



Effects of ultrasonication and high hydrostatic pressure on functional, thermal, structural, rheological, and pasting properties of gluten-free substitutes for enhanced breadmaking

Mahsa Farrokhi, Ines N. Ramos, Cristina L.M. Silva ^{*} 

CBQF - Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia, Universidade Católica Portuguesa, Rua Diogo Botelho 1327, 4169-005, Porto, Portugal

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ABSTRACT

The demand for gluten-free (GF) products has increased due to the rising prevalence of gluten-related disorders. However, GF products often face challenges related to nutritional value, techno-functional, and structural properties. To address these challenges, researchers are investigating GF flours, starches, and protein isolates from pulses, cereals, and pseudocereals. However, in their native forms, these ingredients show poor stability, low solubility, and a high tendency for retrogradation, limiting their suitability for high-quality GF formulations. Techno-functional and structural modifications are essential to overcoming these limitations.

Ultrasound (US) and high hydrostatic pressure (HHP) are innovative processing techniques that can enhance GF ingredients' techno-functional and nutritional properties while maintaining product integrity. This review examines the effects of US and HHP on the structural, techno-functional, thermal, pasting, and rheological properties of GF ingredients, from pulses, cereals, and pseudocereals, and their implications for breadmaking. Research indicates that US decreases water absorption capacity (WAC) but enhances solubility, while HHP increases WAC at higher intensities and decreases solubility. Both treatments reduce particle size, with HHP inducing more pronounced morphological changes. Additionally, both techniques lower gelatinization temperatures and enthalpy, improving dough hydration. Rheological studies suggest that US and HHP promote gel-like behavior, increasing the elastic modulus and reducing viscosity parameters, ultimately enhancing dough handling and bread structure.

In conclusion, US and HHP show great potential for improving dough performance, bread volume, and texture in GF baking. However, optimizing treatment conditions is crucial, as their effects depend on the type of flour, starch, or protein and processing parameters.

1. Introduction

Gluten is a type of protein found in wheat, rye, and barley that plays a key role in giving bread and other baked goods their texture (Hassan et al., 2024). It comprises two main protein groups: gliadins, which help the dough stretch, and glutenins, which provide strength and elasticity. When flour is mixed with water, these proteins form a network that traps air, allowing the dough to rise and maintain its shape during baking (Fig. 1). The absence of this network in gluten-free formulations compromises dough cohesiveness, gas retention, and elasticity, resulting in products with inferior texture and volume (Gómez & S. Sciarini, 2015; Lancelot et al., 2021).

However, despite gluten's critical technological role, its removal is essential for individuals with gluten-related disorders and is increasingly sought after for broader lifestyle reasons. Certain people have trouble digesting gluten, leading to conditions known as gluten-related disorders. Gluten-related health issues are broadly categorized into three groups: first is the autoimmune disorders—such as celiac disease (CD) and dermatitis herpetiformis (DH, or Duhring's disease); second are allergic reactions, like wheat allergy; and the third is other immune-mediated conditions, including non-celiac gluten sensitivity (NCGS) (Perez-Perez et al., 2023). Celiac disease is an autoimmune condition where the immune system reacts to gluten, damaging the small intestine (Zannini et al., 2012). It affects up to 1 % of the population and requires

^{*} Corresponding author.

E-mail address: clsilva@ucp.pt (C.L.M. Silva).

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a strict gluten-free diet to prevent symptoms and long-term complications (Aramburo-Galvez et al., 2020; Kurppa et al., 2024). Dermatitis herpetiformis (Duhring's disease) is a chronic, blistering skin condition associated with celiac disease, characterized by intensely itchy rashes that typically resolve with a gluten-free diet (Reunala et al., 2018). Wheat allergy is a different condition in which the immune system treats wheat proteins as harmful, triggering allergic reactions. NCGS is less well understood but causes symptoms similar to celiac disease without the same immune response or intestinal damage (Aramburo-Galvez et al., 2020; Singla et al., 2024).

For individuals with gluten intolerance, consuming gluten can lead to digestive discomfort and other health issues. Because symptoms vary, diagnosing these conditions requires medical tests and evaluations. The only reliable way to manage celiac disease is to follow a gluten-free diet, avoiding foods that contain wheat, rye, and barley (Singla et al., 2024). Beyond medically diagnosed disorders, the growing demand for gluten-free products is also driven by consumer perceptions that gluten-free diets are healthier and can contribute to improved well-being, weight management, and digestive comfort, despite limited scientific evidence supporting these claims in the general population (Perez-Perez et al., 2023).

1.1. Challenges and limitations of gluten-free products

According to EC Regulation No. 828/2014, food labelled as “gluten-free” must contain no more than 20 mg of gluten per kilogram, while “very low gluten” products may contain up to 100 mg/kg, provided the gluten content has been reduced during processing (Regulation, 2014). These definitions ensure proper labelling and consumer protection for individuals with gluten-related disorders. Despite this regulation, gluten-free products face several limitations in terms of availability, their sensory characteristics, and overall quality, which often fall short of consumer expectations. Key areas of concern regarding quality include taste, texture, aroma, and the general eating experience (Hassan et al., 2024). The absence of gluten results in doughs with lower cohesiveness and elasticity, leading to bread with reduced specific volume, poor texture, and less appealing colour. Additionally, gluten-free products often suffer from a dry mouthfeel, shorter shelf life, and unsatisfactory taste, making them less desirable to consumers (Cappelli et al., 2020).

Furthermore, a gluten-free diet (GFD) is associated with significant nutritional deficiencies. For instance, Hassan et al. (2024) reported that 70 % of children with celiac disease were vitamin D deficient at diagnosis, with only slight improvement after six months on a GFD. Women on a GFD consumed just 46 % of their daily fibre, 44 % of their iron, and 31 % of their calcium needs, while men met 88 % of fibre, 100 % of iron, and 63 % of calcium requirements (Hassan et al., 2024). Sensory quality

also remains a challenge. Another study identified that improving the texture of gluten-free bread, making it moister and softer, as well as enhancing the taste, were critical areas for product development (Alencar et al., 2021).

Despite significant advancements in gluten-free product development, many challenges remain in mimicking gluten-containing products' structure, techno-functionality, and sensory attributes. To address these issues, researchers and food technologists have explored alternative ingredients that can enhance gluten-free formulations textural, nutritional, and techno-functional properties.

1.2. Plant-based alternatives for gluten-free products

Replicating gluten's structural and techno-functional properties in gluten-free products requires innovative approaches. Several strategies have been explored, including using hydrocolloids, combining alternative proteins (such as soy, pulses, and insects) and starches subjected to physical or enzymatic treatments (such as high-pressure processing, dry heat treatment, or fermentation), and incorporating plant-based alternatives (Cappelli et al., 2020). Among these, gluten-free plant-based ingredients—such as pulses, cereals, and pseudocereals—have gained significant attention (Fig. 2).

Plant-based alternatives not only improve the structural and techno-functional properties of gluten-free formulations but also enhance their nutritional value. Rich in protein, fibre, vitamins, and minerals, they help address common deficiencies in commercial gluten-free products (Foschia et al., 2017). Pulses like lentils, beans, chickpeas, and peas are valued for high protein and fibre, while cereals such as rice and teff offer good digestibility and low allergenicity. Pseudocereals—including amaranth, quinoa, and buckwheat—are notable for their amino acid profiles and bioactive compounds, making them ideal for those with celiac disease. These sources also provide key techno-functional traits, including solubility and water-binding capacity, which are vital for gluten-free dough development. For instance, particle size and distribution, milling yield, and flour treatment methods significantly affect texture and stability outcomes, such as softness, cohesiveness, and reduced staling. Moreover, the concentration of pseudocereal flour and processing conditions modulate these effects, as seen in various studies where partial substitution levels altered bread volume and dough strength (Hoehnel et al., 2019; Serventi et al., 2018). This versatility expands product applications in bakery products, dairy alternatives, and protein-enriched foods (Houben et al., 2012; Zhang et al., 2024).

These alternative gluten-free (GF) sources contain mainly two types of biopolymers: starches and proteins. Starch, the main energy reserve in plants—including cereals, pulses, roots, and tubers—is a fundamental ingredient in GF formulations. It significantly influences texture, appearance, and overall acceptability by forming a matrix that entraps

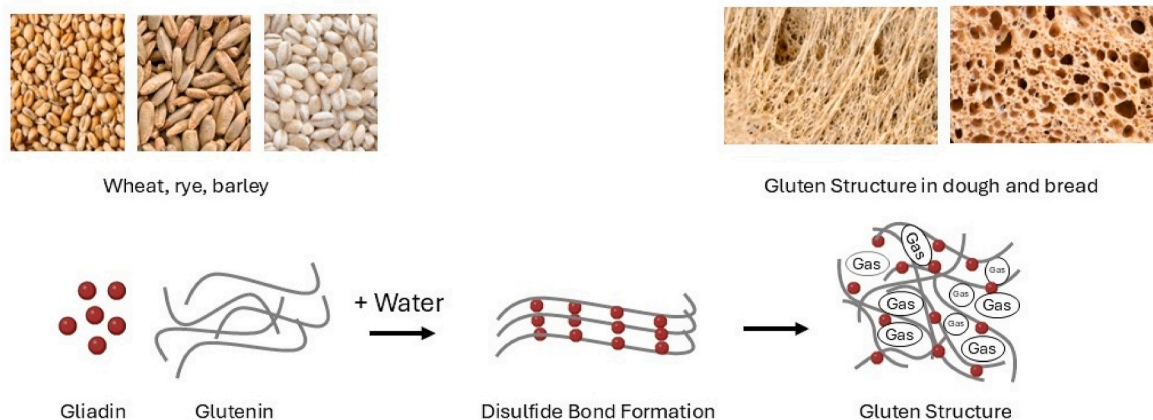


Fig. 1. Formation and structure of gluten in dough.

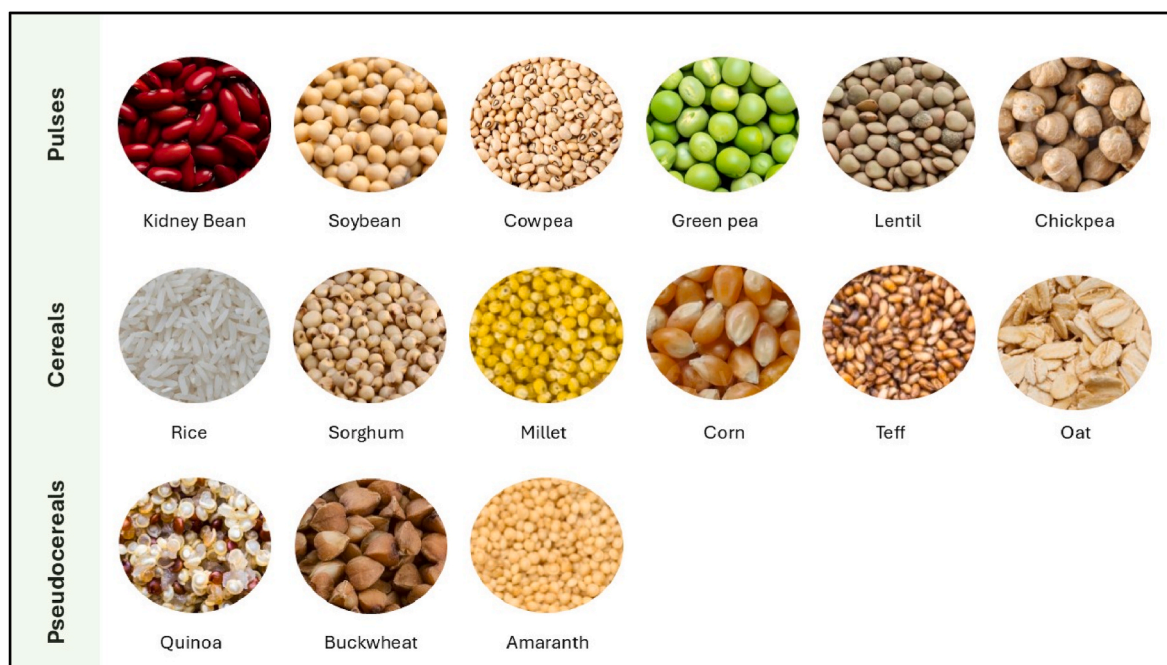


Fig. 2. Classification of pulses, cereals, and pseudocereals relevant for breadmaking gluten-free alternative formulations.

air bubbles, thereby contributing to the structure of baked goods (Witczak et al., 2016).

Proteins typically constitute 4–20 % of these sources by weight. Beyond their nutritional value—particularly their high content of essential amino acids—proteins from pulses, cereals, and pseudocereals offer techno-functional benefits. They exhibit emulsifying, foaming, and gelation properties that enhance GF products' texture, stability, and overall quality. Additionally, they can contribute bioactive compounds with antioxidant and anti-inflammatory effects, further boosting the health profile of GF formulations (Zhang et al., 2024).

A key factor in optimizing gluten-free formulations is the interaction between starches and proteins. These interactions influence processing behavior, structural integrity, and sensory attributes, directly impacting product quality and digestibility (Quiroga Ledezma, 2018). Understanding these mechanisms enables the development of gluten-free products with improved textural, sensory, and techno-functional properties, expanding their applications through advanced food technologies.

1.3. Overcoming limitations of native gluten substitutes

Gluten-free formulations depend on starch and protein for structure and texture, but their native forms often fall short of industry requirements (Singh et al., 2007). Native starches, despite being abundant, biodegradable, and cost-effective, exhibit several limitations in gluten-free applications. Their poor solubility in cold water, rapid retrogradation, susceptibility to syneresis, low viscosity, and limited resistance to shear stress and thermal processing hinder their techno-functionality (Castro et al., 2023). Similarly, protein isolates from legumes, cereals, and pseudocereals face structural and techno-functional challenges. Many exhibit poor solubility, emulsification, foaming, and water-binding, making them less effective. Additionally, their undesirable sensory attributes - such as beany, bitter, or astringent flavours - can negatively affect consumer acceptance. Some protein sources, particularly legume-derived isolates like soy, also pose allergenic risks, further limiting their application. Structurally, the spatial arrangement of amino acids and polypeptide chains can limit hydration, gelation, and texturization, highlighting the need for functionalization to enhance their role in gluten-free products (Zhang et al.,

2024).

A strategy adopted by the food industry is the application of modifications by different techniques (i.e., genetic, mechanical, physical, chemical, or enzymatic) to alter the natural physicochemical properties of GF sources so they can adapt better to specific processing requirements (Yang et al., 2019; Zhu, 2015). The modification of raw GF ingredients before the dough making is essential to improve the bread quality since it has been demonstrated that the characteristics of starch and protein granules have a strong influence, derived from their interaction with other compounds present in the bread system (Witczak et al., 2016).

Compared to chemical modifications, physical methods are better perceived in the food industry for their environmental sustainability and ability to produce 'clean label' products. Among the physical processing techniques, ultrasonication and high hydrostatic pressure have gained significant attention as innovative, non-thermal processing techniques for modifying gluten-free flours, starches, and proteins. These methods potentially enhance functional properties, gelatinization, pasting behavior, and rheology, making them relevant strategies for improving gluten-free formulations (Qin et al., 2022; Villanueva et al., 2019).

This review examines the impact of ultrasound and high hydrostatic pressure on gluten-free alternative flours, starches, and protein isolates from pulses, cereals, and pseudocereals, emphasizing their role as innovative physical modification techniques. While various physical processing methods have been studied for starches and flours, a direct comparison of US and HHP in gluten-free ingredients remains unexplored. By evaluating how these treatments modify their techno-functionality and properties, we aim to assess their potential suitability for gluten-free dough and bread formulations. To provide a comprehensive overview, we first outline the fundamental principles and processing conditions of the US and HHP. Structured tables summarizing the existing literature, detailing processing conditions and the resulting modifications in techno-functional properties, starch composition, thermal behavior, structural changes (XRD and FTIR), and rheological and pasting characteristics, are then developed. Finally, we will critically analyse the mechanisms driving these changes, systematically evaluating how US and HHP influence gluten-free formulations and their potential role in improving breadmaking performance.

2. Overview of US and HHP applications in gluten-free ingredients

2.1. US and HHP applications: key principles and processing conditions

Both ultrasound (US) and high hydrostatic pressure (HHP) have gained widespread use in the food industry for processing, preservation, and modification due to their clean, non-toxic, and environmentally sustainable nature (Bhargava et al., 2021; Huang et al., 2020). These methods are increasingly applied in the development of gluten-free substitutes, offering significant changes in techno-functional, structural, and rheological properties.

Ultrasound refers to mechanical waves with frequencies exceeding 20 kHz, generated by piezoelectric or magnetostrictive transducers within high-frequency electrical fields. These waves produce high-energy vibrations that are amplified and transmitted to a probe, sonotrode, or bath in direct contact with the fluid being treated. The sample, typically mixed with mostly water to facilitate homogenization, undergoes sonication while being continuously agitated to prevent sedimentation. This ensures an even distribution of the sound waves throughout the sample (Vela et al., 2024). In contrast, HHP involves placing food items in a flexible, hermetically sealed container inside a pressure chamber. A pump and pressure intensifier build up uniform pressure, which is transmitted to the food regardless of its size and shape, via a liquid transfer medium (typically water), ensuring uniform and instantaneous application of pressure across the food item (Gutierrez et al., 2023) (Fig. 3).

Both technologies involve key mechanisms for processing. The US relies primarily on the cavitation effect, where the rapid formation, growth, and collapse of bubbles cause mechanical bond fracture and free radical oxidation, leading to changes in the structure of compounds and, ultimately, in their composition (Pingret et al., 2013). Additionally, HHP exerts pressure that can enhance tissue structures, inactivate microorganisms, and modify the speeds of enzyme reactions through principles like the isostatic principle and Le Chatelier's principle (Castro et al., 2020).

The impact of ultrasonication is primarily influenced by parameters like frequency, intensity, duration, and the ratio of sample-to-water (referred to as hydration), temperature, as well as the type of starch or protein used (Zhu, 2015). Similarly, the impact of HHP depends on pressure levels ranging from 100 to 600 MPa, holding time, temperature, and hydration or sample-to-water ratio, all of which influence the modification process (Gutierrez et al., 2023). Both technologies typically use water as the solvent due to its safety and effectiveness in food applications (Vela et al., 2024).

In both US and HHP, sample recovery is crucial to maintaining the structural and techno-functional integrity of the modified materials. The most common recovery methods are freeze-drying and centrifugation,

followed by low-temperature drying. Freeze-drying involves freezing the sample and removing the water content through sublimation under vacuum conditions, which helps preserve the structural integrity and techno-functionality of the modified material. In contrast, centrifugation separates solid particles from the liquid medium by applying high rotational forces. After centrifugation, the separated solid is typically subjected to low-temperature drying to remove residual moisture while minimizing potential thermal damage to the sample's properties (Vela, Villanueva, Nathia-Neves, & Ronda, 2023).

Both US and HHP can cause significant modifications to starch and protein structures through different mechanisms. Ultrasound induces structural changes through cavitation and free radical formation, which leads to the degradation of starch polymers and the modification of protein interactions (Jamalabadi et al., 2019). Similarly, HHP can cause unfolding and partial denaturation of proteins, modifying the electronic configuration of amino acid side chains and altering non-covalent interactions within starch compounds (Baldelli et al., 2024). However, these structural effects are highly dependent on the specific matrix (e.g., starch versus protein) and the processing parameters applied (such as pressure level, treatment time, and ultrasound intensity). These structural modifications can impact the water-binding capacity, gelatinization behavior, and emulsifying properties of starches and proteins, opening up new possibilities for their application in gluten-free products, especially in baking (Wang et al., 2023; Zhu & Li, 2019b).

2.2. Overview of the literature on the effects of US and HHP on gluten-free substitutes

Tables 1 and 2 provide an overview of the application of ultrasonication (US) and high hydrostatic pressure (HHP) treatments to gluten-free alternatives (flours, starches, and protein isolates) derived from pulses, cereals, and pseudocereals. The processing conditions, including frequency, amplitude, and energy input for US treatments, and pressure levels for HHP processing are summarized in Tables 1 and 2, respectively. Hydration conditions and recovery methods are also compiled.

Subsequently, the observed effects on several key parameters are presented, namely techno-functional properties, starch composition, thermal characteristics, structural attributes (XRD and FTIR), and rheological and pasting properties.

The information is organized by product type, specifying whether the material under study is flour (F), starch (S), or protein isolate (P). The results are presented in comparison with the corresponding untreated control samples. An upward arrow (↑) indicates an increase in the respective parameter following treatment, a downward arrow (↓) indicates a decrease, the abbreviation 'ns' denotes a not significant change and 'nd' denotes a not detected change.

3. Effects of US and HHP on breadmaking gluten-free alternatives

3.1. Effects on techno-functional properties (WAC, OAC, WSI, SP)

Measuring the techno-functional properties of flours is essential for several physical-chemical and/or organoleptic aspects of food production that enable food scientists and developers to innovate and tailor ingredients and processes to produce high-quality and appealing food products (Patil & Arya, 2017). Examples of flour techno-functional properties include Water Absorption Capacity (WAC), Oil Absorption Capacity (OAC), Water Solubility Index (WSI), and Swelling Power (SP). These properties influence the sensory attributes of food, such as texture, taste, and appearance, which are crucial for consumer acceptance. Knowing the techno-functional characteristics of flour helps determine how novel proteins, fats, fibres, and carbohydrates behave in each food system and whether they can be used in a range of food applications without affecting texture and taste (Adebawale & Lawal,

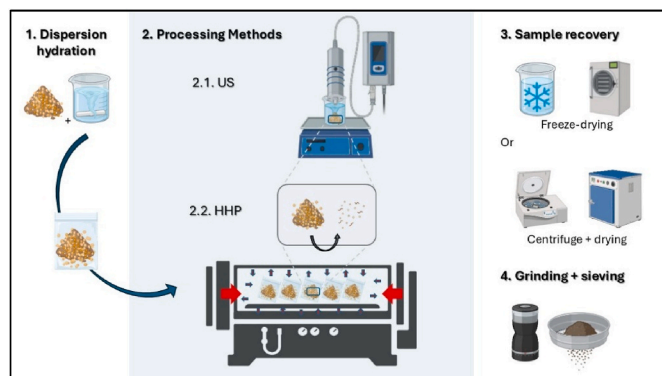


Fig. 3. Schematic representation of US and HHP processing applied to gluten-free alternative breadmaking ingredients.

2004). Additionally, knowledge of techno-functional properties allows for optimizing ingredient mixes, particularly determining the ideal ratios of gluten-free flour for healthier products (Poshadri et al., 2023).

The effects of US and HHP on WAC of flours and starches are profound and diverse (Tables 1 and 2). WAC reflects the maximum amount of water that flour, starch, or protein can retain. A study on rice flour (Vela, Villanueva, & Ronda, 2021) reported that ultrasonication did not create additional water-binding sites. However, increasing the temperature during ultrasonication enhanced the interaction of water with double helices. A similar effect was observed in another study on teff flour (Vela, Villanueva, Ozturk, et al., 2023), leading to the reorganization of starch molecules and the creation of more water-binding sites (Zavareze & Dias, 2011). Additionally, higher power and intensity of ultrasonication, as shown in studies on oat starch (Falsafi et al., 2019) can break down particles, increasing their water accessibility. Conversely, HHP enhanced WAC by breaking covalent bonds and starch polymers, especially under higher pressure conditions (400–600 MPa)

and longer durations (30 min), as demonstrated in studies on pearl millet (Mirzababae et al., 2022) and black rice starch (Almeida et al., 2023). This increase in WAC contributes to higher dough viscosity and leads to bread with greater volume and uniformity (Fiorda et al., 2013).

OAC, defined as the weight of oil absorbed per weight of flour, starch, or protein isolates, involves the capillary entrapment of oil molecules within granular channels and pores and the occupation of intergranular spaces by oil. The lipid absorption capacity is crucial in food formulation as it helps retain flavours, enhancing the mouthfeel and acceptability of products (Sujka & Jamroz, 2013). Ultrasonication has been shown to increase OAC, particularly with longer US durations, as observed in quinoa protein isolates (Mir et al., 2019) and oat starch (Falsafi et al., 2019). This effect is attributed to the prolonged exposure to acoustic waves, which disrupt surfaces and expose hydrophobic groups, facilitating oil entrapment. On the other hand, starches modified by HHP at intense pressures and durations exhibit a decrease in OAC, attributed to the destruction of granules, which reduces their oil

Table 1
Comparative effects of Ultrasound (US) on gluten-free ingredients from pulses, cereals, and pseudocereals relative to untreated samples.

Product		Ultrasound Processing Conditions					Techno-functional Properties ⁽³⁾				Starch Content ⁽⁴⁾			Thermal Properties ⁽⁵⁾			XRD & FTIR ⁽⁶⁾			Rheological & Pasting Properties ⁽⁷⁾								Reference
Name	Type (F, S, P) ⁽²⁾	Hydration	Time (min)	Temp (°C)	Frequency (kHz), Amplitude (%), Energy (W) ⁽⁸⁾	RM (1)	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	ΔH _{gel} (J/g)	Tp _{gel} (°C)	DC (%)	1045 / 1022	1022 / 995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)			
Rice	F	25% (w/w)	2	20	24, 80, 180	FD	-	-	-	-	-	-	-	ns	ns	-	-	-	ns	↓	↑	↓	ns	ns	ns	(Vela, Villanueva, & Ronda, 2023)		
			5	-			-	-	-	-	-	ns	↓	-	-	-	ns	↓	↑	↓	↓	ns	ns					
			10	-			-	-	-	-	-	ns	↑	-	-	-	ns	↓	↑	↓	ns	ns	ns					
			20	-			-	-	-	-	-	ns	ns	-	-	-	ns	↓	↑	↓	↑	ns	ns					
Rice	F	10 g /100g	2	20	24, 80, 180	FD	↑	-	↑	↑	-	-	↑	↓	↓	↓	↓	↑	ns	↓	↑	↓	↓	↓	↓	(Vela, Villanueva, Solaesa, et al., 2021)		
		10 g /100g	5	↑			-	↓	↑	-	-	↑	↓	↓	-	↓	↑	ns	↓	↑	↓	↓	↓	ns				
		10 g /100g	10	ns			-	↓	↑	-	-	↑	↓	↑	↓	↓	↑	ns	↓	↑	↓	↓	↓	ns				
		10 g /100g	20	↓			-	↓	↑	-	-	↑	↓	↓	↑	↓	↑	ns	↓	↑	↓	↓	↓	↓				
		10 g /100g	40	↓			-	↓	↑	-	-	↑	↓	↓	-	↓	↑	ns	↓	↑	↓	↓	↓	↓				
		10 g /100g	60	↓			-	↓	↑	-	-	↑	↓	↓	↑	↓	↑	ns	↓	↑	↓	↓	↓	↓				
		5 g /100g	60	↑			-	↓	↑	-	-	↑	↓	↓	↑	↓	↑	ns	↓	↑	↓	↓	↓	↓				
		10 g /100g	60	↓			-	↓	↑	-	-	↑	↓	↓	↑	↓	↑	ns	↓	↑	↓	↓	↓	↓				
		20 g /100g	60	↓			-	↓	↑	-	-	↑	↓	↓	↑	↓	↑	ns	↓	↑	↓	↓	↓	↓				
		30g /100g	60	↓			-	↓	↑	-	-	↑	↓	↑	↑	↓	↑	ns	↓	↑	↓	↓	↓	↓				
Rice	F	25%	10	20	24, 80, 180	FD	↓	-	↑	ns	↑	-	-	ns	ns	-	↓	↑	↓	↓	↑	ns	↓	ns	↓	(Vela, Villanueva, Nathia-Neves, et al., 2023)		
						CD	↑	-	↓	ns	↓	-	-	↓	↑	-	↓	↑	↑	ns	↑	↑	↑	ns	↑			
Rice	S	30% (w/w)	20	25	22, nm, 150	VfD	-	-	-	-	-	-	-	ns	ns	↓	ns	ns	-	-	↓	↑	ns	↑	ns	(Yang et al., 2019)		
				22, nm, 300	-	-	-	-	-	-	↓	ns	↓	ns	ns	-	-	↓	↑	ns	↑	↓						
				22, nm, 450	-	-	-	-	-	-	↓	ns	↓	ns	↑	-	-	↓	↑	ns	↑	ns						
				22, nm, 600	-	-	-	-	-	-	ns	ns	↓	ns	↑	-	-	↓	↑	ns	↑	ns						

Product		Ultrasound Processing Conditions					Techno-functional Properties				Starch Content			Thermal Properties		XRD & FTIR			Rheological & Pasting Properties								Reference
Name	Type (F, S, P)	Hydration	Time (min)	Temp (°C)	Frequency (kHz), Amplitude (%), Energy (W)	RM	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	ΔH _{gel} (J/g)	T _{p-gel} (°C)	DC (%)	1045 / 1022	1022 / 995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)		
Rice	S	50 ml (total)	15	nm	24, 100, 100	CD	-	-	⬆	⬆	-	-	-	-	-	ns	-	-	-	-	-	-	-	-	-	-	(Kaur & Gill, 2019)
			30				-	-	⬆	⬆	-	-	-	-	-	ns	-	-	-	-	-	-	-	-	-	-	
Quinoa	F	10g / 200ml	1.2h	<25	20, 80, 250	FD	-	-	⬆	⬇	-	-	-	⬇	⬇	-	-	-	-	-	-	-	⬇	⬇	⬆	⬆	(Zhu & Li, 2019b)
			2.4h				-	-	⬆	⬇	-	-	-	⬇	⬇	-	-	-	-	-	-	⬇	⬇	ns	⬆		
			4.8h				-	-	⬆	⬇	-	-	-	⬇	⬇	-	-	-	-	-	-	⬇	⬇	⬇	⬇		
			9.6h				-	-	⬆	⬇	-	-	-	⬇	⬇	-	-	-	-	-	-	nd	⬇	nd	nd		
			19.2 h				-	-	⬆	⬇	-	-	-	⬇	⬇	-	-	-	-	-	-	-	nd	⬇	nd	nd	
Quinoa	F	25%	10	20	24, 80, 180	FD	⬇	-	⬆	ns	⬆	-	-	ns	ns	-	⬇	⬇	⬇	⬇	⬆	ns	⬇	ns	⬇	(Vela, Villanueva, Nathia-Neves, et al., 2023)	
						CD	⬆	-	⬇	ns	⬇	-	-	⬇	⬆	-	⬇	⬇	⬆	ns	⬆	⬆	⬆	ns	⬆		
Quinoa	P	8% (w/v)	5	nm	20, 25, 500	FD	⬆	⬆	-	-	-	-	-	-	-	-	-	-	⬆	⬆	-	-	-	-	-	(Mir et al., 2019)	
			15				⬆	⬆	-	-	-	-	-	-	-	-	-	⬆	⬆	-	-	-	-				
			25				⬆	⬆	-	-	-	-	-	-	-	-	-	⬆	⬆	-	-	-	-				
			35				⬆	⬆	-	-	-	-	-	-	-	-	-	⬆	⬆	-	-	-	-				
Teff	F	25% (w/w)	10	20	24, 80, 180	FD	⬇	-	⬇	⬆	⬆	-	-	⬇	⬇	-	⬇	ns	ns	⬇	⬆	⬇	⬇	⬇	⬇	(Vela, Villanueva, Nathia-Neves, et al., 2023)	
						CD	⬆	-	⬇	⬆	⬇	-	-	⬇	⬇	-	⬇	ns	⬆	⬇	⬆	ns	⬆	⬇	⬇		⬆
White teff	F	25% (w/w)	10	20	24, 80, 180	FD	⬇	-	⬆	⬆	⬆	-	⬆	⬇	ns	ns	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇	⬇	(Vela, Villanueva, Li, et al., 2023; Vela, Villanueva, Ozturk, et al., 2023)	
			40				⬇	-	⬇	⬆	⬆	-	⬆	⬇	ns	ns	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇	⬇		
			45				⬇	-	⬇	⬆	⬆	-	⬆	⬇	ns	⬆	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇	⬇		⬇
			50				⬇	-	ns	⬆	⬆	-	⬆	⬇	ns	⬆	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇	⬇		⬇
			55				⬇	-	⬇	⬆	⬆	-	⬆	⬆	ns	⬆	⬇	⬇	⬆	⬇	⬆	⬇	⬆	⬇	⬇		⬇
Brown teff	F	25% (w/w)	10	20	24, 80, 180	FD	⬇	-	⬇	⬆	⬆	-	⬆	⬇	ns	ns	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇	⬇	(Vela, Villanueva, Li, et al., 2023; Vela, Villanueva, Ozturk, et al., 2023)	
			40				⬇	-	⬇	⬆	⬆	-	⬆	⬇	ns	⬆	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇	⬇		
			45				⬇	-	⬇	⬆	⬆	-	⬆	⬇	ns	ns	⬆	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇		⬇
			50				⬆	-	⬇	⬆	⬆	-	⬆	⬇	ns	ns	⬆	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇		⬇
			55				⬆	-	⬇	⬆	⬆	-	⬆	⬇	ns	ns	⬆	⬇	⬇	⬆	⬇	⬆	⬇	⬇	⬇		⬇

Product		Ultrasound Processing Conditions					Techno-functional Properties				Starch Content			Thermal Properties		XRD & FTIR			Rheological & Pasting Properties								Reference
Name	Type (F, S, P)	Hydration	Time (min)	Temp (°C)	Frequency (kHz), Amplitude (%), Energy (W)	RM	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	AH _{gel} (J/g)	Tp _{gel} (°C)	DC (%)	1045 / 1022	1022 / 995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)		
Corn	F	25% (w/w)	10	20	24, 80, 180	FD	↓	-	↑	↑	↑	-	-	ns	↓	-	↓	↑	ns	ns	↑	↑	ns	↑	ns	Vela, Villanueva, Nathia-Neves, et al., 2023)	
						CD	ns	-	↓	↑	ns	-	-	ns	↓	-	↓	ns	↑	↑	↑	↑	↑	ns	↑		
Corn	S	30% (w/v)	5	25	25, nm, 300	CD	-	-	-	-	↓	-	-	ns	↓	-	↑	-	↑	↑	-	-	-	-	-	(Zhang et al., 2021)	
			10				-	-	-	-	ns	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-	-		
			15				-	-	-	-	ns	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-	-		
			20				-	-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-	-		
			25				-	-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-	-		
			30				-	-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-	-		
							-	-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-	-		
Corn	S	30% (w/v)	10	25	25, nm, 100	CD	-	-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-	-	(Zhang et al., 2021)	
			25, nm, 200		-		-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-				
			25, nm, 300		-		-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-				
			25, nm, 400		-		-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-				
			25, nm, 500		-		-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-				
			25, nm, 600		-		-	-	-	↓	-	-	↓	↓	-	↑	-	↑	↑	-	-	-	-				
Maize	S	50 ml (total)	15	nm	24, 100, 100	CD	-	-	↑	↑	-	-	-	-	ns	-	-	-	-	-	-	-	-	-	(Kaur & Gill, 2019)		
			30				-	-	↑	↑	-	-	-	-	-	ns	-	-	-	-	-	-	-	-			
Millet	S	5% (w/w)	nm	25	80, nm, 720	FD	-	-	-	↑	-	-	-	↑	↓	↓	ns	ns	-	-	-	ns	ns	ns	ns	(Hu et al., 2019)	
			25	40+80, nm, 720	-		-	-	↑	-	-	-	↑	↓	↓	ns	ns	-	-	-	ns	ns	ns	ns			
			60	80, nm, 720	-		-	-	↓	-	-	-	↑	↓	↓	ns	ns	-	-	-	↓	↑	↓	↑			
			60	40+80, nm, 720	-		-	-	↓	-	-	-	↑	↓	↓	ns	ns	-	-	-	↓	↑	↓	↑			
Pea	S	30% (w/v)	5	25	25, nm, 300	CD	-	-	-	-	↓	-	-	ns	↓	-	↓	-	↑	↑	-	-	-	-	-	(Zhang et al., 2021)	
			10				-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-		
			15				-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-		
			20				-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-		
			25				-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-		

Product		Ultrasound Processing Conditions					Techno-functional Properties				Starch Content			Thermal Properties		XRD & FTIR		Rheological & Pasting Properties								Reference
Name	Type (F, S, P)	Hydration	Time (min)	Temp (°C)	Frequency (kHz), Amplitude (%), Energy (W)	RM	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	ΔH_{gel} (J/g)	T_{p-gel} (°C)	DC (%)	1045/1022	1022/995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)	
Pea	S	30% (w/v)	30	25	25, nm, 300	CD	-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-	(Zhang et al., 2021)
Pea	S	30% (w/v)	10	25	25, nm, 100	CD	-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-	(Zhang et al., 2021)
					25, nm, 200		-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-	
					25, nm, 300		-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-	
					25, nm, 400		-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-	
					25, nm, 500		-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-	
					25, nm, 600		-	-	-	-	↓	-	-	↓	↓	-	↓	-	↑	↑	-	-	-	-	-	
Oat	S	5% (w/w)	10	25	20, nm, 350 - bath	CD	ns	ns	↑	↑	ns	-	-	ns	↑	↓	-	-	-	-	-	ns	-	-	-	(Falsafi et al., 2019)
							↑	↑	↑	↑	ns	-	-	ns	↑	↓	-	-	-	-	↑	-	-	-	-	
			10	25	20, nm, 150 - probe	CD	↑	↑	↑	↑	ns	-	-	ns	↑	↓	-	-	-	-	↓	-	-	-	-	
							↑	↑	↑	↑	ns	-	-	ns	↑	↓	-	-	-	-	ns	-	-	-	-	
			10	25	20, nm, 250 - probe	CD	↑	↑	↑	↑	ns	-	-	ns	↑	↓	-	-	-	-	↓	-	-	-	-	
							↑	↑	↑	↑	ns	-	-	↓	↑	↓	-	-	-	-	↓	-	-	-	-	
			10	25	20, nm, 350 - probe	CD	↑	↑	↑	↑	ns	-	-	↓	↑	↓	-	-	-	-	↓	-	-	-	-	
							↑	↑	↑	↑	↑	-	-	↓	↑	↓	-	-	-	-	↓	-	-	-	-	
Cassava	S	5% (w/v)	5	nm	nm, 40, 750	CD	-	-	-	↑	-	-	-	↓	ns	↓	ns	↑	-	-	-	-	-	-	-	(Monroy et al., 2018)
							-	-	-	↑	-	-	-	↓	ns	↓	↓	ns	-	-	-	-	-	-	-	
							-	-	-	↑	-	-	-	↓	ns	↓	↓	↑	-	-	-	-	-	-	-	
			5		nm, 60, 750		-	-	-	↑	-	-	-	↓	ns	↓	↓	↑	-	-	-	-	-	-	-	
Soy	P	10% (w/w)	10	nm	20, 20, 750	FD	↓	-	↑	-	-	-	-	↑	↑	-	-	-	-	-	-	-	-	-	-	(Khatkar et al., 2020)
							↑	-	↓	-	-	-	-	↑	↑	-	-	-	-	-	-	-	-	-	-	
							↓	-	↑	-	-	-	-	↑	↑	-	-	-	-	-	-	-	-	-	-	
		10% (w/w)	10	nm	20, 30, 750	FD	↑	-	↑	-	-	-	-	↑	↑	-	-	-	-	-	-	-	-	-	-	
							↑	-	↓	-	-	-	-	↑	↑	-	-	-	-	-	-	-	-	-	-	
							↓	-	↑	-	-	-	-	↑	↑	-	-	-	-	-	-	-	-	-	-	

⁽¹⁾RM- recovery method: FD- freeze drying, CD - centrifuge and drying, Vfd - Vacuum filter drying

⁽²⁾Type: F - Flour, S - Starch, P - Protein isolate

⁽³⁾Techno-functional Properties: WAC - water absorption capacity, OAC - oil absorption capacity, WSI - water solubility index, SP - swelling power

⁽⁴⁾Starch Content: AM - amylose, AMP- amylopectin, DS - damaged starch

⁽⁵⁾Thermal Properties: ΔH_{gel} - enthalpy of gelatinization, T_{p-gel} - peak temperature of gelatinization

⁽⁶⁾XRD & FTIR: DC - degree of crystallinity, 1045/1022 - ratio used as an index of short-range crystallinity, 1022/995 - ratio indicative of the state of double helices organization inside the crystallites

⁽⁷⁾Rheological & Pasting Properties: G' - elastic modulus, G'' - viscous modulus, PT - pasting temperature, PV - peak viscosity, FV - final viscosity, BV - breakdown viscosity, SV - setback viscosity

⁽⁸⁾nm – not mentioned

Table 2
Comparative effects of High Hydrostatic Pressure (HHP) on gluten-free ingredients from pulses, cereals, and pseudocereals relative to untreated samples.

Product		HHP Processing Conditions						Techno-functional Properties (3)				Starch Content (4)				Thermal Properties (5)		XRD & FTIR (6)			Rheological & Pasting Properties (7)								Reference
Name	Type (F, S, P) (2)	Hydration	Time (min)	Temp (°C)	Pressure (MPa)	RM (l)	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	ΔH _{gel} (J/g)	T _{p-gel} (°C)	DC (%)	1045 / 1022	1022 / 995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)				
Black rice	S	20% (w/v)	30	30	200	D	↑	↑	-	-	↓	-	-	↓	↓	ns	↓	↑	-	-	-	-	-	-	-	-	(Almeida et al., 2023)		
					400		↑	↑	-	-	↓	-	-	↓	↓	↓	↓	↑	-	-	-	-	-	-	-	-	-		
					600		↑	↑	-	-	↓	-	-	↓	↓	↓	↓	↑	-	-	-	-	-	-	-	-	-	-	
Black Quinoa	F	1:5 (g/g)	60	20-25	200	FD	-	-	↑	↑	-	-	-	↓	ns	-	-	-	-	-	-		↓	↓	↓	↓	(Zhu & Li, 2019a)		
				400	-		-	↑	↑	-	-	-	↓	ns	-	-	-	-	-		↓	↓	↓	↓	↓	↓			
				500	-		-	↑	↑	-	-	-	↓	ns	-	-	-	-	-	nd		↓	nd	nd	nd				
				600	-		-	↑	↑	-	-	-	ns	↑	-	-	-	-	-	-	↓	↓	↓	↓	↓	↓			
Product		HHP Processing Conditions						Techno-functional Properties				Starch Content				Thermal Properties		XRD & FTIR			Rheological & Pasting Properties								Reference
Name	Type (F, S, P)	Hydration	Time (min)	Temp (°C)	Pressure (MPa)	RM	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	ΔH _{gel} (J/g)	T _{p-gel} (°C)	DC (%)	1045 / 1022	1022 / 995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)				
White Quinoa	F	1:5 (g/g)	60	20-25	200	FD	-	-	↑	↑	-	-	-	↓	ns	-	-	-	-	-	-	-	ns	ns	ns	ns	(Zhu & Li, 2019a)		
					400		-	-	↑	↑	-	-	-	↓	ns	-	-	-	-	-	-	↓	↓	↓	↓	ns			
					500		-	-	↑	↑	-	-	-	↓	↑	-	-	-	-	-	-	-	↓	↓	↓	↓	↓		
					600		-	-	↑	↑	-	-	-	nd	nd	-	-	-	-	-	-	-	↓	↓	↓	↓	↓		
Red Quinoa	F	1:5 (g/g)	60	20-25	200	FD	-	-	↑	↑	-	-	-	↓	ns	-	-	-	-	-	-		↑	ns	ns	ns	(Zhu & Li, 2019a)		
				400	-		-	↑	↑	-	-	-	↓	ns	-	-	-	-	-	-	↓	ns	↓	ns					
				500	-		-	↑	↑	-	-	-	↓	↑	-	-	-	-	-	-	↓	↓	↓	↓	↓				
				600	-		-	↑	↑	-	-	-	nd	nd	-	-	-	-	-	-	nd	↓	nd	nd	nd				
Acorn	S	8% (w/v)	17.4	20	333	CD	-	-	↑	↑	↑	↓	↑	ns	↓	ns	↓	↓	↑	↑	-	-	-	-	-	(Castro et al., 2023)			
			20		460		-	-	↑	↑	↑	↓	↑	ns	↑	ns	↓	↓	↑	↑	-	-	-	-	-				
Pearl millet	S	10% (w/w)	10	max 30	200	D	↑	↓	↓	↓	-	-	-	ns	ns	-	-	-	↓	↓	↑	↓	ns	ns	↓	(Mirzababaei et al., 2022)			
			20				200	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↓	↓	↑	↓	↓	↓	↓			
			30				200	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↓	↓	↑	↓	↓	↓	↓			
			10				400	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↓	↓	↑	↓	↓	↓	↓			
			20				400	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↓	↓	↑	↓	↓	↓	↓			
			30				400	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↑	↑	↑	↓	↓	↓	↓			
			10				600	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↓	↑	↑	↓	↓	↓	↓			
			20				600	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↑	↑	↑	↓	↓	↓	↓			
			30				600	↑	↓	↓	↓	-	-	-	↓	↓	-	-	-	↑	↑	↑	↓	↓	↓	↓			
Buckwheat	S	20% (w/w)	20	20	120	FD	-	-	↑	↑	↑	-	-	↓	ns	ns	-	-	-	-		↑	↓	↓	↓	↓	(Liu et al., 2016)		
				240	-		-	↑	↑	↑	-	-	↓	↓	↓	-	-	-	-		↑	↓	↓	↓	↓				
				360	-		-	↑	↑	↑	-	-	↓	↓	↓	-	-	-	-		↑	↓	↓	↓	↓				
				480	-		-	↑	↑	↑	-	-	↓	↓	↓	-	-	-	-		↑	↓	ns	↓	↓				
				600	-		-	↑	↑	↑	-	-	↓	↓	↓	-	-	-	-		↑	↓	↓	↓	↓				
lentil	S	1:4 (w/v)	10	26-38	400	FD	↓	-	↑	-	-	-	↑	-	↓	↑	↓	↑	↑	-	↑	↑	↓	↓	↓	(Ahmed et al., 2016)			

Product		HHP Processing Conditions					Techno-functional Properties				Starch Content			Thermal Properties		XRD & FTIR			Rheological & Pasting Properties								Reference
Name	Type (F, S, P)	Hydration	Time (min)	Temp (°C)	Pressure (MPa)	RM	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	ΔH_{gel} (J/g)	T_{p-gel} (°C)	DC (%)	1045 / 1022	1022 / 995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)		
lentil	S	1:4 (w/v)	10	26-38	500	FD	⬆	-	⬆	-	-	-	⬆	-	⬇	⬆	⬇	⬆	⬆	-	⬆	⬇	⬇	⬇	⬇	(Ahmed et al., 2016)	
					600	⬆	-	⬇	-	-	-	⬆	-	nd	⬆	⬇	⬆	-	⬆	⬇	⬇	⬇	⬇	⬇	⬇	⬇	
Sorghum	S	25% (w/w)	10	20	300	FD	-	-	-	-	-	-	⬆	ns	ns	-	-	-	-	-	-	-	-	-	-	(Vallons & Arendt, 2009)	
					400	-	-	-	-	-	-	⬆	⬇	⬆	-	-	-	-	-	-	-	-	-	-	-		
					500	-	-	-	-	-	-	⬆	⬇	⬆	-	-	-	-	-	-	-	-	-	-	-	-	
					600	-	-	-	-	-	-	⬆	nd	nd	-	-	-	-	-	-	-	-	-	-	-	-	
chickpea	F	1:5 (w/v)	15	25	150	nm	-	-	-	-	-	-	-	⬇	⬆	-	-	-	⬆	⬇	-	-	-	-	-	(Alvarez et al., 2014)	
					300	-	-	-	-	-	-	-	⬇	⬆	-	-	-	ns	⬆	-	-	-	-	-			
					450	-	-	-	-	-	-	-	⬇	⬆	-	-	-	ns	⬆	-	-	-	-	-			
					600	-	-	-	-	-	-	-	nd	nd	-	-	-	⬇	⬆	-	-	-	-	-			
		1:4 (w/v)	15	25	150	nm	-	-	-	-	-	-	-	⬇	⬇	-	-	-	⬆	⬇	-	-	-	-	-		
					300	-	-	-	-	-	-	-	⬇	⬆	-	-	-	⬇	ns	-	-	-	-	-			
					450	-	-	-	-	-	-	-	⬇	⬆	-	-	-	⬆	⬆	-	-	-	-	-			
					600	-	-	-	-	-	-	-	nd	nd	-	-	-	⬇	⬆	-	-	-	-	-			
		1:3 (w/v)	15	25	150	nm	-	-	-	-	-	-	-	⬇	ns	-	-	-	ns	ns	-	-	-	-	-		
					300	-	-	-	-	-	-	-	⬇	⬇	-	-	-	⬆	⬆	-	-	-	-	-			
					450	-	-	-	-	-	-	-	⬇	⬆	-	-	-	⬆	⬆	-	-	-	-	-			
					600	-	-	-	-	-	-	-	nd	nd	-	-	-	⬆	⬆	-	-	-	-	-			
		1:2 (w/v)	15	25	150	nm	-	-	-	-	-	-	-	⬇	⬆	-	-	-	⬆	ns	-	-	-	-	-		
					300	-	-	-	-	-	-	-	⬇	⬇	-	-	-	⬆	ns	-	-	-	-	-			
					450	-	-	-	-	-	-	-	⬇	⬇	-	-	-	⬆	ns	-	-	-	-	-			
					600	-	-	-	-	-	-	-	nd	nd	-	-	-	⬆	⬆	-	-	-	-	-			
Kidney bean	P	1:4 (w/v)	15	23-26	200	FD	-	-	-	-	-	-	-	ns	ns	-	-	-	⬆	⬆	-	-	-	-	(Ahmed et al., 2018)		
					400	-	-	-	-	-	-	-	-	ns	ns	-	-	-	⬆	⬆	-	-	-	-			
					600	-	-	-	-	-	-	-	-	ns	ns	-	-	-	⬆	⬆	-	-	-	-			

Product		HHP Processing Conditions					Techno-functional Properties				Starch Content			Thermal Properties		XRD & FTIR			Rheological & Pasting Properties								Reference
Name	Type (F, S, P)	Hydration	Time (min)	Temp (°C)	Pressure (MPa)	RM	WAC (g/g)	OAC (g/g)	WSI (g/100g)	SP (g/g)	AM (%)	AMP (%)	DS (%)	ΔH_{gel} (J/g)	T_{p-gel} (°C)	DC (%)	1045 / 1022	1022 / 995	G' (Pa)	G'' (Pa)	PT (°C)	PV (Pa.s)	FV (Pa.s)	BV (Pa.s)	SV (Pa.s)		
Kidney bean	P	1:5 (w/v)	15	23-26	200	FD	-	-	-	-	-	-	-	-	ns	ns	-	-	-	⬆	⬆	-	-	-	-	-	(Ahmed et al., 2018)
					400	-	-	-	-	-	-	-	-	ns	ns	-	-	-	⬆	⬆	-	-	-	-	-		
					600	-	-	-	-	-	-	-	-	nd	nd	-	-	-	⬆	⬆	-	-	-	-	-		

⁽¹⁾RM- recovery method: FD- freeze drying, CD - centrifuge and drying, D - drying, nm- not mentioned

⁽²⁾Type: F - Flour, S - Starch, P - Protein isolate

⁽³⁾Techno-functional Properties: WAC - water absorption capacity, OAC - oil absorption capacity, WSI - water solubility index, SP - swelling power

⁽⁴⁾Starch Content: AM - amylose, AMP- amylopectin, DS - damaged starch

⁽⁵⁾Thermal Properties: ΔH_{gel} - enthalpy of gelatinization, T_{p-gel} - peak temperature of gelatinization

⁽⁶⁾XRD & FTIR: DC - degree of crystallinity, 1045/1022 - ratio used as an index of short-range crystallinity, 1022/995 - ratio indicative of the state of double helices organization inside the crystallites

⁽⁷⁾Rheological & Pasting Properties: G' - elastic modulus, G'' - viscous modulus, PT - pasting temperature, PV - peak viscosity, FV - final viscosity, BV - breakdown viscosity, SV - setback viscosity

absorption capacity (Mirzababae et al., 2022). However, studies on black rice starch (Almeida et al., 2023) have shown an increase in OAC with increased pressure, highlighting the influence of molecular characteristics such as weight, conformation, polymerization, and amylopectin branching on the association forces within the granule (Pérez et al., 2021).

Ultrasonication can enhance the solubility of starches by releasing amylose chains, which have less structural integrity compared to amylopectin and are more susceptible to ultrasonic disruption. This leads to an increase in the WSI of starches, as evidenced by some studies (Amini et al., 2015; Falsafi et al., 2019; Kaur & Gill, 2019). Increased solubility is particularly beneficial in dough formulation, as it enhances hydration, promotes uniform ingredient distribution, and improves gel formation, contributing to better gas retention and a more cohesive gluten-free bread structure. However, the impact of US on flours is less consistent due to other components that may affect solubility in sonicated samples. For instance, while US increased the solubility in corn and quinoa flours (Vela, Villanueva, Nathia-Neves, & Ronda, 2023; Zhu & Li, 2019b), it had a mitigated effect on teff flour (Vela, Villanueva, Nathia-Neves, & Ronda, 2023; Vela, Villanueva, Ozturk, et al., 2023), highlighting the variable impact of US parameters and the specific type and composition of the flour treated. Although enhanced solubility improves certain functional properties, excessive release of soluble components may reduce dough viscosity and lead to higher water release during baking, ultimately compromising the structural integrity and volume of gluten-free bread. In support of this (Benavent-Gil & Rosell, 2019), reported a moderate negative correlation between amylose content and final viscosity ($r = -0.56$), indicating that increased amylose leaching and solubility can lower viscosity in starch systems. Regarding HHP, it was found to increase the solubility of various quinoa flours (red, black, and white) (Zhu & Li, 2019a) with rising pressure levels. However, it was also observed that HHP treatment decreased solubility in starches derived from lentils, Tartary buckwheat, pearl millet, and acorn (Castro et al., 2023; Liu et al., 2016; Mirzababae et al., 2022; Zhu & Li, 2019a). The reduction in solubility under HHP is often attributed to the formation of amylose-lipid complexes within the starch granules, which inhibit the release of amylose molecules and thereby reduce their solubility (Mirzababae et al., 2022). It was suggested that the development of amylose-lipid complexes in HHP-treated starches is influenced by both pressure and temperature conditions, as these complexes can intertwine with amylopectin molecules to further reinforce the granular structure. Importantly, these effects do not occur uniformly across all starch or flour matrices, since differences in composition and lipid content determine the extent of complex formation and the resulting functional properties (Oh et al., 2008).

In studies on swelling power (SP) of flours and starches, amylopectin plays a primary role in enhancing this property, whereas amylose and amylose-lipid complexes tend to inhibit swelling (Tester & Morrison, 1990). Ultrasonication disrupts starch granules and breaks down their crystalline structures, allowing water molecules to bind to the free hydroxyl groups of amylose and amylopectin through hydrogen bonds, thereby enhancing water absorption and retention. Research has shown that increasing the sonication temperature to around 65 °C (Amini et al., 2015; Falsafi et al., 2019; Monroy et al., 2018; Vela, Villanueva, Ozturk, et al., 2023), extending the sonication duration (Zhu & Li, 2019b), raising the concentration of flour or starch to water (Amini et al., 2015), and applying dual-frequency treatment (80 kHz & 40 kHz) (Hu et al., 2019) in comparison with single frequency, can all significantly increase the SP of starch or flour. On the other hand, in HHP treated samples, the SP of starch decreased with increased temperature and pressure, as observed in Tartary buckwheat starch (Liu et al., 2016), pearl millet starch (Mirzababae et al., 2022), and acorn starch (Castro et al., 2023). This reduction suggests that HHP modifies the molecular interactions within the starch granules, rendering them less capable of swelling and dissolving in water. Such changes are likely due to the formation of amylose-lipid complexes and a realignment of starch molecules, which

reinforce the structural integrity of the granules against water-induced disintegration. Additionally, the extent of changes in SP caused by HHP in quinoa flour varied depending on the specific type of quinoa flour used (Zhu & Li, 2019a).

3.2. Effects on morphology and particle size diffraction (granule size, SEM findings)

One of the most important factors affecting the quality of bread and bakery products is the flour particle size (Abebe et al., 2015). Granulation and particle size homogeneity are key factors influencing the processing performance of flours. Starch granule size distribution in cereals is categorized into three categories, with A-type (large), B-type (medium), and C-type (small) granules, measuring approximately 15 µm, 5–15 µm, and less than 5 µm, respectively (Kaur & Gill, 2019). However, this classification is primarily applied to cereal starches and may not directly correspond to the starch granule size distribution in pulses or pseudocereals, which display distinct morphological and dimensional characteristics. For example, pseudocereal starches are among the smallest known starch granules: granule diameters are typically less than 3 µm in quinoa and 0.3–2.5 µm in amaranth (Bender & Schönlechner, 2021). Buckwheat starch granules are larger, ranging from 2 to 15 µm with an average diameter of 6–7 µm (Zhu, 2016). In pulses, starch granules are generally oval but can also be spherical, round, elliptical, or irregular in shape, with granule size varying widely in width (5–55 µm) and length (5–70 µm), depending on the species (Foschia et al., 2017). The size of starch granules critically influences microstructural changes because their larger volume allows for more effective absorption and dissipation of kinetic energy during processing (Carmona-García et al., 2016). Especially for gluten-free varieties of bread, the particle size of flour is crucial. Larger particles enhance bread volume and softness, although sizes above 200 µm can impart a sandy texture. Conversely, small particles (below 80–100 µm) are typically avoided as they decrease the gas retention in dough and batter, thus reducing bread volume (Gómez & S. Sciarini, 2015). Ultrasonication modifies native flour and starch's structure and particle size by causing fragmentation and partial depolymerization through the cavitation process. This fragmentation results from mechanical collisions and high shear forces generated by acoustic waves that progressively erode the particle surfaces until they break apart (Qin et al., 2022).

Several factors influence ultrasound's effect on starch granule morphology, including concentration, temperature, frequency, intensity, power, duration, and single vs. dual frequencies, and the mode of application (e.g., probe vs. bath) (Jamalabadi et al., 2019). Higher temperatures increase size reduction, as seen in teff flour (Vela, Villanueva, Li, et al., 2023) and cause surface damage to particles. In contrast, millet starch exhibited minimal structural changes under similar conditions (Hu et al., 2019). Prolonged sonication roughens granule surfaces, forming fissures and fragmentations, though the overall structure remains intact. In corn starch (Amini et al., 2015), lower temperatures with extended sonication reduce particle size significantly. Concentration variations have little impact but increasing ultrasound power decreases rice starch (Yang et al., 2019) particle size through cavitation, which breaks down aggregates into finer, more uniform particles.

HHP significantly affects the particle size and morphological characteristics of flours, starches, and protein isolates. Under HHP, particle size diffraction studies indicate that there is generally a reduction in particle size as pressure increases. For example, in studies on acorn starch (Castro et al., 2023) and various types of quinoa flour (Zhu & Li, 2019a), increasing pressure was associated with these changes. Conversely, in lentil starch (Ahmed et al., 2016), HHP treatment at 600 MPa caused a notable shift in the particle size distribution curve, with an increase in the range and peak size (from 7 to 48 µm with a peak at 22 µm to 14–55 µm with a peak at 38 µm), likely due to the aggregation of granules or structural rearrangements rather than a reduction in particle

size. Additionally, at 600 MPa, a transformation occurs where the second curve (ranging from 50 to 600 μm) flattens into a plateau, indicative of complete gelatinization and disintegration of many granules into a gel-like structure. SEM studies reveal that at pressures below 500 MPa, surface changes are limited to cracks and pores, whereas at 600 MPa, granules swell, deform, and collapse into a viscous, gel-like structure.

3.3. Effects on starch composition (amylose, amylopectin, and damaged starch)

Cavitation from ultrasonication ruptures the α -1,6-glucosidic bonds in amylopectin's side chains, increasing linear amylose chains. However, this increase in amylose content is not universally observed across all flours and seems to depend heavily on the specific conditions of the ultrasonication treatment and the inherent properties of each sample (Table 1). For instance, studies on corn starch (Amini et al., 2015) emphasize that treatment temperature is a crucial factor in determining the extent of modification by ultrasonication. Furthermore, it has been noted that a higher sample concentration in the medium does not significantly affect the cavitation impact on the starch composition. On the contrary, studies on white and brown teff flour (Vela, Villanueva, Ozturk, et al., 2023) found that varying temperatures did not yield significant differences, suggesting that other ultrasonication parameters such as treatment duration, power, frequency, and particularly the nature of the sample, play a more significant role in influencing amylose content changes. Moreover, the impact of cavitation on starch damage, while expected to increase with ultrasonication, only became substantial when the temperature of the ultrasonication treatment was increased (Vela, Villanueva, Ozturk, et al., 2023; Vela, Villanueva, Solaesa, & Ronda, 2021). This suggests that higher treatment temperatures are necessary to amplify the disruptive effects of cavitation, leading to more pronounced structural changes in the starch. Such structural disruption, commonly referred to as damaged starch, occurs when starch granules are cracked, fractured, or crushed, and the amylopectin regions partially or completely break down into a more amorphous form (McAllister et al., 2008).

Damaged starch absorbs significantly more water than intact granules and is more susceptible to enzymatic hydrolysis, which plays a key role in dough hydration and fermentation. While a moderate level of damage can improve breadmaking performance, excessive damaged starch can overhydrate the dough, increase stickiness, and impair handling and product quality. In addition to milling, treatments like ultrasonication can therefore contribute to starch damage through the combined action of cavitation, shear forces, and elevated temperatures (Barros et al., 2023).

HHP treatment, particularly at pressures around 400 MPa, results in a significant increase in damaged starch content of lentil, acorn, buckwheat and sorghum starch (Ahmed et al., 2016; Castro et al., 2023; Liu et al., 2016; Vallons & Arendt, 2009), which may be due to the rearrangement of amylose and amylopectin under higher pressures, leaving the chains more susceptible to enzymatic action and/or amylopectin degradation into amylose. The mechanical forces generated during pressurization may lead to the break of covalent bonds along the polymeric chains. Since amylopectin is more susceptible to degradation than amylose, higher amylose content is released with the rupture of α -D-(1, 6)-glucose bonds (Angioloni & Collar, 2012). Furthermore, the increase in amylose content in starches modified by HHP is likely due to the leaching of amylose from amylose-amylopectin and amylose-lipid interactions during the treatment. In the studies reviewed, while the effect of varying treatment temperatures during high hydrostatic pressure (HHP) processing was investigated, starch composition was not included among the parameters analysed. Consequently, a more comprehensive understanding of the changes in amylose content and damaged starch formation requires systematic investigation of HHP under varying conditions—including temperature—across different starch sources and botanical varieties.

Building upon these findings, Hüttner et al. (2009) explored how the structural and functional modifications induced by HHP impact the performance of gluten-free oat dough systems. Their study demonstrated that treatment at moderate pressures—particularly around 200 MPa—caused partial starch pre-gelatinization and contributed to a more elastic batter network. This increased elasticity enhanced gas retention, improved dough handling, and resulted in bread with a softer crumb and reduced firming during storage, suggesting delayed staling. According to the authors, the improved texture was attributed to stronger protein-starch interactions and protein denaturation and crosslinking that occurred under moderate pressure, which increased batter viscosity without causing the extensive granule disruption typical of thermal treatments. Notably, they observed limited amylose leaching, which was associated with reduced starch retrogradation—an important factor in staling. However, at higher pressures (≥ 350 MPa), these beneficial effects diminished as the protein-starch network began to break down, leading to poorer crumb structure and less desirable bread quality (Hüttner et al., 2009).

3.4. Effects on thermal properties (gelatinization, enthalpy, DSC analysis)

The gelatinization temperature and enthalpy of starches and flours analysed by DSC (Differential Scanning Calorimetry), modified by US and HHP, vary according to the botanical origin of the starches and the processing conditions (Tables 1 and 2, respectively for US and HHP). Gelatinization of starch granules is a thermal process characterized by the energy required to disrupt their crystalline structure, known as the enthalpy of gelatinization (ΔH_{gel}). It represents the amount of heat energy (measured in joules per gram, J/g) needed to break the crystalline regions within starch granules during heating in the presence of water, facilitating their transition from a semi-crystalline to an amorphous state. The key temperatures in this process are the onset temperature ($T_{\text{o-gel}}$), peak temperature ($T_{\text{p-gel}}$), and conclusion temperature ($T_{\text{c-gel}}$). $T_{\text{o-gel}}$ and $T_{\text{c-gel}}$ represent the disruption of the weakest to the strongest bonds, respectively (Chakraborty et al., 2022). This review focuses on peak temperature, which indicates the highest energy absorption required to gelatinize the starch granules. $T_{\text{p-gel}}$ serves as an index of crystallinity, which is related to the length of the double helix. Most studies on ultrasonicated starches and flours show a decrease in $T_{\text{p-gel}}$ (Vela, Villanueva, Nathia-Neves, & Ronda, 2023; Vela, Villanueva, & Ronda, 2023; Vela, Villanueva, Solaesa, & Ronda, 2021; Zhang et al., 2021; Zhu & Li, 2019b). This decrease indicates that cavitation energy disrupts the starch granule structure, increasing the mobility of starch molecules and allowing water to penetrate and swell the crystalline structure at lower temperatures, thus reducing the thermal energy needed for gelatinization.

However, in some cases, sonication produces an inverse relationship between $T_{\text{p-gel}}$ and ΔH_{gel} . For example, in oats and corn starch, ΔH_{gel} decreased while $T_{\text{p-gel}}$ increased, likely due to selective crystalline modifications and formation of less stable structures (Amini et al., 2015; Falsafi et al., 2019). Conversely, millet starch showed lower $T_{\text{p-gel}}$ but higher ΔH_{gel} , indicating more crystalline disruption and stronger water-starch interactions, making gelatinization more energy-intensive despite occurring at a lower temperature (Hu et al., 2019). These contradictory patterns can arise not only from the intrinsic differences in starch structure and composition but also from variations in ultrasound treatment conditions (e.g., frequency, power, and duration). Such parameters determine the extent of cavitation and energy transfer, which in turn control the balance between crystalline disruption and recrystallization, leading to diverse effects on gelatinization behavior. In line with the role of structural reorganization, another study reported that post-treatment processes such as heat-moisture treatment can enhance amylose-amylopectin interactions and promote retrogradation, thereby altering gelatinization behavior by increasing chain mobility and re-aligning double helices (Hoover, 2010). However, the treatment also makes the gelatinization more energy-intensive due to greater

water-starch interactions, the formation of newly ordered structures, granule fragmentation, and partial gelatinization followed by reorganization. These factors lower the temperature needed to start gelatinization but increase the overall energy required to complete it. In the case of sonicated rice starch, no significant changes in peak temperature and enthalpy were observed, likely due to mild treatment conditions (short duration and high concentration) and the lower susceptibility of the matrix to modification by ultrasonication (Yang et al., 2019).

In flours altered by HHP, a similar trend to that observed with ultrasound treatment is seen, with a general decrease in T_{p-gel} and ΔH_{gel} . Intensified applied pressure on treated flours and starches leads to the destruction of the semi-crystalline structure of starch granules and the melting of amylopectin crystals, which decreases T_{p-gel} and ΔH_{gel} , as noted in several studies (Almeida et al., 2023; Liu et al., 2016; Mirzababae et al., 2022; Zhu & Li, 2019a). At a pressure intensity of 600 MPa, studies often show complete gelatinization of starch, with no endothermic thermogram peak observed, except in black quinoa (Zhu & Li, 2019a). In acorn starch (Castro et al., 2023), no significant changes were noted in treated starches compared to control samples, suggesting that treatment conditions did not affect the thermal properties of the starches or that pressurizing encourages amylose-lipid bonding, preventing free amylose from impacting gelatinization properties.

The study of gelatinization properties of modified starches/flours is crucial for gluten-free bread production. Decreased T_{p-gel} improves the consistency and viscosity of the dough, facilitating faster and more complete gelatinization at lower temperatures. This enhancement leads to better dough stability and handling during mixing and shaping. In the final bread product, these modifications result in a softer crumb, improved volume, and a more uniform texture due to better moisture retention and structural support during baking. Additionally, the ability to trap and retain moisture extends the bread's freshness (Smidova & Rysova, 2022).

3.5. Effects on crystallinity structure (XRD data)

X-ray diffraction is a valuable technique for analysing the crystallographic structure of materials. Based on diffraction patterns, starches are classified as A-, B-, or C-type polymorphs. A-type starch has a dense structure with water between double helices, while B-type is less compact and more hydrated. A-type crystals have seven double helices in a monoclinic lattice with eight water molecules, whereas B-type has six helices and a larger void holding up to 36 water molecules. C-type is a blend of A- and B-types (Castro et al., 2023). Ultrasonication causes minor changes in the crystallinity of starch and flour, primarily by degrading amorphous regions while leaving crystalline structures relatively intact (Amini et al., 2015; Luo et al., 2008; Vela, Villanueva, & Ronda, 2021). This occurs because amorphous domains are less densely packed and more susceptible to ultrasonic energy than the highly ordered crystalline regions. The impact of ultrasonication on crystallinity varies depending on the starch type and processing conditions, leading to an increase, decrease, or no significant change in crystallinity (Carmona-García et al., 2016; Luo et al., 2008) (Table 1). Temperature plays a crucial role in these variations. At higher temperatures, particularly when flour is suspended in excess water, starch chains can interact more effectively, reorganizing into a more compact structure that enhances crystallinity by increasing amylopectin double helices (Zavareze & Dias, 2011). This effect was observed in teff starch (Vela, Villanueva, Li, et al., 2023). The mobility of amorphous regions at high temperatures allows for better packing, mimicking an increase in crystallinity.

Conversely, another study on corn starch reported a decrease in crystallinity at higher sonication temperatures, as evidenced by reduced diffraction intensities of characteristic peaks (Amini et al., 2015). Sonication below the starch's onset gelatinization temperature (T_{o-gel}) typically degrades amorphous regions while preserving crystalline structures.

Additionally, factors like sonication time and flour-to-water ratio

influence crystallinity changes. Most studies found no significant effect under moderate conditions, with slight reductions only occurring under intense sonication (longer treatment times and lower flour/starch concentrations) (Kaur & Gill, 2019; Monroy et al., 2018; Vela, Villanueva, Solaesa, & Ronda, 2021).

Regarding HHP, it was found that the crystallinity of starches and flours decreased after pressurization (Table 2). With extensive pressurization levels (500–600 MPa), the crystallinity of the granules was significantly disrupted (Ahmed et al., 2016; Liu et al., 2016; Mirzababae et al., 2022). This decrease in crystallinity is attributed to the penetration of water molecules into the crystalline structure of the starches, which increases the distance between the double helices and ultimately leads to the destruction of the crystalline regions.

The crystallinity level of starches directly influences the retrogradation process, positively impacting the shelf life of bread (Farrokhi et al., 2025). New bonds form during the cooling and storage phases, causing the starch granules to dehydrate. In this process, linear amylose granules retrograde more quickly by reforming double helices, when compared to the branched amylopectin granules. Consequently, the higher crystallinity and a more organized structure contribute to a slower retrogradation rate and extended shelf life for the bread (Cappelli et al., 2020).

3.6. Effects on short-range Structure (FTIR analysis)

Fourier Transform Infrared Spectroscopy (FTIR) is used to assess molecular changes in starch's short-range/double helical order ($900\text{--}1300\text{ cm}^{-1}$), primarily through C–O and C–C stretching vibrations. This region includes three key peaks: 1045 cm^{-1} (ordered crystalline regions), 1022 cm^{-1} (amorphous regions), and 995 cm^{-1} (hydrated carbohydrate helices) (Kunyanee et al., 2023; Monroy et al., 2018). The short-range structural analysis of sonicated flours and starches reveals that ultrasonication disrupts the crystalline architecture of starch granules through cavitation-induced shear forces (Vela, Villanueva, Li, et al., 2023; Vela, Villanueva, Nathia-Neves, & Ronda, 2023; Vela, Villanueva, Solaesa, & Ronda, 2021; Yang et al., 2019; Zhang et al., 2021). This disruption is reflected in a decrease in the 1045/1022 ratio observed in the FTIR analysis, indicating the disruption of crystalline regions and an increase in amorphous structures due to chain breakage (Li et al., 2022; Lu et al., 2021). Simultaneously, the 1022/995 ratio increases, further confirming the transition toward more amorphous and non-ordered structures (Rahaman et al., 2021). These FTIR spectral shifts are consistent with partial depolymerization, increased amylose content, and reduced gelatinization enthalpy, as reported in complementary previous analyses (Sections 3.3 and 3.4). Table 1 provides a comparative view of these transformations across different sonication conditions. Importantly, these molecular changes can exert both positive and negative effects on gluten-free dough functionality and bread quality, depending on the degree of disruption. Moderate loss of crystallinity often improves hydration properties by increasing water solubility and swelling power, which can enhance dough softness, gas retention, and crumb elasticity (Jafari & Koocheki, 2024). Enhanced leaching of amylose from the amorphous zones also contributes to better initial gelatinization and water uptake. However, excessive breakdown of crystalline regions and over-release of soluble components may lead to a decline in pasting viscosity, reduced gel strength, and weakened dough structure, potentially resulting in poor volume and water loss during baking (Benavent-Gil & Rosell, 2019). Therefore, while the decrease in the 1045/1022 ratio is a useful marker of sonication-induced amorphization, its functional consequences are context-dependent, and a balance must be achieved between improved hydration and structural integrity.

HHP treatment similarly affects the short-range structure of starches and flours as revealed by FTIR analysis (Table 2). As pressure increases, starch and flour granules undergo more profound structural changes, where the granules swell, and their internal structure becomes more

disordered. This transformation is evidenced by an increase in the 1022/995 ratio, which indicates the formation of more amorphous and non-ordered structures (Ahmed et al., 2016; Almeida et al., 2023; Castro et al., 2023; Mirzababaei et al., 2022; Zhu & Li, 2019a). Like ultrasonication, the extent of these changes influences the hydration behavior, solubility, and gelatinization response of starch, all of which play key roles in determining the final quality of gluten-free dough and bread.

FTIR studies have also shown protein structural changes upon US and HHP treatment. In flours (rice, teff, corn, quinoa), US generally decreased α -helix and β -sheet contents while increasing random coils, indicating partial unfolding of protein structures (Vela, Villanueva, Nathia-Neves, & Ronda, 2023; Vela, Villanueva, Solaesa, & Ronda, 2021). Similar effects were observed in soy and quinoa protein isolates (Khatkar et al., 2020; Mir et al., 2019), where US introduced new random coil bands or induced shifts in amide I. In contrast, HHP effects on proteins are less reported, with one study on kidney bean protein isolate (Ahmed et al., 2018) showing a shift of the amide I band toward lower wavenumbers, consistent with β -sheet rearrangements.

3.7. Effects on rheological properties (elastic and viscous modulus)

For the production of optimal baked goods, it is crucial to investigate the mechanical properties of the dough. Rheological analysis is fundamental for predicting the dough's behavior during mixing, proofing, and baking, as well as for ensuring the desired bread structure and texture (Dobraszczyk & Morgenstern, 2003). In this review, the rheological results discussed are mainly based on gels prepared from starches or flours rather than dough systems. Since starch and flour are the main structural components of gluten-free dough, studying the gel behavior still provides important insights into the viscoelastic properties that ultimately influence dough performance.

Rheological analyses of ultrasonicated starches/flours, particularly amplitude sweep tests, commonly report an increase in shear stress (τ_{max}) and the cross-over point. Shear stress is defined as the max stress that the gel can take before collapse, which marks the end of the linear viscoelastic region (LVR), and the cross-over point is when the elastic modulus (G') is equal to viscous modulus (G''). This increase, observed in white and brown teff as well as rice flours, indicates stronger gels with improved stability post-sonication (Vela, Villanueva, Ozturk, et al., 2023; Vela, Villanueva, Solaesa, & Ronda, 2021). Conversely, a study on different flour recovery methods post-sonication (Vela, Villanueva, Nathia-Neves, & Ronda, 2023) revealed a decrease in shear stress and the cross-over point in teff, quinoa, and corn. Moreover, centrifuged samples presented lower values when compared to freeze-dried ones, likely due to soluble compound loss leading to weaker gels. Frequency sweep tests consistently demonstrated that sonicated samples exhibited a higher G' than G'' , confirming a dominant solid-like behavior indicative of a "true" gel. This effect, attributed to cavitation-induced starch fragmentation and hydrogen bonding with water, was observed even at elevated temperatures (20–55 °C) in brown and white teff, suggesting temperature independence. Additionally, the reduction in G'' post-sonication may result from amylose molecule straightening, which reduces shear interactions between fluid layers (Kaur & Gill, 2019).

Similar to US, HHP significantly affects the rheological properties of starches and flours. HHP-treated gels consistently exhibit higher G' than G'' , indicating stronger gel networks due to enhanced intermolecular interactions. A study on lentil starch (Ahmed et al., 2016) showed that at lower pressures, G' remained frequency-dependent, reflecting weaker gel structures. However, at higher pressures, elasticity became frequency-independent, which has been associated with gradual starch gelatinization during HHP treatment and the formation of a more cohesive gel network. Research on kidney bean protein isolate (Ahmed et al., 2018) found that the protein isolate dispersion, treated under different protein-to-water ratios, showed minimal influence on rheological behavior during frequency sweeps. At lower ratios, a slight

reduction in network strength was observed with increasing frequency, indicating a less resistant protein structure. This reduction was absent at higher ratios, where the dispersion exhibited more solid-like behavior. Similarly, in chickpea flour (Alvarez et al., 2014), both G' and G'' increased with higher flour-to-water ratios during HHP treatment, particularly under high-pressure conditions (450–600 MPa). These findings emphasize the role of concentration and pressure in defining gel strength, with higher values enhancing gel formation.

3.8. Effects on pasting properties

Evaluating pasting properties, which indicate viscosity changes during heating and cooling, is crucial for understanding starch gelatinization and retrogradation in gluten-free doughs (Batey & Curtin, 2000). In starch isolates, pasting viscosity is influenced by starch type, the molecular structure of amylose and amylopectin, and non-starch components that interact with starch (Meadows, 2002). Granule size and internal organization also affect pasting behavior (Hu et al., 2019).

Modification methods like sonication significantly influence the pasting properties of native starch granules. Sonication increases pasting temperature (PT), indicating a strengthened crystalline structure requiring more heat for disintegration (Villanueva et al., 2019). A higher PT reflects the need for elevated temperatures to raise gel viscosity. Additionally, sonication reduces peak (PV), trough (TV), final (FV), breakdown (BV), and setback (SV) viscosities due to cavitation-induced molecular chain breakage and weakened gel formation (Yang et al., 2019; Zhu & Li, 2019b). The mechanical effects of cavitation disrupt the integrity of starch granules and degrade amylose and amylopectin chains, weakening their gel-forming capacity and lowering viscosity during pasting. Prolonged or intense sonication amplifies these effects. Temperature also plays a role in viscosity reduction, as lower viscosity values can result from increased amylose content and greater crystallinity following molecular rearrangement of starch granules (Wang et al., 2018).

The delayed PT and decreased PV observed in sonicated flours suggest partially reorganized and compacted starch structures that resist initial swelling, requiring longer heating for gelatinization. This is consistent with previous findings, which indicate that PV positively correlates with the number of amylopectin branches, as these absorb more water during heating (Li et al., 2020). Since sonication tends to degrade medium-chain amylopectin branches, particularly those involved in short-term retrogradation, this explains the reductions in FV and SV seen in ultrasonicated samples. The decrease in SV is particularly notable, as SV is linked to short-term starch retrogradation dominated by amylose (Yang et al., 2019). Viscosity development also depends on starch interactions with other flour components, such as proteins and fibres, with ultrasonication shown to increase water-binding capacity (Mir et al., 2019). Increased protein-water interaction can limit water availability for starch hydration, further reducing viscosity. Although this reduction weakens the structural integrity of starch-based systems, it enhances dough handling and reduces stickiness, which is beneficial in gluten-free applications. Therefore, optimizing sonication parameters—such as power, time, and temperature—is crucial to balance viscosity reduction with desirable dough and product characteristics.

The impact of HHP on pasting properties depends on starch type and processing conditions such as pressure, temperature, and hydration (Wang et al., 2008). Like sonication, HHP often increases pasting temperature, as seen in Tartary buckwheat (Liu et al., 2016) and pearl millet starches (Mirzababaei et al., 2022). Conversely, in lentil starch (Ahmed et al., 2016), a decrease in pasting temperature was observed, likely due to amylopectin degradation, which increased the starch's susceptibility to swelling. HHP generally reduces viscosity parameters by fragmenting starch granules and facilitating water penetration, leading to modified gelatinization with incomplete granule disruption (Li et al., 2015).

This leads to a modified gelatinization pathway, where starch swells without complete granule disintegration. The effect is strongly

influenced by hydration concentration. For example, at pressures ≥ 500 MPa, reduced peak viscosity indicates weakened starch swelling. Setback viscosity (gel re-formation during cooling) and FV (extent of retrogradation) also decrease in HHP-treated starches due to amylose leaching, which hinders gel formation during cooling (Chen et al., 2023; Jia et al., 2023). Lower BV suggests greater shear resistance, advantageous for structurally stable food products. These changes highlight HHP's potential to tailor starch functionality and improve gluten-free texture (Vallons et al., 2011). Tables 1 and 2 provide a comparative overview of these pasting changes under different US and HHP conditions, respectively.

4. Conclusions and future Perspectives

This comprehensive review has elucidated the significant impacts of ultrasonication and high hydrostatic pressure treatments on the structural, functional, thermal, rheological, and pasting properties of gluten-free flours, starches, and protein isolates derived from cereals, legumes, and pseudocereals. Both techniques show considerable potential for enhancing the breadmaking performance of these gluten-free alternatives, thereby addressing a critical need in the expanding market for such products. Our analysis reveals that US and HHP treatments generally lead to reduced particle sizes, altered granule morphology, and decreased crystallinity in gluten-free flours and starches. These modifications typically increase water absorption capacity and alter pasting behaviors, crucial for gluten-free dough development and bread structure. The observed reductions in gelatinization temperatures and enthalpies, along with enhanced gel strength and more solid-like rheological behavior, suggest a greater potential for breadmaking applications. Specifically, ultrasonication tends to decrease viscosity parameters such as peak, breakdown, and setback viscosities, which can facilitate dough handling and reduce stickiness. Similarly, high hydrostatic pressure decreases these viscosity parameters while promoting a stronger gel network, potentially improving the mechanical stability of gluten-free doughs. Both methods can increase water absorption and delay gelatinization, leading to more stable starch and protein networks, essential for enhancing gluten-free bread texture and structure. Notably, the effects of these treatments vary depending on the type of flour or starch, as well as on the specific processing parameters employed. This variability highlights the importance of optimizing treatment conditions for each gluten-free substrate to achieve desired functional improvements without compromising other quality attributes.

The findings of this review have significant implications for the food industry, particularly in the development of higher-quality gluten-free baked goods. By strategically applying US or HHP treatments, manufacturers may be able to improve dough handling, increase bread volume, enhance texture, and potentially extend the shelf life of gluten-free products. This advancement may lead to more consumer-acceptable alternatives for individuals with celiac disease or gluten sensitivity. However, it is important to acknowledge the limitations of the current body of research. Despite these promising outcomes, important limitations remain. Most studies to date have focused on single-component systems, such as individual flours or starches. More research is needed to understand how US and HHP treatments affect complex flour blends, which are more representative of commercial gluten-free formulations. Additionally, the impact of these physical modifications on nutritional quality and sensory properties of final baked products remains underexplored and should be addressed in future work.

To move the field forward, future research should investigate the synergistic use of US and HHP with other emerging technologies. Enzymatic treatments (e.g., transglutaminase), fermentation, and thermal extrusion may complement the structural changes induced by US or HHP, further improving protein network formation or starch functionality. Novel technologies such as cold plasma and microwave-assisted hydration could also be explored to fine-tune ingredient behavior in a

more energy-efficient and targeted manner.

Application-based studies are especially needed to translate ingredient-level findings into practical improvements in gluten-free breadmaking. This includes evaluating dough rheology (viscoelasticity, extensibility, gas retention), crumb structure (via imaging techniques), and staling behavior over time. Comprehensive sensory assessments—supported by descriptive and consumer testing—are essential to ensure that technological advances lead to perceptible quality improvements. Furthermore, nutritional profiling, including glycemic response, resistant starch content, and digestibility, should be prioritized to align product development with health-focused consumer demands.

In conclusion, ultrasonication and high hydrostatic pressure offer promising strategies for improving the quality and functionality of gluten-free ingredients. When combined with other innovative processing methods and validated through real-world applications, these treatments have the potential to transform gluten-free product development and deliver baked goods with superior texture, structure, nutritional value, and consumer acceptance.

Author contributions

Mahsa Farrokhi: Structured the review topic, conducted the literature search, analysed and synthesized the findings, and drafted the manuscript.

Ines N. Ramos: Supervised the work and contributed to writing, review, and editing.

Cristina L.M. Silva: Conceptualized the review topic, acquired funding, provided resources, supervised the work, and contributed to writing, review, and editing.

All authors have read and approved the final manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used OpenAI's ChatGPT solely to enhance the readability and language of the text. All output was carefully reviewed and edited by the authors, who take full responsibility for the final content.

Competing interests

All authors declare no conflicts of interest.

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Data availability

This study is a review article and does not involve original experimental data. All data supporting the findings discussed in this paper are available in the referenced literature.

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