The determination of bread dough readiness during kneading of wheat flour: A review of the available methods

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The determination of bread dough readiness during kneading of wheat flour: a review of the available methods

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Corresponding Author:	Lorenzo Guerrini Firenze, ITALY
First Author:	Ottavia Parenti
Order of Authors:	Ottavia Parenti
	Lorenzo Guerrini
	Sara Bossa Mompin
	Mònica Toldrà
	Bruno Zanoni
Abstract:	Bread dough Kneading is one of the most important steps in the bread-making process of wheat flour. The quality of wheat breads mostly depends on the proper development of the gluten network, making the measurement of dough readiness or development a key processing factor. This paper provides a review of both standard and alternative methods of measuring bread dough readiness. Although optimum dough development is commonly measured using descriptive rheological tests (i.e., Farinograph and Mixograph tests), the reference methods showed several limits, resulting in a poor correlation with bread quality. Some alternative methods were proposed considered for a more accurate determination of bread dough readiness and their potentiality is discussed as a function of the field of application. online bread dough monitoring and measuring the dough's chemical properties can be interesting approaches . However, the scant information about alternative methods reported in the literature outlines the necessity to encourage further investigations on this topic.

Lorenzo Guerrini
University of Florence
Piazzale delle Cascine 16, 50144, Florence, Italy
Tel: +39 055 2755932
lorenzo.guerrini@unifi.it

Dr. R.P. Singh
Editor-in-Chief
Journal of Food Engineering

September 10, 2020

Dear Dr. R.P. Singh:

I am pleased to submit an original research article entitled "The determination of bread dough readiness during kneading: a review of the available methods" for consideration for publication in *Journal of Food Engineering.*

This manuscript reviewed the standard and alternative methods of measuring the dough readiness. In the scientific literature it is well-known that dough kneading is one of the most important steps of the bread-making process since the quality of wheat breads mostly depends on the proper development of the gluten network. Therefore, the correct determination of the dough readiness represents a key factor for process control in both academic and industrial areas. This topic could be considered even more important considering the increasing interest in the nutritional value of foods. Indeed, at present time there has been an increasing use of flours with a low degree of refinement as well as flours from different sources (cereals, pseudo-cereals, pulses etc.), which often show poor technological properties, making the control of the kneading step crucial for the quality of the final product.

We believe that this manuscript is appropriate for publication by *Journal of Food Engineering* since the reviewed topic focused on the determination of bread dough readiness during the kneading step, which is at the interface between food and engineering and has particular relevance for the baking industry. To the best of the authors' knowledge this is the first review article that reviewed all the available methods for the determination of dough readiness. The paper also includes a critical evaluation of the reviewed methods, including their potential and most appropriate application in the scientific research and baking industry.

This manuscript has not been published and is not under consideration for publication elsewhere. We have no conflicts of interest to disclose.

Thank you for your consideration!

Sincerely,

Dr. Lorenzo Guerrini
Department of Agricultural, Food and Forestry Systems Management (DAGRI)
University of Florence, Italy

Ms. Ref. No.: JFOODENG-D-20-01887R1

Title: The determination of bread dough readiness during kneading of wheat flour: a review of the available methods

We summarized in the following points the modifications made to the first version of the Manuscript according to the reviewers' comments:

- We tried to address every issue outlined by the reviewers, giving a point by point answer and accordingly modifying the Manuscript;
- The literature research was carried out again. The total number of references cited increased from 57 to 168. Within the new references added, we included 40 references published in the last 5 years. We also included older articles which were considered particularly relevant for the revised scientific topic. In fact, to the best of the authors' knowledge a similar review of the literature has been not performed before, hence we tried to be as most comprehensive as possible. An important outcome showed by the review article is that scant and old information is reported in the current literature about the topic revised. However, the topic is very relevant for artisan and industrial bread-making, hence with this review we would like to encourage further investigation on this topic;
- Paragraph 2 (i.e., Paper selection criteria) and Table 1 (i.e., A schematic representation of the main references obtained from the literature search about wheat dough kneading) were added to the Manuscript, in order to give a clear explanation of the literature search and to ensure literature research replicability;

We used the entire time allowed by the Journal to do our best in the revision of the Manuscript. We think that the Manuscript has been substantially improved from the first version.

Highlights

- Key role of the kneading step for the correct development of bread dough structure
- Bread dough readiness represents the optimal dough development during kneading
- Review of all the available methods to determine bread dough readiness
- Discussion of strengths and weaknesses of the methods for dough readiness
- Evaluation of the potential applicability of the methods to improve process control

Title

The determination of bread dough readiness during kneading of wheat flour: a review of the available methods

Authors

Ottavia Parenti[1], Lorenzo Guerrini[1]*, Sara Bossa Mompin[1,2], Mònica Toldrà[2], Bruno Zanoni[1]

[1] Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, Università degli Studi di Firenze, Piazzale Delle Cascine 16, 50144, Firenze, Italia

[2] Institut de Tecnologia Agroalimentària, Escola Politècnica Superior, Universitat de Girona, Placa Sant Domenec, 3, Girona, Spain

*Correspondence to: Lorenzo Guerrini, lorenzo.guerrini@unifi.it

Tel: +39 055 2755932

Abstract

~~Bread dough~~ Kneading is one of the most important steps in the bread-making process of wheat flour. The quality of wheat breads mostly depends on the proper development of the gluten network, making the measurement of dough readiness or development a key processing factor. This paper provides a review of both standard and alternative methods of measuring bread dough readiness. Although optimum dough development is commonly measured using descriptive rheological tests (i.e., Farinograph and Mixograph tests), the reference methods showed several limits, resulting in a poor correlation with bread quality. Some alternative methods were proposed ~~considered~~ for a more accurate determination of bread dough readiness and their potentiality is discussed as a function of the field of application. ~~online bread dough monitoring and measuring the dough's chemical properties can be interesting approaches~~. However, the scant information about alternative methods reported in the literature outlines the necessity to encourage further investigations on this topic.

Keywords

~~Wheat flour~~, Mixing, Bread-making, Dough development, Process control

1. Introduction

Kneading is one of the most important steps in the bread-making process; in this step, the dough ingredients are mixed homogeneously, the flour constituents are hydrated, the gluten network is formed giving a viscoelastic wheat dough structure, and air bubbles are trapped within the dough matrix (Quaglia, 1984; Pézolet et al., 1992; Cuq et al., 2003; Robertson et al., 2006; Haegens, 2006a; Kokawa et al., 2012; Schiedt et al., 2013; ~~Zhou et al., 2014~~; Cauvain, 2015a,b; Mijnsbrugge et al., 2016; Guerrini et al., 2019; Parenti et al., 2021). The terms "kneading" and "mixing" are often used as synonyms in the scientific literature, even though they actually explain a temporal sequence of physico-chemical phenomena: dough mixing refers to the initial phenomena of homogenization and hydration of the ingredients, whereas dough kneading refers to the subsequent development of the gluten network (Cuq et al., 2003; Haegens, 2006a; Cauvain, 2015a). Following the literature approach, in this review, both kneading and mixing terms are used ~~is used as the term~~ to refer to all of the above phenomena.

Cuq et al. (2003) set out a theoretical state diagram describing the physical changes and phase transitions occurring to the main wheat flour biopolymers during kneading as a function of temperature and water amount. At room temperature, the presence of a sufficient amount of water allows the flour constituents to hydrate; the amorphous polymers (i.e., wheat flour proteins) and amorphous region of the semi-crystalline polymers (starch) achieve glass transition, going from a glassy to a rubbery state (Cuq et al., 2003). Simultaneously, the input of mechanical energy leads to new interactions between the gluten proteins (i.e., gliadins and glutenins) through disulphide bonds, resulting in the gradual development of the gluten network; an optimum structure is reached, but if the mechanical energy is excessive, protein depolymerization occurs (Quaglia, 1984; Cuq et al., 2003; Haegens, 2006a; Cauvain, 2015a,b).

Following the definition proposed by some scientific articles (Perez Alvarado et al., 2016; Rachok et al., 2018a; Hammed et al., 2016; Oliinyk et al., 2020), in the present review the term "dough readiness" is used ~~order~~ to define a specific dough status which is characterized by the optimum development of the gluten network, meaning that the wheat dough is in the best physico-chemical conditions to give an ~~high-quality~~ end product with the desired characteristics. Despite the high differentiation of bread typologies, in the literature dough readiness is commonly evaluated using standard quality parameters of dough and bread. The evaluation of dough quality mainly relays 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 to optimal dough development. The higher the bread specific volume, the softness of the crumb and the fineness of the crumb structure, the higher the product quality (Sahi et al., 2006; Pagani et al., 2014a; Cauvain, 2015c,e). Undermixed dough does not have an optimally developed gluten structure, resulting in doughs with a low gas bubble retention capacity, and low-volume breads with too hard ~~a~~ texture; similarly, in overmixed doughs the gluten network is gradually depolymerized, with an increase in free water, resulting in poor-quality breads (Haegens, 2006a; Kaddour et al., 2007; Cauvain, 2015a,b; Perez Alvarado et al., 2016; ~~Zhou et al., 2014~~). Therefore, dough readiness is a key parameter in controlling ~~the~~ bread quality, a complex concept associated to different characteristics as a function of bread typology ~~bread-making process~~.

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Measuring dough readiness still represents a challenge for both the academic sphere and the bread-making industry. The complexity of obtaining a reliable determination of the optimal dough development is further enhanced by the wide variety of bread-making conditions, which account for the diversification of breads (Haegens, 2006b; Zhang & Chen, 2014; Pagani et al., 2014b; Osorio-Diaz et al., 2014; İnan & Yurdugül, 2014; Cauvain, 2015c,d). Several variables affect dough development, including the technological quality of the flour, the bread dough formula, the operating conditions adopted during kneading, the bread-making method and the environmental conditions (~~Zhou et al., 2014~~; Dobraszczyk & Morgenstern, 2003; Haegens, 2006a; Amjid et al., 2013; Tucker et al., 2014; Cauvain, 2015a,b,e,f).

In the scientific literature and in the baking industry, the reference methods for measuring dough readiness mainly rely on descriptive rheological tests (i.e., Farinograph and Mixograph tests); baking trials and visual evaluation of the dough by expert bakers are also included among the standard bread-making methods (AACC 10-09.01 and 10-10.03). However, the above reference methods have some weaknesses. The experimental data obtained from the descriptive rheological methods are inevitably affected by the operating conditions adopted during the tests, which are different from those used in the experimental trials and the bakeries; as a result, a biased measurement of the dough readiness may give an unexpected bread quality. Baking trials require large amounts of resources in terms of time and ingredients and are affected by several variables that are difficult to control; expert evaluation is also an empirical approach, based on subjective judgements and affected by the baker's personal skills and level of fatigue (Dobraszczyk & Morgenstern, 2003; Haegens, 2006a; Amjid et al., 2013; Tucker et al., 2014; Pagani et al., 2014a; Cauvain, 2015e). Therefore, alternative methods have been proposed, including offline and inline/online techniques, the latter being particularly interesting owing to the possibility of performing real-time monitoring in real ~~experimental and industrial~~ kneading conditions.

Furthermore, recently there have been great changes in the baking industry's main objectives. After the Industrial Revolution, the main efforts were directed towards developing processes which were able to produce cereal-based products of high technological quality through the standardization of the chemical composition of the raw materials (~~Zhou et al., 2014~~; Pagani et al., 2014a; Cauvain, 2015e). Now, since the products' nutritional quality has gained equal or even greater importance than the technological quality, the process needs to adapt to the inherent characteristics of the different ~~cereal~~ flours used (Cappelli et al., 2019; Guerrini et al., 2019; Gómez et al., 2020; Parenti et al., 2020a). Increasing consumer sensitivity to the nutritional value of foods has incremented the use of flours with a low degree of refinement as well as flours from different sources, such as other cereals, pseudo cereals, pulses etc. (Torres et al., 2017; Schaffer-Lequart et al., 2017; Boukid et al., 2019; Guerrini et al., 2019; Parenti et al., 2020b), which show a richer nutritional value than the standard refined wheat flours. However, they are generally characterized by an inferior technological performance and low stability during kneading (Guerrini et al., 2019; Parenti et al., 2020b; Gómez et al., 2020). As a result, the use of the above flours makes it even more important to measure dough readiness properly, since the time interval corresponding to optimum dough development will be much shorter than with flours of a high technological quality (Pagani et al., 2014a; ~~Zhou et al., 2014~~; Cauvain, 2015e; Guerrini et al., 2019; Gómez et al., 2020; Parenti et al., 2020b).

This paper presents a complete review of the procedures available for the measurement of bread dough readiness, including both ~~the~~ standard and alternative methods. Then, the above methods are discussed in order to evaluate the suitability of the different techniques as a function of the field of application. Finally, the paper proposes some advancements in the bread readiness measurement procedures.

2. Paper selection criteria

In the present review, literature search focused on the kneading step of wheat flours using the most popular databases without applying temporal restrictions. "Wheat dough kneading" and "Wheat dough mixing" were used as keywords for article selection. The initial research gave hundreds of scientific studies; papers out of the review scope were discarded. Table 1 listed the most relevant papers resulting from the first selection which were classified in six categories as a function of the main focus studied: (i) Correlation between different methods and dough/bread quality; (ii) Effects of different kneading conditions on dough/bread properties; (iii) Prediction of bread-making performance; (iv) Wheat protein structure/development; (v) Dough development; (vi) Methods/promising approaches for the determination of dough readiness. Only the articles that proposed methods/promising approaches for the determination of dough readiness were included in the review. Despite wheat dough kneading has been widely investigated in the literature, to the authors' best knowledge, articles facing with the determination of dough readiness were limited in number and quite old. This latter issue disclosed that there has been a constant interest in the literature in wheat dough kneading; however, few attempts have been made on improving the determination of the optimal dough development.

3. ~~The~~ Reference methods

The measurement of bread dough readiness is included in two groups of standard bread-making methods: the AACC methods and the Chorleywood Bread Process method.

The AACC methods are standard bread-making methods proposed by the Cereals & Grains Association; they are as follows: (i) the basic straight dough bread-making method with long fermentation (the AACC 10-09.01 method) and (ii) the optimized straight dough bread-making method (the AACC 10-10.03 method).

The AACC 10-09.01 method is designed both to evaluate the quality of flours using a straight dough process with a long fermentation time and to assess the effect of ingredients and processing conditions on bread quality. It includes standardization of the apparatus, the bread recipe and the processing conditions. The dough has to be mixed in a Swanson pin-type kneader or equivalent (100-500 g capacity); orbital speeds of 100-125 rpm and 80-90 rpm are recommended for 100 g and 200 g of dough, respectively. The measurement of dough readiness is based on: (i) descriptive rheological tests; (ii) baking tests; (iii) work input measurement by means of a W-h meter or similar device connected to the kneader and (iv) visual inspection of the dough's appearance.

The AACC 10-10.03 method is conceived to evaluate the wheat flour quality and the effect of different variables such as environmental factors, bread dough ingredients, wheat variety, wheat flour proteins, and processing techniques on the bread quality. It uses a McDuffee-type bowl kneader (500 g capacity) or a pin-type kneader (10 g or 100 g capacity) with a head speed of 100-125 rpm. The dough readiness measurement can be obtained through a descriptive rheological test and a visual inspection of the dough's appearance (Finney, 1984). The method outlines that the mixing requirements determined in a 100 g pin-type kneader are approximately equal to those determined in a 100 g Mixograph. For mixers that develop doughs more slowly or more rapidly than

100 g mixers, it is necessary to calculate the factor to correct the Mixograph kneading time to the kneading time in real baking conditions. Hence, the AACC 10-10.03 method considers the impact of the kneader variables on the determination of dough readiness; however, it does not specify how to determine the correction factor between the different mixers.

The Chorleywood Bread Process (CBP) is a no-time dough-making process based on the mechanical development of wheat dough widely used in many industries ~~(Cauvain, 2015)~~. The dough is developed rapidly since the mixing and kneading operations are performed simultaneously; the bread recipe includes the addition of an oxidizing agent, a high shortening and/or emulsifier melting point, and large amounts of water and yeast. Dough readiness is achieved by applying a fixed amount of energy to develop the dough in an interval of between 2 and 5 min. The readiness is measured as the work input, which is defined as the energy required to mix the dough to the point of peak torque, and it is conventionally expressed on a dough-weight basis (Fortmann et al., 1964; Heaps et al., 1967; Kilborn & Tipples, 1972, 1973; Frazier et al., 1975; Atkins & Larsen, 1990; Oliver & Allen, 1992; Wilson et al., 1997; Zounis and Quail, 1997; Anderssen et al., 1998; Wilson et al., 2001; Chin et al., 2005a; Muscalu et al., 2017; Cauvain, 2015a). Preliminary results from a limited number of flours have revealed that the ideal energy input at a kneading speed of 300 rpm is 11 W-h/kg. Further studies on flours of different technological qualities have shown that the optimal energy input varies as a function of the flour properties, with “extra-strong” flours requiring the highest energy inputs (Cauvain, 2015a). A modified CBP method – the Mechanical Dough Development (MDD) method – which applies different energy amounts as a function of the flour quality has also been proposed (Wilson et al., 2001). The main features of MDD are high-speed mixers which work intensively on the dough for a short period, the use of an oxidizing agent and the absence of any brew or pre-ferment.

3.1 Visual inspection

A widely implemented practice to directly measure dough readiness is visual inspection of the dough by the test baker. Visual inspection is an empirical approach based on the subjective visual (i.e., homogeneity, smoothness, brightness) and sometimes tactile (i.e., dough consistency, stickiness) sensory evaluation of the dough. The dough quality evaluation varies greatly depending on the baker’s personal skills and experience, hence it does not provide a reliable dough readiness measurement (Perez Alvarado et al., 2016). Indeed, when Perez Alvarado et al. (2016) used the bakers' visual evaluation of the dough readiness to determine the optimal kneading time, it resulted in a high standard deviation (300 ± 200 s).

3.2 *Baking trials*

Baking trials are widely adopted in the baking industry to indirectly measure dough readiness, which is expressed as the optimum kneading time. The dough is kneaded at a constant speed and for different kneading times, with intervals of 0.5 min; after kneading, the standard bread-making steps are performed. The bread quality parameters (i.e., loaf volume and crumb hardness) are processed as a function of the kneading time in order to identify the time that optimizes bread quality. Although this method leads to reliable results, it requires a large amount of effort in terms of ingredients and time.

3.3 *~~Descriptive~~ Rheological tests*

Descriptive rheological tests have been extensively applied in the cereal industry, since they provide a direct measurement of the dough readiness, which is expressed as consistency, hardness or texture, and can predict an optimal kneading time to reach the desired dough texture. Figure 1 shows the dough consistency profile as a function of the kneading time measured using a consistency probe. Descriptive rheological tests are performed with robust instruments, are easy to perform and do not require highly trained personnel (Dobraszczyk & Morgenstern, 2003). Some of the differences from the fundamental rheological tests are that: (i) the sample geometry is variable and not well defined; (ii) the stress and strain states are uncontrolled, complex and not uniform and (iii) it is impossible to define any rheological parameters such as stress, strain, strain rate, modulus and viscosity (Dobraszczyk & Morgenstern, 2003). Therefore, the descriptive rheological tests give parameters that are strictly dependent on the conditions adopted during the test, such as type of instrument, size and geometry of the test sample, standard dough recipe and temperature, which are not necessarily able to simulate the real kneading operating conditions (Dobraszczyk & Morgenstern, 2003). The Farinograph (twin z-arm mixer, 60 rpm mixer speed) and the Mixograph (pin mixer, 88 rpm mixer speed) are the laboratory-scale mixers most recommended in the literature for the measurement of bread dough readiness expressed as an apparent optimal kneading time.

Several studies have been carried out to investigate and improve the accuracy of the measurement of dough readiness using descriptive rheological tests. Tanaka & Tipples (1969) found that increasing the Farinograph speed (from 60 rpm to 90-120 rpm) improved the relationship between the predictive kneading time and the bread quality parameters. Similarly, Zounis & Quail (1997) found that the standard Farinograph speed showed no correlation with the kneading time in real baking conditions; instead, the Farinograph test at a high kneading speed (i.e., 120-180 rpm), the Mixograph test and direct use of the bakery pin mixer gave good predictions of the kneading time with the highest bread score. The Mixograph test gave a reliable measurement of dough readiness in the study by Burrows & Gras (1990), with a good correlation occurring between the time of peak dough resistance predicted by the Mixograph and the peak resistance obtained in the pin mixer. Oliver & Allen (1992) showed that the optimal kneading time (i.e., the time maximizing the loaf volume) corresponded to doughs kneaded to the end of the Farinograph plateau period, independently of the kneading speed; it was found easier to identify the above time at a Farinograph speed of 140-180 rpm than at the standard speed.

The bread ingredients have also been found to affect the optimal kneading time. Oliver & Allen (1992) observed different peak torque and work inputs for the Farinograph standard recipe (wheat flour and distilled water) compared to commercial bread recipes. Oliver & Allen (1993) and Oliver & Allen (1994) reported a different farinographic consistency when adding commercial improvers to the standard formula, and found the best correlation with the real kneading requirements using the Farinograph at 180 rpm with a flour-water-2% salt recipe. In the research by Zounis & Quail (1997), a bakery recipe (i.e., 100% flour, 2% salt, 2% fat, 1% improvers and 2.5% compressed yeast) tested in the Farinograph at 120 rpm decreased the height of the peak consistency, increased the kneading time and the energy requirements, and showed the presence of a second peak; the kneading time of the second peak was better correlated with the bread score than the first peak. The bakery recipe in the Mixograph test also gave similar results to the Farinograph test. The above results were consistent with Tanaka & Tipples (1969), who observed that bread recipes with salt and/or yeast had a much higher tendency to exhibit a double-peak curve.

The alternative application of fundamental rheological tests has been proposed by some authors since they give parameters independent~~ly~~ of the kneading conditions. Ross et al. (2004) used a controlled stress rheometer to perform both strain and frequency sweep experiments. The authors observed, in different flour samples, that both the storage (G’) and loss (G’’) moduli peaked at the point of optimum dough development, which was expressed as the time corresponding to the highest dough elasticity (maximum G’) and viscous component (maximum G’’) of the dough. Other authors (Hwang & Gunasekaran, 2001; Alava et al., 2001) have proposed the above tests too;

however, they are not commonly used as a standard method for the measurement of dough readiness. Many reasons may be put forward for this; fundamental rheological tests are complex and expensive, they are difficult to maintain in an industrial environment, they require a high level of technical skill, the experimental data are often difficult to interpret, and slip and edge effects occur during testing (Dobraszczyk & Morgenstern, 2003).

Mixolab is a new tool for quality control of cereals and cereal products. It offers enhanced functionality over existing devices because of the geometry of the mixing blades and mixing bowl and the variable operating condition options (kneader speed and temperature), which allowed to assess kneading parameters, dough behaviour during heating cycles, and the effect of ingredients addition (Dubat, 2016). Several authors reported a good correlation between standard rheological tests and the Mixolab in the determination of the kneading time of wheat flour dough (Dapčević et al., 2009; Zhang et al., 2009; Koksel et al., 2009; Rosell et al., 2010; Caffe-treml et al., 2010; Ohm et al., 2012; Moreira et al., 2012; Blandino et al., 2015; Vàzquez & Veira, 2015; Doubat et al., 2016; Torbica et al., 2016; Xhabiri et al., 2016; Singh et al., 2019).

Some authors evaluated the potential of other methods for the evaluation of the bread-making quality of wheat flour, including kneading time (Ram et al., 2005; Tietze et al., 2019). Ram et al. (2005) found a good correlation between Lactic Acid Solvent Retention Capacity with Farinograph and Mixograph parameters related to gluten strength, including the peak time. Tiezte et al. (2019) showed that micro-scale shear mixing (MSSM) technique can be a reliable method for the rapid evaluation of flour and dough properties. Indeed, the authors found a good correlation between rheological properties of MSSM dough and those of dough mixed in a z-blade mixer, including the determination of optimum dough development time.

3.4 Work input measurement

The work is the energy required to mix the dough to the kneader's point of peak torque (Wilson et al., 2001). ~~It~~ The work is related to the kneader power (*P*) as follows:

$$P = T \cdot \omega \qquad [1]$$

where *T* is the peak torque and *ω* is the angular velocity, which is:

$$\omega = 2\pi \cdot s \qquad [2]$$

where *s* is the kneading speed at the point of peak torque.

Then, the work input (*WI*) can be determined as follows:

$$WI = P \cdot t = T \cdot \omega \cdot t \qquad [3]$$

where *t* is the kneading time. The work input is commonly expressed in W-h/kg of dough weight.

If the work input amount is indirectly related to the dough readiness, in ideal conditions this work amount is independent of the kneader type, since, by applying equation 3, it can be obtained from different combinations of the kneader power - P at peak torque - T and the kneading time - t. Therefore, several studies have been carried out in order to test the suitability of work input to measure bread dough readiness.

The CBP method, based on the mechanical development of the dough, reported that for kneading speeds above a certain threshold value, dough readiness was produced by a fixed energy amount. Conversely, the MDD method showed the necessity of a preliminary measurement for a specific wheat flour's energy requirements since the fixed CBP energy value is not appropriate for high-strength flours (Wilson et al., 2001).

Heaps et al. (1967) found that, when using the descriptive rheological parameters of the Extensograph test (i.e., maximum of the stress work component and minimum of the extensibility), the dough readiness corresponded to the rate of work input that gave inflection points of the parameters (i.e., minimum or maximum values, where the derivative of the function representing the parameter trend is equal to zero). However, in baking trials, the highest bread volume was obtained at a different work input rate corresponding to a lower level of total work input. Different independent factors may account for this different result: a change in the bread recipe and/or different dough readiness requirement in real bread-making situations compared those adopted during the rheological test.

Oliver & Allen (1992) showed that, consistently with the above CBP results, at higher Farinograph kneading speeds (140-180 rpm) than the standard, the work input was independent of the variation in kneading speed; work input rather than kneading time appeared a suitable parameter for obtaining the dough readiness.

Zounis & Quail (1997) found a high correlation between work input and kneading time for optimum dough consistency in both the Farinograph and Mixograph tests. The energy amount to reach dough readiness increased as the kneading speed increased in 8 of the 28 flour samples and remained constant in the others. These results were not consistent with what was observed by Oliver & Allen (1992) and Kilborn & Tipples (1972), who found that at high kneading speeds the work input was independent of the rotational speed. However, both Zounis & Quail (1997) and Kilborn & Tipples (1972) stated that kneading to the maximum peak consistency represents a better method for measuring dough readiness than kneading with a fixed work input, since the latter is affected by the processing conditions and the technological quality of the flour. The mixing method used by Kilborn & Tipples (1972) included a short premix period at a slow speed, before application of the desired kneading speed. Frazier et al. (1975), who did not use slow-speed premixing, found that the work input to reach the maximum dough consistency increased as the kneading speed increased; higher work inputs were probably required for high kneading speeds due to the time-dependent hydration effect.

In performing the Mixograph test at low kneading speeds, Anderssen et al. (1998) reported a significant difference in the work input amount as a function of the flour technological quality. However, at speeds higher than 90 rpm the work input was found to be independent of the kneading speed for all flour types.

Wilson et al. (2001) found that as the kneading speed increased, the work input decreased, and then remained constant for a specific mixer speed range and before growing again. Slightly different work input trends as a function of the mixer speed were observed according to the flour strength. Above different thresholds, the number of kneading arm revolutions at which the peak torque occurred was constant as a function of the flour strength; the work input appeared independent of the kneader speed in one range only, which was instead dependent on the kneader type and flour used.

Fortmann et al. (1964) and Kilborn & Tipples (1973) found different work input requirements for the same flour using both different laboratory mixers and the same laboratory mixer with different arm shapes. Wilson et al. (1997) found that the work inputs obtained in laboratory and industrial-scale MDD mixers were highly correlated ($R^2 = 0.88$) but they showed a large offset since the industrial mixer required a higher energy amount. This result could be interpreted in terms of the different rate of work inputs and the different mixing actions between the two kneaders, but it could be also related to the fact that the initial processes of hydration and ingredient homogenization occurring within the dough are more time-dependent than energy-dependent. According to this latter interpretation and to the results shown by Kilborn & Tipples (1972) using a slow pre-mixing step, Wilson et al. (1997) proposed mixing the ingredients slowly before selecting a high mixer speed as a strategy to reduce the industrial-scale MDD mixers' higher energy requirements.

Chin et al. (2005a) monitored work inputs of dough during mixing in a lab-scale Tweedy-type MDD mixer. The peak torque increased with increasing mixing speed and headspace pressure. Furthermore, results showed ~~reported~~ that the number of kneading arm revolutions needed for dough readiness ~~in a Tweedy-type mixer~~ decreased as the kneading speed increased, showing that the work input was not independent of the rate in this mixer type; they confirmed what was reported by Skeggs & Kingswood (1981): mixing at a fast speed was more efficient, since a lot of work was supplied to the dough with each revolution of the kneading arm.

Atkins & Larsen (1990) compared the Farinograph with Mechanical Dough Development tests for flour quality evaluation. They found that a Farinograph can be successfully used to predict the water absorption, stability, development time and breakdown for MDD system. However, only development time was significantly correlated with bread volume, probably because the Farinograph did not simulate the intensive mixing of MDD.

Muscalu et al. (2017) tested different levels of work input in order to optimize the bread volume of a weak flour dough. A system for kneading process optimization called SOPF was used to monitor the energy amount during kneading, which was stopped at the point of dough readiness. However, a preliminary evaluation of the optimal energy amount required by the flour sample was needed.

A schematic overview of all the above methods is reported in Table 2.

4. ~~The~~ Alternative methods

~~3~~ 4.1 Torque and power consumption measurements

The torque and power consumption methods indirectly measure dough readiness by monitoring its trend as a function of time and can therefore predict an optimal kneading time to reach the desired dough texture using the same principle as descriptive rheological tests (Wesley et al., 1998; Alava et al., 2001; Kaddour et al., 2007; Kaddour et al., 2008a; Perez Alvarado et al., 2016). Figure 2 shows the power consumption profile as a function of the kneading time measured using a current transducer (Hwang & Gunasekaran, 2001). Indeed, a positive proportionality exists between the dough consistency and the torque/power consumption value although this relationship is not always easy to prove since the power consumption also includes energy losses in the motor and drive chain. Differently from descriptive rheological tests, the above methods are ~~online~~ inline methods, which can be applied in real kneading conditions; the torque/power consumption values are monitored during kneading by applying a power or electrical current transducer to the kneader. Wang et al. (1993) proposed the instantaneous input power data acquisition system (DAS) and digital signal processing (DSP) system combined with fuzzy set theory as a non-intrusive real-time gluten development sensing control, since the three phase instantaneous input power has a significant relationship with gluten development. Zounis & Quail (1997) found that the kneading time giving the highest bread score was longer than the peak of power consumption in 70% of the tested samples, which included ~~those dough samples using~~ wheat flours with the highest protein content, the highest farinographic water absorption, and the best overall bread quality. Depending on the flour technological quality, different regions of the power consumption curve could be considered to correspond to the best measurement of the dough readiness; the flours most suited to bread-making needed longer kneading times than those predicted using the peak of power consumption method. Wilson et al. (2001) observed that as the kneading speed increased, the rate at which the torque increased was slower than the rate commonly predicted using a power method. The authors hypothesized that at a higher kneading speed more air is included within the dough; this phenomenon decreased the density and apparent viscosity of the dough, changing the relationship between torque and kneading speed. Hwang & Gunasekaran (2001) analysed some peaks in the power consumption trend during dough kneading. Comparison with the storage (G’) and viscous (G’’) moduli showed that power consumption can be used to determine the optimum dough development. Pereira et al. (2013) monitored dough kneading at constant speed using the electrical changes of the motor as affected by machine torque. This system was sensitive to the dough formula and was proposed to provide useful information for quality control and decision-making during food processing. Altuna et al. (2016) developed a methodology to measure torque during large-scale kneading. The dough was kneaded in a large-scale dynamic rheometer measuring instant torque and speed in real time through a personal computer (PC) interface. Maximum torque during mixing showed significant fit to linear model on the basis of which the effect of resistant maize starch and bread enzymes could be estimated. Aljaafreh (2017) proposed a non-invasive sensor for real-time monitoring of mixing and agitation processes based on current sensing and online learning through reinforcement learning (RL). The method enabled the sensor to learn how to control and automate the mixing and agitation processes based on Q-learning. The sensor learns the electric current pattern and utilizes user feedback to learn the optimal stopping time based on the characteristics of the mixture.

~~3~~ *4.2 NIR Spectroscopy*

Near infrared (NIR) spectroscopy measures the interaction between the dough and NIR radiation in the wavelength range of 400-2500 nm, detecting molecular vibrations at specific overtones. In the literature it is widely known that the majority of changes occurring during dough development involve chemical modifications of the flour constituents (Haegens, 2006a; Kaddour & Cuq, 2011; ~~Zhou et al., 2014~~; Cauvain, 2015a). The main issues concern both identification of the NIR wavelengths that are mostly correlated with dough readiness and the selection of a common method to perform the chemometric spectra analysis. ~~The Principal component analysis (PCA) raw spectra, second derivative spectra and peak area at a specific wavelength range are processed in order to create a NIR curve as a function of the kneading time (Figure 3).~~

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Different devices have been proposed in the literature to monitor dough development using the NIR technique. Wesley et al. (1998) designed a support tray which was placed over the kneading bowl with the dough at the nominal focal point of the NIR instrument. Kaddour et al. (2007) used a fibre optic probe in direct contact with the dough, whereas Alava et al. (2001) proposed a system in which the fibre optic remains 4 cm above the dough surface.

Several studies have been performed in the NIR range of 400-2500 nm, at 2 or 5 nm intervals (Kaddour & Cuq, 2011). The wavelengths have been related to different chemical reactions occurring during the dough development while the data extracted from the raw NIR spectra have been associated with physical changes in the dough during kneading (Alava et al., 2001; Kaddour et al., 2007; Kaddour & Cuq, 2011). Conversely, the second derivative NIR spectra have mainly been associated with changes in water interactions and chemical reactions between the wheat components (Kaddour & Cuq, 2011).

Delwiche & Weaver (1994) investigated the potential of using NIR technique in the range of 1100-2498 nm to determine flour technological parameters, including dough kneading time. Reasonably good models could be developed for water absorption, moderately good models for loaf height, and poor models for the other indices, including kneading time, probably due to the complexity of interactions between flour constituents.

Dempster et al. (1998) used NIR technique to monitor dough development during kneading. The procedure used a ratio of two specific NIR wavelengths at 1455 nm and 1205 nm to obtain NIR dough development curve. The authors hypothesised that this parameter tracks protein-starch interactions in the presence of water. NIR kneading time was validated with the empirical judgment of an expert operator, hence required further confirmations.

Wesley et al. (1998) found two peaks at 1160 nm and 1200 nm and the kneading curves at these wavelengths were developed by plotting the NIR peak area as a function of the kneading time. The peak areas of both 1160 nm and 1200 nm decreased as the kneading proceeded, showing a minimum at the optimum dough development point, before increasing when the dough was overmixed. The peak area at 1160 nm was related to changes in water mobility during kneading; the peak at 1200 nm was difficult to interpret, since it could be linked to the overlapping absorbances of the glutenins and gliadins. The NIR kneading time was close to the maximum power consumption time, but slightly longer (by approx. 20%). Similar results were also found using different kneaders and flour types. Wesley et al. (2002) patented an NIR spectroscopy method for monitoring dough development. The research recommended monitoring the absorbance of the second derivative spectra at the following wavelengths: (i) absorbance at 1160 nm, related to the stretch-bend combination band of water and highly sensitive to the local environment of the water molecules; (ii) absorbance at 1200 nm, related to a C-H stretch second overtone which was predominantly due to proteins and (iii) absorbance at 1430 nm, related to the two absorbances due to water and proteins. All these bands were reported as showing a minimum at the dough readiness point. The method also suggested monitoring both the absorbance of the glutenins, which showed a minimum at 2350 nm, and the absorbance of gliadins, which displayed minimum values at 2340 nm and at 2310 nm, and a maximum at 2195 nm.

Alava et al. (2001) observed the most consistent NIR changes in the 1125-1180 nm wavelength region. The NIR kneading time was longer than the kneading time obtained using the traditional methods (i.e., torque and elastic modulus of gel protein fraction G’ measurements), but it showed a better correlation with the bread quality. NIR spectroscopy allowed the kneading conditions to be optimized as a function of the characteristics of the wheat flour variety or flour blend.

Kaddour et al. (2007) monitored the kneading step of different wheat varieties using an FT-NIR spectrometer in the range of 1000-2500 nm. The raw NIR spectra showed the dominant contribution of physical mechanisms such as the granular state and surface appearance of the dough. The second derivative spectra in the 1000-2325 nm wavelength range and in some specific wavelength ranges (1352-1485 nm, 17778-2052 nm, 2109-2325 nm) allowed a physico-chemical description of the NIR absorbance variations which was associated with the evolution of the hydrogen bond vibrations. The greatest changes were reported in the 1778-2052 nm wavelength due to O-H vibrations. The predicted kneading time resulting from the NIR raw spectra was higher than the time of maximum consistency, whereas the NIR kneading time from the second derivative treatment was more similar to the time of maximum dough consistency.

~~3~~ 4.3MIR spectroscopy

The Mid-infrared (MIR) spectroscopy range (2500 and 5000 nm) is the principal spectroscopic region for evaluating molecular vibration; it is able to give precise and directly accessible information on X-H chemical bonds (X: C, H, O and N), which is useful in determining the chemical composition of food products (Kaddour et al., 2008a). In a batter dough system, Robertson et al. (2006) showed that FT-MIR spectroscopy can be used to monitor relative changes in the protein secondary structures. Since gluten development is the key factor determining the dough properties, the possibility of monitoring the formation of the gluten network could make it an interesting tool for a precise and reliable determination of dough readiness.

While different approaches have been used in the literature for the offline monitoring of dough kneading with MIR spectroscopy and for the chemometric analysis of the data, the information available is scant. One such approach was taken by Kaddour et al. (2008a) who collected a dough sample with a spatula and immediately transferred it to the measurement cell; after 60 s a MIR spectrum was obtained.

Different results about protein secondary structure changes have been reported in the literature (Wellner et al., 1996; Seabourn et al., 2004; Robertson et al., 2006); the reason for this could be the different amide bands studied (amide I and amide III) or the different products analysed (i.e., bread dough, batter and gluten). Hence, it is reported that large changes occur in protein secondary structures during both hydration of the wheat gluten proteins and gluten mechanical development (Belton et al., 1995; Wellner et al., 1996).

Seabourn et al. (2008) used a different offline system in which all dough samples were measured after 1 min of kneading. They used Fourier Transform Horizontal Attenuated Total Reflectance (FT-HATR) spectroscopy in the amide III band to measure the dough development after a short Mixograph mixing cycle (1 min). The ratio between the α-helix (1336 cm^{-1}) and β-sheet (1242 cm^{-1}) second derivative band areas (SDBA) was calculated, and its relationship to optimum Mixograph kneading time was studied ~~increased in a non-linear manner with the mixing time~~. The ~~spectrophotometric kneading time was highly correlated with the Mixograph kneading time; the~~ α-helix/β-sheet SDBA ratio resulted highly correlated with the Mixograph kneading time, hence it was highly predictive of the dough readiness, and confirmed that β-sheet structures are the structures that develop most during kneading (Seabourn, 2002; Popineau et al., 1994; Wellner et al., 2005). Flours with a short kneading time showed a faster β-sheet structure development than those with a long developing time (Seabourn et al., 2008).

Kaddour et al. (2008a) showed that the amide III band correlated better with the chemical properties of the dough than the amide I band; there was no interference from water and the different protein secondary structures overlapped less, resulting in better resolved bands. The second derivative spectra of the amide III bands were analysed to identify changes in the peak maximum absorbance during kneading; the α-helical (1319 cm^{-1}), β-turn (1288 cm^{-1}) and β-sheet (1242 cm^{-1}) structures increased, whereas the random coil structure (1265 cm^{-1}) decreased, suggesting that the gluten network becomes a highly ordered structure. The maximum value of the α-helical, β-turn and β-sheet structures and the minimum value of the random coil structure were used to determine the MIR kneading time, which showed a good correlation with the time at which the torque started to collapse (Figure 4). MIR monitoring of the amide III band during kneading could provide an interesting method for measuring dough readiness.

~~*3 4.4 Computer vision*~~

~~Since visual inspection is a widespread but not reliable method, computer vision-based imaging methods have been developed in the food industry as an objective technique for quality control. A computer vision system generally consists of basic components: (i) an illumination source, (ii) a camera, (iii) an image capture board, (iv) computer hardware and software. The image analysis includes the following steps: (i) capturing, (ii) processing and (iii) analysing the acquired images in order to produce an objective evaluation. This technique is an automated, non-contact, non-destructive and cost-effective method for accurate, fast and objective quality determination (Brosnan & Sun, 2004).~~

~~Perez Alvarado et al. (2016) proposed an online system to monitor dough kneading, consisting of a camera placed above the kneader. The bakers' visual inspection and the torque trend were used to stop kneading in lab and spiral kneaders with the minimum error in optimum kneading time. A grey-level co-occurrence matrix (GLCM) texture analysis allowed the development of an algorithm to~~

~~emulate the bakers' visual inspection of the dough readiness. At the beginning of kneading, the ingredients were not uniformly mixed, showing a low value of homogeneity, while the homogeneity increased after some minutes. A linear relationship was obtained between the variation in homogeneity and the kneading time; the optimum kneading time was determined by the torque trend of the kneader. The above algorithm was tested in many experiments and it produced an average error of 33.9 s compared to the optimal kneading time.~~

~~Van der Mijnsbrugge et al. (2016) showed that during kneading, the gluten agglomerates grew steadily and finally turned into a filamentous network at the point of optimal dough development. Although the authors did not correlate the gluten structures with a method for measuring the dough readiness, these findings increased the comprehension of complex phenomena occurring during dough kneading and they could be useful in the development of online computer vision techniques. Brosnan & Sun (2004) emphasized that computer vision has the potential to become a vital component of automated food processing since computer capabilities and algorithm processing speeds are continually developing and approaching the necessary online speeds. The continued development of computer vision techniques such as X-ray, 3-D and colour vision will ensure the higher implementation and uptake of this technology in order to meet the ever-expanding requirements of the food industry (Brosnan & Sun, 2004). For example, Perez Alvarado et al. (2016) suggested reducing the wavelength of the visual spectrum (using a helium laser as a coherent light source) to increase the accuracy of the visual surface analysis and to reduce the time gap between determination of the steady state and dough readiness time.~~

~~*3.5*~~ *4.4 Ultrasounds*

Ultrasounds (US) are an oscillating sound pressure wave with a greater frequency than the upper limit of the human hearing range. The basic principle of this technique is that different materials absorb US waves ~~radiation~~ differently and that the waves travel at different speeds in different materials as well (Koksel et al., 2016). The US frequency interval includes frequencies from 20 kHz to 10 MHz which have been further subdivided into three characteristic regions: (i) low-frequency high-power US (20 kHz-100 kHz), (ii) intermediate-frequency medium-power US (100 kHz-1 MHz), and (iii) high-frequency low-power US (1 MHz-10 MHz) (Chandrapala, 2015; Koksel et al., 2016; Scanlon, 2013; Scanlon & Page, 2015). The US waves can be longitudinal (compressional) waves, shear waves or surface waves. Only the longitudinal waves are sensitive to bubbles and can propagate into useful depths in foods (Koksel et al., 2016). Longitudinal waves are quite easy to generate, detect and propagate through solid as well as fluid media, while shear waves are much more attenuating and they are not able to propagate into liquids and gases (Létang et al., 2001).

US sensors are widely used in the food industry as a cheap, rapid, non-destructive and non-contact technique for quality control and they have proven suitable for studying optically opaque systems such as bread dough (Létang et al., 2001; Salazar et al., 2002; Chandrapala, 2015; Koksel et al., 2016). The longitudinal waves are the most suitable for dough testing; wheat flour dough is a highly attenuating material, hence low-frequency US should be used for this food matrix (Létang et al., 2001).

Létang et al. (2001) used high-frequency low-power longitudinal US (2-10 MHz) to evaluate the physical properties of dough during kneading and resting. The US parameters were sensitive to overmixing at frequencies lower than 5 MHz, producing a sharp increase in both the US velocity and attenuation. The variation in the US parameters during overmixing was strongly dependent on the water content; an increase in both parameters was observed in 50% water doughs, no changes in 53% water doughs and a decrease in attenuation with no change in velocity in 56% water doughs. These results are consistent with Kidmose et al. (2001) who reported that the amount of water affected the US parameters more significantly than the differences in dough structure and rheological properties.

Salazar et al. (2002) and Garcia-Alvarez et al. (2006) investigated the rheological properties of dough using the US technique (100 kHz). The US velocity and attenuation changed as a function of the dough water content, confirming previous findings (Kidmose et al., 2001, Létang et al., 2001). The highest value of velocity was found for the stiffest dough at the lowest water content, whereas attenuation increased as the water content increased. The US velocity was significantly affected by the technological quality of the flour. The maximum value of the US velocity may correspond to the optimum development of the gluten network, but further research is required to confirm this hypothesis, while evaluating the possibility of using this parameter to measure dough readiness.

Ross et al. (2004) used high-frequency US (3 MHz) to monitor dough kneading in a Mixograph. The US velocity, US attenuation and rheological parameters (storage G’ and loss G’’ moduli) showed inflection points at the optimum dough development time. The US velocity and attenuation showed a maximum value at the optimum dough development point, which is probably associated with the state of hydration of the dough since both parameters were shown to be affected by the water content (Johnston et al., 1979; Hoseney, 1998; Sakai et al., 1989; Létang et al., 2001; Salazar et al., 2002). The US velocity may reflect the optimum hydration state of the dough, whereas attenuation has been reported to change as a function of the friction of the system: the higher the friction forces (at the beginning of kneading), the lower the attenuation value (Johnston et al., 1979). During kneading, the hydration promotes the glass transition of the amorphous polymers which become rubbery and a more lubricated system with a higher attenuation value (Hoseney, 1998). The good correlation found between the rheological and US parameters showed the potentiality of the US technique as an alternative method for determining dough readiness (Ross et al., 2004).

Nassar et al. (2006) proposed an acoustic device to study the mechanical development of the dough during kneading. A piezoelectric sensor captured the noise during kneading; the recorded electric signal reflected the physical properties of the dough. The evolution of the maximum amplitude of the signal reached a maximum value indicating the critical phase transition which corresponded to optimal dough development.

Mehta et al. (2009) tested the effect of shortening as an ingredient and kneading time on the mechanical properties of bread dough using the US technique (50 kHz). US velocity and attenuation were evaluated in comparison with the kneading. The US velocity followed the trend of the dough density: it decreased as the air bubbles within the dough increased and then showed a discernible relative peak at the optimum dough development point, which was interpreted as the maximum alignment of the glutenin polymers. The different trend in US velocity observed by Ross et al. (2004) could be due to the use of different US frequencies and tested dough water contents (Figure 5). The US attenuation tended to increase, showing a minimum at the optimum dough development time; however, the trend was not as pronounced as the increase in the US velocity (Mehta et al., 2009). Ross et al. (2004), using US frequencies of 3-5 MHz, observed the opposite result: the US reached maximum attenuation at the dough readiness point.

Peressini et al. (2016) using principal component analysis (PCA) showed that mean values of ultrasonic attenuation and phase velocity at frequencies between 0.3 and 3 MHz are good predictors for rheological and bread scoring characteristics prepared with a wide range of dough formulations. Indeed, lower frequency attenuation coefficients correlated well with conventional quality indices of both the dough and the bread.

Bowler et al. (2020) showed the potential of using an industrially applicable ultrasonic sensing technique combined with machine learning (ML) to predict dough readiness in a batter system. Two ultrasonic sensors were used for data acquisition and different ML engineering methods were compared. The superior accuracy obtained as a result outlined the efficacy of this approach for the monitoring of dough kneading.

A schematic overview of all the above alternative methods is reported in Table 3.

4.5 Other alternative methods

In the literature we found single paper proposing alternative methods to determine dough readiness which were reported below.

Ndiaye et al. (2009) investigated the qualitative modelling of French bread-making process represented as a sequence of steps. Each step is defined through control variables, state variables of its output, and causal relation between the control and state variables. A qualitative model of the kneading step was developed through cognitive operations representing human expertise and qualitative algebra. The validation of this approach was made performing 81 simulation cases which showed positive results.

The same research group applied qualitative algebra to predict the wheat flour dough behaviour from kneading settings (Kansou & Della Valle, 2012). The state of the dough was modelled at the end of two successive operations of kneading: (i) ingredient homogenization, (ii) dough development from the initial consistency and operating conditions. The qualitative model was validated and implemented as a knowledge-based system accessible and understandable by scientists and technologists in bread-making.

Kansou et al. (2014) reported an extensive evaluation of the above expert system by comparing simulation results first to experts' prediction and second to experimental results. The good matching level proved the accuracy and the robustness of the expert-system in predicting actual dough properties starting from ingredient characteristics.

Ruan et al. (1995) designed a neural network trained with the recorded mixer torque (input) and the measured rheological properties (output) to predict dough rheological properties. An accuracy of the prediction higher than 94% was obtained outlining the potential of this method to minimize process variability during dough kneading.

Oestersotebier et al. (2016) aimed to develop an intelligent kneading machine able to set kneading speed and time to obtain consistent dough quality regardless the variability of environmental conditions and flour characteristics. The system was based on intelligent information processing algorithms validated with the expertise of professional bakers. Reliable detection of phase-shift and model-based prediction of dough was obtained.

Garcia et al. (2016) proposed 3-D-front-face-fluorescence (3D-FFF) spectroscopy in the 250-550 nm domain to follow the dough development as influenced by formulation and kneading time. Three regions of maximum fluorescence intensities are concerned by the above variables. The first two regions were probably due to aromatic amino acid residues of gluten proteins, and ferulic acid esterified to arabinoxylans, whereas the third has still to be found. The final aim of this approach is to develop an online-sensor based on fluorescence measurements to obtain real-time monitoring of dough development.

Sangpring et al. (2017), investigated the relationship between the development of wheat dough expressed as the net energy of kneading and the colour of the mixture. The authors added caramel colour reagent as the indicator of dough development and monitored the colour changes using a colour difference meter. As the net energy increased, the L^* and H values decreased, whereas the a^* and ΔE values increased. The decreasing trend of the L^* value as increasing net energy showed that the caramel solution was well mixed. These results indicated that the colour change can be used to determine the kneading state of wheat dough.

Perez Alvarado et al. (2016) proposed an online system to monitor dough kneading, consisting of a camera placed above the kneader. The bakers' visual inspection and the torque trend were used to stop kneading in lab and spiral kneaders with the minimum error in optimum kneading time. A grey-level co-occurrence matrix (GLCM) texture analysis allowed the development of an algorithm to emulate the bakers' visual inspection of the dough readiness. At the beginning of kneading, the ingredients were not uniformly mixed, showing a low value of homogeneity, while the homogeneity increased after some minutes. A linear relationship was obtained between the variation in homogeneity and the kneading time; the optimum kneading time was determined by the torque trend of the kneader. The above algorithm was tested in many experiments and it produced an average error of 33.9 s compared to the optimal kneading time.

5. Critical evaluation of the methods

Table 4 shows a synoptic comparison of ~~all~~ the ~~above~~ reference and alternative methods mostly investigated ~~methods~~ for the determination of dough readiness ~~measurement~~.

In the baking industry, the most common approach is to use flour blends of specific technological quality, determined in the bakery or provided by the producer with reference methods (i.e. Farinograph and Mixograph). Similarly, in the scientific literature, descriptive rheological tests using the Farinograph and Mixograph laboratory-scale mixers are the reference methods for measuring dough readiness. These instruments have been developed to evaluate the technological quality of wheat flours, which includes measuring dough readiness (AACC method 10-09.01, 10-10.03; ~~Zhou~~

~~et al., 2014~~; Quaglia et al., 1984; Pagani et al., 2014a; Cauvain, 2015e). These tests are easy to perform and the tools are available in many laboratories, but they are strictly dependent on the operating conditions adopted during the test. The standard dough recipe of wheat flour and distilled water, the kneader geometry, the arm shape, the kneading speed and temperature conditions applied enable the prediction of an apparent optimal dough kneading time, which may be not applicable in the real processing conditions (Quaglia et al., 1984; Dobraszczyk & Morgenstern, 2003; Pagani et al., 2014a; ~~Zhou et al., 2014~~; Cauvain, 2015e). The Farinograph, which was designed before high-intensity mixers became widely used, has a low kneading speed (60 rpm), imparting a gentle kneading action on the dough (Oliver & Allen, 1992; Zounis & Quail, 1997). It has been reported that the standard Farinograph speed does not develop dough strength, resulting in inaccurate measurements of the dough readiness, and that higher speeds of 90-180 rpm should be used instead (Tanaka & Tipples, 1969; Oliver & Allen, 1992; Zounis & Quail, 1997). The Mixograph, having a higher rate of work input (88 rpm) than the Farinograph, reflects modern mixers more closely and gives a better correlation with dough readiness (Burrows & Gras, 1990; Zounis & Quail, 1997). Some scientific data have shown that a significant improvement in dough readiness measurements by the above laboratory mixers may be obtained using similar kneader speeds to the modern kneaders (Tanaka & Tipples, 1969; Oliver & Allen, 1992; Zounis & Quail, 1997) and real bread recipes (Oliver & Allen, 1992, 1993, 1994; Zounis & Quail, 1997).

In the baking industry, ~~measurement approach is~~ beside the information on flour technological quality, the baker's visual inspection is often used as an aid to set standard operating conditions. Visual inspection is a direct measurement to predict the optimal kneading time, but it is a subjective practice with a high degree of variability.

Baking tests are widely used in both the industrial and scientific areas. They are included in the AACC methods and are commonly applied since bread quality parameters are often used to calibrate the other methods of measuring dough readiness. However, baking trials are time- and resource-consuming methods and they may be affected by a high degree of experimental error, since the different processing conditions adopted in the various phases of bread-making after kneading may alter the prediction of the optimal kneading time.

~~In the scientific literature, descriptive rheological tests using the Farinograph and Mixograph laboratory-scale mixers are the reference methods for measuring dough readiness. These instruments have been developed to evaluate the technological quality of wheat flours, which includes measuring dough readiness (AACC method 10-09.01, 10-10.03; Zhou et al., 2014; Cauvain,~~

~~2015). These tests are easy to perform and the tools are available in many laboratories, but they are strictly dependent on the operating conditions adopted during the test. The standard dough recipe of wheat flour and distilled water, the kneader geometry, the arm shape, the kneading speed and temperature conditions applied enable the prediction of an apparent optimal dough kneading time, which may be not applicable in the real processing conditions (Dobraszczyk & Morgenstern, 2003; Zhou et al., 2014; Cauvain, 2015). The Farinograph, which was designed before high-intensity mixers became widely used, has a low kneading speed (60 rpm), imparting a gentle kneading action on the dough (Oliver & Allen, 1992; Zounis & Quail, 1997). It has been reported that the standard Farinograph speed does not develop dough strength, resulting in inaccurate measurements of the dough readiness, and that higher speeds of 90-180 rpm should be used instead (Tanaka & Tipples, 1969; Oliver & Allen, 1992; Zounis & Quail, 1997). The Mixograph, having a higher rate of work input (88 rpm) than the Farinograph, reflects modern mixers more closely and gives a better correlation with dough readiness (Burrows & Gras, 1990; Zounis & Quail, 1997). Some scientific data have shown that a significant improvement in dough readiness measurements by the above laboratory mixers may be obtained using similar kneader speeds to the modern kneaders (Tanaka & Tipples, 1969; Oliver & Allen, 1992; Zounis & Quail, 1997) and real bread recipes (Oliver & Allen, 1992, 1993, 1994; Zounis & Quail, 1997~~).

The work input method has been used for measuring dough readiness independently of the kneading operating conditions. Indeed, it has been reported that for a specific wheat flour and mixer type, after a certain kneading speed threshold, the amount of work input to achieve dough readiness is constant and independent of the mixer speed (Oliver & Allen, 1992; Zounis & Quail, 1997; Anderssen et al., 1998). However, contradictory results are present in the literature; Oliver & Allen (1992) and Anderssen et al. (1998) considered work input better than kneading time to express dough readiness, whereas the opposite conclusion was reported by Kilborn & Tipples (1972) and Zounis & Quail (1997).

The following alternative methods have been proposed to measure dough readiness (Table ~~1~~ 2), even though the baking industry and scientific research still prefer the above reference methods, which have a known standard procedure.

Torque and power consumption are parameters which may be related to dough texture in order to measure the dough readiness in the actual processing conditions. This method of measurement has been widely used since it is online, cost-effective and easy to perform; it does not require highly trained personnel and gives a clear kneading curve as a result (Wang et al., 1993; Pereira et al., 2013;

Wesley et al., 1998; Alava et al., 2001; Kaddour et al., 2007; Kaddour et al., 2008a; Mehta et al., 2009; Perez Alvarado et al., 2016; Hwang & Gunasekaran, 2001; Zounis & Quail, 1997; Altuna et al., 2016; Aljaafreh, 2017). However, there are still contradictions about the correlation between the torque/power consumption profiles and dough readiness, since there is not a clear reference point for the torque/power consumption trends which can be associated with dough readiness (Hwang & Gunasekaran, 2001; Pereira et al., 2013; Zounis & Quail, 1997). The majority of the studies have correlated dough readiness with the time corresponding to the peak of the torque/power consumption trends, following the approach of the descriptive rheological methods (Wang et al., 1993; Perez Alvarado et al., 2016; Hwang & Gunasekaran, 2001; Pereira et al., 2013; Altuna et al., 2016; Bowler et al., 2020), but Zounis & Quail (1997) found that for high-protein flours the time at the end of the plateau period correlated best with dough readiness, showing a possible interaction with the technological quality of the flour.

Spectroscopic methods to measure dough readiness include the NIR and MIR techniques. NIR spectroscopy is an online method that can monitor dough in real time; when processing the raw NIR spectra data, they resulted mostly associated with the physical properties of the dough, whereas the second derivative treatment gave important insights into the chemical reactions occurring during the dough kneading (Kaddour & Cuq, 2011). The second derivative spectra showed a better correlation with the dough readiness, expressed as NIR kneading time, than the raw NIR spectra (Wesley et al., 1998; Alava et al., 2001; Kaddour et al., 2007; Wesley et al., 2002; Kaddour & Cuq, 2011). The main changes occurring during kneading are related to modifications of the protein secondary structures which lead to the development of the gluten network (Kaddour & Cuq, 2011), and the absorbances due to water and proteins were reported to reach a minimum at the dough readiness point (Wesley et al., 2002). The time for dough readiness proved longer than the times measured using the descriptive rheological tests (Wesley et al., 1998; Alava et al., 2001; Kaddour et al., 2007; Wesley et al., 2002), but it resulted better correlated with the bread quality parameters (Alava et al., 2001). The main barriers against using the NIR technique concern identifying the specific wavelength range and the data analysis method. Since chemical reactions in the NIR range have been differently associated with the various flour constituents (Kaddour & Cuq, 2011), different wavelength ranges have been used to determine dough readiness (Demster et al., 1998; Wesley et al., 1998; Alava et al., 2001; Kaddour et al., 2007; Wesley et al., 2002; Kaddour & Cuq, 2011). Water, protein and starch molecules absorb in the same wavelength range, making it difficult to isolate the main actors in the dough development, that is, the gluten proteins (Kaddour & Cuq, 2011). Although all these studies found a better correlation using the second derivative NIR spectra, different techniques were adopted, increasing the variability of the method (Demster et al., 1998; Wesley et al., 1998; Alava et al., 2001; Kaddour et al., 2007; Wesley et al., 2002; Kaddour & Cuq, 2011). Furthermore, the different NIR devices need to be improved, since the presence of flour particles in the environment could damage the instruments (Kaddour & Cuq, 2011).

Little information is present in the literature about the use of MIR spectroscopy to measure dough readiness (Seabourn et al., 2008; Kaddour et al., 2008a), but this technique appeared even more appropriate than NIR spectroscopy. It is an offline method which is able to directly monitor changes in the protein secondary structures; monitoring of the amide III band has been associated with the gluten network development (Kaddour et al., 2008a). Kaddour et al. (2008a) found longer MIR kneading times than the peak dough consistency time of the descriptive rheological test, whereas Seabourn et al. (2008), using α-helix/β-sheet SDBA ratio, found a good correlation with the Mixograph kneading time.

~~The computer vision method used the external appearance of the dough as an indicator of the dough readiness by means of online or offline techniques. This method has only been proposed by Perez Alvarado et al. (2016) and it is based on an algorithm which combines the parameter mostly used in the baker's visual inspection method (i.e., dough homogeneity) with the dough texture. The computer vision monitors the dough in the actual processing conditions and it is sensitive to the dough recipe, but it has been subjected to scant investigation (Perez Alvarado et al., 2016).~~

The ultrasound (US) method has been ~~proposed~~ studied as a tool to monitor dough development (Létang et al., 2001; Salazar et al., 2002; Nassar et al., 2006; Garcia-Alvarez et al., 2006; Ross et al., 2004; Mehta et al., 2009; Peressini et al., 2016; Bowler et al., 2020), since US parameters are able to detect both the physical and chemical properties of the bread dough samples (Koksel et al., 2016). Nassar et al. (2006) showed that the maximum amplitude of the signal received by acoustic sensor corresponded to the optimal dough development. ~~The US parameter that seemed most appropriate for measuring dough readiness was~~ Ross et al. (2004) and Mehta et al., (2009) reported that US velocity~~, which~~ showed a maximum at the optimum dough development point, whereas they found ~~US attenuation revealed~~ a poorer correlation and an inconsistent trend of US attenuation ~~(Ross et al., 2004; Mehta et al., 2009)~~. However, Létang et al. (2001) found no change of US velocity in highly hydrated doughs. Following this contradictory results, Bowler et al. (2020) decided to combine US method to Machine Learning techniques in order to achieve a better determination of dough readiness; results showed a superior prediction accuracy, outlining the efficacy of this approach.

The US method was reported to be sensitive to several variables: (i) US frequencies (Ross et al., 2004; Peressini et al., 2016); (ii) water amount in the dough (Kidmose et al., 2001; Létang et al., 2001; Salazar et al., 2002; Garcia-Alvarez et al., 2006; Bowler et al., 2020); (iii) kneading work input (Salazar et al., 2002; Garcia-Alvarez et al., 2006); (iv) flour quality (Salazar et al., 2002; Garcia-Alvarez et al., 2006; Ross et al., 2004); and (v) the bread recipe (Létang et al., 2001; Kidmose et al., 2001; Mehta et al., 2009; Peressini et al., 2016). Since the literature data have adopted different US frequencies and tested different dough samples, no exhaustive results can be drawn. The main issue in applying the US method is that dough is a highly attenuating material; hence, the major part of the studies proposed offline methods ~~have only been proposed~~ to analyse a thin dough sample. However, in the recent paper by Bowler et al. (2020) highly hydrated dough were monitored using inline sensors. The authors proposed the application of this approach for industrial kneading performed at low pressure or under vacuum, since in these conditions the dough remains in contact with the kneader. The complexity of the US techniques outlined that further investigations are required to achieve a better comprehension of its applicability to determine dough readiness. ~~At present, the complexity of a US offline technique makes the US method suitable for scientific research only and not appropriate for the baking industry.~~

Methods included in the paragraph “Other alternative methods” could be promising but they have been scarcely investigated in the literature, hence further investigations are necessary.

6. Future perspectives

The present review outlines the importance of measuring dough readiness for the scientific and industrial fields. Although kneading is considered one of the most important steps in the bread-making process and it has been extensively studied, ~~the~~ methods for measuring dough readiness have been poorly investigated. ~~A useful method should perform a reliable dough readiness measurement in the real processing conditions.~~ Owing to the increasing interest of consumers in high-nutrition breads made from weak flours which often are characterized by poor technological properties, the possibility of performing inline/online monitoring of dough development could be important ~~above issue is becoming even more important~~; bread recipes with low technological properties require accurate process controls to obtain highly nutritional products with an acceptable technological and sensory quality.

The Farinograph and Mixograph tests are the most widely used reference methods in the scientific literature and baking industry, but they do not provide a reliable measurement of dough readiness. These methods need to be adjusted; the use of both modern mixer speeds and real bread recipes can improve the ability of the above methods to predict the optimal kneading. Most literature studies have also evaluated the optimal dough development according to dough properties which did not always reflect bread quality. Therefore, at present, despite being time- and resource-consuming, the “baking trials” reference method is still able to give a reliable measurement of dough readiness.

~~The~~ Alternative methods to measure dough readiness need further research to improve their implementation. A focus is required both on standardizing the alternative parameters to monitor the dough kneading, ~~and~~ on the data processing (if performed), and on deeper investigations of methods proposed by single papers.

The suitability of a specific method changes as a function of the field of application. ~~However,~~ In the baking industry the use of the torque/power consumption method may be a first good alternative to the reference methods to improve the use of weak flours, since it enables the identification of dough readiness in real operating conditions. ~~For this reason, the above method could help in the situation of increased weak flour use in the baking industry.~~ ~~Concerning the strong flours used in dough recipes, they can be evaluated simply using baking trials, since their high stability and low degree of softness make the measurement of the dough readiness less sensitive to the great variability of this method.~~

~~For~~ In the scientific research ~~studies~~ the suitability of a method has to be evaluated in function of the aim of the study. For studies requiring a ~~focused on kneading~~ standardization of the kneading step, both the torque/power consumption method and the spectroscopic methods may be useful. On the other hand, research studies testing kneading variables may require a more accurate evaluation of the dough development ~~by monitoring~~ evaluating the chemical properties of the dough; hence, the spectroscopy methods may be more appropriate. Further research is required to improve the challenging issue of determining dough readiness.

~~Finally, the computer vision and US methods appear promising techniques, but further investigation is necessary in order to improve the scientific knowledge on their potential application in monitoring dough kneading.~~

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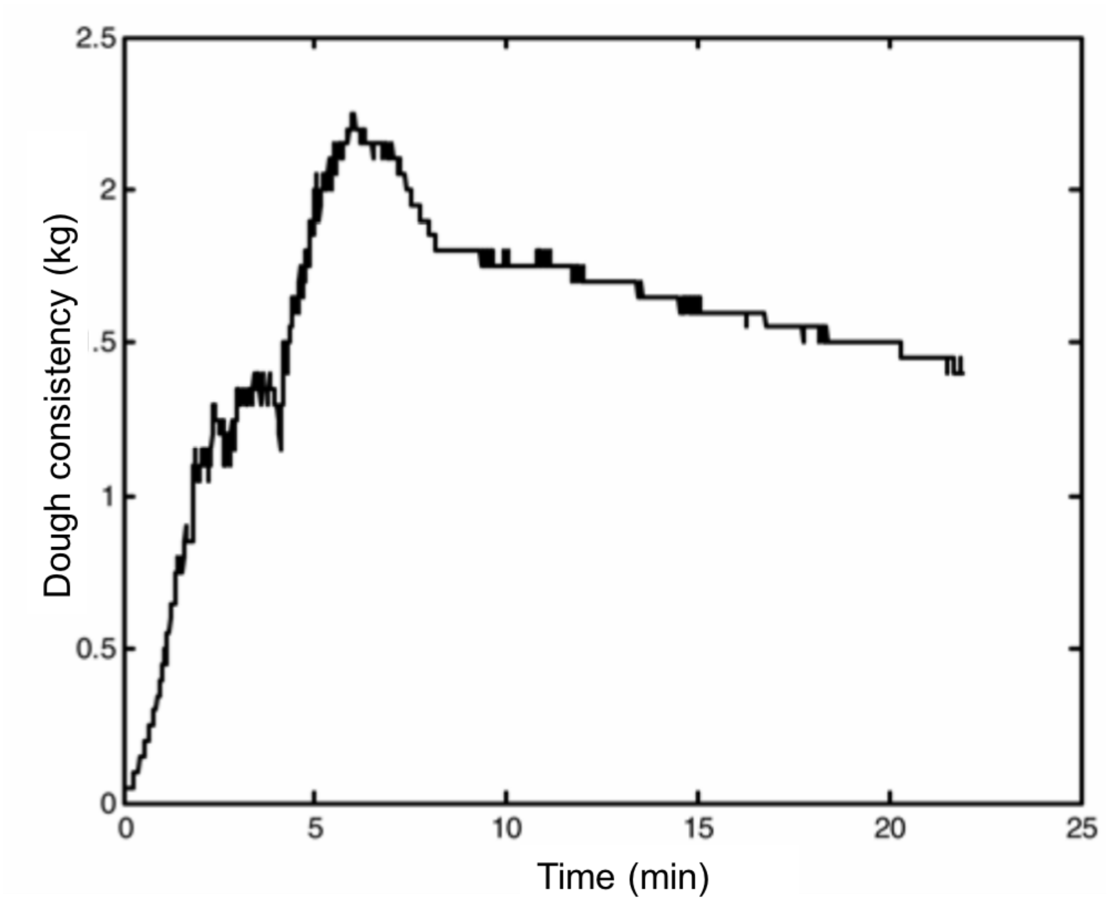

Figure 1 Changes in wheat dough consistency as a function of kneading time measured using a consistency probe. (Reprinted from Kaddour et al., 2007, with permission from Elsevier).

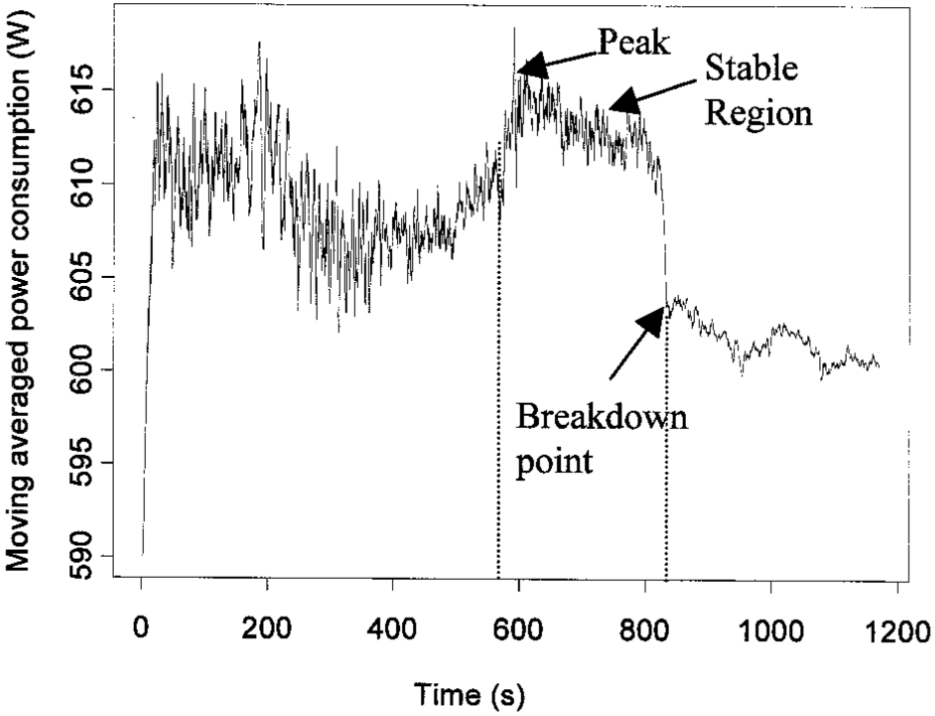

Figure 2 Moving averaged power consumption profile during kneading time of wheat flour dough measured using a current transducer. (Reprinted from Hwang & Gunasekaran, 2001, with permission from Elsevier).

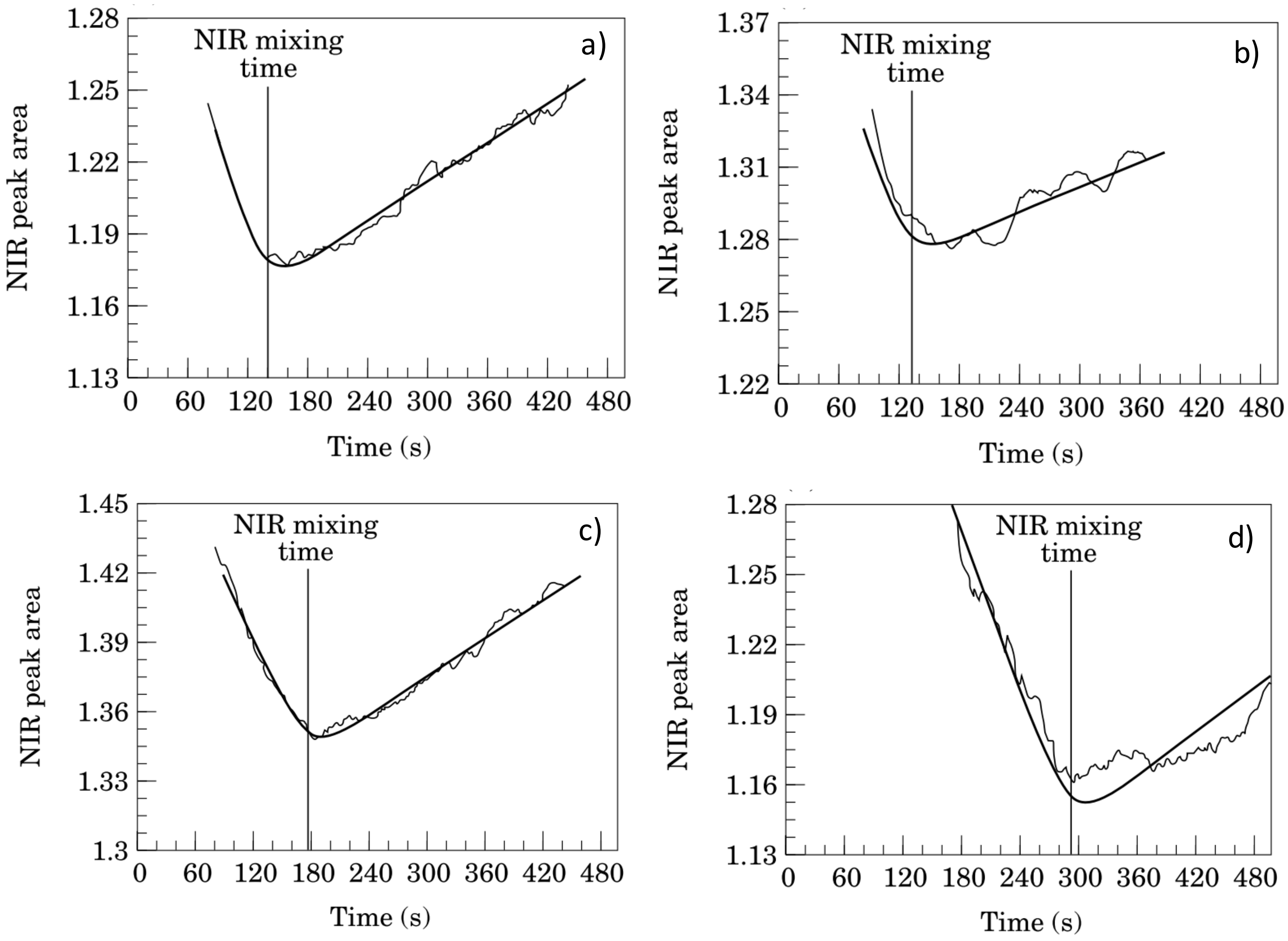

Figure 3 NIR peak area at 1125-1180 nm wavelength (thin line) and fitting curves (thick line) versus kneading time of wheat flours with different bread-making performances: standard weak biscuit-making, cv Riband (a); slightly weak bread-making, cv Rialto (b); bread-making, cv Hereward (c); strong bread-making, cv Soisson (d), kneaded in a laboratory-scale Morton mixer. (Reprinted from Alava et al., 2001, with permission from Elsevier).

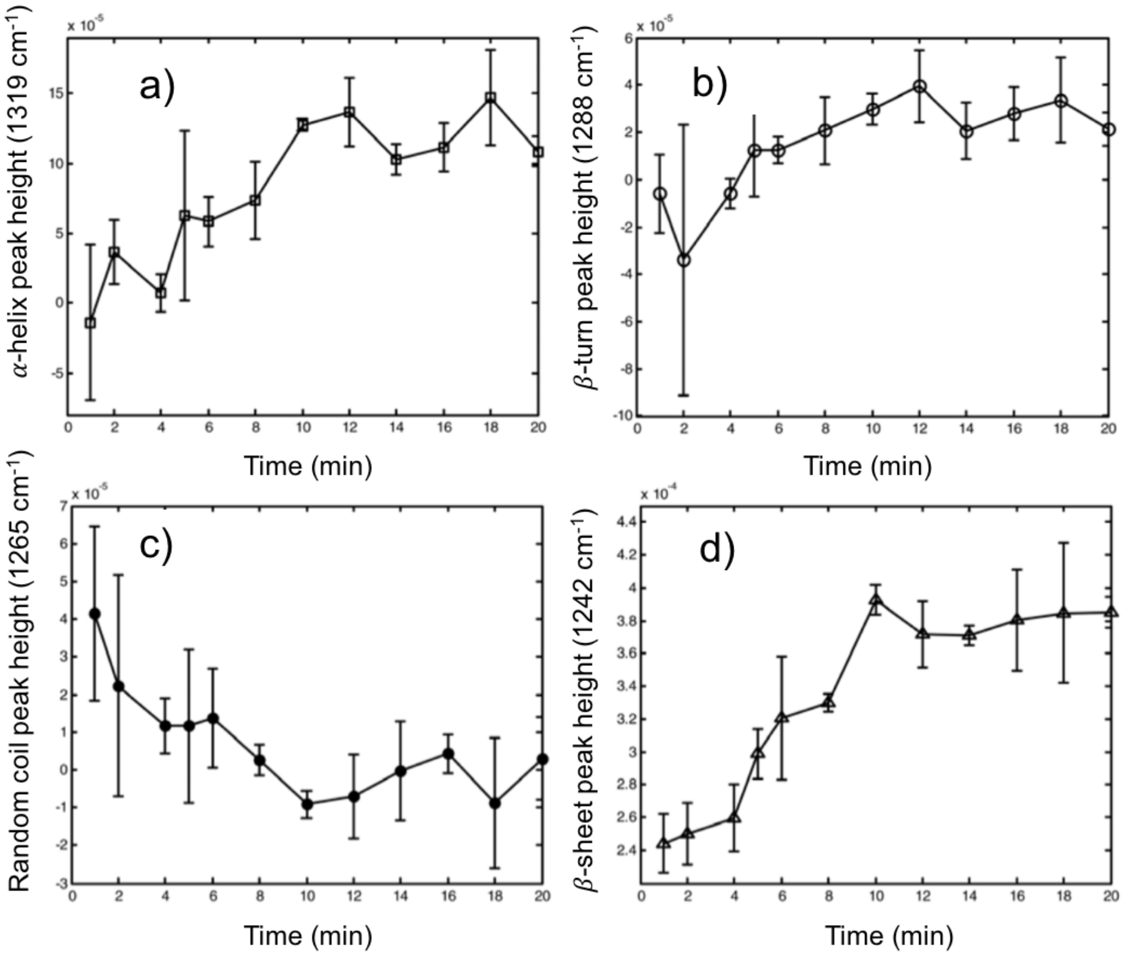

Figure 4 Changes in amide III band maximum absorbance values during bread dough kneading time; (a) α-helical (1319 cm^{-1}), (b) β-turn (1288 cm^{-1}), (c) random coil (1265 cm^{-1}) and (d) β-sheet (1242 cm^{-1}). (Reprinted from Kaddour et al., 2008, with permission from Elsevier).

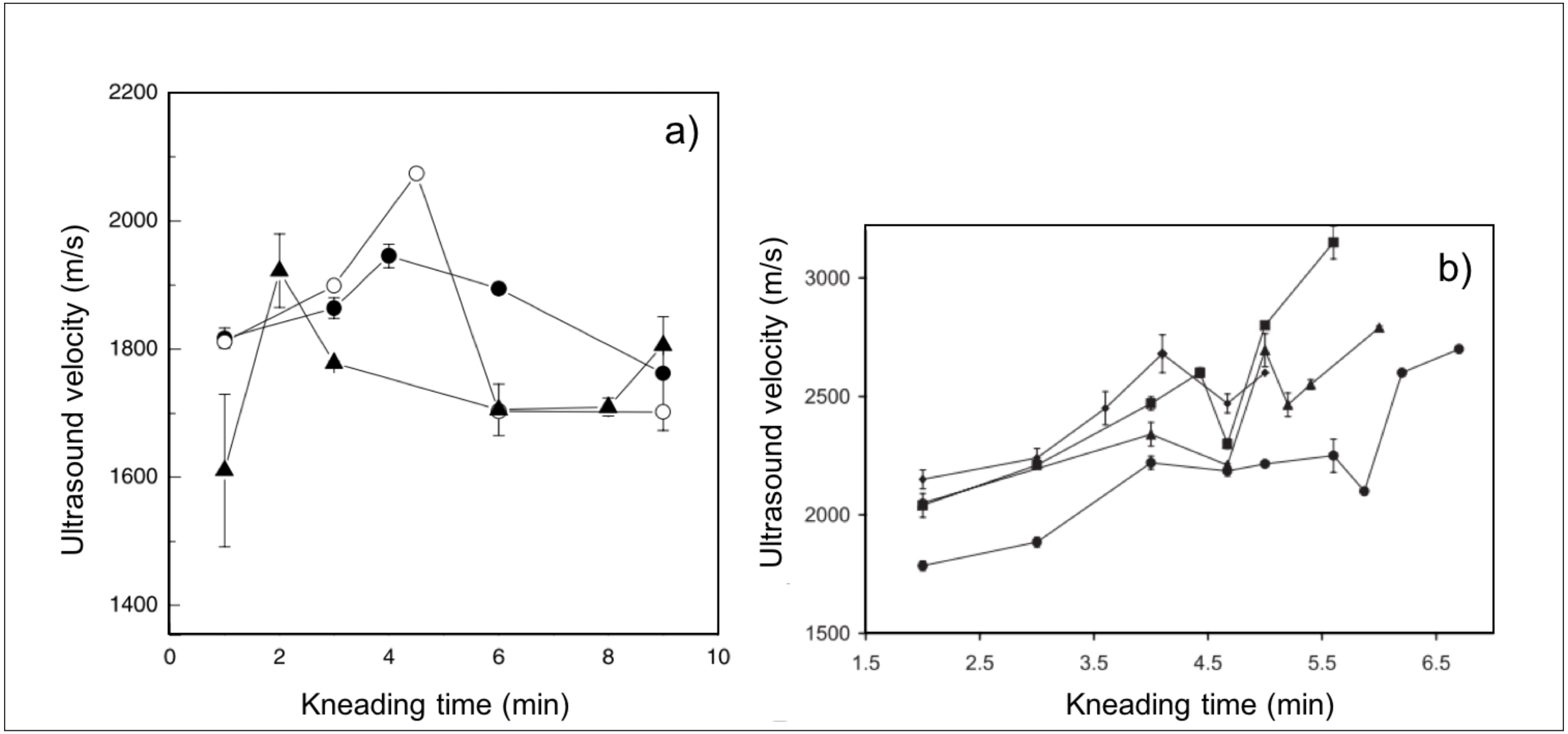

Figure 5 a) Ultrasound velocity as a function of kneading time for different types of flour: black circles = all purpose flour – optimum kneading time 4 min; empty circles = bread flour – optimum kneading time 4.5 min; black triangles = cake flour – optimum kneading time 2 min. b) Ultrasound velocity as a function of kneading time for doughs containing different percentage of shortening: balck circles = doughs with 0% shortening; balck triangles = doughs with 2% shortening; balck squares = doughs with 4% shorteing; balck diamonds – doughs with 8% shortening (% flour weight basis) (a. Reprinted from Ross et al., 2004 with little modifications and b. reprinted from Mehta et al., 2009, with permission from Elsevier).

Figure captions

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Table 1 Schematic representation of the main references obtained from the literature search about wheat dough kneading.

Main focus	***Reference***
Correlation between different methods and dough/bread quality	Frazier et al. (1975); Atkins et al. (1990); Weipert (1990); Autio et al. (2001); Jekle et al. (2011); Aydogan et al. (2015); Barbec et al. (2015); Xhabiri et al. (2016); Tietze et al. (2017)
Effects of different kneading conditions on dough/bread properties	Frazier et al. (1975); Larsen et al. (1991); Létang et al. (1999); Zheng et al. (2000); Autio et al. (2001); Cuq et al. (2002); Lee et al. (2002); Esselink et al. (2003); Calderón-Domínguez et al. (2004); Kuktaite et al. (2005); Chin et al. (2005b); Peighambardoust et al. (2006); Chenlo et al. (2006); Peighambardoust et al. (2007); Osella et al. (2007); Auger et al. (2008); Kim et al. (2008); Peressini et al. (2008); Connelly et al. (2008); Ktenioudaki et al. (2010); Shehzad et al. (2010); Tlapale-Valdivia et al. (2010); Jekle et al. (2011); Shehzad et al. (2012); Parenti et al. (2013); Bozkurt et al. (2014); Pastukhov et al. (2014); Brabec et al. (2015); Van Der Mijnsbrugge et al. (2016); Meerts et al. (2017); Rachok et al. (2018b); Cappelli et al. (2019)
Prediction of bread-making performance	Wooding et al. (1997); Stojceska et al. (2008); Migliori et al. (2013); Lucas et al. (2019)
Wheat protein structure/development	Amend et al. (1991); Pézolet et al. (1992); Bache et al. (1998); Lee et al. (2002); Belton et al. (2005); Robertson et al. (2006); Peighambardoust et al. (2007); Auger et al. (2008); Peighambardoust et al. (2010); Jekle et al. (2011); Belton et al. (2012); Kokawa et al. (2012); Bozkurt et al. (2014); Van Der Mijnsbrugge et al. (2016); Lucas et al. (2018)
Dough development	Prakash et al. (1999); Létang et al. (1999); Gras et al. (2000); Zheng et al. (2000); Cuq et al. (2003); Esselink et al. (2003); Kaddour et al. (2008b); Peighambardoust et al. (2010); Belton et al. (2012); Schiedt et al. (2013); Rachok et al. (2018a); Ščepanovic et al. (2018); Parenti et al. (2021)
Methods/promising approaches for the determination of dough readiness	Fortmann et al. (1964); Heaps et al. (1967); Tanaka et al. (1969); Kilborn et al. (1972, 1973); Frazier et al. (1975); Burrows et al. (1990); Atkins et al., (1990); Wang et al., (1993); Oliver et al. (1992, 1993, 1994); Delwiche et al. (1994); Ruan et al. (1995); Wilson et al. (1997); Zounis and Quail (1997); Anderssen et al. (1998); Demster et al. (1998); Wesley et al. (1998); Wilson et al. (2001); Létang et al. (2001); Hwang et al. (2001); Alava et al. (2001); Wilson et al. (2001); Salazar et al. (2002); Wesley et al. (2002); Ross et al. (2004); Chin et

	al. (2005a); Garcia-alvarez et al. (2006); Nassar et al. (2006); Aït Kaddour et al. (2007); Seabourn et al. (2008); Aït Kaddour et al. (2008a); Mehta et al. (2009); Ndiaye et al. (2009); Pereira et al. (2013); Altuna et al. (2016); Peressini et al. (2016); Oestersotebier et al. (2016); Doubat et al. (2016); Garcia et al. (2016); Perez Alvarado et al. (2016); Aljaafreh et al. (2017); Sangspring et al. (2017); Muscalu et al. (2017); Bowler et al. (2020)

Table 2 Schematic overview of the main results reported in the literature for reference methods.

Reference	***Reference Method***	***Instrument used***	***Parameter considered***	***Determination of dough readiness***	***Quality evaluation***	***Results/Quality of the determination of dough readiness***
Farinograph AACC 10-09.01, 10-10.03	Descriptive rheology	Farinograph	Dough consistency	Peak of consistency	Maximum of dough consistency	–
Mixograph AACC 10-09.01, 10-10.03	Descriptive rheology	Mixograph	Dough consistency	Peak of consistency	Maximum of dough consistency	–
Tanaka and Tipples (1969)	Descriptive rheology	Farinograph	Dough consistency	Peak of dough consistency	Bread quality parameters	Farinograph speeds higher than the standard value (90 - 120 rpm) improved the relationship between Farinograph kneading time and bakery optimum kneading time
Burrows and Gras (1990)	Descriptive rheology	Farinograph, Mixograph, pin mixer	Dough consistency (resistance)	Peak of dough consistency	Baking scores	High correlation between the kneading time predicted in a Mixograph and that of the pin mixer
Oliver & Allen (1992)	Descriptive rheology	Farinograph, national pin mixer	Dough consistency	The end of the Farinograph plateau period	Maximum loaf volume, Extensograph height and extensibility	Good prediction of optimum dough development when Farinograph mixing speed was higher (140-180 rpm) than the standard (60 rpm)
Zounis & Quail (1997)	Descriptive rheology	Farinograph, Mixograph, bakery pin mixer	Dough consistency	Peak of consistency (Farinograph and Mixograph), peak of power consumption (bakery pin-mixer)	Highest bread score evaluated by experienced baker.	Good prediction of optimum dough development using Farinograph at 120-180 rpm, Mixograph and bakery pin-mixer (bakery formula). Best prediction: bakery pin mixer. Selecting the Farinograph point at the end of the plateau region or the second peak obtained with bakery formula gave a better prediction of bread quality.
Dapčević et al. (2009), Zhang et al. (200), Koksel et al. (2009), Rosell et al. (2010), Caffe-treml et al. (2010), Ohm et al. (2012), Moreira et al. (2012), Blandino et al. (2015), Vàzquez & Veira (2015), Doubat et al. (2016), Torbica et al. (2016); Xhabiri et al. (2016), Singh et al. (2019)	Descriptive rheology	Mixolab	Dough consistency	Peak of dough consistency	Mixolab optimum kneading time	Good correlation with standard rheological tests (Farinograph and Mixograph)
Cauvian (2015a)	Work input (Chorleywood Bread Process, CBP)	High speed mixer	Fixed amount of energy (300 rpm, 11 W-h/kg); total	Peak of consistency	Maximum of dough consistency	–

			kneading time 2-5 min			
Wilson et al. (2001)	Mechanical Dough Development (MDD) (CBP modified method)	High speed mixer	Specific amount of energy as a function of the flour technological quality	Peak of consistency	Maximum of dough consistency	–
Oliver & Allen (1992)	Work input	Farinograph	Work input	Specific work input amount to optimum dough development	Maximum loaf volume	Work input in a Farinograph at faster speeds (140-180 rpm) than the standard is independent from the mixing speed. Fixed work input
Zounis & Quail (1997)	Work input	Farinograph, Mixograph, bakery pin mixer	Work input	Specific work input amount to optimum dough development	Highest bread score evaluated by experienced baker:	Work input in a Farinograph at faster speeds (140-180 rpm) than the standard is independent from the mixing speed on 20 of the 28 flours. Conversely work inputs depended on mixing speed on 8 of the 28 flours (interaction work input*flour type)
Anderssen et al. (1998)	Work input	Mixograph	Work input	Amount of work input expressed as number of mixer revolutions to reach optimum dough development	Optimum kneading time determined in a Mixograph; extension test (R_{max})	When mixing speeds were higher than 90 rpm the number of mixer revolutions (work input) to reach optimum dough development was constant . The resistance of the dough at peak development time well correlated with R_{max} of extension test (R=0.64), whereas the number of mixer revolutions to reach dough readiness showed a poor negative correlation with R_{max} (R=-0.33) (doughs prepared in a 2 g Mixograph)
Wilson et al. (1997)	Work input	MDD laboratory-scale and industrial-scale mixers	Work input	Amount of work input to reach maximum dough consistency	Maximum dough consistency	High correlation between the work input determined in a laboratory-scale and industrial-scale mixers, although a large off-set was shown since industrial mixers required higher work input.
Wilson et al. (2001)	Work input	MDD mixer	Work input	Amount of work input to reach peak torque	Peak of torque	Above specific mixing speed threshold, the work input was independent of the mixing speed but depended on flour quality and kneader type
Chin et al. (2005a)	Work input	Tweedy-type mixer	Work input	Amount of work input to reach peak torque	Peak of torque	Work input was not independent of mixing rate in this mixer
Atkins & Larsen (1990)	Work input	Farinograph	MDD parameters	Development time in MDD system	Bread volume	Farinograph can be used to determine MDD development time

Visual inspection AACC 10-09.01, 10-10.03	Visual inspection	–	–	–	Subjective visual/tactile sensory evaluation	Poor; Perez Alvarado et al. (2016) reported high standard deviation 300 ± 200 s
Baking trials AACC 10-09.01, 10-10.03	Experimental trials	Mixers	The dough is kneaded at a constant speed and for different kneading times, with intervals of 0.5 min	–	Bread quality parameters	Reliable results of the optimal kneading time but large amounts of efforts (ingredients and time)
Ross et al. (2004)	Fundamental rheology	Controlled stress rheometer: strain and frequency sweep experiments	Storage modulus (G’), loss modulus (G’’)	Maximum of G’, Maximum of G’’	Mixograph optimum kneading time	Maximum of G’ and G’’ corresponds to Mixograph optimum kneading time
Ram et al. (2005)	Lactic Acid Solvent Retention Capacity (LASRC)	SRC test	SRC method as described by Guttieri et al. (2001)	LASRC	Farinograph and Mixograph optimum kneading time	LASRC showed significant positive correlation with Farinograph and Mixograph optimum kneading time
Tietze et al. (2019)	Micro-scale shear mixing (MSSM) technique	Rheometer	Relaxation spectra during kneading	The point of the relaxation spectra where the peaks stop drifting	Optimum kneading time determined in a z-blade mixer	Good correlation between kneading time of doughs obtained in MSS and those developed in a z-blade mixer

Table 3 Schematic overview of the main results reported in the literature for alternative methods.

Reference	***Alternative Method***	***Instrument used***	***Parameter considered***	***Determination of dough readiness***	***Quality evaluation***	***Results/Quality of the determination of dough readiness***
Wang et al. (1993)	Power consumption	Horizontal mixer	Three phase input power	Instantaneous input power data acquisition system (DAS) and digital signal processing (DSP)	DAS: development of gluten protein (empirically related to the instantaneous input power signal) DSP: dough strength, cohesiveness, viscoelasticity	DAS, DSP and Fuzzy logic control system were proposed for dough mixing control
Zounis & Quail (1997)	Power consumption	Bakery pin mixer	Power consumption	Maximum power consumption	Highest bread score evaluated by experienced baker	For kneading time below 400 s a good correlation between power consumption and the kneading time that maximized bread quality was found. In 20 (high protein contents) of the 28 samples the kneading time that optimized bread quality was longer than the peak of power consumption
Hwang & Gunasekaran (2001)	Power consumption	Hobart mixer with a pin-type attachment	Power consumption	Maximum power consumption	Maximum storage and viscous moduli (G' and G'')	The spectral analysis of the power consumption can be used to identify the peak mixing time from the signal amplitude data; good correlation between power consumption and G'; the trend of G'' were similar to G' hence results were not reported
Pereira et al. (2013)	Power consumption	Mixer machine CSLA1CD	Power consumption	Maximum power consumption	Peak of torque	Power consumption was highly correlated with torque
Aljaafreh (2017)	Power consumption	Current sensing and online learning through reinforcement learning (RL)	Power consumption	User feedback	Characteristics of the mixture	Non-invasive sensor for real-time monitoring of kneading based on power consumption and RL
Altuna et al. (2016)	Torque	Large-scale dynamic rheometer	Torque	Peak of torque	Peak of torque	New methodology to measure torque during dough kneading
Delwiche & Weaver (1994)	NIR spectroscopy	Hobart mixer	NIR reflectance spectra in the range of 1100-2498 nm	Regression model were developed using the score of each spectrum	Optimal dough consistency	Poor models for the determination of dough readiness were obtained

Dempster et al. (1998)	NIR spectroscopy	Hobart mixer	NIR radiation in the range of 400-1700 nm	Algorithm based on the ratio 1455 nm/1205 nm wavelength to obtain peak of NIR curve	Empirical evaluation of a trained mixer operator	Good correlation between NIR peak curve and optimum kneading time as judge by trained mixer operator (empirical evaluation)
Wesley et al. (1998)	NIR spectroscopy	Spiral, morton z-arm, and pin-mixer	Second derivative of raw NIR spectra. Peak areas at 1160 nm and 1200 nm plotted against mixing time	Minimum NIR peak areas at 1160 nm (water) and 1200 nm (probably glutenin macropolymer and extractable gliadins)	Maximum of power consumption	NIR kneading time from second derivative spectra (minimum at 1160 nm and 1200 nm) was close to the maximum power consumption although slightly longer independently from the kneader and flour typology
Alava et al. (2001)	NIR spectroscopy	Two high speed CBP mixers	Second derivative of raw NIR spectra and PCA. Peak areas at 1125-1180 nm (hydration of the flour to form a dough) plotted against mixing time	Minimum NIR peak area at 1125-1180 nm	Maximum torque and elastic modulus of gel protein fraction G', bread quality parameters (loaf volume and crumb cell area)	NIR kneading time from second derivative spectra (minimum at 1125-1180 nm) was longer than the optimum kneading time predicted with traditional methods (torque and G') but a better prediction of bread quality was obtained
Kaddour et al. (2007)	FT-NIR spectroscopy	6-kg Mahot mixer	Raw spectra (physical properties), second derivative of raw NIR spectra (physicochemical properties) at 1352-1485, 1778-2052, 2109-2325 nm (greatest change at 1778-2052 nm associated to O-H vibrations) by using PCA	Minimum of NIR kneading curve (NIR kneading time) obtained from PC1 scores at 1000-2500 nm and 1778-2052 nm (associated to interactions of water molecules with flour components)	Maximum torque and dough consistency	NIR kneading time from raw NIR spectra was longer than the optimum kneading time predicted by maximum dough consistency; NIR kneading time from second derivative treatment (1000-2500 nm and 1778-2052 nm) was more similar to the time at maximum consistency
Wesley et al. (2002)	Patent NIR spectroscopy method	–	Absorbances of NIR second derivative spectra at 1160 nm (water), 1200 nm (predominantly proteins), 1430 nm (water and proteins); preferentially also adsorbances at 2350 nm (glutenin), 2340, 2310 and 2195 nm (gliadins)	Minimum of NIR second derivative spectra at 1160, 1200, 1430 nm and at at 2350, 2340, 2310 and maximum at 2195 nm indicated the optimum kneading time;	Based on previous results (Wesley 1998)	NIR kneading time obtained at minimum 1160, 1200, 1430 nm and at at 2350, 2340, 2310 and maximum at 2195 nm gave a good prediction of the kneading time that optimized bread quality (Wesley et al. 1998)
Seabourn et al. (2008)	FT-HATR MIR spectroscopy	Mixograph	MIR absorbances in amide III band region were analysed after a short-duration mixing cycle (1 min)	Ratio of the Second Derivative Band Area (SDBA) between α-helix (1336 cm^{-1}) and β-sheet (1242 cm^{-1})	Optimum kneading time predicted in a Mixograph	High correlation between SBDA α-helix (1336 cm^{-1}) and β-sheet (1242 cm^{-1}) and optimum kneading time predicted by the Mixograph (R^2=0.81)
Kaddour et al. (2008)	ATR FT-MIR spectrometer	6-kg Mahot mixer	MIR spectra analysed after standard normal variate (SNV) using PCA and after second derivative treatment of amide III (α-helical 1319 cm^{-1}, β-turn 1288 cm^{-1}, β-sheet 1242 cm^{-1},	MIR maximum score value on the PC1 score plot ; MIR maximum absorbance in amide III band; maximum of α-helical 1319 cm^{-1}, β-turn 1288 cm^{-1}, β-sheet 1242 cm^{-1}	Maximum torque value	Analysis of the amide III band (α-helical 1319 cm^{-1}, β-turn 1288 cm^{-1}, β-sheet 1242 cm^{-1}, random coil structures 1265 cm^{-1}) related to changes in the secondary protein structures gave the optimum MIR

			random coil structures 1265 cm^{-1})	, minimum of random coil structures 1265 cm^{-1}		mixing time associated to the time at which the torque began to collapse. Good prediction of the optimum kneading time
Salazar et al. (2002), Garcia-alvarez et al. (2006)	Ultrasounds	Morton mixer	Monitoring of ultrasound velocity and attenuation parameters	Ultrasound velocity seemed to be dependent on flour quality and to be correlated to optimum kneading time	Work input, bread quality parameters (loaf volume, cell diameter)	Limited levels of work input were considered. No conclusive result
Ross et al. (2004)	Ultrasounds	Mixograph	Monitoring of ultrasound velocity and attenuation parameters	Maximum ultrasound velocity and attenuation parameters	Optimum kneading time determined in a Mixograph; fundamental rheological parameters (G' and G'')	Ultrasound velocity and attenuation parameters showed maximum values at the optimum kneading time of the Mixograph
Nassar et al. (2006)	Ultrasounds	Alveograph kneader bowl	Monitoring of the ultrasound signal amplitude	Maximum of the ultrasound signal amplitude	Phase transition of the signal corresponded to optimal dough development according to Zheng et al. (2000)	Acoustic measurement can potentially be used as an effective on line dough quality control technique
Mehta et al. (2009)	Ultrasounds	GRL-200 mixer	Monitoring of ultrasound velocity and attenuation parameters	Discernible peak in the decreasing trend of ultrasound velocity; reduction in the increasing trend of attenuation parameter	10% past peak resistance in the mixing curve	The discernible peak of ultrasound velocity was correlated with the optimum kneading time determined as 10% past peak resistance in the mixing curve
Peressini et al. (2016)	Ultrasounds	Farinograph kneader bowl	Monitoring of ultrasound velocity and attenuation parameters	Mean values of ultrasound velocity and phase velocity in the range of 0.3-3 MHz	Large-strain conventional rheological tests and bread quality	Ultrasound parameters had predictive capacity for bread-making performance
Bowler et al. (2020)	Ultrasounds	Kneader machine	Acoustic paramaters (speed of sound, acoustic impedance, reflection coefficient)	Ultrasound technique combined with Machine Learning (ML) engineering method	Maximum of power consumption	Ultrasound technique combined with ML showed the potential to determine the dough readiness

Table 4 A synoptic comparison between ~~the~~ reference methods and the main alternative methods of dough readiness measurement**.**

Reference Methods	***Dough readiness measurement principle***	***Predictive action on kneading***	***Strengths***	***Weaknesses***	***References***
Visual inspection	Visual and tactile dough sensory attributes	Optimal kneading time	Direct measurement	Subjective measurement	AACC 10-09.01 and 10-10-03 methods
Baking trials	Bread quality parameters	Optimal kneading time	End product quality prediction	Time- and resource-consuming	AACC 10-09.01 method
Descriptive rheological tests	Trend of dough texture as a function of time	Apparent optimal kneading time	Direct measurement	Different operating conditions between lab test and bakery	AACC 10-09.01 and 10-10-03 methods; Tanaka & Tipples (1969); Burrows & Gras (1990); Oliver & Allen (1992, 1993, 1994); Zounis and Quail (1997); Doubat et al., 2016
Work input measurement	Energy to mix dough to kneader point of peak torque	Fixed energy amount to achieve dough readiness	Independent of kneading type	Not applicable at all kneading speeds	Fortmann et al. (1964); Heaps et al. (1967); Kilborn & Tipples (1972, 1973); Frazier et al. (1975); Atkins et al., (1990); Oliver & Allen (1992); Wilson et al. (1997); Zounis and Quail (1997); Anderssen et al. (1998); Wilson et al. (2001); Chin et al. (2005a); Muscalu et al. (2017)
Alternative Methods	***Dough readiness measurement principle***	***Predictive action on kneading***	***Strengths***	***Weaknesses***	***References***

Torque and power consumption measurements	Trend of torque and power consumption as a function of time	Optimal kneading time in terms of dough texture	Online measurement	Relationship between torque/power and dough texture not always applicable	Wang et al., (1993); Zounis and Quail (1997); Wilson et al. (2001); Hwang & Gunasekaran (2001); Pereira et al. (2013); Altuna et al. (2016); Aljaafreh et al. (2017)
NIR spectroscopy	Spectra analysis in NIR range of 400 - 2500 nm	Optimal kneading time in terms of dough physico-chemical changes	Independent of kneading operating conditions	Identification of specific wavelength range and data processing	Delwiche et al. (1994); Demster et al. (1998); Wesley et al. (1998); Alava et al. (2001); Wesley et al. (2002); Aït Kaddour et al. (2007)
MIR spectroscopy	Spectra analysis in MIR range of 2500 - 5000 nm	Optimal kneading time in terms of dough physico-chemical changes	Good monitoring of gluten network formation	Offline measurement	Seabourn et al. (2008); Aït Kaddour et al. (2008a)
~~Computer vision~~	~~Image analysis of dough homogeneity~~	~~Optimal kneading time in terms of visual inspection and torque trend~~	~~Automated and cost-effective method~~	~~Little research on the method~~	~~Perez Alvarado et al. (2016)~~
Ultrasounds	US velocity and attenuation of longitudinal waves from 20 kHz to 10 MHz	Optimal kneading time in terms of dough texture	Good evidence of water effect on dough development	Contradictory experimental data	Létang et al. (2001); Salazar et al. (2002) and Garcia-alvarez et al. (2006); Ross et al. (2004); Nassar et al. (2006); Mehta et al. (2009); Peressini et al. (2016); Bowler et al. (2020)

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- ✓ ☒ The The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript:

Authors's name	**Affiliation**
Ottavia Parenti	Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, Università degli Studi di Firenze, Italia
Lorenzo Guerrini	Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, Università degli Studi di Firenze, Italia
Sara Bossa Mompin	Institut de Tecnologia Agroalimentària, Escola Politècnica Superior, Universitat de Girona, Spain
Mònica Toldrà	Institut de Tecnologia Agroalimentària, Escola Politècnica Superior, Universitat de Girona, Spain
Bruno Zanoni	Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, Università degli Studi di Firenze, Italia