has been shown to promote fibrous structures in meat analogues made from soybean and wheat protein mixtures. This is attributed to the polysaccharides' ability to enhance protein-protein interactions and stabilize the protein matrix, which ultimately improves the texture and mouthfeel of the final product (Wang, Gao, et al., 2023; Wang, Lian, et al., 2023). Furthermore, polysaccharides can modulate the viscosity of dough, affecting the water absorption capacity and the overall processing behavior of wheat flour (Desai et al., 2020). Quality attributes of heat-induced wheat protein products are also significantly affected by the type and concentration of polysaccharides used. For instance, the presence of β-glucans has been linked to improved nutritional profiles and functional properties, such as increased water retention and enhanced fiber content, which are beneficial for health-conscious consumers (Rakszegi et al., 2017). Additionally, polysaccharides derived from wheat bran have been noted for their immunomodulatory effects, suggesting that they not only contribute to the physical properties of food products but also offer potential health benefits (Hu et al., 2021). Wheat bran dietary fiber affects the molecular forces of glutenin and gliadin, enhancing hydrophobic interactions at lower temperatures and altering structural properties significantly during heating (Bao et al., 2024). On the other hand, the incorporation of polysaccharides like alginate in wheat protein films can modify mechanical properties and reduce water solubility, which can be beneficial for nutritional quality by providing a more stable product (Bishnoi et al., 2022). Moreover, the interaction of polysaccharides with proteins during heat treatment can lead to changes in protein solubility and molecular weight distribution, which are critical for the quality of baked goods. Heat treatments can modify the solubility and functional properties of wheat proteins, enhancing their performance in various applications, including cakes and breads (Liu et al., 2023b; Neill, Al-Muhtaseb, & Magee, 2012). The structural integrity of proteins is maintained or even improved through the formation of stable disulfide bonds, which are facilitated by the presence of polysaccharides during processing (Wang, Gao, et al., 2023). The interactions between proteins and polysaccharides can lead to phase separation or aggregation, affecting the microstructure and rheology of the composite gels. For instance, wheat protein tends to aggregate within the continuous phase, altering the gel's elasticity and flow properties (Firoozmand & Rousseau, 2015).

4.2. Interaction between wheat protein and water and its impact on product processing quality

The interaction of water with wheat proteins during heat-induced processing is critical in determining the structure, functional properties, and overall quality of wheat-based products. Water acts as a solvent and plasticizer, facilitating the hydration of proteins and starches, which is essential for the formation of a cohesive dough matrix. Water content plays a crucial role in determining the extent of these changes during heat treatment, impacting the rheological properties, protein interactions, and overall quality of wheat-based products. Heat treatment induces structural changes in wheat proteins, such as gluten, glutenin, and gliadin, with water content influencing these transformations. Gliadin, for instance, exhibits high thermal stability, which affects gluten network formation by impeding glutenin aggregation (Xu & Kuang, 2024). The presence of water facilitates the rearrangement of intermolecular interactions, such as disulfide and non-covalent bonds, which are crucial for protein network formation. This is particularly evident in the interaction between wheat bran dietary fiber and gluten, where water aids in the depolymerization and subsequent reformation of gluten networks at varying temperatures (Bao et al., 2023). Water content significantly affects the functional properties of wheat proteins during heat treatment. For example, the addition of water during heat moisture treatment enhances the visco-elastic properties of dough and improves pasta cooking quality by increasing resistant starch content and reducing pasta breakage (Ungureanu-Iuga & Mironeasa, 2023). In the context of mixed protein systems, water facilitates the interaction between wheat proteins and other protein sources, such as egg or soy, impacting the rate and extent of protein network formation. This interaction is crucial for the quality of products like noodles and pound cakes, where water aids in the incorporation of gliadin into the protein network (Lambrecht et al., 2018; Luo et al., 2016). On the other hand, the synergistic effect of water and heat treatment also improves the functional and antioxidant properties of wheat gluten hydrolysates, making them suitable for inclusion in functional foods (Elmalimadi et al., 2017). The structural changes that occur during the hydration of wheat proteins are significant for the quality of heat-induced products. When water is added to flour, gluten proteins (gliadins and glutenins) undergo hydration and swelling, leading to the formation of a visco-elastic network (Zhou et al., 2021). This network is essential for trapping gas produced during fermentation or leavening, which ultimately affects the rise and texture of bread and other baked goods. The formation of disulfide bonds between gluten proteins is also influenced by water content, which can enhance the stability and elasticity of the dough (Song et al., 2020). Moreover, the presence of water can promote the solubility of proteins, which is vital for their functional properties, including emulsification and foaming. In addition to structural changes, water significantly impacts the functional properties of wheat proteins. For example, during cake production, the emulsifying properties of wheat proteins are enhanced by the presence of water, which helps to stabilize oil-water interfaces and reduce agglomeration of oil droplets (Liu et al., 2023b). This emulsification is crucial for achieving a uniform batter consistency, which directly influences the final texture and quality of the cake. Furthermore, the water absorption characteristics of flour affect the rheological behavior of dough, influencing attributes such as hardness, cohesiveness, and resilience (Friday & Chituru, 2021). The ability of flour to retain water during processing also plays a role in the shelf-life and freshness of baked products, as it can mitigate staling and maintain moisture levels (Neill et al., 2012).

4.3. Interaction between wheat protein and salt ions and its impact on product processing quality

The effect of salt on the structure, functional properties, and quality of heat-induced wheat protein processing products is a multifaceted topic that encompasses various biochemical and physical interactions. Salt, particularly sodium chloride, plays a critical role in modifying the rheological and functional properties of wheat proteins, which are essential for the quality of wheat-based products. Salt influences the viscoelastic behavior of wheat dough, as evidenced by studies showing that increasing salt concentrations lead to higher maximum torque values during gluten aggregation, particularly in weaker doughs. This phenomenon is attributed to the alteration of hydrophobic interactions among gluten proteins, which are primarily driven by hydrophobic amino acids (Amoriello & Carcea, 2019). The presence of salt enhances the solubility of certain non-gluten proteins, such as albumins and globulins, which can significantly affect dough properties and the overall texture of the final product (Cho et al., 2017). Furthermore, the addition of salt has been shown to increase viscosity parameters in dough, indicating that salt modifies the protein matrix and enhances the dough's stability and elasticity (Carcea et al., 2020). The presence of salt ions, particularly Na+ and Ca2+, enhances the water holding capacity (WHC), storage modulus (G'), and texture properties of wheat gluten-based gels. This is achieved by promoting hydrophobic interactions and disulfide bond formation, leading to a denser gel network (Guo et al., 2023; Zhang, Chen, et al., 2022). At optimal concentrations, salt ions improve the gel's mechanical properties by increasing the α-helix and β-sheet content, which contributes to a more stable and compact gel structure. However, excessive salt can disrupt the gel network, reducing stability (Zhang, Chen, et al., 2022). The structural changes induced by salt are further compounded by heat treatment, which can lead to protein denaturation and the formation of disulfide bonds among gluten proteins. This cross-linking is crucial for the development of the dough's strength and elasticity, which are vital for the quality of baked goods (Rooyen et al., 2022). Salt ions facilitate protein denaturation, which is essential for gelation. The addition of salt before processing, such as spray drying, can expose functional groups within the protein matrix, improving protein-protein interactions and resulting in a more uniform and smooth gel structure (Zheng et al., 2019). Heat treatment alters the molecular order of starch and proteins, influencing their functional properties, such as water absorption and gelatinization, which are critical for achieving desired textures in products like bread and pasta (Hu et al., 2017). The interplay between salt and heat treatment thus not only affects the protein structure but also the overall quality of wheat products. Salt ions influence the rheological properties of wheat protein gels by increasing their extensibility and enhancing protein aggregation. This results in a more cohesive and resilient gel network, as observed through techniques like scanning electron microscopy (SEM) (Han et al., 2021; Zheng et al., 2019). The microstructure of the gel becomes more ordered and stable with the appropriate concentration of salt, as evidenced by the formation of fine-stranded gel matrices (Guldiken et al., 2021; Ren et al., 2023). The atomic force microscopy (AFM) images also revealed that both salt and alkali treatments induced the formation of high molecular weight polymers with larger particle sizes and a more compact structure at elevated temperatures (75 and 95 °C). This indicates that heating, in conjunction with salt or alkali, enhances the aggregation of gluten proteins (Han et al., 2021) (Figure 4). The increase in chain width observed in the AFM images is attributed to the aggregation of gluten chains, primarily driven by non-covalent interactions such as hydrophobic bonds and hydrogen bonds. Gluten proteins are crucial for dough properties, and various strategies, including the use of additives, have been employed to modify gluten network structure and functionality (Ooms & Delcour, 2019).

5. Comparative evaluation of heat treatment techniques and their applications

Heat treatment represents a crucial intervention in modifying wheat proteins to optimize their functional performance in food systems. The various thermal processes can induce fundamental changes in protein structure and functionality, influencing solubility, emulsification, and gelation. The appropriate selection of heat treatments will depend on the specific food context and desired functional attributes. Table 2 presents the key features and applications of various thermal processing methods. Wet heating facilitates protein denaturation primarily through mechanisms involving prolonged exposure to heat, leading to the disruption of the native protein structure. This denaturation is characterized by the unwinding of the protein's secondary and tertiary structures, which can significantly affect functionality. The moderate temperatures between 60 and 80°C are particularly effective for improving protein solubility, foaming, and emulsifying ability. For instance, treatments at these temperatures have been observed to yield a high residual content of soluble protein in pasta, which highlights the beneficial role of wet heat in maintaining protein solubility compared to more intense heat treatments that can lead to aggregation and reduced solubility (Wagner et al., 2011). SST provides quick thermal energy transfer, ensuring that the proteins experience high temperatures (typically between 150°C and 170°C) for 1–3 minutes uniformly and in a fraction of the time compared to other methods. This rapid heating helps minimize undesirable reactions that could lead to protein degradation (Ma et al., 2023b; Ma et al., 2023c). This efficient thermal processing minimizes protein degradation while enhancing gelation properties, making it particularly suitable for structured plant-based foods and protein-fortified instant mixes. In the context of TWP production, the optimal temperature for extrusion appears to be in the range of 120°C to 160°C. Wu et al. (2019b) indicate that while an increase in temperature can enhance protein texturization, excessively high temperatures (over 170°C) can disrupt the organization and structural integrity of the extrudate, resulting in less desirable textures. This disruption is attributed to the greater thermal energy promoting increased product temperatures that can lead to excessive denaturation and a lack of organized fibrous structure necessary for quality TWP (Wu et al., 2019b). Regarding moisture content, the literature suggests that an ideal range is typically between 20% and 30% for high-quality TWP (Ferawati et al., 2021). The power settings for microwave treatment can significantly influence the properties of wheat proteins. Mastani et al. report that treatment at 100 W for 10 minutes yielded the highest foaming capacity for wheat gluten protein, reflecting the effectiveness of this specific power setting in enhancing functional properties (Mastani et al., 2024). Conversely, they found that a higher power of 300 W for 15 minutes also resulted in improved foam capacity for wheat protein concentrates. This indicates that while lower power settings can be effective, higher powers can also contribute positively but need careful monitoring to prevent degradation of the protein structure due to excessive thermal exposure (Mastani et al., 2024). Moreover, Qin et al. (2016) found that as microwave power increased, the soluble protein content in gels formed from a mixture of soybean protein isolate and wheat gluten decreased,

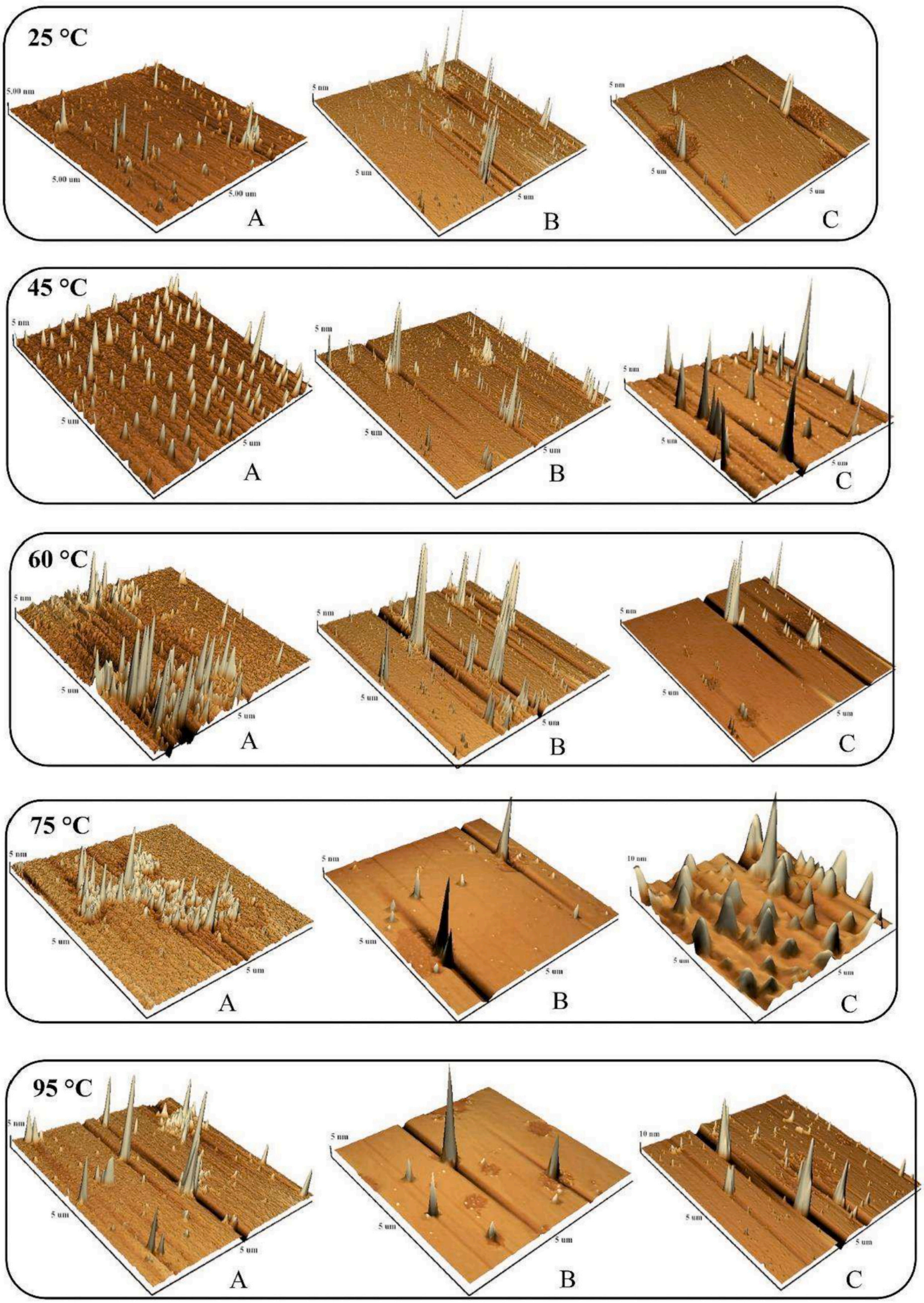

Figure 4. Atomic Force Microscopy (AFM) 3D morphology images depicting gluten (A), gluten combined with 2% salt (B), gluten with 1% alkali (C), and the molecular chain dimensions—height (E) and width (F)—across various heating temperatures. Data is from Han et al. (2021).

Table 2
Key features and applications of various thermal processing methods

Heat Treatment	Conditions	Principle	Functional improvement	Recommended application	Advantages	Limitations	Reference
Wet heating	< 100 °C	Using a water bath for heating with water as the heat transfer medium	Solubility, emulsification	Beverages, bakery	Consistent heating and precise control	Time-intensive	(Abedi & Pourmohammadi, 2021; Wang et al., 2021)
Superheated steam treatment	>100 °C	Utilizing saturated vapor that is maintained at a consistent pressure to heat substances	Gelation, water holding	Instant mixes, restructured products	Short thermal response time, high thermal efficiency, and efficient heat transfer	Equipment-intensive	(Fang et al., 2023; Hu et al., 2017; Liu et al., 2020; Liu et al., 2023c; Ma et al., 2023b)
Extrusion heat induction	Temperature (120–160 °C), Moisture content (10–30%), high shear force	Heat production during extrusion results from mechanical shear and friction (altering protein structure), external heating (via electrically regulated barrel segments), and viscous dissipation (heat generated by resistance at elevated pressure).	Texture, digestibility	Meat analogs, snacks	It provides a wide range of functions, low production costs, high energy utilization efficiency, and no pollutant emissions by integrating multiple unit operations, including material blending, homogenization, maturation, and molding.	Nutrient loss	(Ferawati et al., 2021; Fischer, 2004; Leonard et al., 2020; Wang et al., 2023)
Microwave	Frequency (300 MHz to 300 GHz)	Microwave heating utilizes dielectric heating, where electromagnetic radiation causes rapid oscillation of polar molecules, primarily water, generating heat.	Emulsifying, reduced allergenicity	Bakery, emulsions	Rapid structural modifications, changes in secondary and tertiary structures.	Uneven heating risk	(Vicente et al., 2024; Wang et al., 2023c; Zhang et al., 2023)

indicating a careful balance must be struck to avoid detrimental effects on protein interactions at excessive power levels. This reinforces the idea that while specific power settings can enhance certain properties, they can also compromise others if not optimized correctly. The duration of microwave exposure is another critical factor in the treatment process. In the context of wheat proteins, a treatment time of 10 to 15 minutes has been frequently validated. For instance, Mastani et al. (2024) highlighted the potential of maintaining moderate treatment durations (e.g., 10 minutes at lower power) as being adequate for enhancing wheat protein functional properties without the side effects commonly associated with prolonged exposure. In general, wet heating under moderate conditions is the optimal method for applications that necessitate high solubility and emulsifying capacity, such as in drinks or sauces. Due to their capacity to enhance texture and stability, superheated steam or extrusion are the preferred methods for structured or gelled products. Microwave treatment provides a low-water, rapid alternative for improving the emulsifying behavior and functional properties with minimal processing time. The thermal treatment chosen must be consistent with the textural, nutritional, and sensory goals of the target product.

6. Challenges and future work

Various thermal treatments, such as wet heating, superheated steam, extrusion, and microwave treatments, have been extensively studied for their impact on the structure, functional properties, and quality of wheat protein processing products. Each treatment induces different effects on the molecular structure of wheat proteins. For example, SST enhances protein aggregation and alters disulfide bond contents, affecting molecular weight distribution (Liu et al., 2023b). Conversely, extrusion at high temperatures may lead to protein denaturation and a loss of functional properties (Liu et al., 2019). These contrasting outcomes highlight the need for further investigation into the conditions under which each thermal treatment optimally modifies protein structures. The functional properties of wheat proteins, such as solubility, emulsification, and foaming capacity, vary with different processing methods. Wet heating, for instance, may cause protein aggregation and reduced solubility (Choi et al., 2016). Understanding the mechanisms behind these variations is crucial for optimizing processing conditions to achieve desired functional characteristics. Thermal treatments can also negatively impact the nutritional quality of wheat protein products. SST, for example, has been reported to reduce protein content in processed products (Cho & Choi, 2021), while extrusion may cause the volatilization of nitrogenous compounds, lowering crude protein values (Liu et al., 2019). Future research should focus on balancing functional property enhancement with nutritional quality preservation. Processing parameters, such as temperature, time, and moisture content, play a significant role in determining the effectiveness of each treatment. Optimal conditions for SST, for instance, significantly reduce deoxynivalenol (DON) in wheat (Liu et al., 2019). Comprehensive studies are needed to establish these optimal conditions for each treatment, maximizing benefits while minimizing adverse effects. Comparative studies across different thermal treatments will help elucidate their specific effects on wheat protein structure and functionality. Research into the synergistic effects of combining different treatment methods, such as microwave with enzymatic treatments, may enhance wheat protein properties beyond what each method achieves alone. In addition to processing considerations, the interactions between wheat proteins and other components, such as polysaccharides, water, and salts, significantly affect the structure, functionality, and quality of wheat protein products. Polysaccharides play a vital role in enhancing water retention and improving the viscoelastic properties of dough, which are critical for desirable baking qualities (Nimitkeatkai et al., 2022; Rooyen et al., 2022). However, the mechanisms through which polysaccharides interact with wheat proteins under heat stress remain inadequately understood (Mann et al., 2013). Exploring these interactions could lead to improved wheat protein products. Water availability also influences wheat protein quality. Insufficient hydration exacerbates the negative effects of heat stress on dough rheology, impairing baking performance (Shamim, 2024). Additionally, competition for water between gluten proteins and starch can alter dough mixing properties, affecting product quality (Balla et al., 2011; Labuschagne et al., 2021). Sodium ions play a role in protein solubility and gluten network formation, which are critical for dough properties. Research into how sodium ions interact with wheat proteins under heat stress could reveal new methods for enhancing product quality (Abbas, 2024; Pflaum et al., 2013). Future research should focus on optimizing these interactions to improve wheat protein processing outcomes. Future research should examine the effects of innovative thermal processing technologies, including infrared heating, radiofrequency heating, ohmic heating, and inductive electric field heating, on the structure and functionality of wheat proteins. These methodologies have exhibited promising results in modifying the physicochemical characteristics of several protein systems, including soy and milk proteins. Nonetheless, their particular impacts on wheat proteins have mainly gone uninvestigated. Examining these methodologies may provide significant insights for improving the functional performance and processing quality of wheat-based goods.

7. Conclusions

Heat induction plays a critical role in the production of wheat protein products, as it significantly influences the structure and functional properties of wheat proteins. The primary objective of research in this area is to explore the effects of different heat induction methods on the quality of wheat protein products and their processing systems under varying thermal conditions. Heat processing is a targeted approach that involves adjusting temperature and heating techniques to improve the quality of wheat protein by altering its structure and enhancing its functional properties. One area of focus is the inherently weak gel-forming ability of wheat protein, which limits its application in certain food products. Further research is needed to improve the texturization of extruded wheat tissue protein and expand the development of wheat protein-based artificial meat products. This can be achieved by modifying the gel properties of wheat protein through heat induction, adjusting the addition of salt ions, altering pH, or modifying the glutenin/gliadin ratio. Additionally, the interaction between wheat protein and other macromolecules, such as starch, fat, water, and additives, under heat-induced conditions, can lead to significant changes in the functional properties of wheat protein. These interactions are particularly complex in food systems, where proteins interact with various other components. Further investigation is required to better understand these interactions. To produce high-quality wheat protein products, it is essential to strengthen the relationship between heat induction and the structural properties of wheat protein, as well as its interactions with macromolecules during processing. This will help to optimize the processing and development of wheat protein products with improved quality and functionality.

CRediT authorship contribution statement

Hong-Ju He: Writing – original draft, Validation, Software, Investigation, Formal analysis, Data curation. **Guanglei Li:** Writing – review & editing, Supervision. **Mohammed Obadi:** Writing – review & editing, Supervision, Conceptualization. **Xingqi Ou:** Validation, Supervision, Resources, Funding acquisition, 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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Data availability

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

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