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Technological approaches applied in the design of gluten-free bakery products

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Abstract: Gluten-free (GF) bakery products differ significantly from standard wheat flour products, usually with inferior characteristics. To reproduce the visco-elastic properties of wheat flour dough, GF bread is balanced by complex formulations based on gluten-free flour and starches, including hydrocolloids. They must ensure maximum similarity with conventional products to reduce the resistance of final consumers to GF products. Identifying formulations or technologies that would help mimic the gluten matrix has been and remains the focus of research in GF product design. Most research focuses on ingredients. This study provides an overview of the various technological strategies in designing GF bakery products: technologies applied to cereals, flours, dough, and final products. The study could broaden the boundaries regarding developing, selecting, and using technologies to design GF products. It would also serve as a support for further research into the development of GF products, perhaps by leveraging local products and ingredients and adapting efficient, low-cost, environmentally friendly (including combined) technologies in such a way as to obtain products with high nutritional, rheological and organoleptic value.

Keywords: technological strategies; organoleptic indices; rheological properties; nutritional value

The ubiquity of bread and bakery products in the diets of many countries is apparent, being the most consumed cereal products. The secret of the wheat flour bread dough's quality lies in the unique properties of gluten proteins (Kovács et al. 2021). Gluten is a mixture of protein fractions, mainly prolamin and glutelin, whose weight varies depending on the variety and cereal crop. Wheat prolamins and glutelins comprise numerous protein components characterised by minimal structural, compositional differences (micro-heterogeneity) (Siminiuc and Țurcanu 2020; Chirsanova et al. 2021). In an aqueous solution, bonds are formed between prolamin and glutelin, leading to a three-dimensional protein reticulum, which offers elasticity and resistance to dough stretching (Rosell 2011). Starch granules from flour and gas bubbles remain fixed in the gluten network, which supports the dough during fermentation. These properties justify the primary role of gluten in manufacturing bakery products.

Sufficiently elastic and extensible gluten ensures a well-developed bread with fine, uniform porosity and thin pore walls. Excessively resistant and extensible

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gluten, however, leads to poorly developed products with a dense crumb and, respectively, to flat products with coarse porosity. Prolamins control the extensibility and volume of the bread, and glutelins are responsible for the elasticity of the dough and its kneading properties (Siminiuc et al. 2012). The tertiary and quaternary structure of proteins determines the properties of gluten. There is a correlation between the rheological properties of the dough and the content of groups – SH- and -SS- (Mrak et al. 1968). As the strength of the flour increases, the content of -SS- groups increase, and that of SH- decreases. It is considered that for a -SS-/SH- ratio of 15/19, a maximum volume of bread is obtained (Pomeranz 1968). The bread volume depends on the flour protein's content and quality. The disulphide bond is a cross-link between two cysteine residues and plays a vital role in the structure/function of proteins (Yano 2019). The gluten matrix and its operations are essential to determine the quality of bread dough and other bakery products. Gluten can act as a binding and expanding agent and is commonly used as an additive in processed foods to improve texture, flavour, and moisture retention (Ziobro et al. 2016; Biesiekierski 2017; Naqash et al. 2017).

Various research have been conducted on the structure of protein fractions of gluten-free (GF) ingredients, but the structural explanation of their properties is still poorly understood (Ziobro et al. 2016; Silventoinen et al. 2019; Ortolan et al. 2022). Over the years, new materials, ingredients, and equipment have been introduced to produce better quality bread, and the bakery industry benefits from research to improve industrial bread production (Gerardo-Rodríguez et al. 2016). Despite all the achievements, bakery products show poor crumb and crust characteristics and fast staling (Naqash et al. 2017). Attempts to improve the quality of bread are actual and are achieved both by optimising technologies and by involving new bioactive, nutraceutical and functional constituents.

This study aims to provide an overview of the various technological strategies for designing GF bakery products, which tend to ensure the stability and elasticity of the dough and the optimal nutritional and sensory qualities of the finished products, increasing the shelf life at an acceptable cost. The technological approaches reviewed in the paper are structured in strategies applied to cereals, flours, dough, and technologies used in final products (Figure 1).

Gluten-free bakery products

Nutritional therapy is imperative for people with disorders associated with gluten consumption.

The effects of a GF diet on the well-being of healthy people are not sufficiently elucidated. Some gluten-tolerant consumers believe that GF products are more beneficial. According to a survey, 41% of non-celiac athletes, including Olympic medallists, follow a GF diet 50–100% of the time (Lis et al. 2015). In most cases, adherence to the GF diet has no medical justification and may have been driven by the perception that eliminating gluten offers health benefits and an ergogenic advantage (Yano 2019).

Designing gluten-free products remains a significant challenge, both from a nutritional point of view and especially from a technological point of view. GF bakery products differ significantly from standard wheat flour products, usually having lower quality. The lack of a vital protein matrix capable of expanding and retaining gases leads to weak doughs with high permeability to carbon dioxide and great difficulties in maintaining the structure, which reduces bread volume (Ren et al. 2020). The absence of gluten affects the quality of the dough, such as the lack of cohesion and elasticity and low gas retention capacity, and gluten-free bread is characterised by low volume, friable texture and rapid firming compared to heated bread (Matos and Rosell 2015; Bourekoua et al. 2018). Due to the inclusion of starch in the recipes and the short

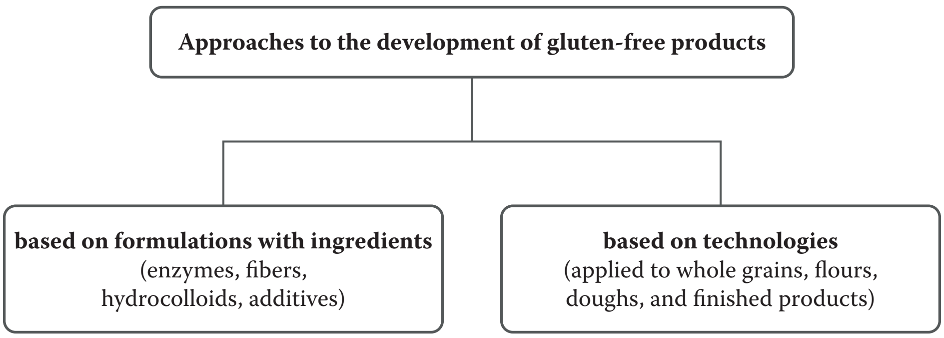

Figure 1. Approaches to the development of gluten-free bakery products

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mixing and fermentation time, GF bakery products have a poor texture and pale colour with a non-pronounced taste (Cappelli et al. 2020). To reproduce the visco-elastic properties of wheat flour dough, GF bread is balanced by complex formulations based on GF flours and starches, including hydrocolloids (Conte 2019). Those ingredients must ensure GF products have maximum similarity with conventional bakery products for better consumer acceptance (Padalino et al. 2016; Chiș et al. 2020; Šmídová and Rysová 2022). The design of GF bakery products is challenging for the scientific community and food technologists. The formulations or technologies that would contribute to the gluten matrix's mimicry have been identified. It remains the main objective of research in GF product design (Fetouhi et al. 2019). High-quality GF bakery products are developed through technological and formulation-focused approaches (Cappelli et al. 2020) (Figure 2).

Most research focuses on ingredients that include starch, GF flour, hydrocolloids, proteins, enzymes, emulsifiers. The elements and combinations between them often mimic a conventional dough's cohesion and elasticity and improve the final product from a technological and sensory point of view (El Khoury et al. 2018). However, the incorporation of raw materials into GF bakery products, which are often nutritionally advantageous, can adversely affect the rheological properties of the dough and, consequently, the quality indices of the final products.

Technological strategy applied to cereals

Germination of cereals is carried out mainly to initiate changes in the composition of nutrients, which are associated with health benefits. Scientific results show that grain biopolymers degrade during germination due to increased enzymatic activity (Zhang et al. 2015; Nkhata et al. 2018). And as a result, it improves the digestibility and bioavailability of nutrients and bioactive molecules. The involvement of germinated cereals in the fortification and natural enrichment of gluten-free foods has excellent potential and conquers new frontiers (Omary et al. 2012; Banu et al. 2020). Germination helps to the reduction of starch gelatinisation and retrogradation ability as a result of hydrolysis,

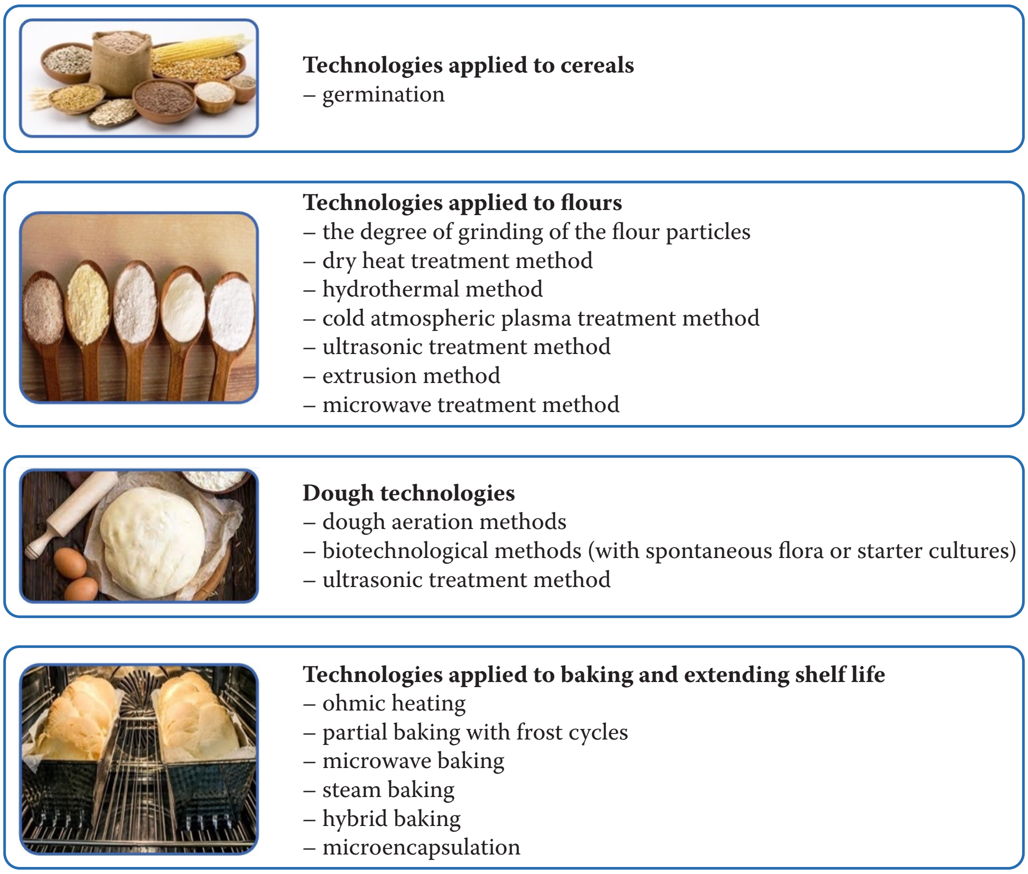

Figure 2. Gluten-free product processing strategies

Source: Authors own elaboration based on Ramos et al. 2021; Dapčević-Hadnađev et al. 2022; Šmídová and Rysová 2022

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improves the texture of the crumb, making it softer; more intense colouring of the bread crust due to the higher content of reducing sugars; increases the shelf life of bread and sensory indices due to increased α-amylase activity (Dapčević-Hadnađev et al. 2022). Research on germinated rice flour (for 24 h) and legumes (chickpeas, lupine) has shown adequate functionality to be used as a raw ingredient in the manufacture of GF bread, helping to improve the texture and colour of bread (Cornejo and Rosell 2015). Although germinated seeds have multiple benefits in food, more research is needed to improve GF products' texture and sensory properties and gain wider consumer acceptance (Atudorei et al. 2021).

Technological strategies applied to flours and starches

Degree of grinding of flour particles. An essential parameter in the bakery product design is the flour's granulometry. The degree of grinding has a differentiated impact on the chemical and physical properties of the flours, changing the water absorption capacity, adhesiveness, thickening power, emulsifying properties, and pasting properties, and as a result, changes the rheological properties of the dough and the quality of the finished products (Gómez and Martínez 2016). It also increases the content and degree of starch damage due to grinding, tendency, and characteristics of rice flour, corn, legumes (Barak et al. 2014; Trappey et al. 2015; Bourré et al. 2019). Some studies show that rice batter's elastic and viscous modulus increased as particle size decreased, except > 200 μm. Moreover, rice bread made from rice flour with larger particle size had a significantly lower volume, rougher crumb structure and more complex bread texture than that made from smaller particle size, leading to an undesirable rice bread quality. The results indicated that the rice flour with particle size 75–100 μm could exhibit preferable characteristics of rice flour, which could be used to produce similar desirable qualities of rice bread to the wet-ground rice flour (Coțovanu and Mironeasa 2022; Dapčević-Hadnađev et al. 2022). Small particles improve water and oil retention, enzyme release, and functional-technological properties by exposing a large surface area during processing (mixing, fermentation or baking) (Coțovanu and Mironeasa 2021; Qin et al. 2021; Coțovanu and Mironeasa 2022). In contrast to rice flour, the coarser maize flours provide bread with more volume and less firmness than the finer flour bread due to the higher availability of dough to retain the gas produced during fermentation and increase its volume (De la Hera et al. 2013). The impact of flour's granulometry characteristics of flours on baking properties also depends on the origin of the flour, the variety, and the milling process. These factors should be studied in more depth.

Dry heat treatment method. Dry heat treatment is a physical method whose primary purpose is to modify the physicochemical properties of starch, which is simple, safe, and produces no pollution (Qin et al. 2016). The method is often applied to improve the functionality of alternative cereal flour. Experiments with sorghum flour showed that heat treatment causes the formation of starch aggregates and changes the interactions between them, affecting the dough's viscosity and the final product's volume (Marston et al. 2016). Heat treatment increased the ability to form rice starch gel with xanthan gum and the viscosity of corn starch paste with sodium alginate and carboxymethylcellulose (Qin et al. 2016). Also, the dry heat treatment increased fat, fibre, and water absorption capacity. In contrast, the moisture, protein, ash, water retention capacity, solubility index, foaming capacity, and FT-IR absorption bands characteristic of phytic acids decreased with the temperature applied raised (Batariuc et al. 2021). Research has shown that the functionality of sorghum flour is conditioned by temperature and heat treatment time. Heat treatment for 30 min at 125 °C increases the gas retention capacity and dough expansion, improving GF bread's structure, strength, and volume. The improvement in the strength of the structure and volume is related to the increased viscosity of the dough, which in turn is due to the swelling and gelatinising properties of the starch granules (Marston et al. 2016; Perraulta Lavanya et al. 2021).

Hydrothermal methods. Hydrothermal methods are considered accessible, simple, and safe. They involve the controlled application of moisture and heat, which leads to changes in the physicochemical properties of starch. Research results show that hydrothermal treatment improves the textural quality of products through the starch-protein interaction (Majzoobi et al. 2016; Malik et al. 2021). The protein and starch interaction affecting dough properties is a complex phenomenon seldom studied because of its intricate, multidimensional nature (Gao et al. 2020).

During hydrothermal treatment, proteins and polysaccharides may interact via non-covalent bonding such as hydrogen bonding/dipole-dipole interactions and electrostatic interactions. The starch-protein interaction/coacervation may affect starch gelatinisation and properties of the resultant biopolymer gel (Kumar et al. 2022). Starch-globular protein interplay accelerated the swelling of starch granules, and reduced the

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paste stability during heating (higher breakdown) and cooling (higher setback) (Wang et al. 2021).

Numerous studies have been carried out on the influence of hydrothermal treatment on starches from different plant sources: finger millet, Bambara groundnut, mucuna bean, sorghum, pea, lentil, navy bean, corn, pea, lentil, potato, and rice (Adebowale et al. 2005, 2009; Hormdok and Noomhorm 2007). Most findings on the studies conducted revealed that hydrothermal treatment executes structural changes in the amorphous and crystalline regions in the starches, thus having marked effects on granular swelling, functional, thermal properties, molecular, crystalline structure and susceptibility towards enzyme and acid (Chung et al. 2010; Mathobo et al. 2021).

In hydrothermal treatment, through a competitive and simultaneous process, protein denaturation and starch gelatinisation occur. When the denaturation of proteins predominates the gelatinisation of starch, the coagulation of proteins occurs in a continuous network in which starch particles remain encapsulated. Such a network is characterised by structural integrity and well-preserved shapes of the final product.

On the other hand, if starch gelatinisation predominates over protein coagulation, then protein coagulates in discrete entities and lacks a continuous framework. Because of this, the product so formed lacks structural integrity (Malik et al. 2021). In addition, creating more ordered intermolecular bonds between amylose-amylopectin, amylopectin-amylopectin, and amylose-amylose during retrogradation also imparts stability to the structure of the product (Tang and Copeland 2007; Malik et al. 2021). When hydrothermal treatments are performed above the gelatinisation temperature, the starch granules irreversibly lose their integrity, a process known as pre-gelatinization (Gómez and Martínez 2016; Malik et al. 2021). The advantages of using modified (pre-gelatinized) starch is explained by its viscosity in cold water, which leads to a higher adhesion of the system and dough formation. It is also a welcome method for frozen doughs: reducing the number of ice crystals in the dough caused by temperature fluctuations. Temperature fluctuations destroy yeast cells during storage by freezing. This reduces the fermentation capacity of the dough after thawing. Pre-gelatinised starch contributes to higher water absorption, forming gel in cold water (Ma et al. 2022). The degree of substitution is considered to have a more substantial influence on the rheological properties of the dough compared to the degree of gelatinisation of the substituents (Fu et al. 2016). The hydrothermal method's impact on the dough's quality largely depends on the flour used. In the multi-cereal bread formulations, with increasing native starch concentration, the dough storage modulus was reduced. In those with pre-gelatinized starch, the linear viscoelastic interval of the dough was increased. This indicated that the viscoelastic strength of the batters increased with increasing starch concentration (Onyango et al. 2011). The sorghum-based dough, which contained native starch, gave the bread better crumb properties than the dough, which had pre-gelatinized starch. Cohesion, elasticity, and strength increased with increasing native starch content but were minimally affected by increasing pre-gelatinized starch content. Thus, sorghum bread with acceptable crumb properties can be made from batters containing native cassava starch and sorghum flour, and it is unnecessary to add pre-gelatinised starch. The inferior breadmaking quality of sorghum-based batter containing pre-gelatinized starch is because of the ability of gelatinised starch to bind large amounts of water, which is not lost during baking but is retained in the crumb (Schober et al. 2005; Onyango et al. 2011).

Gluten-free bread made from rice flour had low elasticity and hardness and increased resistance to deformation. An increase in the specific volume of the bread was observed at a pre-gelatinized starch concentration of 10% (Pongjaruvat et al. 2014). Some studies have shown that the hydrothermal treatment of rice and corn flour, carried out by suspending the flour in water heated to 65 °C, increased the viscosity of the dough, and subsequently increased the specific volume of the bread, reduced the hardness and chewing time of the bread samples (Bourekoua et al. 2016). Pre-gelatinization of rice flour at 121 °C for 15 min in an autoclave also increased dough moisture, specific bread volume and elasticity. Reduction of retrogradation during storage has also been observed (Choi and Jung 2021).

Cold atmospheric plasma treatment methods. Plasma is the fourth aggregate state of matter, after solid, liquid, and gaseous, composed of free photons, ions and electrons, and atoms in their ground states or excited with a net neutral charge (Chaple et al. 2020; Caba et al. 2022). Cold atmospheric plasma has emerged as a new, non-thermal processing technology with proven efficacy in microbial inactivation and extending the product's shelf life (Chaple et al. 2020). Although the detailed mechanism of action of plasma on biomaterials is not yet fully understood, some basic principles are known. The importance of the method is justified, thanks to the potential interactions of cold plasma species with food components, its effects

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on food quality, and the convenience of application, being the preferred treatment in food science (Mollakhalili-Meybodi et al. 2021).

Cold plasma is produced by providing adequate energy to a neutral gas, which results in its ionisation with the release of chemically active species: charged particles, including excited or unexcited molecules; reactive oxygen species, reactive nitrogen species and ultraviolet radiation, which may interact with food constituents, including food proteins. The interaction of cold plasma with proteins leads to oxidation, dimerisation, deamidation, sulfoxidation, nitration, dehydrogenation, and hydroxylation of amino acids (Mollakhalili-Meybodi et al. 2021).

The applied voltage and exposure time have conditioned the impact of cold plasma treatment technology on gluten-free flours. Active plasma species induced by cold plasma treatment can significantly influence the structure of proteins and starch, especially hydrogen bonds formation (Zare et al. 2022).

A study on the impact of cold atmospheric plasma (CAP) treatment on the structural properties and immunoreactivity of celiac toxic-peptides and wheat storage proteins reported that prolonged plasma treatment resulted in a higher figure of carbonyl and hydroxylation products, and, as a result, the size of the aggregates formed was smaller. Moreover, the immunoreactivity of gliadin in wheat was successfully attenuated via CAP-plasma modification, with oxidation and hydroxylation being of major importance. The CAP plasma could initiate depolymerisation of gluten polymer, thereby reducing the amounts of large-sized polymers. Structural changes in the two model peptides and quantitative modifications in gliadin after plasma treatment have favoured the design of new GF products for patients with gluten-related disorders. (Sun et al. 2020).

The effect of treatment with CAP (for 2–10 min) on the number of microorganisms during storage (up to 6 days) of gluten-free bread and bread made from a mix of wheat and rye flour was investigated. The results showed no mesophilic bacteria or fungi after ten minutes of the bread exposure to CAP. In addition, only 2-min non-thermal sterilisation inhibited yeast and mould growth in the gluten-free and wheat-rye bread. A decrease in the microbial growth in the bread was noted; however, a simultaneous reduction in the moisture content of the bread was observed. The use of CAP in the storage of bread is promising; nevertheless, it is necessary to further study the effect of this treatment in bread with improvers, especially with hydrocolloids and fibres (Starek-Wójcicka et al. 2022).

Ultrasonic treatment methods. Developing new food processes based on innovative non-thermal technologies is one of the biggest trends for the coming years. In this context, low-frequency and high-intensity ultrasonic technology are promising strategies for producing high-tech food and ingredients. The oldest application, the exploitation of diagnostic ultrasound, only dates back to the beginning of the 20th century and ultrasound in processing is even more recent.

Ultrasound comprises mechanical sound waves from molecular movements oscillating in a propagation medium. The waves have a very high frequency, approximately 20 kHz (Chemat et al. 2011; Gallo et al. 2018).

Ultrasonic treatment is non-thermal technology that offers multiple possibilities for efficient and reliable food processing applications. In the food and research industry, high-intensity (> 1 MHz) and low-intensity (20–100 kHz) ultrasound treatment is more frequently applied (Zhu and Li 2019). The use of the method is justified by improving the products' nutritional characteristics, changing the colour, flavour, texture, and safety of food due to the evolving proteins and polysaccharides (Zhang et al. 2022). These lead to the formation of a series of functionalities. Ultrasonic cavitation creates 'micro-jets', 'shears', and free radicals, which interact with food systems (Zhu and Li 2019). Ultrasonic exposure mechanisms of different intensities allow the adjustment of technological parameters to intensify production processes, improve product properties and increase the preservation of its properties during storage (Naumenko et al. 2022). Ultrasonic treatment is applied to both flours and doughs. The ultrasonic approach to modifying cereal products satisfies consumers' demand for physically and more 'natural' modified ingredients and food products (Zhu and Li 2019). The results of the research regarding the impact of ultrasound on the functional properties (swelling power, absorption capacity, viscosity, gel hardness, gelatinisation temperature) of gluten-free flours (whole meal quinoa flour, buckwheat, and rice) are contradictory (Zhu and Li 2019; Harasym et al. 2020; Vela et al. 2021). However, several researchers believe the treatment duration significantly affects flour's ultrasonic modulation (Harasym et al. 2020; Zhang et al. 2021). When talking about the effect of dispersion concentration, opinions vary: according to some researchers (Vela et al. 2021), the result of ultrasound treatment is independent of the concentration of treated flour dispersion up to 30%, and in all treated distributions (5–30%) the particle size of rice flour has been reduced. On the contrary, ultrasonic treatment of (buckwheat) grains

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resulted in particle agglomeration in concentrated dispersions (solid/liquid ratio 1 : 5 and 1 : 2.5), while higher dilution (1 : 10) increased the smaller particle fractions (Harasym et al. 2020). The ultrasound induces the dough components' mechanical, physical, and chemical/biochemical changes through cavitation. The sonication causes a doubled dough volume increase followed by an additional mass yield of the dumplings equal to 2–10% per kilogram of dough. Besides the extra beneficial economic effect, this technology provides an additional sterilisation effect on the fabricated dough (Ulasevich et al. 2020).

Extrusion method. The extrusion cooking method is an emerging alternative technology the food industry applies to develop GF products with acceptable nutritional (Sajid Mushtaq et al. 2021), sensory and functional characteristics (Silva et al. 2016). Extrusion is a versatile, high-temperature-short-time technology that allows producing fully cooked, low-moisture, and shelf-stable food products (Ciudad-Mulero et al. 2022). Cooking-extrusion (extrusion) modifies the functional properties of flour due to the gelatinisation of starch along with protein unfolding and aggregation. Extrusion improves emulsifying and foaming properties of flours, making them more suitable for some gluten-free products (Offiah et al. 2019; Ek et al. 2020; Bouasla and Wójtowicz 2021; Ciudad-Mulero et al. 2022). For example, using extruded quinoa flour with low lactic acid levels has led to a gluten-free bread with high specific volume and low firmness (Murgueytio and Santacruz 2020). In snacks from extruded flour mixtures (rice, peas, locust bean flour), the soluble protein content, the resistant starch content, the fat content, and the total dietary fibre content were reduced. Still, the in vitro protein digestibility was increased (Arribas et al. 2017). The need to design unique food formulations and the extrusion process to meet the requirements of gluten-intolerant patients is current. Further efforts are needed to develop, strengthen, and evaluate extruded GF products.

Microwave treatment method. Heating the dry ingredients can influence the properties of the GF dough. Microwaves cause molecular movement through the migration of ionic particles or the rotation of dipolar particles (Kutlu et al. 2022). Microwave radiation is classified as a thermal treatment since microwaves enhance the agitation of water molecules, increase thermal energy, and denature proteins by modifying mainly through unfolding (Bourekoua et al. 2018; Espinoza-Herrera et al. 2021). Microwave technology offers many advantages in food preparation: appearance, flavour, and nutritional composition of products heated by microwave radiation, at a level of quality that far exceeds conventional methods, while surface hardening of some products and other pitfalls can be avoided (Hu et al. 2021). Investigations were carried out into the physical modification of rice flour by heat-moisture treatment, assisted by microwave radiation and its effect on the rheological and glueing properties of GF dough and the physical quality of the resulting bread. More commonly, microwave heating has been used to treat rice flour. Rice flour, with a moisture content of 20–30%, improved the elasticity and specific volume of the bread and reduced the starch retrogradation (Šmídová and Rysová 2022). Hydrated rice flour, enriched with β-glucans and microwave-treated, did not change the molecular weight of bioactive polysaccharides when baked. In general, microwave-treated rice flour (MW-20% and MW-30%) has led to bread with a higher specific volume, a softer crumb, and an increased shelf life. Heat treatment of hydrated (moistened) microwave-assisted rice flour seems valuable to improve the viscoelastic behaviour and manufacturing performance of gluten-free dough bread (Pérez-Quirce et al. 2017; Villanueva et al. 2019). However, microwave technology is still inadequate; excessive microwave heating rate leads to the destruction of the sample's internal structure; rapid water loss causes the reaction to stay in an intermediate stage; there are many influencing factors, and the process is not easy to control.

Technological strategies applied to the dough

GF dough is a complex, semi-fluid system that combines different primary and secondary ingredients responsible for forming the dough's structure, viscosity, and stability. The percentage of water in GF dough is about twice as high as in conventional dough. It depends on the nature of the raw materials and the size of their particles, but also on the ability to absorb and retain water. Technological processes (duration and speed of kneading) applied to the dough influence the quality of the bread (Šmídová and Rysová 2022). GF doughs lack glutenins and gliadins, which are responsible for the expansion and strength of the dough, inhibiting the formation of networks and reducing the viscoelastic structure of the dough (Yildiz et al. 2019).

Nutritional quality is an essential asset in the development of gluten-free bakery products. It depends on the combination of ingredients and additives, but processing can also improve the quality of bread (Matos and Rosell 2015).

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Dough aeration methods. An essential indicator of the quality of the baking dough is the ability to retain gases during fermentation and baking. The ability to retain gas is mainly due to the presence and quality of gluten. In gluten-free mixtures, gas retention is due to ingredients (most often hydrocolloids, fibres, or other polymers) capable of simulating a gluten network. Aeration and gas retention can be ensured by producing natural gases by microorganisms, which, in turn, can improve the gas retention capacity by synthesising hydrocolloids (Elgeti et al. 2015).

Mechanical aeration. The most recent approaches in designing GF bakery products focus on mechanical aeration: introducing gases into the dough by intense mixing/foaming (Elgeti et al. 2015). This technology mainly applies to fluid doughs and replaces the traditional kneading stage. The mechanical aeration method demonstrated an increase in the final volume of GF bread from 12 to 21% (Paulik et al. 2021).

The headspace atmosphere. Another more recent method is the introduction of pressurised air – the headspace atmosphere. It is worth noting that the dough was prepared using rice flour with the addition of hydroxypropylmethylcellulose (HPMC). By trapping gas in the GF dough matrix, the specific volume of gluten-free bread was improved, and the hardness of the crumbs was reduced. The result is explained by the introduction of pressurised air during mixing and adjusting the blending speed and duration, considering that the formulation included HPMC, a hydrocolloid with well-known interfacial properties (Paulik et al. 2021). Although further studies are needed, the method could be a potential alternative in improving GF bakery products without adding food additives (Sadot et al. 2017).

Biotechnological methods. The beneficial properties offered by dough fermentation can be translated into developing new GF products, which could improve their technological and nutritional properties (Ramos et al. 2021). Most biotechnological strategies for designing gluten-free bakery products involve enzymes and lactic acid bacteria (LAB) strains. Fermentation of the dough with spontaneous sourdough microbiota, although it is ancient biotechnology, is justified by the beneficial properties caused by the native microbiota, with an optimal ratio of lactobacilli (homofermentative and heterofermentative, LAB) and yeasts of 100 : 1. LAB contributes to the acidification of the dough, and the primary function of the yeast is the production of carbon dioxide (Ramos et al. 2021). Studies have been carried out on obtaining spontaneous sourdough microbiota, including gluten-free flours (sorghum flour, amaranth, quinoa) and its benefits related to exopolysaccharide production, proteolytic, amylolytic and phytase activity, volatile and antimicrobial production (Siminiuc 2020; Dapčević-Hadnađev et al. 2022). All of those contributed to the improvement of the nutritional and sensory value of the finished products, especially the capacity of expansion and gas retention and increased shelf life (Ramos et al. 2021).

The results of the studies support the hypothesis that sourdough (with spontaneous microbiota or starter cultures) is a possible strategy to improve the quality of GF bread. At the same time, some researchers recommend the use of both sourdough and yeast. Combining these two agents reduced the fermentation time of the dough and formed better-developed products with a softer core and lower ageing kinetics (Cappa et al. 2016).

Ultrasonic treatment method. Ultrasound induces mechanical, physical, chemical, and biochemical changes in the dough components by cavitation. Ultrasonic dough treatments have improved the rheological and sensory properties of gluten-free corn flour bakery products: they have reduced the firmness of the dough and bread but increased the porosity, specific volume, and overall acceptance score. Applying ultrasonic treatment at a frequency of 35 kHz during the dough preparation leads to the dough's homogenisation and changes the dough's rheological properties (Ulasevich et al. 2020). Ultrasound treatment leads to the decrease of β-turn and the increase of α-helix and thus to the strengthening of the starch structure and the modification of the secondary structure of proteins (Qin et al. 2022).

Combining ultrasound with the gelatinization of starch has had a more visible impact on the dough's technological properties and the finished products' sensory properties (Strieder et al. 2021). Sonication doubled the volume of the dough, followed by the additional mass yield of the dumplings (2–10% per kilogram of dough). In addition to economic efficiency, technology provides another sterilising effect for manufactured dough (Ulasevich et al. 2020). Ultrasonic-assisted dough freezing has improved the distribution of water in the frozen dough and the stability of the molecular structure of the protein (Zhang et al. 2022).

Technological strategies applied to baking and for extending shelf life

Unconventional cooking methods have gained prominence in recent years. When the dough is placed

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in a preheated oven, the hot air promotes the formation of a film on the surface of the bread (Matz 1992). The expansion of gluten-free bread is directly associated with the starch present in the dough and the different gelatinisation temperatures, which favour the swelling of the starch granules, leading to the expansion of the specific volume of the bread (Horstmann et al. 2016; Ziobro et al. 2016). Along with browning, there are reactions with the production of aromas and tastes (Gasparre and Rosell 2019).

Ohmic heating. A recent and promising alternative to conventional baking is ohmic heating. In traditional doughs, water is about 55–60% by mass. The absence of the gluten network in the GF formulations assigns starch and hydrocolloids primary roles in controlling gas retention, with a water intake about twice as high as wheat bread. Ohmic heating is a method of volumetric heating, which is based on an electric current passing through a food matrix. Due to its volumetric and uniform heating principle, the final product is alveolar, with a well-developed crumb and, consequently, with volume, which improves the overall quality of bakery products (Waziiroh et al. 2022). The method is not based on conventional heat transfer based on conduction, convection, or radiation (Masure et al. 2019). The main parameters that affect heat generation during ohmic heating are the material's electrical conductivity and the electric field's intensity. Both determine the electric current and aim to increase the temperature based on the total specific energy applied and the specific thermal capacity of the material. The applied power affects the heating speed. In a heterogeneous material, such as food, the electrical conductivity depends directly on specific properties (composition, pH, concentration, and ion mobility). Usually, it increases with temperature, water, and salt content. The impact of some parameters of the ohmic heating process on the quality indices (specific volume, firmness and elasticity of the crumb, alveolar size, colour, starch gelatinisation, and digestibility) of GF products was investigated (Bender et al. 2019). Few studies using ohmic heating for baking GF bread have shown a significant reduction in baking time, resulting in only a few minutes of fully expanded GF bread. The functional properties of GF bread (specific volume, core elasticity, porosity) were superior to GF bread baked by conventional methods (baked). Ohmic heating reduces the humidity of the products and affects the colour of the crust (Šmídová and Rysová 2022).

Figure 3 describes the relationship between ingredient functionality and ohmic baking properties. An in-depth study of the impact of ohmic heating on gluten-free bread ingredients highlighted two significant issues to consider: *i*) the influence of the ingredients used due to the chemical composition and physical and functional properties; *ii*) structural de-

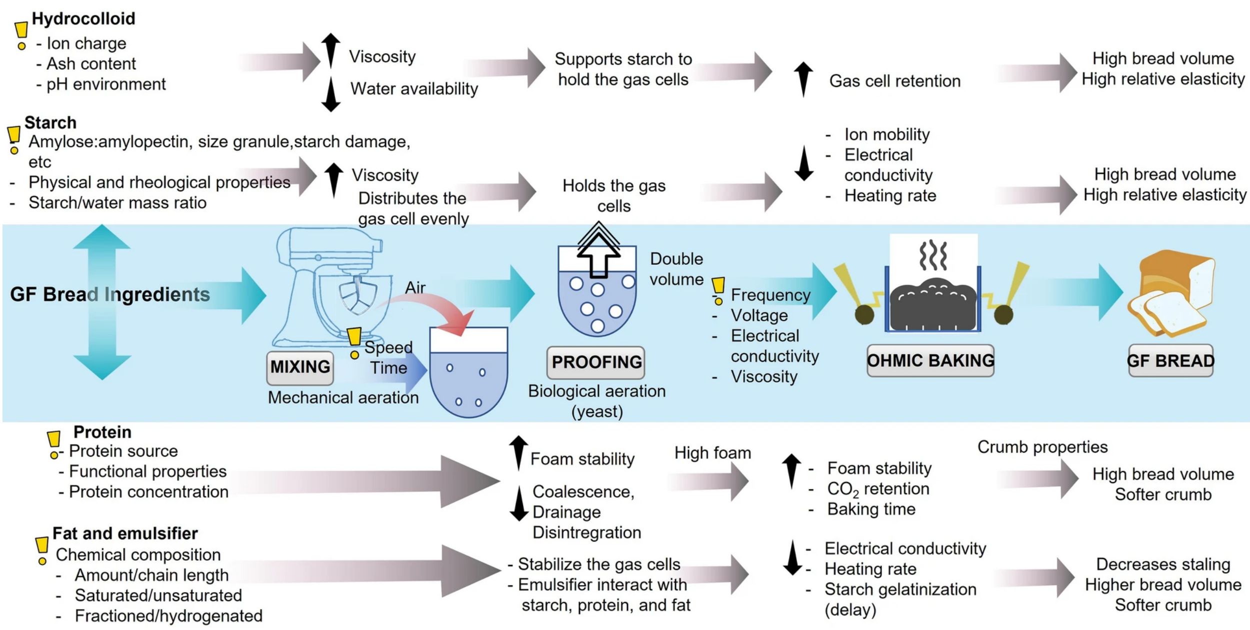

Figure 3. Overview of the influence of gluten-free (GF) bread ingredients on dough and bread characteristics during ohmic baking

Source: Waziiroh et al. 2022

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velopment of ingredients during processing, which leads to changes in viscosity, porosity, and density inside the dough.

Each GF formulation requires a custom ohmic heating regime, considering the steps and the directional adjustment of the processing parameters (Waziiroh et al. 2022). Research into the impact of the ohmic heating process on the quality of traditional bread, as well as GF bread, requires further research to understand the behaviour of the dough and its components during ohmic heating, as well as the primary factors that should be taken into account when using this technology for baking GF products. The colour of the bread crust and crumb remains mostly unaffected by the different Ohmic heating (OH) treatments, but it is brighter than bread baked by conventional methods (Bender et al. 2019). Due to the short heating time at high temperatures and evenly distributed heat, Maillard reactions can be controlled or even minimised during OH, which would explain the colour differences (Lund and Ray 2017).

Partial baking with frost cycles. Freezing food is a unitary operation that aims to preserve food without significant changes in nutritional and sensory quality, involving a decrease in food temperature below freezing. During freezing food, the state of the water changes from liquid to solid, forming ice crystals. Two critical aspects will be taken into account regarding the freezing of the products: the aqueous components are concentrated in the liquid (non-frozen) phase; there is an increase in the volume of about 9% associated with the transformation of liquid water into ice, a phenomenon known as abnormal dilation of water (Sun et al. 2020). Freezing speed is vital in frozen products' final quality, determining the number and size of ice crystals formed (Teotônio et al. 2021). A fast freezing pace is recommended, from 30 min to 4 h until the product temperature reaches –20 °C (Gerardo-Rodríguez et al. 2021). Physico-chemical and microbiological changes are the factors that most interfere with the shelf life of bakery products. Production alternatives are used to achieve satisfactory technological qualities, such as the partial baking of bread and the freezing of dough. Par-baked bread is produced similarly to the conventional process; however, in the baking step, the product is partially baked. After this stage, the product is packed and stored. Only after the tawing process or directly introduced in the heated oven it is submitted to cooking again to conclude completing the process (Barcenas and Rosell 2006). Due to the possibility of delaying this last re-baking step, this processing technology makes it possible to obtain fresh products anytime. The use of freezing appears like an excellent alternative for the production of bread, cheese bread, biscuits and cakes, offering excellent application advantages, such as the extension of the shelf life and the prevention of starch retrogradation, characterised by the reapproximation of the molecules due to the reduction of temperature during cooling of the gelatinised starch, promoting the formation of intermolecular hydrogen bonds, since the syneresis and the release of water existing between the starch molecules polymer-polymer, the combination of these phenomena directly affects the shelf life of bakery products (Teotônio et al. 2021). The general production schedule for bread baked with icing cycles is shown in Figure 4.

Microwave baking. Microwave technologies have also been tested in the GF bread-baking process. Mi-

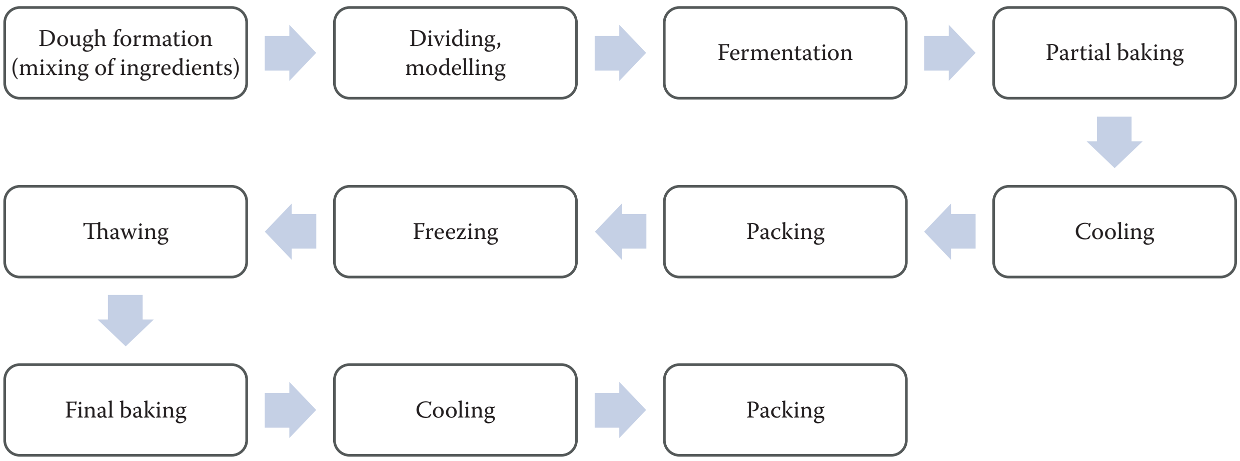

Figure 4. General production schedule for bread baked with icing cycles

Source: Adapted after Teotônio et al. 2021

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crowaves are generated by a magnet that converts electricity into electromagnetic energy. Heat transfer occurs inside the product, and the range of microwave energy penetration varies depending on the composition of the food. The advantages of using a microwave oven as an unconventional way of baking are fast heating, short time, automatic process, adaptability, and accessible equipment handling. Disadvantages include uneven heating, insufficient gelatinisation of starch, gummy texture, lack of colour formation and high moisture loss. A combination of hot air and microwave cooking can reduce the moisture loss caused by indoor heating. To improve the appearance of colour, microwave energy-absorbing susceptors can be used, turning it into heat or a combination of microwave and infrared heating (Yildiz et al. 2019). The degrees of the starch gelatinization of bread baked in infrared– microwave combination and conventional ovens were compared. Conventionally baked bread prepared with a tiger nut flour/rice flour ratio of 10 : 90, and the infrared-microwave combination-baked bread prepared with tigernut/rice flour ratio of 20 : 80 had the most acceptable firmness and specific volume values. This bread had similar colours (Demirkesen et al. 2013).

Gluten-free steamed bread. A traditional Chinese product, steamed bread, has gained worldwide popularity, with widespread distribution in Eastern countries, the USA, Canada, and some European countries. Compared to conventional baked bread, steamed bread has several advantages, such as: *i*) slowing down the rate of glucose uptake and, respectively, slowing down blood sugar; *ii*) the absence of the melanoid formation reaction, which reduces the loss of lysine and other water-soluble amino acids; *iii*) the lack of harmful acrylamides, which do not form during steam treatment (Lee 2010; Shanina et al. 2020); *iv*) the acrylamide content and loss of soluble amino acids in steamed bread are less than those of baked bread (Liu et al. 2019).

There are three technologies for obtaining steamed bread: the sourdough method, the pre-fermentation method, direct method (Shanina et al. 2020).

The sourdough method involves using sourdough (either with spontaneous microbiota or starter cultures). It is a long technological process (involves two stages of fermentation), which consists of improving the finished products' nutritional qualities (Siminiuc 2020; Siminiuc and Țurcanu 2020b). At the end of the first fermentation stage, an essential condition is to reach a pH of 3.7–4.0, which must be alkalised with Na_2CO_3 (40% of the dough or 0.5% of the flour mass) until the pH reaches 6.4–6.7. The introduction of an alkaline solution neutralises acids released by lactobacilli when the dough precipitates, which helps to increase the release of carbon dioxide (Di et al. 2018; Shanina et al. 2020). Advantages: the possibility of developing a flexible fermentation program for different batches of bread; the bread acquires a homogeneous crumb structure, fine, porous, and shiny appearance.

The pre-fermentation method involves two steps: the first includes a mixture of water, yeast and only a part of the flour (80%), after which the mixture is fermented. In the second stage, add the rest of the flour (20%) with the rest of the ingredients, followed by another fermentation step (Fu et al. 2015).

Disadvantages: both the sourdough method and the pre-fermentation method require high costs, labour, space, and a lengthy production process.

The direct method involves mixing all the ingredients in the formulation in one batch to develop the dough, followed by a period of rest, shaping, fermentation and baking. Advantages: significantly short technological process. Disadvantages: the method is unstable (Kawamura-Konishi et al. 2013; Shanina et al. 2020). The technical parameters to be considered for the three technologies are in Figure 5.

The impact of steam baking on the rheological properties of the dough and the quality of the gluten-free bakery products made from rice and maize flour, which were balanced in some proportions with sorghum flour, quinoa, and sunflower-defatted flour, was investigated. The results showed reduced irreversible deformation, and plasticity and increased elasticity, and strength (Shanina et al. 2020). The antioxidant activity increased in the GF bread with adding potatoes and increased fibre content (about 8.4%), compared to bread with wheat flour (about 2.65%). Still, the glycaemic index decreased because the steamed bread presented a higher resistant starch (RS) content (38.46 g·100 g^{-1}) than that of steamed wheat bread (16.26 g·100 g^{-1}), as well as the specific volume (SV) and the granule surface area of GF steamed bread was lower than those of wheat steamed bread (Liu et al. 2019; Romão et al. 2021). This suggests that cooking combined GF products with balanced ingredient formulations may help improve the final product's nutritional parameters (Liu et al. 2019; Perraulta Lavanya et al. 2021).

Hybrid methods of baking. Hydrothermal treatments, extrusion, high-pressure baking, ultrasound aeration (Naqash et al. 2017), microwave-assisted baking and low-pressure (vacuum) baking (Rondeau-Mouro et al. 2019) are novel technologies that have been applied to improve the quality and storage

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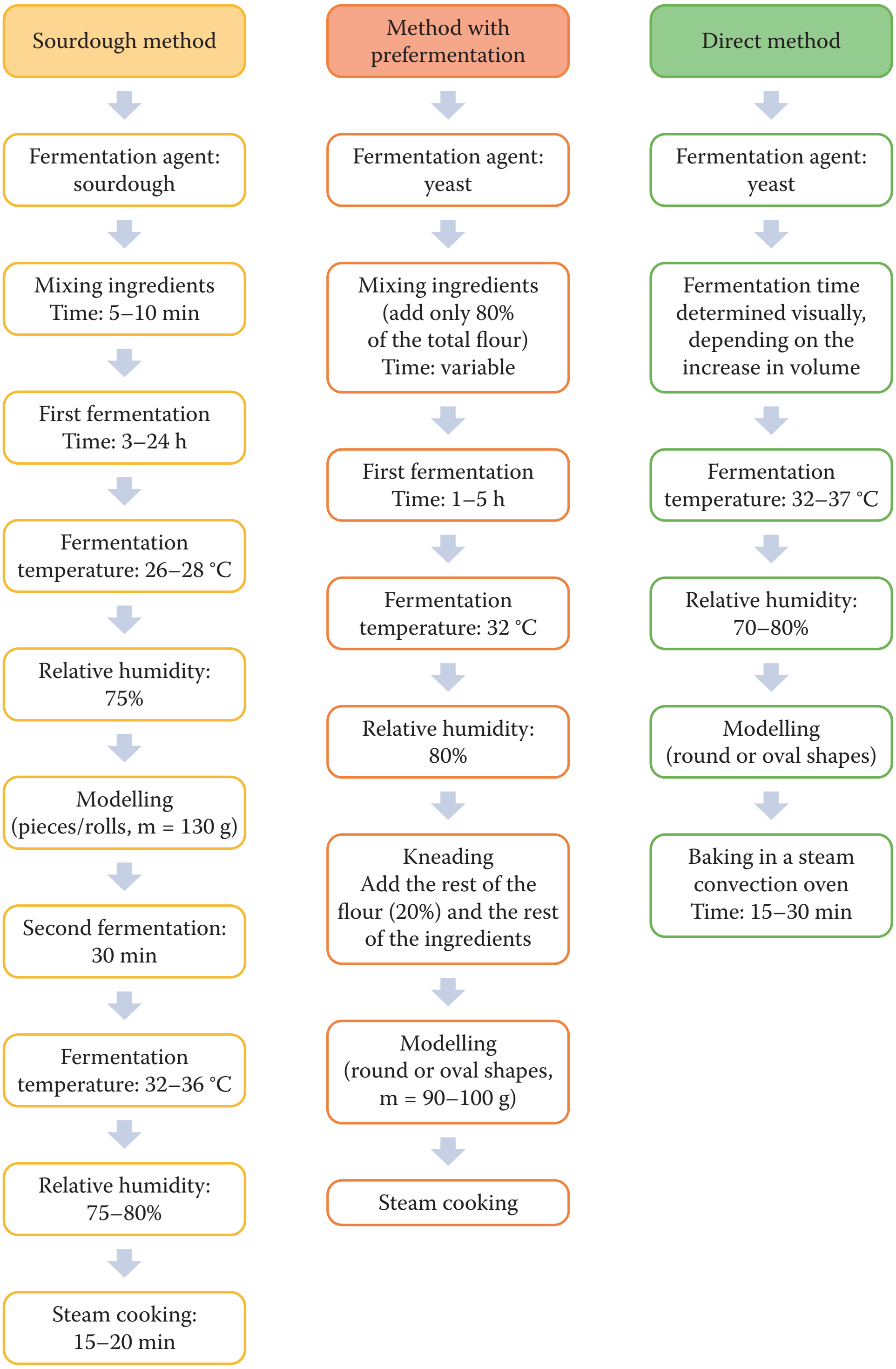

Figure 5. Technological parameters for the development of steamed bakery products

Source: Authors' own elaboration based on Shanina et al. 2020; Luiz and Vanin 2022

properties of gluten-free bread (Tuta Şimşek 2020). It was reported that using a vacuum in conventional baking resulted in a softer bread product than traditional methods during yeast-free bread production using supercritical fluid extrusion of dough (Ruttarattanamongkol et al. 2011; Rondeau-Mouro et al. 2019). A combination of them can be applied to increase the potential of non-conventional baking techniques while minimising the disadvantages (Dapčević-Hadnađev et al. 2022). Some researchers have proposed hybrid

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baking methods, which include conventional methods (180 °C for 30 min at atmospheric pressure) and partial vacuum (180 °C for 15°min at atmospheric pressure and 180 °C for 15 min at 60 kPa pressure). These hybrid methods aimed to increase the quality of GF products and their storage properties. The partially baked samples had a softer texture and a longer shelf life due to the change in the bread microstructure (Tuta Şimşek 2020).

A combination of infrared lamps and electric heating coils enables a 28% reduction in baking time while resulting in bread comparable with bread baked in conventional electrical heating in terms of crumb firmness, volume, moisture content and colour. However, limited studies apply hybrid heating to produce alternative cereals bread (Dapčević-Hadnađev et al. 2022).

Microencapsulation (to extend the shelf life). Microencapsulation is a modern technology, expanding in various fields. It protects food components or functional constituents against different processing conditions. Microencapsulation efficiency for preserving bioactive compounds differs depending on the techniques used, the type of active substance and the coating material used. Only by considering these parameters can microencapsulation be designed in the food matrices of GF products, helping to improve their quality indices. Biologically active substances (omega-3 and omega-6 fatty acids, vitamins, phenolic compounds, and carotenoids) are often used to develop products with functional properties and high nutritional value. The instability of these substances during food processing requires methods and conditions of protection by coating with polymeric or non-polymeric materials and the controlled release of active substances (Choudhury et al. 2021). Microcapsules usually range from 0.2 to 5 000 μm in diameter (Calderón-Oliver and Ponce-Alquicira 2022).

An exciting aspect of the application of microcapsules in food, particularly the materials and techniques with which they are made, is that: in some cases, the microcapsules serve to preserve a bioactive compound or extract in the product, controlling its release during storage. And in other cases, the microcapsules promote the product's release in vivo during digestion (Calderón-Oliver and Ponce-Alquicira 2022).

The encapsulation of α-amylase (α-amylase size encapsulated between 3.98 and 69.53 μm) in beeswax showed the stability of the dough's acidity and the reduction of its catalytic efficiency compared to the free enzyme. Applying α-amylase in GF bakery products has contributed to reducing product hardness and improving sensory qualities, demonstrating efficacy in delaying the ageing of GF bread (Haghighat-Kharazi et al. 2018). The effects of encapsulated maltogenic amylase depend on the enzyme concentration and the encapsulation material (wax). They have given the products a darker crust, whiter and softer core, higher porosity, and better sensory acceptability (Haghighat-Kharazi et al. 2020). The method increases food safety by inhibiting microbial growth and shelf life. It also improves sensory quality. Microencapsulation can increase GF products' shelf life and texture.

CONCLUSION

The growing demand for GF products is forcing research and the food industry to innovate in technologies that allow consumers to access safe products without sacrificing taste or texture. Over the years, various technologies have been tested to obtain GF bakery products. Some of the technologies described have aimed to improve sensory and nutritional characteristics. Other technologies tended to enhance shelf life and reduce the cost of products. Most of the mentioned technologies have sought to increase the functionality of starch, considering its importance in a dough matrix in which gluten is missing. Despite the advantages offered, they are conditioned mainly by the quality and quantity of the ingredients used in the formulation of GF products and by the parameters (quantitative and qualitative) with which the components are acted upon. The study could broaden the boundaries regarding developing, selecting, and applying technologies for designing GF products. It would also serve as a support for further research into the development of GF products, perhaps by leveraging local products and ingredients and adapting efficient, low-cost, environmentally friendly (including combined) technologies in such a way as to obtain products with high nutritional, technological, and sensory value.

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