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Influence of processing on the technological and sensory quality of bread: an overview

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REVIEW ARTICLE

Abstract

The quality of bread is mainly affected by three key phases of production: mixing, leavening, and baking. Each step contributes to the final rheological and sensory properties of the bread. However, especially during the mixing phase, the choice of ingredients and the processing parameters, such as mixing time, dough temperature, mixing speed, and total water content, affect the development of the dough. The properties and behavior of dough are measured by rheological tests, which are crucial from the perspective of optimization. This paper aims to shed light on both technological and sensory aspects of factors that affect the quality of bread.

Keywords: bakery products; dough rheology; mixing; processing parameters; sensory evaluation; wheat flour

Introduction

The baking industry plays an important role in the global food industry. Bread is a staple bakery product, and its widespread consumption ensures a steady and significant demand and allows it to dominate the market. According to the last forecast, the bread market is expected to grow annually by 6.34% (compound annual growth rate [CAGR] 2024–2029; Statista Inc., 2024).

Wheat is the most cultivated cereal after corn; over 95% of the wheat cultivated worldwide is soft wheat (cv. *Triticum aestivum* spp. *vulgare* L.) used for producing cakes, biscuits, and other baked goods (Food and Agriculture Organization [FAO], 2023). On the other hand, hard wheat (cv. *Triticum turgidum* L. subsp. *durum* Desf.) usually provides strong flour with higher protein levels, suitable for bread production (Morris, 2021). Unlike other cereals, wheat has a unique feature of adding energy during mixing—hydrated proteins connect and create a spatial network commonly referred to as gluten. The dough also contains dispersed gas and a certain amount of free water in which water-soluble components are dissolved. Among dough components, gluten proteins primarily define the sensory and rheological properties of the final product. Glutenins and gliadins are major protein fractions of gluten. While gliadins provide viscosity and extensibility in a dough system, glutenins are responsible for elastic and cohesive properties of dough (Demirkesen *et al.*, 2010). In dough, gluten gives viscoelastic properties, structure, mixing tolerance, and the ability to retain gas during leavening (Peighambardoust *et al.*, 2006). Generally, the quantity and quality of proteins in wheat grains affect raw material prices, trading relationships, and establishing differences between various types of wheat.

From the first stage of the production process (mixing flour and water with other ingredients) to the last stage (baking), several chemical and physical changes occur during the mixing of ingredients (Córdoba, 2010; Dobraszczyk and Morgenstern, 2003). Each stage of breadmaking has optimal processing parameters, that is optimal water absorption, mixing time, and resting time, to mention a handful of the numerous processing variables employed in the baking process. Each of these parameters must be adjusted to the type of product, such as bread, biscuits, or cakes, and the production phases, according to the variability of the characteristics of the raw materials employed. The incorrect control of these variables can affect the characteristics of dough and impair final quality of the product. Therefore, it is essential to accurately determine and apply the best conditions to produce a high-quality final product.

The mechanical properties of wheat flour dough are very significant because they affect dough-handling behavior during processing and also influence interactions among dough components. Numerous rheological tests are usually conducted to imitate the performance of dough during mixing, sheeting, leavening, and baking stages. Moreover, rheology is closely related to the microstructure and composition of dough and aids in controlling and predicting the quality of the final product (Dobraszczyk and Morgenstern, 2003; Patel and Chakrabarti-Bell, 2013).

In general, the quality of food can be measured by instrumental or sensory methods. Instrumental methods concern physical, chemical, or mechanical tests that result in numerical values. The textural attributes most frequently evaluated for bread by instrumental methods include hardness, cohesiveness, springiness, and chewiness. Sensory methods determine the same qualities. They involve sensory organs as measurement tools. The assessment of instrumental data (structural features and appearance) and sensory data (profiles) could provide a combined approach to describe the quality of bread (Guiné, 2022). For example, although the ‘texture’ of the finished product is fundamentally a physical property, its perception is influenced by chemical–physical factors as well as psychological and cultural aspects (Barbieri *et al.*, 2018). Numerous researchers have examined the debated topic of correlations between instrumental and sensory methods (Barbieri *et al.*, 2018; Lassoued *et al.*, 2008; Matos and Rosell, 2012; Szczesniak and Kahn, 1971). However, these relationships are difficult to be determined due to the complex composition and structure of bread as well as the difficulties in accounting the changes to the food during chewing process. Because creating and maintaining a trained panel is more expensive than instrumental analyses, researchers frequently use instrumental, rather than sensory methods to evaluate the rheological characteristics of goods (Joyner, 2018). Sensory methods are usually employed to assess the formulation of a new product or changes in a recipe. Although some studies have shown the influence of formulation and processing steps in the sensory attributes of wheat bread, this aspect needs to be examined in more detail (Mollakhalili-Meybodi *et al.*, 2023; Tamba-Berehoiu *et al.*, 2014). Therefore, the interaction of process design stages, processing conditions, and sensory attributes should be evaluated during the handling of finished products.

This review aims to analyze available literature of last 20 years about the influence of processing on the technological and sensory qualities of bread, considering the importance of assessing the rheological behavior of dough in the prediction of textural properties of the finished product.

Gluten: Structure and Function

According to the so-called Osborne fractionation, gluten proteins are divided into two equal fractions, based on their solubility in gluten–alcohol–water solutions (e.g. 60% ethanol)—soluble gliadins and insoluble glutenins. They differ in one important aspect: the gliadins are monomeric whereas the glutenins form polymers stabilized by inter-chain disulfide bonds. Both fractions contribute significantly to the rheological properties of dough but their functions are different. Hydrated gliadins impart low elasticity and are less cohesive than glutenins, contributing mainly to the viscosity and extensibility of dough. In contrast, hydrated glutenins are responsible for the strength and elasticity of dough (Patel and Chakrabarti , 2013; Shewry and Belton, 2024). Glutenin polymers are formed by high molecular weight (HMW) glutenin and low molecular weight (LMW) glutenin subunits, which are cross linked by intermolecular disulfide bonds. The HMW and LMW glutenins represent about 30% and 60% of glutenin polymer, respectively, whereas the remaining 10% is composed by chain terminator proteins and thiols. The HMW glutenin plays a major role in determining dough strength, accounting for up to 70% of variation in breadmaking characteristics, despite representing only about 10–12% of total grain proteins (corresponding to about 1–1.7% of flour dry weight) (Lafiandra and Shewry, 2022). However, gluten proteins are among the most complex protein networks because of numerous different components and sizes and the variability caused by genotype, growing conditions, and technological processes. A correct mixture of both fractions is essential to impart viscoelastic properties to dough, combining the properties of a purely viscous fluid and an elastic solid, and the quality of the final product (Li *et al.*, 2021; Wieser, 2007). Optimization of the proportion of protein components in wheat flour allows greater control over the structural characteristics of bread.

Rheological Tests of Wheat Dough

Rheology plays a key role in the food industry and especially in the bakery process because it describes the macroscopic and molecular structure of dough. The macroscopic behavior of dough depends on its composition and microstructure, such as the spatial arrangement of its components and type of bonds. Dough rheology analyses are carried out to measure the mechanical properties of dough, determine the relationship between the rheology of dough and its molecular structure and composition, study the process performance of dough, and predict and optimize quality of the final product. This characteristic is also useful for industrial plants, because the machines are sized and optimized according to the rheological properties of the product to be formulated (Dobraszczyk and Morgenstern, 2003).

The rheological methods are usually classified according to the type of the method, such as fundamental and empirical. Additionally, they are also classified based on the extent of deformation imposed, namely small or large deformation (Yazar, 2023; Table 1). Empirical methods are developed to monitor dough behavior during various processing steps, such as mixing, shaping, proofing, and baking. Recording mixers, such as mixograph, alveograph, extensograph, and farinograph, use large deformations by shearing and stretching to develop and subsequently break down dough structures. Various flour parameters, such as development time, stability, and dough softening, are recorded during mixing by measuring the resistance of dough to mixing. A relatively new device for dough analysis, Mixolab, measures the behavior of dough during mixing and heating by simulating a baking process. Empirical tests are easy to perform and are often used in practice in the industry. They provide useful real-time data to evaluate performance during processing and for quality control. They have common features, that is, the sample is subjected to a high load of strain, temperature, pressure, time, or energy input. In every case, this is accompanied by the destruction of sample or the alteration of structure, as they are designed to simulate the use, manipulation, or consumption of intermediate or final product (Tietze *et al.*, 2016). However, the stress and deformation conditions that are applied to dough in empirical tests are uncontrolled, complex, and nonuniform. As a result, defining rheological parameters, such as stress, strain, strain rate, modulus, or viscosity, is impossible.

Fundamental rheological properties are considered to overcome the limitations of empirical measurements. However, there is not yet a single fundamental rheological method that can completely replace empirical methods. This is mainly because dough systems are far more complex than the synthetic polymers for which fundamental methods are used routinely. The most common types of fundamental rheological tests used in grain testing are (i) small strain dynamic shear oscillation; (ii) shear creep and stress relaxation for small and large deformations; (iii) extensional measurements of large deformations; and (iv) flow viscometry. The results of fundamental measurements provide valuable information on the relationship between complex systems of dough chemical and rheological properties and how these are influenced by processing conditions. In the case of fundamental rheological methods, only one of the basic types of deformation is applied during measurements. The advantages of fundamental rheological methods include robustness, non-destructiveness, ease of handling, and easy computation of dough's physical properties. Small samples are used to avoid inertia and the samples are protected against alterations such as drying out. These methods are very common in science but not in the cereal industry (Amjid *et al.*, 2013; Tietze *et al.*, 2016).

The problems encountered with such fundamental tests are related to complex instrumentation, which is expensive, time-consuming, difficult to maintain in an industrial environment, and requires high levels of technical expertise. A direct comparison and correlation between empirical and fundamental methods can lead to incorrect conclusions. In recent years, fundamental rheological methods are developed for the correct prediction of properties of bakery products (Tietze *et al.*, 2016). Because the purpose of empirical dough testing methods is to quantify changes in the rheological properties of dough under deformations similar to those occurring during some stages of dough processing, these methods involve large deformations. However, it is possible to apply fundamental rheological methods with both small and large deformations.

The linear viscoelastic properties of dough are mainly determined by fundamental small-amplitude oscillatory shear (SAOS) tests conducted under small deformations. SAOS allows analysis of linear viscoelastic response by observing the strain and frequency dependence of elastic modulus (G') and viscous modulus (G'') at small strains. Furthermore, under a comparatively wide range of conditions, linear methods display molecular interactions, microstructure, and structural characteristics of the material. However, the wheat flour dough is mostly subjected to significant deformations during processing, such as mixing, proofing, sheeting, and oven-rise, at deformation rates ranging from low (i.e. from

Table 1. Advantages and drawbacks of main rheological tests.

		Tests	Advantages	Drawbacks	References
Nature of method	Empirical	Mixograph, Alveograph, Extensograph, Farinograph, Mixolab, Rheofermentograph	Easy, robust, capable, do not require technically trained personnel	The sample geometry is variable and not well-defined, the stress and strain states are uncontrolled, complex and non-uniform	Dobraszczyk *et al.*, 2003; Yazar, 2023
	Fundamental	Small deformation dynamic shear oscillation, small and large deformation shear creep and stress relaxation, large deformation extensional measurements, flow viscometry	One type of deformation is applied, scientific instruments, small number of samples required	Complex instrumentation, expensive, time-consuming, difficult to maintain in an industrial environment and require high levels of technical skill	Dobraszczyk *et al.*, 2003; Yazar, 2023
Deformation applied	Small amplitude oscillatory shear (SAOS)	Linear deformation, analyzes the linear viscoelastic response by observing the strain and frequency dependence of the elastic modulus (G′) and viscous modulus (G″) at small strains	Understanding molecular interactions and micro-structure, material structural properties under a relatively extended range of conditions	Little relationship with end-use performance, not being appropriate in practical processing situations due to the rates at which the test can be used	Dobraszczyk *et al.*, 2003; Yazar, 2023
	Large amplitude oscillatory shear (LAOS)	Non linear deformation, capillary flow, lubricated squeezing flow, Stress relaxation, Stress growth, Creep and creep recovery, Large amplitude oscillatory shear tests	Provide structure of complex food in real-time, Differentiate different types of wheat flours, Characterise the viscoelastic properties of flour, dough is mainly exposed to large deformations	Requiring complex computation with data processing software	Dobraszczyk *et al.*, 2003; Yazar, 2023; Wang and Selomulya, 2022.

fermentation or resting) to high (i.e. mixing) (Upadhyay *et al.*, 2012). Because small deformation tests are typically carried out under deformation conditions unsuitable for breadmaking, they consequently exhibit little correlation with end-use performance. Therefore, a deeper comprehension of dough rheological responses under real processing conditions is obtained by characterizing their nonlinear rheological properties. Under controlled conditions, nonlinear rheological testing methods provide quantitative measures of dough deformation experiences.

Fundamental nonlinear rheological methods include lubricated squeeze flow, nonlinear creep and creep recovery, and large-amplitude oscillatory shear (LAOS) testing. The latter testing has been increasingly used over the past several decades to provide a fuller picture of food rheological behavior. LAOS has the potential to be a valuable tool for investigating food structure–function–texture relationships, but much work remains to develop the connection between LAOS and sensory attributes. Large strain tests have several benefits, but they also have drawbacks that limit the development and application of LAOS rheology in the food industry (Joyner *et al.*, 2021; Wang *et al.,* 2022). They characterize the viscoelastic properties of flour dough, which is primarily exposed to large deformations, and they show the real-time structure of complex food. They also separate different types of wheat flour. Analysis of LAOS data requires data processing software, which is more complicated than that used in SAOS (Amjid *et al.*, 2013). On the other hand, the long-term instrumentation costs may be compensated by data acquisition under controlled deformations that result in precise and timely interventions in industrial productions. Early experiments with the fundamental rheological methods described by Dobraszczyk and Salmanowicz (2008) showed that these instruments were inadequate in the industrial field because of interference and random errors. Therefore, nowadays, owing to better computing power, it is easier to use scientific rheometers for industrial applications, such as quality control or product development. These inconveniences could be avoided or eliminated. Therefore, large strain rheology provides a basis for studying structural changes during the protein phase of dough microstructure, which explains its viscoelastic behavior and end-use quality. Many food processes operate with large-strain extension flow whereas most food rheological tests are performed with small-strain shear oscillations. Measurements under large strains often show a very different rheological response than those under small strains, especially if the material contains HMW polymers (Peighambardoust *et al.*, 2006). It is necessary to define the set of deformation conditions that the food undergoes in practice and carry out tests under similar conditions.

Factors Affecting the Quality of Bread

The optimized breadmaking process is a prerequisite in providing high-quality bread. Breadmaking is considered as a dynamic process in which continuous physicochemical, microbiological, and/or biochemical changes occur by endogenous microorganisms and/or enzymes and thermal action (Stribiţcaia *et al.*, 2020). The sensory characteristics of wheat bread are mainly developed during the different stages of processing as a result of interactions between the ingredients added and the processing conditions (Haegens, 2014; Koksel *et al.*, 2016). Important flavor compounds are formed during baking, when Maillard reaction and caramelization between sugars and proteins in dough take place. Enzymatic and fermentation reactions influence the flavor of bread crumb (Mollakhalili-Beybodi *et al.*, 2023). The texture of bread is formed through different steps of its making process, including mixing of ingredients (gluten development and gas nuclei inclusion), moulding (redistribution of bubbles), fermentation (inflation of bubbles), and baking (expansion and coalescence of bubbles) (Gao *et al.*, 2018). Therefore, controling the correct amount of ingredients mixed and process parameters applied are essential to produce bread with desired sensory characteristics.

Ingredients

The main ingredients in the breadmaking process are flour, water, and yeast (Farahnaki and Hill, 2007). However, other ingredients, such as salt, sugars, lipids, and dough improvers, could be added. Each of these ingredients has a function in the preparation of the final product. For this reason, it is necessary to evaluate their chemical and technological effects in dough and their contribution to the sensory quality of the finished product. The particle size of wheat flour, wheat bran, water content, salt, and flour improvers are considered in this paper.

Raw material: size of wheat flour particles

Production of a high-quality bakery product begins from the mill with the choice and good raw material processing. Bread is generally prepared with wheat flour, but other flour types can be employed as well. In this section, wheat milling and wheat flour particles' size are considered. Wheat milling is a key process involving the removal of germ and bran layers from endosperm and gradually decreasing its size to flour (Saini *et al.*, 2023). A variety of processing parameters are considered while milling of wheat, including the type of mill used (Aprodu *et al.*, 2010), the hardness of grain (Choy *et al.*, 2015), the amount of water the grain absorbs before grinding (Meneghetti *et al.*, 2019), and the physicochemical structure of the grain (Li *et al.*, 2014; Patwa *et al.*, 2014). Because flour is generally the most abundant ingredient in the formulation of bread, the milling conditions of the wheat affect flour quality and final characteristics of bread.

Usually in breadmaking. refined flour with a particle size of <200 μm is used. However, the size of wheat flour particles is affected by wheat milling, mainly by milling intensity and the mechanical force applied. Various types of equipment apply different mechanical force to wheat flour, consequently differences in particle size are expected. Additionally, using the same equipment while modifying processing parameters or processing duration affects the particle size of wheat flour (Ma *et al.*, 2020). The particle size of flour has an important effect on rheological, baking, and mixing properties that have a close connection to the quality of gluten network and sensory attributes. Mirza Alizadeh *et al.* (2022) showed that a particle size of <125 μm provide dough with the highest extensibility because of high-quality gluten content and relatively strong gluten network, which minimized dough rupture and increased gas-retention capacity during leavening stage, resulting in high-volume products. Moreover, dough prepared with a particle size of <125 μm exhibited higher development time and stability than dough prepared with >150-μm size. The authors reported that the wet gluten content decreased with increasing particle size in the outermost layer of wheat grain.

Furthermore, the flour particle size influences dough properties, such as water absorption, dough softening degree, and bread texture. As reported by Sakhare *et al.* (2014), the finer fractions resulted in bread with a softer texture and improved sensory qualities. In particular, the bread prepared from the finer particle size of flour (<75 μm and 75–118 μm) showed significantly higher sensory scores for color, texture, layers, mouthfeel and the overall quality score than the coarser fractions (118–150 μm and >150 μm). Contrarily, the bread with coarser fractions showed dense crumb grain with thick cell walls and slight residual formation during chewing. In general, gluten is more affected by coarse particles, which result in a lower specific volume of baking and less stability and resistance to extension (Hemdane *et al.*, 2016). However, the studies concerning the final characteristics of bread in relation to bran particles are contradictory. While some researchers reported that whole-grain bread prepared with finer particles had a lower volume of bread (Lin *et al.*, 2020), others stated that bread prepared with flour containing brans with smaller particle size had better millet grain and greater specific volume (Wang *et al.*, 2017). This could be due to different particle size range of bran particles considered in different studies or different breadmaking.

Additionally, the most noticeable result of the flour particle size reduction is an increase in the amount of damaged starch. It impacts quality of the final product because it absorbs much more water than intact starch (Putri *et al.*, 2020). However, a certain degree of damage to starch granules is desirable to facilitate the yeast fermentation of dough (Wang et al, 2020). Usually, the degree of starch damage in wheat flour types is 4–10%. In general, hard wheat flour shows higher values of damaged starch, while soft wheat flour has a lower degree of damaged starch (Jukic *et al.*, 2019). An excessively damaged starch level causes accelerated enzymatic action and excessive water absorption, resulting in sticky dough, strong proofing, reduced bread volume, and an undesirable red crust color (Barak *et al.*, 2014; Ghodke *et al.*, 2009; Hatcher *et al.*, 2009). In this regard, Jukic *et al.* (2019) showed that the level of starch damage (high, 6–13% or low, 3–15%) had an increased water absorption level, dough stability and the decreased specific volume of bread. Particle size may also affect the nutritional composition of flour. Refining of flour reduces protein and mineral contents (Tian *et al.*, 2022). Memon *et al.* (2020) found a positive correlation between the content of some phenolic acids and high flour particle size, and a negative correlation between particle size and carbohydrate content and energy.

Generally, after wheat milling, the bran and germ parts are reserved as animal nutrition, which lead to the loss of many potentially beneficial micronutrients, antioxidants, minerals, and fiber. Therefore, considerable attention must be paid for producing whole wheat flour. Producing flour that fulfills the requirement of being a whole grain is achieved by blending bran and germ back with endosperm flour in naturally occurring proportions (Liu *et al.*, 2015). However, the addition of fiber negatively influences the appropriate formation of dough, irrespective of the amount of addition (0–12%). Owing to their longer formation period, shorter stability period, and notably higher weakening degree, fiber-fortified doughs usually do not reach their optimal state during the mixing stage. These dough properties could be measured using fundamental rheological methods, such as frequency sweep, strain sweep, and creep recovery test. In general, as shown by Bonilla *et al.* (2019), the elasticity of dough increases significantly if fiber is present, but if strain is applied, then dough becomes more brittle. This could be due to the redistribution of water in gluten and distruption to gluten matrix caused by fiber. Indeed, fiber generally has detrimental effects on the formation of gluten network, which may decrease gluten viscoelasticity and decrease the quality of products prepared with fiber-enriched flour. Conversely, higher fine whole-grain wheat flour baking quality involves a greater contact surface that provides a combination of physical and chemical mechanisms that act efficiently on the development and function of gluten network (Bressiani *et al.*, 2017).

Moreover, according to extensograph test, fine bran resulted in greater dough resistance than coarse bran after a 180-min resting time. A reduction in gluten quality and a weakening of gluten network resulting from the presence of flour of larger particle size decreased some rheological properties (energy and dough extension), which may contribute to dough rupture.

Whole-wheat products offer a clear nutritional advantage, compared to the products containing refined flour. However, one of the main problems is their overall low sensory acceptance, which has not been investigated as carefully as the sensory liking of white bread. To enhance the sensory quality of whole wheat bread, further studies are required to evaluate taste, aroma, perception in the mouth, and the overall acceptability, besides instrumental analysis for evaluating variables, such as texture, volume, or honeycombing (Gómez *et al.*, 2020). Navrotsky *et al.* (2019) reported a significant increase in firmness and hardness of crumb with the addition of wheat bran or whole wheat flour in high concentrations. Moreover, a lower specific volume of bread, a lower consistency of crumb, and a darker color of bread crumb were observed. In the last few years, several strategies have been investigated to improve the technological functionality of bran and the sensory aspects that are typically associated with wheat bran incorporation in breadmaking. Among strategies, there is the use of high-protein flour, adding water, adjusting processing, and adding bread improvers, such as surfactants, enzymes, and commercial gluten (Heiniö *et al.*, 2016; Hemdane *et al.*, 2016).

The particle size of flour significantly impacts the technological and sensory qualities of the final product. For this reason, flour generally contains a combination of small and large particle sizes (Dziki *et al.*, 2024; Sakhare *et al.*, 2014).

Water

After wheat flour, water is the second most important ingredient added to dough (Sun *et al.*, 2022). Hydration and mixing of gluten proteins significantly influence the structure and mechanical properties during dough formation. Dough properties greatly depend on water content and mixing energy. As a solubilizer, water acts as a plasticizer and increases the mobility of the system. It affects functional properties by inducing conformational changes that enable hydrophobic interactions. Water also acts as a solvent for hydrophilic low-molecular weight gluten proteins. Hydration is associated with mixing results in the breakdown and unfolding of tightly packed gluten proteins and in the formation of a viscoelastic network, which contributes to the optimal volume of bakery products during baking (Wang *et al.*, 2015). The viscoelastic properties of dough depend on quantity and quality (i.e. hardness and pH) of the water added. Insufficient water content results in a stiff dough and causes problems during the production process. On the other hand, dough with excessive added water shows low viscosity/could lose its shape, and it sticks to processing equipment. Water levels in dough also depends on bread's variety, breadmaking process, and processing methods (Luchian, 2013). The water content in bread dough is around 65% (Meerts *et al.*, 2017). In this system, water forms hydrogen bonds with water-soluble components, such as proteins, and solubilizes starch and sugars. An independent, continuous aqueous phase is formed in dough if the overall water content reaches between 23% and 35% on total basis (Upadhyay *et al.*, 2012). Chemical reactions that take place during development and fermentation of dough are mediated by this 'free' water phase. Furthermore, it is probable that during mixing, air bubbles are trapped in this liquid phase, where they expand during fermentation (Pauly *et al.*, 2014). The rheological behavior and quality of the final product are influenced by the water content of dough (Jia *et al.*, 2022). The viscoelastic behavior of wheat dough samples with different water content is investigated through farinograph and oscillation frequency sweep experiments conducted in linear viscoelastic range (Letang *et al.*, 1999). The effect of reducing added water in dough from about 44% to 34% on the rheological characteristics of dough was examined by Hardt *et al.* (2014). As a result, the maximum creep compliance reduced by 1–2 orders of magnitude, with increased mixing resistance, Farinograph Brabender unit values, and G' (indicating the elastic nature of dough) and G" (indicating the viscous behavior of dough) values.

Farahnaki and Hill (2007) evaluated the interaction of three main processing parameters on rheological parameters, such as temperature, water content, and salt levels. The addition of salt decreased consistency and total energy but increased hydration time at low water content due to its competition with flour in water absorption. Water softened dough, and decreased hydration time and the energy required for mixing. Temperature increase had a negative effect on consistency, hydration time, and total energy.

For bread wheat, flour varieties with high water absorption and good dough strength are preferred by bakers. In order to control water consistency and absorption, hydrocolloids or enzymes are added to dough (Farahnaki and Hill, 2007; Zhang *et al.*, 2023). Linlaud *et al.* (2009) compared the effects of increased hydrocolloid concentrations, such as guar gum, xanthan gum, etc., on the absorption capacity of flour.

The Farinograph test is one of the most frequently used rheological tests for flour quality. The outcomes serve as parameters in the formulation that decide the quantity of water needed for making dough, evaluate the effects of ingredients on mixing properties, assess flour mix requirements, and verify flour uniformity. Additionally, the results are utilized to predict processing effects, including mixing requirements for dough development, tolerance to overmixing, and dough consistency during production. It is also possible to predict the texture of finished products using Farinograph results. For example, strong mixing properties of dough are associated with firm product texture (Dobraszczyk and Salmanowicz, 2008).

During mixing, shear resistance of the dough at in laboratory scale is recorded by Farinograph. Among the parameters, farinographic water absorption is positively related to protein content. Figure 1 shows a common Brabender Farinograph output and the main parameters along the farinographic curve. In particular, the amount of time that passes after adding water to flour until the dough achieves maximum torque is known as the dough development time. This time depends on the amount and quality of gluten in the flour and its water-binding capacity. Stability is an indicator of flour tolerance to mixing. Higher values suggest a stronger dough. The higher the tolerance, the longer the dough should be mixed. Higher values of the degree of softening indicate that dough is not able to tolerate long mechanical processing strain (overmixing) (Lacko-Bartošová *et al.*, 2019; Torbica *et al.*, 2021).

Following Rohlich and Bruckener's classification, strong flour has a water-absorbing capacity of >59%, a dough development time of >3 min, a dough constancy time of >4 min, and a softening value of <40. Weak flour has softening of >150 Brabender Unit (BU), development time of <2 min, consistency of <1 min, and water-absorbing capacity of <51% (Biel *et al.*, 2021). However, the rheological characteristics of wheat dough can be significantly altered by a slight variation in moisture content (Xie *et al.*, 2024). Thus, it is fundamental to comprehend the rheological characteristics of the wheat flour–water system to improve food manufacturing process control and produce high-quality final goods (Sangpring *et al.*, 2017).

Additionally, the dynamic properties of water and its distribution within dough are important because they can influence its machinability and rheological behavior.

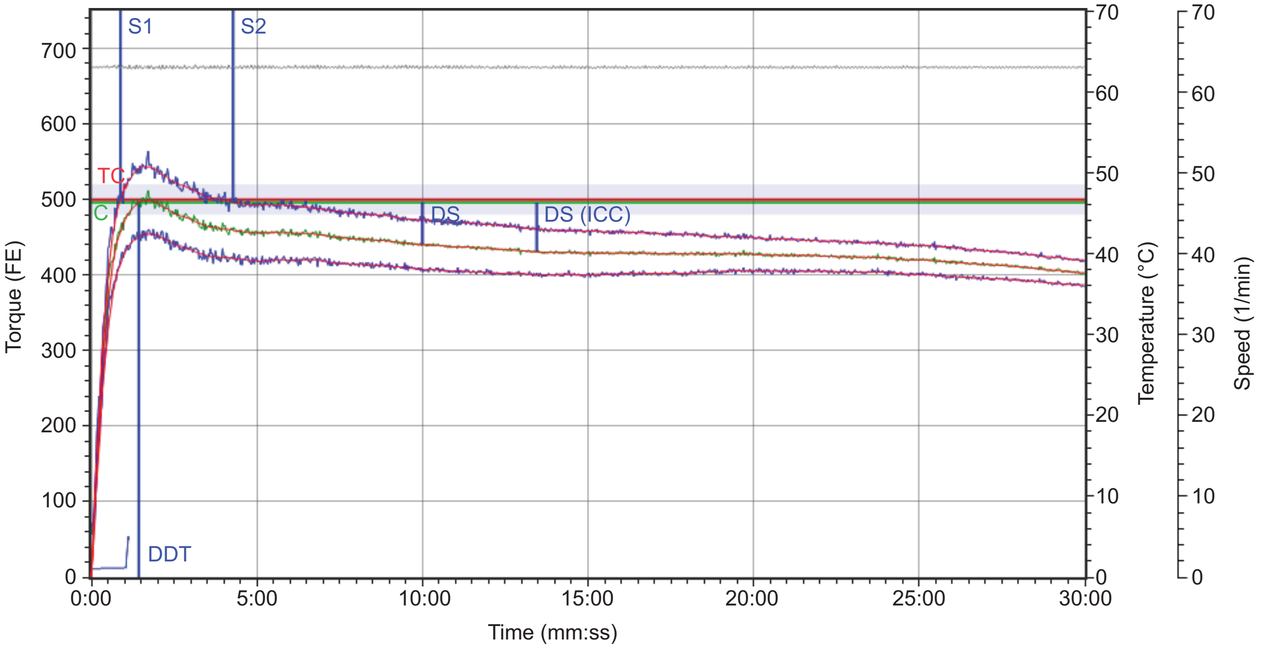

Figure 1. Typical Brabender Farinograph output. DDT: development time of dough; DS: degree of softening 10 min after beginning; DS (ICC): degree of softening 12 min after beginning; S2-S1: stability, and C: consistency.

In this perspective, nuclear magnetic resonance (NMR) spectroscopy is one of the most powerful and versatile analytical techniques that is applied to liquid and solid materials, and it has become increasingly popular in the field of food science for the evaluation and analysis of several foods (Sobolev *et al.*, 2019). The nondestructive character, high accuracy, ease of use, and reproducibility make NMR a very interesting technique in the field of food characterization (He *et al.*, 2020). NMR spectroscopy provides reliable information on water and biopolymer mobility, especially in starch-based systems (Hatzakis, 2019). Modification from flour to bread is a complex process in which several transformations take place, including those associated with changes in water distribution. Knowing the distribution of water in dough can be useful to understand the development of microscructure of dough, the interaction of different ingredients, and the gluten structure (Fanari *et al.*, 2021).

Water quality also plays an important role in defining dough properties. For example, water hardness influences the rheological parameters of dough and its mixing behavior as well as the stability of dough and the Farinograph Quality Number (FQN) (Ștefan *et al.*, 2015). In fact, the hardness of water affects the mixing performance of flour because it increases the time required for mixing and consequently the total energy consumption. In addition, the pH of water contributes to the formation of viscoelastic network of gluten and the development of dough. In a recent study conducted by Sana *et al.* (2022), the use of water with a pH from 9.0 to 9.8 resulted in lower gas production and longer baking period because of the inhibited activity of lactic bacteria, yeast, and diastasis. Water with slight acidity (i.e. pH 5.97) is required because alkaline water negatively affects the shape and plasticity of gluten.

The method used to add water can impact the rheology of dough. Water must be added gradually to allow for the hydration and lubrication of water-soluble ingredients and the development of an optimal gluten structure. Yang *et al.* (2019) reported that the dough obtained by adding water for three times had the largest consistency coefficient, relaxation modulus, and the smallest flow behavior index and creep compliance, thus exhibiting well elasticity and poor viscosity than the dough obtained by adding water to flour all at once.

As far as sensory evaluation is concerned, Mastromatteo *et al.* (2013) showed that by increasing the water added to dough, the only parameters acceptable were color and appearance. The textural qualities of loaf worsened, and its volume collapsed due to the high content of water, giving the appearance of a flat and unevenly distributed loaf filled with large bubbles. Thus, the amount of water added to dough influences the microstructure of dough, which, in turn, affect sensory attributes, such as texture and crumb structure of bread.

Salt

The level of salt used in Italian artisanal and industrial bread is between 0.7% and 2.3% g/100 g (as is basis), with a mean value of 1.5%. Therefore, bread is considered as one of the key contributors for dietary salt intake, accounting for approximately 25% of the total salt consumption (Carcea *et al.*, 2018; Jessen *et al.*, 2022).

Salt affects the breadmaking process in both technological and sensory aspects. The technological effect of salt in dough is easily explained through the rheological measurements of dough. Nurmilah *et al.* (2022) compared salted wheat doughs using the Farinograph and found that dough with 1–2% added salt had an increase in peak time (i.e. increase in dough strength), with decrease in water adsorption (i.e. a decrease in water binding). These results were also reported by Beck *et al.* (2012) on dough prepared without salt that showed significantly lower Farinograph stability than a dough containing 10–20-g salt kg^{-1} wheat flour. No significant differences were observed within the range 10–20-g salt kg^{-1} wheat flour whereas a further increase in Farinograph stability was observed at salt levels of as high as 30–40-g kg^{-1} wheat flour. In addition, the effect of increasing mixing time is to increase loaf height and improvement to the overall bread quality. Lynch *et al.* (2009) used an extensograph to define extensibility and resistance to the extension of doughs containing 0%, 0.3%, 0.6%, and 1.2% salt. It was found that doughs that contained 0.3–1.2% salt did not differ significantly in their resistance to extension (R_{max}) and extensibility (E'). However, dough containing 1.2% salt significantly differed from dough without salt. These results suggest that removing salt affects dough extensibility. According to McCann and Day (2013), dough prepared with 0.05–0.10 M of salt had higher strength than dough with no salt. Additionally, it increases optimum mixing time and stability of dough, enhances its texture, decreases staling, and increases the microbial shelf life of bread by lowering water activity (a_w). Moreover, salt concentration influences the sensory acceptability of bread in terms of taste, improves its flavor and produce brown color of the crust (Pasqualone *et al.*, 2019).

Salt is crucial for the proper development of dough structure. Specifically, interaction of salt with gluten is pivotal to form a high-quality breadcrumb. Gluten protein consists of about 40% hydrophobic amino acids (mainly leucine and isoleucine) and a low proportion of charged amino acids at protein surface. In the presence of salt, some of the charges on these external amino acids are shielded, thus reducing protein hydration. This decrease in protein surface charge reduces electrostatic repulsion among protein molecules, allowing them to interact more closely through strong hydrophobic interactions, thus increasing protein intermolecular β-sheet structure (Silow *et al.*, 2016a).

A reduction in salt levels in dough leads to a weakening of gluten network, increasing dough stickiness. During the industrial manufacture of bread, this could stop processing lines, leading to downtime and wastage. Moreover, the adhesiveness decreased significantly as soon as a small amount of salt (0.35% d.b.) was added (Silow *et al.*, 2016b). On the contrary, Beck *et al.* (2012) reported a decreased dough stickiness with decreasing salt concentration (from 40 to 0 g/kg flour) in bread dough.

Insufficient or an excessive amount of salt in dough could be undesirable. Bread without saltis perceived as tasteless and has yeasty and sourdough-like flavor (Diler *et al.*, 2016). The study conducted by Pflaum *et al.* (2013) revealed that an increase in salt level leads to a decrease in floury/watery, yeasty and musty flavors. It improves the mobility of reactants, enhancing Maillard reactions, and producing a darker-colored crust (Moreau *et al.*, 2009). Conversely, baked bread lacking salt shows a lighter-colored crust (Bredariol and Vanin, 2022).

Recent studies have demonstrated that the excess of sodium intake is a risk factor of chronic diseases, including cardiovascular diseases, hypertension, stroke, kidney diseases, and other noncommunicable diseases (Dunteman *et al.*, 2021). Nevertheless, a report on reduced sodium intake published by the World Health Organization (WHO) revealed that the world is off-track to meet its targeted reduction of 30% by 2025. The global situation regarding salt reduction remains disturbing (Nie *et al.*, 2024). Different salt reduction strategies (e.g. sodium-free mineral salts, hollow salts, uneven salt distribution, amino acids, and plant-based salt boosters) had been assessed to reduce sodium content in wheat bread. Despite their potential efficiency to partially simulate the technological and sensorial characteristics of salt in wheat breads, challenges still exist that restrict their diffusion in the baking industry. In fact, these ingredients do not have the same salt functionality on dough rheology, yeast fermentation rate, control of water activity, inhibition of microbial growth, and salty taste of bread (Codină *et al.*, 2021; Pashaei *et al.*, 2022).

Flour improvers

Flour treatment agents (also called improving agents or dough conditioners) are food additives that are usually combined with flour to improve baking functionality. These are divided as enzymatic and non-enzymatic flour improvers. Non-enzymatic enhancers are added for emulsifying or oxidizing process, such as emulsifier and ascorbic acid. In contrast, enzymatic enhancers are divided into endogenous and exogenous. Endogenous enhancers are present naturally in cereals or are produced during fermentation by microorganisms. The most common are α-amylases, β-amylases, lipases, phosphatases, and oxidases. On the other hand, exogenous enhancers are added to flour to increase its functional and processing characteristics (Liang *et al.*, 2023; Skendi *et al.*, 2021). Proteolytic enzymes are included to modify the rheological properties of dough, particularly their extensibility and to decrease mixing time (Tebben *et al.*, 2018).

However, enzymes and improvers added intentionally to flour must comply with current legislations. If the enzymes are without functional impact on the final product, then they are considered processing aids. Alternatively, they must be listed on the label as food ingredients (Regulation (EC) No. 1333/2008; European Union (EU), 2008). Generally, flour improvers are used to accelerate production processes, adjust the viscosity of dough, allow optimal processing, give resistance to dough during fermentation, improve the structure of crumb, delay the aging of bread, and making dough more extensible. In particular, some of them have an impact on the rheological properties of flour and dough. For instance, oxidizing agents such as ascorbic acid and dry gluten enhance the oxidizing process that takes place in dough and are used to strengthen the gluten network. They create disulphide bonds between individual gluten molecules, resulting in increased resistance of dough and reduced extensibility. In addition, oxidizing agents and ascorbic acid determine an increase in the ability of dough to retain gas and have a noticeable influence on texture, layer formation, mouthfeel, handfeel, and the overall quality of bread. In the case of medium-quality flour types, with strength, $W > 180$, the addition of 50–70 ppm of ascorbic acid is sufficient. Above this threshold, ascorbic acid no longer exert improvement effect (Baratto *et al.*, 2015).

On the contrary, to reduce the strength of flour, protease or cysteine are used. Adding L-cysteine hydrochloride and potassium metabisulphide weakens dough and increases its extensibility. Increased content of reducing agent results in very soft bread lacking the usual chewiness. The effect of L-cysteine on strong, medium, and weak flour varieties is tested (Stoica *et al.*, 2010). Addition of L-cysteine to flour with strong gluten strength improved dough handling characteristics and bread quality (loaf volume and firmness of crumb). As reported by Tozatti *et al.* (2020), addition of L-cysteine to flour varieties with strong gluten reduced mixing time (by up to 47%), and increased loaf volume (by up to 9%) and elasticity of the product, which are the desired characteristics needed to increase the efficiency of breadmaking process.

Among non-enzymatic dough improvers, emulsifiers are surfactant composites used in breadmaking for their ability to stabilize dough through their interactions with gluten proteins. During mixing, the use of emulsifiers increases strength and extensibility of dough; in the fermentation stage, they improve gas retention and avoid dough collapse (Garzón *et al.*, 2018). Studies confirmed the effect of different emulsifiers on breadmaking process, specifically for improving the structure of bread (Garzón *et al.*, 2018). The most used emulsifiers are diacetylated tartaric acid esters of monoglycerides and diglycerides of fatty acids (DATEM) and sodium stearoyl-2-lactylate (SSL) (Gaupp and Adams, 2014). They are usually added up to 0.3% of flour weight in a variety of bread and fermented products (Cauvain, 2020). When added to dough, they improve mixing tolerance, gas retention, resistance of dough to collapse, improves loaf volume (Selomulyo and Zhou, 2007), and endow crumb with a resilient texture, fine grain as well as good slicing properties. Lecithins are a group of naturally occurring complex phospholipids (Cauvain, 2020), and are reported to reduce bread staling (Younus, 2019).

One of the most widespread enzymes used in breadmaking is α-amylase (Tebben *et al.*, 2018). In wheat flour, α-amylases are absent while β-amylases are present in abundant quantity, but they have little or low activity. For this reason, α-amylase is often added to wheat flour to maximise amylase activity. It degrades starch polymers and is employed to promote fermentation, improve texture, increase loaf volume, and decrease bread staling. Nowadays varieties of amylases produced by plants, animals, and microorganisms are commercially available. Dahiya *et al.* (2020) reported that adding fungal and bacterial α-amylases increased specific loaf volume. The addition of α-amylases greatly influences fresh crumb hardness, causing its decrease from 24.14 kPa for control bread to 19.27 kPa and 16.78 kPa for bread with fungal and bacterial α-amylase, respectively. Chen *et al.* (2021) showed that the supplementation of maltogenic amylase did not affect specific volume (3.1 ± 0.1 mL/g), compared to the control bread (2.8 ± 0.1 mL/g). In contrast, a substantial increase in specific volume (3.4 ± 0.1 mL/g) was observed in the bread containing maltotetraose-producing amylase. In addition, compared to maltogenic amylase, maltotetraose-producing amylase demonstrated a better antistaling ability.

In bread formulation, enhancers are often mixed to exploit their synergistic effect. The combined action of ascorbic acid and two commercial enzymatic complexes containing amylase and xylanase/amylase was analyzed to determine their impact on dough rheology and bread quality. The formulation that showed the best dough rheology results was 0.01% xylanase/amylase and 200 ppm of ascorbic acid. It produced good bread characteristics, such as a large volume (Baratto *et al.*, 2015). Similar results were found by Mohamed *et al.* (2019) on the combination of ascorbic acid and amylase in bread formulation by improving rheological and sensory properties of the finished product.

Moreover, the addition of an enzyme cocktail of α-amylases, xylanases and cellulases at 2% concentration to weak wheat flour significantly improved its alveograph characteristics by decreasing the tenacity (P) and extensibility (L) (P/L) ratio from 2.45 to 1.41 and significantly increasing its dough-baking strength from 196.67×10^{-4} J to 368.31×10^{-4} J. Furthermore, the use of enzyme cocktails increased the brown color of bread crust and improved its texture profile (Hmad *et al.*, 2024).

Mixing

One of the essential unit operations in the baking industry is mixing. It increases homogeneity by minimizing phase separation or unevenness in mixtures of multiple components (Cappelli *et al.*, 2020). The ingredients are first dispersed, then the flour particles start to hydrate, and the protein aggregates in the flour are sheared and stretched over time (Biesiekierski *et al.*, 2017; Mirsaeedghazi *et al.*, 2008). The viscoelastic network of gluten is possibly prepared by the hydration of flour and the application of mechanical energy. The dough receives mechanical energy from the mixing component in the form of tension, elongation, compression, and shearing (Yazar, 2023). In particular, during mixing, the strains applied on dough have a substantial impact on the molecular arrangement of gluten. The dough gradually becomes coherent and exhibits elasticity, plasticity, and viscous properties (Chin and Martin, 2014).

Common empirical rheological measurements at large deformation are conducted to determine the mechanical behavior of dough during the mixing process. At small deformations, where the dough responds in a linear viscoelastic manner, the storage and loss modulus (G' and G'') are indicative of elastic and viscous properties of dough and define its fundamental rheological behavior (Hardt *et al.*, 2014; Sun *et al.*, 2022). However, this linear viscoelastic behavior occurs only at small amplitudes of shear strain, that is, $\gamma \leq 0.2\%$ (Leroy *et al.*, 2010). At higher strain amplitudes, G' and G'' display nonlinear viscoelastic behavior. Currently, LAOS has gained increased interest as a method to describe the behavior of food because of its ability to simulate industrial processing conditions (Yazar *et al.*, 2016). Correlation between the behavior of dough and the structure of finished product is assessed by empirical and fundamental rheological tests. For example, empirical rheological studies have reported a positive correlation of crumb uniformity to dough extensograph parameters, that is maximum resistance to extension and the ratio of resistance to extensibility (Horvat *et al.*, 2008). Other studies demonstrated a positive correlation between dough extensibility and loaf volume (Janssen *et al.*, 1996). Fundamental rheological studies have reported an inverse and nonlinear relationship between loaf volume and dough dynamic rheological parameters, specifically storage modulus, G' ($r^2 = 0.75$) and loss modulus, G'' ($r^2 = 0.72$) (Van Bockstaele *et al.*, 2008a). Moreover, loaf volume is also correlated with creep-recovery measurement parameters. For example, the instantaneous recovery of dough was positively correlated with loaf volume ($r^2 = 0.66$) (Van Bockstaele *et al.*, 2008b). Hence, empirical and fundamental tests are crucial for a complete understanding of rheological properties of dough.

Although very useful and performed on-line, torque, power, and consistency measurements are limited to the description of the evolution of the physical properties of dough. They do not provide information about the chemical modifications of dough during the mixing–structuring step. However, these chemical properties are assessed through spectroscopic investigations. Spectroscopy (Fourier Transform Infrared Spectroscopy [FTIR] or Raman) is an upcoming technique regarding the dough characterization field because the measurements are easy to perform and, at the same time, give both qualitative and quantitative chemical information about dough microstructure. In fact, it is possible to correlate gluten protein structures on a molecular level to the macroscopic rheological properties of dough (Fanari *et al.*, 2022; Jerome *et al.*, 2019; Koksel *et al.*, 2016).

As reported by Lancelot *et al.* (2021), among the spectroscopic methods available, both Infrared and Raman spectroscopies can determine changes in the secondary structure of proteins, although Raman spectroscopy also provides information on peptide backbone and the geometry of disulphide bonds. The intermolecular disulphide bonds are decisive in the structural evolution of dough during mixing and for the stability of gluten network, and need to be monitored during processing of bread.

The mixing phase is crucial in breadmaking process and all bakery ingredients are processed with care because correcting a failed dough is impossible. For these reasons, it is necessary to pay attention to every processing parameter that can be controlled and modified to achieve a standardized and optimized production process. In particular, mixing parameters, such as mixing speed, dough temperature, and mixing time, strongly impact the technological and sensory properties of bread (Mollakhalili-Meybodi *et al.*, 2023).

Mixing speed

During the mixing phase, part of the mechanical energy used for the rotation of mixer is released as heat. It spreads throughout dough and air (Canja *et al.*, 2014). This energy facilitates the gluten network development and contributes to the rheological properties of dough, in particular its capacity to retain gas. Many studies have underlined the influence of mixing speed on the aeration of dough (Campbell and Martin, 2020; Peighambardoust *et al.*, 2010). The combined effects of gas production and retention largely determine loaf volume, crumb structure, and the texture of bread. In particular, bread volume is a key determinant of bread quality, with higher volumes usually being preferred (Cappelli *et al.*, 2020). During mixing, dough becomes increasingly resistant to the formation of gluten network, and sustaining the rotation speed demands more power until the gluten network achieves its maximum cohesion. Conversely, overmixing of dough results in the weakening of gluten network, which consequently leads to a sticky texture and the loss of its viscoelastic properties. Even a slight undermixing can result in small, unmixed regions that interfere with the proofing phase. To allow complete development of dough, it must be mixed for a good period (Parenti *et al.*, 2021). Although the mixing speed greatly impacts bread quality, few and contradictory effects are reported in literature about this issue. Laboratory simulation through Farinograph (Connelly and McIntier, 2008) and high-speed mixing (Wilson *et al.*, 2001) are conducted to establish correct mixing rate. Moreover, micro-dough lactic acid bacteria (LAB) was tested to predict dough quality, because the possibility of varying mixing speeds (low speed, 63 rpm, and medium–high speed, 120 rpm) provide better comparison with industrial conditions. Results obtained with micro-doughLAB operating at high mixing speed had larger numbers of strong correlations with quality parameters, such as dough elasticity and mixing tolerance index, of bread produced in high-speed mixer (Torbica *et al.*, 2019).

Sangpring *et al.* (2017) observed that mixing speed had an impact on dough development; specifically, dough consistency increased with increase in dough speed. The same result that increase in mixing speed increased dough consistency, irrespective of mixing temperature, was discovered by Pastukhov and Dogan (2014). The effect of mixing speed is a variable that changes the rate of energy supplied to the developing dough (Haegens, 2014). The studies conducted on wheat flour reported that to achieve dough development, mixing intensity and the amount of work imparted to dough should be above a minimum critical level, which changes with relation to the flour type (Connelly and McIntier, 2008). Increasing the mixing speed resulted in reduced dough mixing stability (Hwang and Gunasekaran, 2001), an increase in dough peak torque (Chin and Campbell, 2005), and a decrease in mixing time (Brabec *et al.*, 2015). However, as demonstrated by Venturi *et al.* (2022), the set speed parameters vary depending on the mixer; different machines could not have comparable mixing speeds.

Dough temperature

The best performance in bread processing is achieved by monitoring dough temperature. Mixing temperature between 29°C and 30°C is the American Association of Cereal Chemists International's (AACC, 1995 standard temperature for producing straight-dough bread (approved method AACCI 10-10.03) and for Farinographic test (approved method AACCI 54-21.02). Although these conditions are important to provide adequate environment to enzymes required for various biochemical reactions needed to produce the desired end results; mixing kneads at 30°C appears as underdeveloped and produces insufficient cooking results. Thus, mixing at 22°C is preferable (Thanhaeuser *et al.*, 2014). Dough mixed at temperatures below 30°C require a longer mixing time to reach the same stage of development as the dough mixed at 30°C (Thanhaeuser *et al.*, 2014). The temperature of dough is managed by either controlling the temperature of the ingredients added to dough or using cooling methods applied to dough. There are several types of mixers in the baking industry. During intense dough mixing, the blades of mixer either pushes the dough toward chamber walls or cuts through it, raising the temperature of dough because of friction. Higher temperatures can lead to irreversible protein denaturation. In high-speed dough mixers, the process is accompanied by a rise in dough temperature of 5–7°C and, in super-high-speed mixers, this increases to 10–20°C (Bayramov and Nabiev, 2019). The production of dough at low temperatures requires additional expenses to maintain temperature, such as water jackets, flour pre-cooling, and cooler room temperature. The obtained dough is less sticky and the bread produced has a higher specific volume and better grain consistency than those produced at conventional mixing conditions (Quayson *et al.*, 2016). Cappelli *et al.* (2020) assessed the effect of addition of CO_2 snow on dough thermoregulation and bread characteristics. Their study found that the addition of high percentage of CO_2 snow (up to 10% of flour weight) maintained a low dough temperature during mixing, and led to increased bread-specific volume and loaf height. The studies conducted by Quayson *et al.* (2016) also indicated that mixing temperature had a significant effect on protein structure characteristics and dough quality. The mixing temperature was observed to have a greater impact on dough consistency and stability than the mixing speed (Muchová and Žitný, 2010; Sangpring *et al.*, 2017).

A low dough temperature during mixing appears to be essential to guarantee correct dough development and bread quality. Low dough temperature improves gluten development because it strengthens and increases hydrogen bonds, which are crucial for preserving and enhancing the network (Cappelli *et al.*, 2020). Farahnaki and Hill (2007) estimated the effect of temperature on dough rheology. The authors tested five levels of dough temperature (20°C, 25°C, 30°C, 35°C, and 40°C). In particular, an increase in temperature decreases the consistency of dough and the hydration time measured by Farinograph.

Başaran and Göçmen (2003) investigated the effects of low-temperature mixing (17°C) versus high-temperature mixing (30°C). The authors showed that the highest loaf volume and the best crumb structure were determined in the bread prepared with dough mixed at 17°C. From the technological point of view, the dough became harder and firmer and reached a higher water absorption value with decreasing dough temperature.

Mixing time

The full breadmaking potential of dough is achieved only at an optimum point of dough development (Calderón-Domínguez *et al.*, 2004). The term 'dough readiness' is used to define a specific dough status, which is characterized by the optimum development of gluten network, meaning that wheat dough under the best physicochemical conditions provides an end product with the desired characteristics. Despite high differentiation in bread typologies, in literature the dough readiness is commonly evaluated using standard quality parameters of dough and bread. The evaluation of dough quality mainly relies on rheological properties whereas bread quality is usually evaluated in terms of specific volume and crumb texture. The peak of dough consistency, and the maximum loss and elastic moduli are the parameters associated with optimal dough development.

During mixing, bread ingredients affect optimal kneading time. Parenti *et al.* (2021) observed different peak torque and work inputs for the Farinograph standard recipe (wheat flour and distilled water), compared to commercial bread recipes. When dough reaches its optimal mixing point, resistance to extension decreases and it starts to break down. As dough breaks down, it becomes wet and sticky and is considered as overmixed (Zghal *et al.*, 2001). Extending the mixing time shows an increase in the values of textural parameters, that is the hardness, adhesiveness, cohesiveness, and consistency of dough. A decrease in these parameters was observed with a further extension of mixing time. When dough is overmixed, there occurs a decrease in the amount of protein aggregates caused by physical disruption of aggregates or chemical breakdown of covalent and noncovalent bonds, and disruption of disulphide bridges caused by a shear stress, leading to the formation of thiol radicals (Krekora *et al.*, 2021; Yang *et al.*, 2024).

Brabec *et al.* (2015) studied the effect of overmixing and undermixing on the final volume of bread loaf. Mixing over the peak for more than 40 s resulted in baked loaf volume losses of 20–60 cm^3. Higher mixing period resulted in smaller average loaf volumes. Moreover, after reaching optimal dough development, additional increase in mixing time led to a decrease in G' and G'' but an increase in tan δ. Therefore, overmixing increases dough softness and decreases dough elasticity (Joyner, 2021).

Considering the results obtained by rheological tests at small strains, the behavior of dough is scarcely affected by mixing time. Instead, the effect of mixing time is observed most clearly at larger strains. Indeed, the gluten network is largely responsible for the behavior of dough at larger strains (Tronsmo *et al.*, 2003). For this reason, the effect of mixing time on G' and G'' curves is very limited: linear rheological tests are not very sensitive to differences in gluten network (Meerts *et al.*, 2017). According to Peighambardoust *et al.* (2006), as mixing time increases, there is decrease in the strength of dough and the degree of strain-hardening. As with linear oscillatory tests, the linear creep tests fail to perceive any substantial differences between doughs mixed for different mixing periods. The effect of mixing period only becomes clear in nonlinear creep tests, as only these tests besides the nonlinear extensional tests adequately investigate the response of gluten network (Sun *et al.*, 2022).

The effect of mixing time on the rheological properties of dough and consumer acceptability was investigated. As shown by Adebowale and Alokun-Adesanya (2022), time taken during mixing phase in breadmaking varied from 10 to 50 min; however, a preference was observed for bread produced from dough that was mixed for 20 min.

Mixing conditions are crucial. Although mixing the ingredients is the most decisive step in determining the final characteristics of the baked product, this relation has not been adequately explored in literature. As shown in the study conducted by Rozyho (2014), the effect of change in process parameters on bread during mixing is determined only through instrumental tests, such as texture analyzer, neglecting sensory analysis. Table 2 summarizes the impact of principal processing conditions and the most common ingredients used in bread recipes on technological and sensory properties.

Leavening

Generally, two categories of leavening agents are used in the bakery industry: chemical and biological (i.e. baker's yeast or sourdough) (Taglieri *et al.*, 2020).

Table 2. Impact of formulation and processing parameters on bread characteristics.

Ingredients / Processing parameters	Limits	Technological effect	Sensory effect	References
Particle size of wheat flour	<125 µm	↑ dough development time; ↑ dough stability; ↓ resistance to extension.	soft texture; ↑ sensory characteristics.	(Mirza Alizadeh *et al.*, 2022)
	>150 µm	↓ dough development time; ↑ water absorption level; ↑ resistance to extension.	dense crumb grain; ↓ overall sensory quality.	(Mirza Alizadeh *et al.*, 2022; SAKHARE *et al.*, 2014)
Water	From 44% to 34%	↑ peak time; ↑ dough consistency; ↑ G' and G".	compact crumb with small bubbles; ↑ crust firmness.	(Hardt *et al.*, 2014; Mastromatteo *et al.*, 2013)
	≈ 74%	↓ dough consistency; ↓ G' and G".	↓ loaf volume; Irregular crumb structure with large bubble.	(Mastromatteo *et al.*, 2013)
Salt	0%	↓ dough strength; ↓ dough stability;	tasteless; ↑ yeasty and sourdough-like flavours.	(Diler *et al.*, 2016)
	1-2%	↑ peak time; ↓ water adsorption; ↑ dough stability.	↑ darker colour crust; ↓ floury and yeasty flavours.	(Moreau *et al.*, 2009; Pflaum *et al.*, 2013)
Wheat bran	From 0 to 12%	↑ dough development time; ↓ stability time; ↑ weakening degree; ↑ water absorption of dough.	↑ crumb firmness ↓ specific volume ↑ dark crumb ↓ overall acceptability	(Hemdane *et al.*, 2016; Navrotskyi *et al.*, 2019)
Ascorbic acid	50-70 ppm	↑ dough strength; ↑ dough elasticity of the dough.	↑ hardness; ↓ handfeel; ↓ texture; ↓ mouthfeel.	(Baratto *et al.*, 2015)
L-cysteine hydrochloride	—	↓ resistance to extension; ↓ extensograph area; ↑ extensibility.	↓ hardness; ↓ texture; ↓ chewiness.	(Baratto *et al*., 2015)
α-amylase	–	↓ dough stability; ↓ Mixograph peak height.	↓ bread hardness; ↑ bread volume; ↑ crumb structure.	(Blaszczak *et al.*, 2004; Chen *et al*., 2021; Tebben *et al*., 2018)
Mixing speed	High (i.e 200 rpm)	↓ dough stability; ↑ dough consistency; ↑ peak time.	↑ loaf volume; ↑ crumb texture.	(Cappelli *et al.*, 2020; Sangpring *et al*., 2017; Torbica *et al.*, 2019)
	Low (i.e 63 rpm)	↓ dough consistency;	↓ loaf volume	Cappelli *et al*., 2020; Sangpring *et al.*, 2017; Torbica *et al*., 2019
Dough temperature	17°C	↑ water absorption level; ↑ dough development time; ↑ dough consistency.	↑ crumb texture; ↑ loaf volume.	Campbell *et al.*, 2020; Cappelli *et al.*, 2020
	30°C	↓ dough consistency; ↓ water absorption time.	↓ loaf volume	Campbell *et al.*, 2020; Cappelli *et al.*, 2020
Mixing time	overmixing	↓ dough consistency; slack and sticky dough.	↓ loaf volume	Canja *et al.*, 2014; Connelly *et al.*, 2008
	undermixing	↑ dough consistency; ↓ leavening ability.	↓ loaf volume	Canja *et al.*, 2014; Connelly *et al.*, 2008

↑: increase; ↓: decrease.

Chemical leavening is used for several products, such as quick bread, cakes, and cookies because a long fermentation is undesirable or impractical. Chemical leavening agents are compounds that release gases when they react with each other, moisture, or heat. Most of them are based on a combination of acid (usually an LMW organic acid) and a bicarbonate salt (HCO^{3-}). The primary role of leavening acids is to produce CO_2 and neutralize sodium bicarbonate. They also have a secondary effect, affecting the taste, texture, and other organoleptic characteristics of baked goods. Van der sman (2021) showed the impact of the use of each leavening acid on the pH variability of dough, volume, texture, and color of bakery products. Moreover, excess acid could provide a bitter aftertaste to end products (Neeharika *et al.*, 2020; Reiss, 2021).

Biological leavening involves the use of biological agents, such as microorganisms. Bread is typically prepared using commercial yeast, a single strain of *Saccharomyces cerevisiae* spp. added to dough to help it swell. However, traditional breadmaking methods use sourdough, which consists of spontaneous fermentation of dough with yeast and LAB available in flour or in the environment. During the biological leavening stage, yeast (*Saccharomyces cerevisae* spp.) convert fermentable sugars of the flour into alcohol, CO_2, and aromatic compounds. The alcohol formed, which is water-miscible, influences the colloidal nature of wheat proteins and alters interfacial tension in dough. In addition, CO_2, which partly dissolves in the aqueous phase of dough, migrates toward the initial nuclei of the air bubbles formed during mixing, causing their growth. The growth of gas cells depends on cell size and dough composition (Romano *et al.*, 2007). The gluten network lends dough the ability to entrap gas bubbles and subsequently form a stable foam structure. In particular, the number and size of bubbles formed during the mixing phase can change the ability to retain gas in the leavening phase. Bread contains about 70% gas that comes from the initial aeration and fermentation that affect dough rheology (Trinh, 2013). Research done by by Chin *et al.* (2009) on measuring the rheology of aerated dough suggested that gas bubbles in dough interrupt the integrity of dough structure, thus confirming the presence of aeration effect on the rheology of dough and establishing a relationship between rheology of dough and aeration as a two-way relationship (Upadhyay *et al.*, 2012).

During the leavening phase, metabolites are produced *in situ* and their concentrations change over time. Yeast activity results in a very complex system that is challenging to characterize from both microstructural and rheological point of view. Although their mechanisms were demonstrated to be significantly different, the most important yeast metabolites soften the unfermented dough. Ethanol, succinic acid, and glutathione radically change the gluten network structure whereas glycerol only had a diluting effect (Meerts *et al.*, 2018).

Furthermore, longer leavening time increases by about 30% the nonlinear mechanical response of wheat dough, an effect probably induced by variations in the secondary structure of wheat proteins and to the gassing of dough microstructure because of yeast metabolic activity. Consequently, LAOS is a suitable method for the characterization of nonlinear mechanical response of wheat dough, especially for assessing the effect of processing conditions (e.g. leavening time and yeast content) (Alvarez-Ramirez *et al.*, 2019).

Because of its technological qualities, Baker's yeast—a commercial term for a yeast strain derived from *Saccharomyces cerevisiae* spp.—is the bakery sector's most common biological leavening agent. Commercial yeast strains are selected industrially for their performance, fermentation power, and flavor development (Islam *et al.*, 2024).

One benefit of using Baker's yeast is that it helps to simplify the production process, maximize yields, and reduce costs (Van Der Sman, 2021). Different factors affect the fermentative performance of yeast cells during dough fermentation, including dough ingredients, fermentation conditions, the type of yeast strain used, and yeast growth conditions (Struyf *et al.*, 2017). They are mainly marketed as fresh compressed yeast, dry active, and instant dry active, differing in appearance because of moisture content (Heitmann *et al.*, 2018). However, in the baking industry, cream yeast is currently the most used type. It is a liquid product and can be transferred into sterile tanks/containers and distributed to bakeries, where it is used to produce yeast-based products. The advantage of cream yeast is that it excludes any human handling, thus reducing the risk of contamination; however, because of its high (water) volume, transportation is expensive (Ali *et al.*, 2012).

During the leavening phase, the choice of yeast produces baked products with different sensory profiles. In particular, sourdough influences the aroma and increases the taste of the finished product (Heitmann *et al.*, 2017; Winters *et al.*, 2019).

The primary chemical groups that contribute to bread crumb aroma are acids, alcohols, aldehydes, esters, and ketones. Flavor and aroma profiles are considered quality parameters during breadmaking because of bread fermentation that modifies bread aroma. The alteration of aroma profiles is primarily caused by genetic variations in *Saccharomyces cerevisiae* strains (Heitmann *et al.*, 2017).

Sourdough is an ancient biological starter that is traditionally used in regional bakery products. This dough, which is prepared of flour and water, is naturally fermented by yeasts and LAB, whose metabolic processes—such as lactic acid fermentation, proteolysis, flavor synthesis, and antimicrobial compound synthesis—have a major impact on the quality of sourdough bread (Rizzello *et al.*, 2019). Gobbetti *et al.* (1995) used a rheofermentometer to investigate the interactions between LAB and yeasts in sourdough. Yeast fermentation in the presence of heterofermentative LAB was faster than that of homofermentative bacteria, and it produced more CO_2, compared to sourdough prepared with yeast alone. The sourdough products had a longer shelf life, a higher flavor concentration, and more elastic dough because of the synergistic growth of LAB and yeasts, compared to other yeast-fermented products (Siepmann *et al.*, 2018). Sourdough fermentation, compared to Baker's yeast, enhanced the rheological qualities of bread, panettone (an *Italian type of sweet bread and fruitcake)*, flat bread (piadina), bread rolls, toast bread, burger buns, pizza, biscuits, cakes, crackers, and puff pastry. Texture (hardness, adhesiveness, resilience, cohesiveness, chewiness, springiness, and gumminess), shape, specific volume, crust and crumb color, moisture, retention, and crumb structure were the main points of improvement. On the other hand, microorganisms utilized moisture, air, and nutrients during proofing to produce metabolites, such as ethanol, organic acids, and exopolysaccharides (EPS), which had significant effects on gluten networks and ultimately altered the rheology of dough (Zhang, 2023).

Notable variations are observed between the dough prepared with sourdough and that obtained with commercially compressed yeast. After proofing, the viscoelastic properties of dough change completely; the final rheological characteristics are influenced by the types of fermentation and pH levels. Various factors, such as variations in the quantity or rate of acid production, could be responsible for these changes. The addition of sourdough resulted in a less elastic and firm dough by changing the protein network physicochemically. It is shown that suscinic acid (SA) is the primary cause of dough's acidification and consequent drop in pH. In addition to SA, fermenting dough included acetic and lactic acids. Thanks to the production of these acids and secondary compounds, the bread aroma profiles and crumb structures are more distinctive with compounds associated with sour aromas produced and preferred by sensory panel (Taglieri *et al.*, 2020; Winters *et al.*, 2019; Zolfaghari *et al.*, 2017). Table 3 reports the impact of chemical and biological leavening on the technological and sensory properties of bread.

Lately, the study and characterization of microbial strains showed that even non-*Saccharomyces* yeasts are capable of fermenting bread. As demonstrated by Condessa *et al.* (2022) and Zhou *et al.* (2021), wild yeasts, *S. cerevisiae* SC 5952 and *Candida tropicalis* ART 101.3, have the potential of application as starter cultures in bakery processes because of their desirable characteristics, resulting in bread with a color similar to the control bread, humidity within the established pattern by law, did not produce biogenic amines, and produced a wide range of volatile compounds that improve bread aroma. The consumer acceptance of bread prepared with *C. tropicalis* ART101.3 was similar to the control bread. More than 70% of the consumers demonstrated purchase intention of the bread produced with both wild yeasts.

In order to assess the leavened dough properties, a variety of techniques and instrumentals are developed. Most of the methods applied to examine the flow and deformation of dough and the release of gas are based on rheological techniques, such as rheofermentometer. However, new techniques concerning dough microstructure investigation through or after fermentation with the bases of photographic, radiographic, or microscopic and scanning procedures have been developed (Jekle and Becker, 2011). However, these techniques have some drawbacks, such as limitations in predicting and monitoring fermentation *in situ* because of fluctuating fermentation conditions. Recently, Nazeri *et al.*, (2021) introduced a new device/technique, namely 'fermetron' for online and continuous monitoring of bread dough fermentation by means of in-contact measurement of dough pressure during fermentation.

Baking

Baking is the final crucial phase in bread production. It requires very high temperatures, usually ranging from 160°C to 250°C. During baking, dough undergoes many physical and chemical changes, including water evaporation, dough-crumb transition, formation of crumb and crust, volume expansion, protein denaturation, and starch gelatinization. A non-optimal baking technique and an inappropriate oven temperature can jeopardize all the progress made by introducing innovations in milling and mixing (Cappelli *et al.*, 2021). During the baking process, heat and mass transfer occur simultaneously, and the transformation of fermented dough into bread requires significant structural changes. Temperature influences product quality, affecting enzymatic reactions, volume expansion, starch gelatinization, protein denaturation, non-enzymatic browning reactions, and water migration. During baking, changes in the temperature profiles of dough are determined by several factors, such as size of the product (i.e. crispbread versus bread loaf), ratio between top, side, and bottom heat flow, and expansion of cells which reduces thermal conductivity. The latter allows the transport of water vapor from surface layers to the core, where it condenses and releases energy. During baking, the starch and protein

Table 3. Impact of Baker's yeast and sourdough on technological and sensory properties of bread.

Leavening agent	Compounds produced	Technological effect	Sensory effect	References
Chemical method	CO_2 NH_3	↓ batter density ↓ baking powder ↑ specific volume ↑ porosity	↑ Leavening acid = will leave a bitter aftertaste in the finished product	Van der Sman, 2021
Baker's yeast (*Saccharomyces cerevisiae* spp.)	CO_2 ethanol organic acid glycerol	ethanol, succinic acid, glutathione alter the structure of the gluten network, ↑ softening effect on dough.	Differences in the genes of Saccharomyces cerevisiae strains play a major role in the change of the aroma profiles	ALI *et al.*, 2012; Struyf *et al.,* 2017
Sourdough (Saccharomyces cerevisiae spp. + Lactic acid bacteria)	CO_2, ethanol, organic acid, glycerol helps to produce enzymes such as maltase, invertase and zymase	↓ elastic and firm dough, ↑ bread-specific volume, ↓ crumb firmness over time, ↑ dough expansion during fermentation.	Bread aroma profiles and crumb structure are more distinctive, due to sour aromas produced, and preferred by sensory panels produced	Crowley *et al.,* 2002; Gobbetti *et al.*, 1995; Winters *et al.*, 2019; Rizzello *et al.*, 2019; Siepmann *et al.*, 2018; Zhang *et al.*, 2023; Jayaram *et al.*, 2014

↑: increase, ↓: reduction

modification, as well as changes in dough temperature and moisture, has a significant impact on dough rheology. In the early stages of baking, at temperatures between 26°C and 60°C, dough consistency softens gradually as an immediate effect of weakening of gluten protein (Takacs *et al.*, 2020).

Water content is a key factor because a variation of 4% leads to a modification in viscosity. When dough achieves a temperature of 55–60 C, the process of starch gelatinization and gluten protein aggregation is triggered, viscosity increases rapidly until the dough achieves a temperature of approximately 75°C. In French bread, using differential scanning calorimetry (DSC), dough/crumb transition starts after the beginning of starch gelatinization, but ends prior to the complete melting of starch. Hence, dough stiffening might be more due to gluten aggregation, rather than to the progressive swelling of starch granules (Rouillé *et al.*, 2010).

A further increase in temperature leads to a reduction in dough viscosity related to the breaking up of swollen starch granules and melting of remaining crystallites (Cappelli *et al.*, 2021). Viscosity diminishing is not observed if the moisture content of crust zone decreases below 37% and a long-lasting plateau of viscosity is evident. In the final baking stage when dough achieves a water boiling point, viscosity increases proportionally to the rate of decrease in water content (Cappelli *et al.*, 2020; Purlis, 2011). Completion of the final baking phase is generally estimated by product's two characteristics: color and moisture content for low-moisture products. Concerning the products with high moisture content, color and starch gelatinization allow to evaluate the final cooking process. In addition, the optimized baking conditions affect appearance and the overall sensory preference of consumers. The baking process involves the formation of color of bakery products because of the Maillard reaction and caramelization of sugars. It is responsible for other relevant changes occurring in bread during baking, that is production of flavor and aroma compounds. Therefore, it is essential to correlate baking time and baking temperature with organoleptic characteristics to obtain the best sensory characteristics on finished product (De Kock and Magano, 2020).

Currently, bakery techniques are essential to improve the qualitative and quantitative parameters of bread baking process. Conventional oven baking is a process with high energy consumption. Ohmic heating is an alternative thermal food processing, whereby the electrical resistance of food itself generates heat as the current is passed through it. Different cooking techniques were compared for the qualitative aspects of bread and energy consumption. According to Panirani *et al.* (2023), the maximum values of specific energy consumption and volume expansion of bread were found in the combined Ohmic-conventional method. Chhanwal *et al.* (2015) showed that baked bread in hybrid heating (infrared + electrical) oven had lower crumb firmness, higher moisture content, and volume expansion. In addition, the results revealed that hybrid method had a higher quality score, compared to the conventional baking process. However, these new technologies need to be further explored to understand effects on the characteristics of bread and their industrial feasibility.

Sensory evaluation

Apart from fulfilling nutritional and energy requirements, bread must ensure sensory satisfaction during and after its consumption. In general, the acceptance of consumers is one of the major factors for the success of new bakery products. Sensory evaluation is defined as 'the scientific discipline which encompasses all methods to evoke, measure, analyze, and interpret human responses to the properties of foods and materials, as perceived by the five senses: taste, smell, touch, sight and hearing' (Civille *et al.*, 2012). Food companies to supply bakery foods must employ sensory tools for decision-making during product formulation, evaluation of ingredients, and optimization of technological processes and finished products. Through sensory evaluation, decisions are made whether further improvement is required prior to product marketing (De Kock and Magano, 2020). Sensory evaluation is also pivotal from technological and economic point of view to minimize losses during production, storage, or transportation (Guiné, 2022). Knowing the parameters that mostly influence hedonic aspects during the distribution chain of bakery products allows to work on the optimization of products and reduce waste in the food industry.

Sensory properties are closely dependent on product's texture besides its physicochemical composition and physical behavior. Since the deformation, fracture, flow, and breakdown of food products influence textural sensations, research is focused on investigating the relationship between food rheological behaviors and sensory texture attributes (Pedreschi *et al.*, 2006).

Bread characteristics are affected by numerous factors, including the type and amount of ingredients used as well as processing conditions, such as mixing, resting, and baking. Human sensory evaluation is of considerable interest and a practical way to conceptualize the overall bread quality and to relate its physical and chemical properties with its behavior and perception in the mouth. These characteristics are used to evaluate the completion of baking (Purlis, 2010). In addition, sensory evaluation is the key to determining the shelf life of bread. Consumers are the most appropriate tool to determine as to when a food product reaches the end of its shelf life (Dong, Y.N. and Karboune, S., 2021; Gauchez *et al.*, 2020).

The 'freshness' property of bread is closely associated with the overall quality of bread and only lasts for a brief period (Rosell, 2011). In fact, bread is a perishable product, with a short mould-free shelf life influenced by storage and treatment conditions because of its high-water activity, being generally around 0.95 (Cauvain, 2012). Additionally, bread is characterized by relative softness while maintaining a certain degree of springiness and chewiness of bread crumb cellular structure while having a dry and thin layer of crust enclosed on the exterior (Longin *et al.*, 2020).

Bread quickly deteriorates during storage, associated with a multitude of alterations and changes, including microbial spoilage, textural loss, and off-flavor developments. The evaluation of changes in bread characteristics over time is important for the baking industry as consumers link it to bread quality. A combined approach based on both physical–chemical and sensory markers could be a valid tool to define primary or secondary shelf-life of bread (Rapp *et al.*, 2017; Bianchi *et al.*, 2024). However, sensory evaluation is mainly accomplished for research and formulation of new products, to predict product acceptance on the market, and to test changes in the formulation of added ingredients. Currently, there is a growing interest in the development of functional foods. Bread serves as an ideal matrix to deliver functional compounds by adding new ingredients to bread formulations. Many researchers have assessed the acceptability of these enriched products as well as the technological impact of new ingredients on the structure of the product. Fortification of traditional bakery products by functional ingredients obtained from by-products enhanced their nutritional value (Bangar and Siroha, 2022; Belghith-Fendri *et al.*, 2016; Khan *et al.*, 2024; Martins *et al.*, 2017; Yalcin *et al.*, 2022). However, these new ingredients impair some sensory properties, such as taste and texture. In addition, recently, a great interest has been observed in the field of gluten-free products. These products often have lower-quality flavor and texture than wheat bakery products (de Kock and Magano, 2020; Di Cairano *et al.*, 2022; Tóth *et al.*, 2022). Therefore, the modification and replacement of an ingredient in a recipe requires adequate sensory evaluation to assess the effect of raw material on end product characteristics and consumer acceptance.

Dough is an intermediate product of flour and finished product, and its rheological properties are of crucial importance as they influence the machinability of dough and the quality of bakery products. Variations in the process parameters and rheological properties of dough can decisively modify sensory attributes and the overall sensory product acceptance. As shown in Table 2, the sensory properties are closely related to the formulation and processing conditions of the bread.

Textural properties are analyzed by either instrumental methods or sensory evaluation, or both. Instrumental methods consist of measuring the physical properties using texture analyzer and penetrometer (Angioloni and Collar, 2009; Carson and Sun, 2001; Liu and Scanlon, 2003; Nagy *et al.*, 2007; Young, 2012).

Textural attributes most frequently considered in bread and baked products include hardness, cohesiveness, springiness, and chewiness, provided by instrumental measurements (Guiné, 2022). Hardness is the force necessary to attain a given deformation; springiness is the rate at which a deformed material returns to its original condition after removal of deforming force; cohesiveness is the strength of internal bonds making up the body of the product; and chewiness is the energy required to masticate a solid product to for swallowing (Szczesniak, 2002). However, the data obtained from the cited measurements are subjected to a large variability depending on the experimental procedures adopted. For this reason, it is difficult to compare results of many published reports obtained with different instruments and procedures (Scheuer *et al.*, 2016).

The same attributes can be evaluated through a panel test. Specifically, the sensory texture attributes are hardness, elasticity, cohesiveness and chewiness, characterized using the definition. According to Civille and Szczesniak (1973), hardness is the force required to compress a component between molar teeth; elasticity is defined as the degree to which the product returns to its original shape after being compressed between teeth; cohesiveness is defined as the degree to which a component is fully compressed between teeth before rupturing; chewiness is defined as the time required to chew a sample at a constant speed of force application to reduce it to a proper consistency for swallowing.

Sensory tests are carried out by some panelists/judges, with or without training, in a standard tasting room. In general, sensory evaluation of food is performed by affective (subjective) methods, such as consumers' acceptance test, and analytical (objective) methods. Analytical methods require a trained panel of judges to describe qualitatively and quantitatively the sensory attributes of a product. In this way, product's sensory profile is generated. Descriptive analysis is also used to evaluate the impact of ingredients (different wheat sources, flour quality, etc.) or processing conditions on bakery product's quality. Consumer test, which is reserved for untrained consumers, is the most used method. It is based on understanding the most important purchasing drivers of a product (using a scale) and generally the intention to repeat purchases by consumers.

The choice of the most appropriate sensory test depends on whether the production environment is an industrial facility or a laboratory-scale product stage. Sensory tests offer comprehensive information that is more compatible with customer perception, while instrumental tests yield faster and more accurate results (Callejo, 2011). According to Guiné (2022), the two types of methods (instrumental and sensorial) can be mixed to analyze the textural parameters of bread. The product texture profile can be measured independently by obtaining precise values using instrumental texture analyzers, producing data that are easily interpreted and compared. However, the methods of sensory analysis are adequate to evaluate appreciation and preference of products based on their textural characteristics, besides other sensory characteristics.

Usually, sensory evaluation is accomplished by changing product formulation, such as enrichment with functional ingredients or ingredients derived from industrial by-products or by different amounts of ingredients normally used in dough.

Sensory analysis is employed after changes in process parameters, such as different mixing speeds or different mixing or leavening temperatures. However, these parameters strongly impact the final characteristics of the product because they can alter the release of volatile components, the final aroma, and the chemical interactions between the added components. The characteristics of bread and bakery products can be examined in more detail by using sensory analysis in order to correlate the effects of various processing parameters to the finished quality product.

Conclusions and Future Perspectives

The mixing phase of raw materials, leavening, and baking are the stages that mostly affect the overall quality of bread, besides the choice and appropriate amount of each ingredient in product formulation. They contribute to create a gluten network and texture of dough, responsible for different rheological behaviors. Rheological parameters are well studied in the baking industry, but the relationship between rheology and sensory analysis, despite being closely related, is neglected. This review summarized knowledge of the factors in the baking process that impact the quality of bread, emphasizing both technological and sensory aspects. Many studies have been conducted on the sensory evaluation of bakery products after changing one or more ingredients. In contrast, occasionally, the impact of process parameters on sensory quality of the product is also considered.

In addition, very often, the texture of bread and bakery products is analyzed only through instrumental methods. Although they provide an objective result, they are never able to replace human perception. Multidisciplinary collaborations must make significant advances in the development of fundamental food structure–function–texture relationships. Thus, it is crucial to deepen the topic with new studies dealing with the relationship between the changes in technological parameters and the sensory characteristics of the finished product, besides the overall consumer acceptance.

Author Contributions

All authors contributed equally to this article.

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