Techniques and technologies for the breadmaking process with unrefined wheat flours

Original
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Abstract

Background: In recent years there has been an increasing interest in the production of wholegrain products owing to the positive effects shown on human health. Although refined flour still represents the standard reference in breadmaking technology, consumer demand for unrefined breads has grown greatly. The different chemical composition of unrefined wheat flours (UWFs), which includes specific fractions of milling by-products (i.e., wheat bran and wheat germ), favours the nutritional value, but it has a negative effect on technological performance. Therefore, it is useful to develop new strategies specifically designed to improve the quality of UWF breads. Scope and approach: The present review aims to set out the techniques and technologies that have been reported in the literature for the breadmaking process with UWFs, that is, from raw material processing to bread formulation and breadmaking methods. Key findings and conclusion: The evaluation of UWF quality is still based on the tests developed for refined flour, which cannot properly estimate UWF technological properties. The greatest efforts to improve the breadmaking performance of UWF have been focused on modifying the bread formula, mainly with the addition of improvers. Conversely, very little investigation has been carried out on adapting the breadmaking process to the different characteristics of the raw material. Overall, the use of UWF in breadmaking may require further investigations into processing strategies to improve the quality of the end product, hence increasing the consumption of healthy foods.

Keywords	bread; wholewheat flour; milling by-products; wheat germ; wheat bran
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Dr. Paul Finglas
Executive Editor
Trends in Food Science & Technology

January 27, 2020

Dear Dr. Paul Finglas:

I am pleased to submit an original research article entitled "Techniques and technologies for the breadmaking process with unrefined wheat flours" for consideration for publication in *Trends in Food Science & Technology*.

This manuscript aims to report the processing strategies that have been developed until now for the breadmaking process with unrefined wheat flours, while suggesting some processing innovations to improve the exploitation of unrefined wheat flours. The main chapters of this manuscript include: (i) the introduction section, (ii) the evaluation of bread quality, (iii) the breadmaking process (reporting the scientific literature about breadmaking with unrefined wheat flours), (iv) the carbon footprint of unrefined wheat flour bread and (v) the conclusion.

We believe that this manuscript is appropriate for publication by *Trends in Food Science & Technology* since the use of unrefined flours for bread production has recently gained attention of the scientific research as well as of consumers. Moreover, reporting the processing strategies that improve the bredmaking process of unrefined wheat flours, may increase their consumption, which is associated to positive effects on human health.
To the authors' best knowledge, the use of unrefined wheat flour in breadmaking has never been reviewed before. The relevance of this study is a literature review about the breadmaking with unrefined wheat flours, from the raw materials to the storage phase.

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

The authors would like to thank the Reviewers for the time spent in improving the paper, and for the important suggestions and corrections proposed. We hope to have addressed all the issues the reviewers outlined. Here following, a point by point reply to the comments received.

-Reviewer 1

- I really enjoyed reading the article, it is written in a clear way and is easy to follow. The different aspects of bread making are discussed in relation to the different flours that can be used and the challenges one faces when shifting from refined to unrefined flour. Mostly, the authors refer to recent literature, outlining the up to date literature available on the topic.

There were a few items that I would like to draw attention to:

Lines 263-265. It is mentioned that the fact that bran addition goes along with increase in ash content is contributing to a decrease in flour properties. Is that what the authors, Banu (2012) concluded? could it also relate to addition of bran fibres which affect flour properties? when you speak about technological properties, are there specific ones you are referring to? if yes, I recommend clarifying that.

Lines 263-265: Banu et al. (2012) studied the rheological properties and bread physical parameters of white flour enriched with different bran streams (3-30%). As reviewer observed, the conclusion of the study is that ash content, a measure of the bran and germ "contamination" on the white flour produced with the only starchy endosperm, significantly decreased the rheological properties of the dough and physical characteristics of breads. However, although they observed a negative impact of ash content on dough and bread quality, the authors identified in the 25% sample a level of ash content equal to that in wholewheat sample, but associated with a significant improvement of dough and bread quality.
According to reviewer observation we added some specifications about the study by Banu et al. (2012) (L 268-273).

L268: This sentence was a little unclear to me. was wheat pearled to 2-25% and was that used to make bread? or, was wheat pearled to X% and added to refined flour at 5-25% level?

Blandino et al. (2013) added 5 different levels of pearled fractions from wheat kernels (5-25%) on refined flours and tested the flour mixtures on dough rheology, bread quality and nutritional properties. We clarified the sentence in the Manuscript (L274-275) according to reviewer observation.

L339. I feel increase needs to be changed into decrease

The sentence has been rephrased (L346).

L400, 429 and 540. Are these percentages additions to the total recipe or expressed on flour weight? Also table 2 mentions percentages of addition and it would be good to clarify whether these are on flour weight or total recipe.

In accordance with reviewer's observation we specified the percentages of addition in L414, 444-445, 556-557. We also modified Table 2 adding the required specifications.

L417: Why does a farinograph not work for UWF?

The farinographic official method was developed to evaluate the water absorption (WA) and the behaviour during the mixing step of refined flour. In refined flour the main components responsible for the WA are the gluten network proteins, which can adsorb up to three time their weight in water (Zaidul, I.S.M., Karim, A.A., Manan, D.M.A., Ariffin, A., Norulaini, N.A.N. & Omar, A.K.M. (2004). A farinograph study on the viscoelastic properties of sago ⁄wheat flour dough. *Journal ofScience and Food Agriculture*, 84, 616–622). In unrefined products the presence of soluble and insoluble fibres as flour constituents significantly increases the flour water absorption (Schmiele et al., 2012). In fact, the hydroxyl groups in fibre structure bind to water molecules and compete with starch and proteins for hydration, altering the water distribution in the dough (Khalid et al., 2017; Curti et al., 2013). Hence, the farinographic WA in unrefined wheat flours does not reflect the amount of water required for the optimal hydration of the gluten proteins to reach the 500BU of consistency, but this value results also from the fibre water absorption.
The authors also added the reference Schmiele et al. (2012) to support the statement in L431 and in the reference list L1149.

L473: Which studies report and increase in stabilisation by DATEM? Tebben (2018) seems to indicate a decrease in stability

Tebben et al. (2018) reported that monoglycerides and diglycerides decreased the final proof time, while DATEM increased the final proof time as measured by Mathurograph. It means that mono- and di- glycerides allowed the dough to perform a faster leavening, whereas DATEM reduced the dough rise. Hence, the authors reported DATEM to increase the fermentation stability in terms of a larger window of time during which the dough can be moved to the leavening to the baking step without loosing its optimal volume (Hrušková, M., Švec, I., & Jirsa, O., 2006. Correlation between milling and baking parameters of wheat varieties. *Journal of Food Engineering*, 77, 439–444; Mettler, E., & Seibel, W., 1993. Effects of emulsifiers and hydrocolloids on whole wheat bread quality - a response-surface methodology study. *Cereal Chemistry*, 70, 373–377). Converseley, a study by Armero, E., & Collar, C., 1996b. Antistaling additives, flour type and sourdough process effects on functionality of wheat doughs. *Journal of Food Science*, 61, 299–303, found that DATEM decreased the fermentation stability and final proof time; for this reasons in the present review we reported that controversial results about the effect of DATEM on fermentation stability are still present in the current literature.

L 474.: You speak about studies looking at emulsifiers, but in the whole paragraph only one reference is used. was there only one study? if yes, mention that you could identify just one study. That indicates a gap in the research simultaneously.

The authors agree with reviewer’s observation. As we stated at the beginning of the paragraph 3.2.3 “UWF bread improvers” (L442-443), the addition of common bread improvers on the breadmaking performance of wholewheat flours has been recently reviewed by Tebben et al. (2018). In a previous version of the Manuscript we included all the references cited in the review Tebben et al. (2018), but unfortunately the final number of references exceeded those allowed by the Journal (at maximum 100 ref). Hence, we had to remove some of the scientific studies, and we limited to cite the review article where the reader could find all the specific references that are briefly summarized in the present review.

At the end of the paragraph we reported that the mentioned studies tested the effects of bread improvers on wholewheat flour, whereas information on the impacts of the same improvers on unrefined flour performances are still missing in the current literature (L519-521). We specify in the text that Tebben et al is a review.

L706-707: The sentence is a little confusing. were 13 or 14 attributes tested by a sensory panel?

We corrected the sentence in L723 according to reviewer's observation. In the mentioned study (Jensen et al., 2011a) a total of 13 sensory attributes was chosen for each of the tested bread samples.

Reference list: the reference to Tebben (2018) is mentioned in the text and tables but missing in the list. Please add this one

We added Tebben et al. (2018) in the reference list (L1173).

Table 2: treatments on whole grain, mainly germination are given. This is what Richter (2014) did as well. I see it in the reference list but not in the table. could it be added?

Table 2: There was an error in the reference name of Table 2, but the reference Ritcher et al. (2014) was already included in the Table. We corrected the mistaken reference, hence Ritcher et al. (2014) is now present in reference of the Table as well as in the reference list of the Manuscript.

Table 4 and **5** show '?' in the last column. What is meant with these? It would be good to clearify that in the foot note of the table. Or, use a - if no real conclusions can be drawn from the study.

Table 3: the authors added some specification about the article by Zilic et al (2016) in the colums "Measurements" and "Main Results".
Table 4: the authors made an in-depth research to include additional information in Table 4, studying the specific literature references of the cited review by Hemdane et al. (2016) and Boukid et al. (2018).
Table 5: the authors added some specification as suggested by the reviewer.
Table 6: the authors added some specification consistently with Table 5.

-Reviewer 2

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The topic is interesting and current, the paper is well written and well argued.
Some suggestions:
- **Page 3 line 67**: In 2019 Whole Grain Initiative sets the following definition of whole grains also approved by ICC, Healthgrain and Cereal & Grain Association: "Whole grains shall consist of the intact, ground, cracked, flaked or otherwise processed kernel after the removal of inedible parts such as the hull and husk. All anatomical components, including the endosperm, germ, and bran must be present in the same relative proportions as in the intact kernel". I suggest referring to this definition because is the most recent.

The authors added the reference suggested by the reviewer in L67-68.

- **page 3 line 79, page 4 lines 126 and 127, page 5 line 132**............. : I suggest changing the term sensory, throughout the text, with sensorial.

As reviewer suggested we changed the word “sensory” with “sensorial” (L80, L127, L128, L133).

- **page 11 line 336**: the term gelatinizing should be changed with gelatinization.

We changed the term “gelatinizing” with “gelatinization” according to reviewer’s suggestion (L342-343)

- **page 14 line 439-442**: other authors than Tebben et al, 2018 reported about the positive role exerted by xylanase:
Katina K., Heiniö R.L., Autio K., Poutanen K. Lebensm. Wiss. Technol., 2006, 39, 1189-1202.
Messia M.C., Reale A., Maiuro L., Candigliota T., Sorrentino E., Marconi M. J. Cereal Sci., 2016, 69, 134-144.
Santala O. , Lehtinen P. , Nordlund E. , Suortti T. , Poutanen K. J. Cereal Sci., 2011, 54 187-194.
However, Tebben et al., 2018 (page 14 line 444) is missing from the references !!

The reference list of the Manuscript already included “Katina, K., Heiniö, R. L., Autio, K., & Poutanen, K. (2006a). Optimization of sourdough process for improved sensory profile and texture of wheat bread. *LWT - Food Science and Technology*, 39, 1189–1202” in L1030 and in the Manuscript L138, L147, L614, L624. However, the aim of the paper was to (i) investigate the effect of sourdough process parameters (ash content of flour, fermentation temperature and fermentation time) on bread quality parameters performing two different types of fermentations (a single strain of lactic acid bacteria or a combination of lactic acid bacteria + yeasts) and (ii) to improve flavour, volume and shelf life of breads by optimizing the fermentation variables. Was the reviewer referring to this or to another paper for the missing reference about xylanase positive effects?

The authors added the reference proposed by the reviewer “Messia, M. C., Reale, A., Maiuro, L., Candigliota, T., Sorrentino, E., & Marconi, E. (2016). Effects of pre-fermented wheat bran on dough and bread characteristics. *Journal of Cereal Science*, 69, 138–144” in the reference list (L1078) and in the Manuscript Paragraph 3.1.2.2 L369. Furthermore, the authors included this reference in Table 4 and L372 since the study also tested the effect of bran pre-soaking on dough rheology and bread physical properties.

The authors added the reference “Santala, O., Lehtinen, P., Nordlund, E., Suortti, T., & Poutanen, K. (2011). Impact of water content on the solubilisation of arabinoxylan during xylanase treatment of wheat bran. *Journal of Cereal Science*, 54, 187–194” in the Manuscript Paragraph 3.1.2.2 L368-369 and in the reference list L1142.

The authors added Tebben et al. (2018) in the reference list (L1173).

- **References section**: page 32 line 938, page 32 line 947, page 35 line 1039, page 36 line 61, page 37 line 1095: in the references section Authors must pay attention to how the surnames and names of the authors are reported. Here are some correct underlined surnames: Fadda C, Sanguinetti A.M., Del Caro A., Collar C., Piga A (2014); Gobbetti M., Rizzello C.G., Di Cagno R., De Angelis M. (2014); Marti A., Cardone G., Nicolodi A., Qualgia L., Pagani M.A., (2017): Otoni C.G., Pontes S.F.O., Medeiros E.A.A., Soares Nde F. (2014).

We corrected the references in the reference list and throughout the Manuscript as reviewer suggested (L965, L1066, L322, L1101).

Furthermore, the authors added in the paragraph 3.1.2.1 (L352-356) “Pre-treatment of wheat kernels: germination” the interesting results recently showed in the paper by Cardone et al. (2020), which was published during the submission process of the present review. The article studied the application of a controlled germination process on rheological characteristics of doughs and physical quality of breads from wholewheat flour showing promising results.

Highlights

- Positive effects on human health shown by the consumption of unrefined wheat products
- Review of the use of unrefined wheat flours in the breadmaking process
- Discussion of the standard criteria for the evaluation of unrefined bread quality
- Description of modifications to the bread formula and process for unrefined flours
- Proposal for new research to improve the employment of unrefined flours

Abstract:

Background: In recent years there has been an increasing interest in the production of wholegrain products owing to the positive effects shown on human health. Although refined flour still represents the standard reference in breadmaking technology, consumer demand for unrefined breads has grown greatly. The different chemical composition of unrefined wheat flours (UWFs), which includes specific fractions of milling by-products (i.e., wheat bran and wheat germ), favours the nutritional value, but it has a negative effect on technological performance. Therefore, it is useful to develop new strategies specifically designed to improve the quality of UWF breads.

Scope and approach: The present review aims to set out the techniques and technologies that have been reported in the literature for the breadmaking process with UWFs, that is, from raw material processing to bread formulation and breadmaking methods.

Key findings and conclusion: The evaluation of UWF quality is still based on the tests developed for refined flour, which cannot properly estimate UWF technological properties. The greatest efforts to improve the breadmaking performance of UWF have been focused on modifying the bread formula, mainly with the addition of improvers. Conversely, very little investigation has been carried out on adapting the breadmaking process to the different characteristics of the raw material. Overall, the use of UWF in breadmaking may require further investigations into processing strategies to improve the quality of the end product, hence increasing the consumption of healthy foods.

Techniques and technologies for the breadmaking process with unrefined wheat flours

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Abstract:

Background: In recent years there has been an increasing interest in the production of wholegrain products owing to the positive effects shown on human health. Although refined flour still represents the standard reference in breadmaking technology, consumer demand for unrefined breads has grown greatly. The different chemical composition of unrefined wheat flours (UWFs), which includes specific fractions of milling by-products (i.e., wheat bran and wheat germ), favours the nutritional value, but it has a negative effect on technological performance. Therefore, it is useful to develop new strategies specifically designed to improve the quality of UWF breads.

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Keywords: bread; wholewheat flour; milling by-products; wheat germ; wheat bran

Abbreviations: unrefined wheat flour (UWF), wheat germ (WG), wheat bran (WB)

1. Introduction

Wheat bread is the staple food in many diets, representing one of the main sources of the daily energy intake. Bread composition is the result of several factors including wheat genotypes, agronomic treatments, environmental conditions, flour composition, breadmaking conditions and product storage.

The wheat species most widely used for breadmaking is *Triticum aestivum* L. or “common” wheat, accounting for 95% of wheat production, followed by *Triticum durum* or “durum” wheat, which is widely used in Mediterranean cuisine for making special breads, couscous, pasta and bulgur.

For most of human history, flour was produced using stone mills, which simultaneously crushed and ground wheat kernels in a single millstream, giving wholewheat flour. The milling process was completely revolutionized during the second half of the 19th century with the introduction of the roller mill, which allowed the three fractions of the caryopsis (i.e., starchy endosperm, bran and germ) to be separated at the beginning of the process, resulting in different millstreams (Jones, Adams, Harriman, Miller, & Van der Kamp, 2015). The refined flour obtained from the starchy endosperm alone shows better technological quality and gives breads with sensory properties that are widely appreciated by consumers. Hence, refined flour has become the standard for the further technological developments in the bakery industry up to the present day. This means that all the knowledge on bread formulation and process implementation has been made by considering refined wheat flour, characterized by a chemical composition mainly composed of starch (80%-85%) and proteins (8%-14%). The other millstreams (i.e., bran, germ) are instead considered milling by-products and mainly used as animal feed.

However, in recent years there has been renewed interest in unrefined wheats, since several studies have shown that regular consumption of these products is associated with health benefits such as a lower risk of chronic-degenerative diseases and improved body weight regulation (Ye, Chacko, Chou, Kugizaki, & Liu, 2012; Hauner et al., 2012) The increased interest in healthy and functional foods has led to a consequent growth in the demand for high nutritional value breads (Gani, & Hameed, 2012). As a result, it has been necessary to re-interpret bread quality, also including nutritional value.

Unrefined wheat flour (UWF) is a composite class which includes flours supplemented with milling by-products at the same or a different relative proportion compared to that of the intact caryopsis (Fig. 1). The official definition for flours containing the same components in the same relative proportions as the wheat kernel is “wholewheat” flour (~~AACC International, 1999~~ Whole Grain Initiative approved by ICC, Healthgrain and Cereal & Grain Association, 2019), although the modern milling process does not allow for the inclusion of wheat germ (WG), but only recovers wheat bran (WB). Hence, the resulting “wholewheat” flour is no more than flour enriched with bran.

Despite the nutritional benefits, the introduction of milling by-products in the breadmaking process has some drawbacks, the solutions to which are still open challenges for bread makers.

First, the outer layers are the most susceptible to contaminants, i.e., mycotoxins and heavy metals (Sovrani et al., 2012). Hence, the possibility of using milling by-products to produce high nutritional value breads requires an integrative approach from the field to the breadmaking. Therefore, appropriate agronomical and/or post-harvest strategies must be adopted to reduce the safety risk and preserve the high nutritional value of the outer layers. Secondly, WG and WB negatively affect the technological quality of doughs and breads (Boukid, Folloni, Ranieri, & Vittadini, 2018; Hemdane et al., 2016). Finally, since the sensorial characteristics of unrefined bakery products are little appreciated by consumers, several scientific studies have dealt with the ~~sensory~~ sensorial profile to increase their acceptability (Gani at al., 2012; Heiniö et al., 2016).

The present review aims to report the processing strategies that have been developed until now for the breadmaking process with UWFs (Fig.2), while suggesting some processing innovations to improve the exploitation of UWFs.

Contents

2. Bread quality

According to the common good manufacturing practices, "bread" must be prepared by baking a dough which consists of flour, yeast, and a moistening ingredient, usually water. In the present review this term refers to all typologies of leavened breads, not including flat breads obtained without any leavening. Bread is one of the most ancient and widespread foods of all over the world. Progressive technical developments over many thousands of years have led to a high diversification of the product. Hence, a “good bread” presents different features depending on cultural background, individual experiences, and personal likes and dislikes. Moreover, quality features change over space, in different regions, and over time, together with food technology innovations. However, despite the large diversity of bread characteristics, in the literature bread quality is mainly evaluated as: (i) bread specific volume, (ii) crumb characteristics and (iii) crust colour (Zhou et al., 2014; Cauvain, 2015). These features are the results of the raw materials and processing conditions adopted during bread production. Almost all of the quality characteristics are related to the gluten network, since it traps the gas produced during the leavening and contributes to the formation of a cellular crumb structure which confers the bread’s volume, texture and eating qualities. The addition of the “right” quantity of water is another key factor affecting dough rheology and the development of gluten; too much or too little water means that the right gluten network cannot be properly developed (Cauvain, 2015).

Although there are not any standard ~~sensory~~ sensorial attributes of wheat bread, they are all considered of maximum importance in the evaluation of the product. ~~Sensory~~ Sensorial features affect consumers' preferences and drive their choices towards the different bread typologies proposed by the current bakery market.

The flour used in the bread formulation plays a critical role for the product characteristics. Refined bread presents a high loaf volume, a light colour, homogeneous crumb porosity and soft crumb. Refined flour results in a fairly bland ~~sensory~~ sensorial attribute with only a slight grain-like flavour or malted note, since most of these sensory contributions come from the WG oils and from the WB particles removed during milling (Callejo et al., 2015; Challacombe, Abdel-Aal, Seetharaman, & Duizer, 2012; Eckardt et al., 2013; Hayakawa, Ukai, Nishida, Kazami, & Kohyama, 2010; Heenan, Dufour, Hamid, Harvey, & Delahunty, 2008; Jensen, Oestdal, Skibsted, Larsen, & Thybo, 2011a; Katina, Heiniö, Autio, & Poutanen, 2006a; Lotong, Edgar-Chambers, & Chambers, 2000). The sensory attributes of refined breads are largely appreciated by consumers, who, despite the proven health benefits of wholewheat consumption, still prefer refined products (Ye, Chacko, Chou, Kugizaki, & Liu, 2012).

The distinctive characteristics of UWF breads include a low loaf volume, coarse and hard texture, dark colour and "speckled" appearance. Moreover, they are characterized by a nutty odour, bitter/sour taste, a grain-like, "seedy" flavour, malted note and musty attribute (Curti, Carini, Bonacini, Tribuzio, & Vittadini, 2013; Callejo et al., 2015; Challacombe, Abdel-Aal, Seetharaman, & Duizer, 2012; Eckardt et al., 2013; Heenan, Dufour, Hamid, Harvey, & Delahunty, 2008; Jensen, Oestdal, Skibsted, Larsen, & Thybo, 2011a; Katina, Heiniö, Autio, & Poutanen, 2006a; Katina, Salmenkallio-Marttila, Partanen, Forssell, & Autio, 2006b).

The sensory profile of UWF breads is one of the major obstacles to increasing their consumption. The most challenging attribute is probably the bitter taste, associated with the presence of bioactive compounds (such as phenolic compounds, amino acids, small peptides, fatty acids and sugar) which are highly concentrated in the outer layers of the wheat kernel (Heiniö, 2009; Zhou et al., 2014; Van Gemert, 2011; Mattila, Pihlava, & Hellström, 2005); rancid sensory defects could also occur relating to oxidation of the WG oil (Heiniö et al., 2016).

The quality characteristics were created for refined breads, but in the literature they are also used for UWF bread. However, well-informed consumers appreciate the better nutritional value of UWF and they have different expectations about the product characteristics.

This can lead implicitly to some questions on bread quality. Does the different chemical composition of UWF require new qualitative standards or are the quality criteria of refined flours still suitable for UWF? Is it right to have the same expectations about the characteristics of the final product? It is hard to answer these questions and they require an in-depth discussion from a wide perspective.

Besides bread quality criteria, some important methods have also been developed for refined flours. This is the case of the optimum water absorption (WA) of the flour, officially determined as the amount of water required to reach 500BU in the farinographic test. However, it has been reported that 500BU underestimates the absorption capacity of UWF (Hemdane et al., 2016). Improper hydration of the dough could lead to i) the wrong evaluation of UWF bread quality, especially when compared to refined bread, and ii) biased results if a new process setting is desired and the tested variables significantly interact with water. Nevertheless, indications regarding the correct amount of water for UWFs are still missing in the literature.

3. Breadmaking process

The literature has shown controversial results regarding breadmaking with UWFs, making it difficult to interpret or compare experimental data in the literature. Indeed, several operating factors have been reported to have a significant effect on bread quality (Table 1):

(i) The composition of UWFs is extremely variable; beside the starchy endosperm they include the presence of specific fractions of milling by-products, WG and WB. The different chemical compositions of UWFs produce great variability in the breadmaking performance.

(ii) The milling method. It is widely known that the milling method has a marked impact on the technological performance of flour (Jones, Adams, Harriman, Miller, & Van der Kamp, 2015). Standard indications about the milling method, and particle size and composition of milling by-products could be useful for a better comprehension of their impacts and could help overcome their adverse effects in breadmaking. It is important to point out that the milling method strongly affects the UWF composition.

(iii) Bread formulation. In the literature there is no official bread formula, but different recipes are adopted. Besides the basic components (i.e., flour, water and the leavening agent), other ingredients are often added to the bread dough, such as salt (NaCl), sugar, shortening and oxidizing agents, which affect the flour performance. This variability of recipes could hinder the comparison and understanding of the effects and results.

(iv) Breadmaking procedure. Owing to the absence of a standard process in breadmaking, operating conditions cannot be standardized, making it difficult to compare and understand the literature data.

The paragraphs below set out to improve the comparability between the different studies in the literature by promoting both a standardization of methods and some technological innovations for UWF processing.

3.1 UWF quality and composition

In recent years several studies have reported the nutritional value, technological impact and sensory profile of the milling by-products WG and WB in the breadmaking process (Hemdane et al., 2016; Boukid, Folloni, Ranieri, & Vittadini, 2018; Heiniö et al., 2016).

WG (2%-3% of the caryopsis) is composed of the embryo and scutellum, the latter being discarded with the bran during the milling process (Boukid, Folloni, Ranieri, & Vittadini, 2018). It is considered the most nutritious part of the wheat kernel, providing 381 cal/100 g: 54% carbohydrates, 23% proteins and 23% lipids (Boukid, Folloni, Ranieri, & Vittadini, 2018; Nutrition data, 2014).

The limited utilization of WG in the bakery industry is primarily due to the high presence of unsaturated fats and hydrolytic and oxidative enzymes (i.e., lipoxygenase and lipase) which favour WG degradation (Boukid, Folloni, Ranieri, & Vittadini, 2018). Several treatments have been developed to improve WG stability while preserving the high nutritional value (Boukid, Folloni, Ranieri, & Vittadini, 2018). The first crucial step is to perform an efficient separation of the WG from the other flour components. Two different approaches have been developed: (i) direct degermination, which is performed before the milling process and (ii) indirect degermination, which is realized through gradual separation phases during the milling process (Boukid, Folloni, Ranieri, & Vittadini, 2018). A high recovery of the WG fraction enables the subsequent adoption of stabilization strategies through the deactivation of the oxidative enzymes or/and removal of the oil fraction. These strategies are based on physical, chemical or biological methods, as extensively revised by Boukid, Folloni, Ranieri, & Vittadini (2018).

WB (17% of the caryopsis), together with the aleurone layer and remnants of the starchy endosperm and WG, produces a range of milling by-products which are recovered at different stages in the mill (Hemdane et al., 2016). The bran fractions can be classified as different by-products (i.e., coarse bran, coarse weatings, fine weatings and low-grade flour), which are roughly distinguishable based on two main characteristics: particle size and endosperm content (Hemdane et al., 2016).

The bran streams recovered further down the milling process consist of finer bran particles and contain relatively more endosperm (Hemdane et al., 2016). Coarse bran mainly consists of non-starch carbohydrates, with 17%-33% arabinoxylan (AX), 9%-14% cellulose, 3%-4% fructan and 1%-3% mixed-linkage β-D-glucan as major components (Hemdane et al., 2016). In order to study the mechanisms through which bran affects breadmaking, multiple approaches which change bran functionality (physical properties, chemical composition, and/or enzymatic load) have been developed. These strategies (i.e., (i) particle size reduction, (ii) (hydro-)thermal treatments, (iii) pre-soaking, (iv) enzymatic treatment, (v) fermentation, and (vi) chemical treatment, reviewed by Hemdane et al., 2016), treat the bran before its re-addition to the flour, and investigate both bran properties and breadmaking performance.

In the literature, great efforts have been made to try to understand the functionality of milling by-products or to develop new strategies to stabilize them. Conversely, far fewer efforts have been made to try to improve the breadmaking with stabilized milling by-products. The combination of stabilizing treatments with roller milling, followed by flour re-combination/re-constitution and/or enrichment, could provide UWFs with a better nutritional and technological quality. Moreover, although it seems that the roller milling method could ensure better preservation of the wheat's nutritional value (Jones, Adams, Harriman, Miller, & Van der Kamp, 2015), the consumer is still highly attracted by the "stone mill" label on flours or baked products, considering this method better than roller milling (Jones, Adams, Harriman, Miller, & Van der Kamp, 2015). This points out that it is pressing to improve the dissemination of scientific knowledge to the final target.

The presence of WB and WG significantly changes the chemical composition of flour. Regardless of the amount of milling by-products added, UWFs show a low endosperm fraction and include specific flour constituents, such as fibre, oil, enzymes, reactive components and anti-nutrients. The amount of the above constituents can change markedly, depending on various factors: (i) level of addition, (ii) milling by-product treatment (if any), (iii) milling process, (iv) bran stream fraction (v) wheat species and cultivar, and (vi) environmental conditions.

Considering WG, the main constraints associated with its utilization in the baking industry are represented by its poor chemical stability, the presence of reducing compounds (glutathione) that degrade breadmaking ability, and the presence of non-polar lipids which tend to destabilize gas cells (Tebben et al., 2018; Boukid, Folloni, Ranieri, & Vittadini, 2018).

On the other hand, flour supplementation at different levels and/or with different bran fractions has shown deleterious impacts on the technological properties of doughs and breads (Hemdane et al., 2016). Overall, flours containing bran produce a poor loaf volume, dark colour, dense and firm texture, and bitter taste (Hemdane et al., 2016). The following reasons account for these negative effects: fibre-gluten interactions, dilution of gluten proteins by non-endosperm proteins, fibre competition for water resulting in insufficient hydration of gluten and starch, physical effects of bran particles and bran constituents on the gluten network and high level of ferulic acid (Tebben et al., 2018).

3.1.1 Unprocessed UWFs

The incorporation of raw milling by-products in flour without introducing some modification of the product formula and/or processing method gives "unprocessed UWF". It generally shows a poor breadmaking performance. However, some studies have introduced raw milling by-products into the flour while maintaining an acceptable bread quality (Table 2).

Banu, Stoenescu, Ionescu, & Aprodu (2012) investigated the addition of bran streams (3%, 5%, 10%, 15%, 20%, 25%, 30% expressed on total flour weight) to refined flour on dough rheology and bread quality. Despite the negative effect of ash on the ~~technological~~ rheological properties of flour and on bread quality, the incorporation of 25% bran streams showed the same ash content as UWF, but ~~with an improvement in bread quality~~ dough rheology and bread physical parameters were significantly improved. Therefore, this level ~~can be used to obtain high nutritional quality bread without improvers in the formulation~~ of incorporation can be used to increase the nutritional value of the breads with less damage on the bread quality compared to wholewheat flour.

Blandino et al. (2013) tested refined flour enriched with selected fractions ~~of the kernel~~ obtained by sequential pearling of wheat kernels and added at 5 different levels (5%, 10%, 15%, 20%, 25% expressed on total flour weight) on dough rheology, bread quality and nutritional properties. The presence of a 10% pearled fraction enhanced the nutritional value of the bread, revealing only a slightly increase in deoxynivalenol contamination and showing a technological quality comparable to the control.

Bagdi et al. (2015) evaluated the breadmaking potential of an aleurone-rich flour (ARF) (40g/100g, 75g/100g) in comparison with refined bread. The ARF was suitable for breadmaking without any flour additives. Bread made with aleurone-rich flour showed better nutritional properties than refined bread, but a low technological quality. The optimal blending ratio for the sensory quality resulted 40g/100g since it showed a similar acceptability to the control sample.

Sun, Zhang, Hu, Xing, & Zhuo (2015) tested different levels (0%, 3%, 6%, 9%, 12% expressed on total flour weight) of WG flour to improve the quality of Chinese steamed bread (CSB). WG negatively affected both the dough and bread properties, and the steaming performance, in proportion to the level of addition. The incorporation of up to 6% WG showed fewer negative effects and gave CSB with acceptable sensory characteristics, suggesting that this blend could be used for the production of functional breads.

Pasqualone et al. (2017) compared the effect on breadmaking ability of two substitution levels (100g/1kg, 200g/1kg) of three different durum wheat milling by-products: i) residuals of the second and third debranning steps (DB), ii) the micronized and air-classified thin fraction from the same residuals (MB), or iii) coarse bran from roller milling of non-debranned durum wheat (B). MB and DB did not alter the textural properties compared to B. Furthermore, the addition of MB (100g/1kg) improved the nutritional value of the bread without reducing its quality. Hence, debranning followed by micronization could represent an interesting strategy for UWF breads from durum wheat.

3.1.2 Processed UWFs

In the literature several treatments have been developed for wheat kernels and milling by-products, namely "processed UWF". The processing treatments that showed technological improvements for the use of processed UWFs in breadmaking are reported below (Table 3).

3.1.2.1 Pre-treatment of wheat kernels: germination

In recent years, several studies have investigated the impact of the germination process on the technological and nutritional quality of cereals, pseudo-cereals and pulses (Lemmens et al. 2019; Bellaio, Kappeler & Bühler, (2013); Richter, Christiansen, & Guo, 2014; Benincasa, Falcinelli, Lutts, Stagnari, & Galieni, 2019). In fact, by inducing the activation of hydrolytic enzymes for plant growth and development, germination leads to a considerable improvement in the product nutritional value, which makes this process attractive for healthy and functional foods. Applications of the germination process in breadmaking are reported in the literature, but most of these studies used refined wheat flours in the bread formula (Lemmens et al., 2019). The main issue of this approach is optimizing the processing conditions: longer germination times (>72 h) are required to improve the nutritional value of the flour, but they negatively impacted the flour technological performance; on the other hand, only shorter times (20-36 h) or low substitution levels (10%-20%) improved the technological properties of doughs and breads, although they showed lower effects on their nutritional value (Lemmens et al., 2019). These results reflect the different degrees of enzyme activities in wheat kernels as a function of the germination time. Activation of the proper alfa-amylase activity can promote yeast fermentation, carbon dioxide production and gas cell expansion, thus determining a higher oven spring and improving bread volume (Lemmens et al., 2019). Moreover, optimized alfa-amylase activity can also improve the product's shelf life and sensory quality (Lemmens et al., 2019).

Marti, Cardone, Nicolodi, Quaglia, & ~~Ambrogina~~ Pagani (2017) proposed the addition of a low amount of germinated wheat flour (1.5%) for a long amount of time (72-90 h) as a natural improver in breadmaking with refined flour. Germinated flour produced similar effects to common improvers (i.e., 0.5% malt or 0.5% enzymatic improver). It could be interesting to test the effect of this natural improver on the technological performance of UWF.

Richter, Christiansen, & Guo (2014) developed a 100% germinated white spring wholewheat flour for bread applications. The authors compared 100% white wholewheat flour (control) with 100% germinated white wholewheat flour, including different additions of vital gluten (0%-5%) in the bread formula (Richter, Christiansen, & Guo, 2014). Germinated wholewheat flour significantly increased loaf volume (5%-9%), independently of the presence of gluten (Richter, Christiansen, & Guo, 2014). Moreover, germinated flour significantly improved the sensory quality of the bread, reducing the bitter taste.

Zilic et al. (2016) investigated the effect of germination on wholewheat flour proteins. Intensive protein hydrolysis was revealed by an increase in free SH groups and a decrease in albumin + globulin polypeptides with a molecular weight of over 85.94 kDa and between 85.94 and 48.00 kDa. Although this modification affected the dough's viscoelastic properties, germinated wheat flour is proposed as a potential food ingredient owing to the high antioxidant capacity and reduced antigenicity of the glutenin fraction (Zilic et al., 2016).

Ding et al. (2018) tested germination time on the functionality of wholewheat doughs. Controlled germination for 5-15 h (T= 28±2°C and RH=95±3%) produced wholewheat flour with improved functionality: enhanced glucose content, reduced starch retrogradation during ~~gelatinizing~~ gelatinization, improved gluten quality, and increased dough stability during mixing (Ding et al., 2018).

Johnston et al. (2019) applied controlled germination in the production of wholewheat. Controlled germination (t=24 h, T=21°C, FN=200 s, excess of water) to increase the activity of α-amylase by decreasing the Falling Number (FN) from 350 s to 200 s reduced dough mixing time and increased bread specific volume (Johnston et al., 2019). Sensory analysis revealed a higher acceptability for germinated wholewheat breads, thanks to their lower degree of bitterness, greater sweetness and moisture (Johnston et al., 2019). Hence, germinating wholewheat flour to an FN value of 200 s proved to be a good strategy to improve flour functionality and consumer preference for wholewheat breads (Johnston et al., 2019).

A very recent work by Cardone, Marti, Incecco, & Pagani (2020) showed promising results on the application of a controlled germination to enhance the quality of wholewheat breads. In fact, under the conditions applied in this study (48h, 20°C, 90% relative humidity), although the decrease in dough rheological features, a significant improvement in gluten stretching ability and bread physical properties was obtained.

Further studies on the application of germination to improve the UWF breadmaking performance could be an interesting field of research. The substitution of refined flour with UWF may not require additional enhancement of the nutritional quality, since the raw material is naturally characterized by a high nutritional value.

3.1.2.2 Pre-treatment of milling by-products

Over time several pre-treatments have been developed for milling by-products to stabilize their chemical composition and better understand their effects on the breadmaking performance (Hemdane et al., 2016; Boukid, Folloni, Ranieri, & Vittadini, 2018). The present review reports the results of the most promising treatments on technological quality (Table 4).

Hemdane et al. (2016) extensively reviewed wheat bran pre-treatments. Chemical treatments did not improve bread quality; very little work has been performed on enzymatic treatments (Santala, Lehtinen, Nordlund, Suortti, & Poutanen, 2011; Messia et al. 2016), while the effects of bran particle size reduction and (hydro)thermal treatments on breadmaking still remain unclear. Pre-soaking appears to be a promising strategy for the incorporation of bran in breadmaking since it generally improved the bread quality (Messia et al. 2016); however, a complete understanding of this approach has yet to be established. In a recent work following the method proposed by Wang et al. (2015a, b), Zhang et al. (2019) developed an arabinoxylan-enriched flour (AXF) (ash content between 39.2%–55.8%) as a fibre supplement (2%, 5%, 10%) for refined bread. AXF pre-soaking positively affected flour functionality, resulting in bread with comparable properties to the control

(Zhang et al., 2019). Fermentation treatment has been reported to enhance breadmaking ability: it was effective in improving bread volume and crumb softness.

The impact of WG supplementation on breadmaking is reviewed by Boukid, Folloni, Ranieri, & Vittadini (2018). The rheological properties of doughs were affected by the different WG treatments. Fermentation by lactic acid bacteria appeared to be the most promising treatment, showing a significant improvement in the dough properties. In all cases, the addition of more than 20% WG severely damages dough quality. Considering bread quality, the addition of up to 5% extruded WG increased bread volume and decreased bread firmness. Sourdough fermentation of WG positively affected bread quality, by decreasing crumb firmness, resilience and fracturability, and enhancing bread shelf life without reducing product acceptability (Boukid, Folloni, Ranieri, & Vittadini, 2018).

These results revealed that the use of sourdough fermentation on milling by-products enhanced the performance of UWF in breadmaking. Indeed, Gobbetti, Rizzello, Di Cagno, & De Angelis (2014) extensively reported the positive effects of using this approach for wholegrain products. Pre-fermentation allowed modification of the techno-functionality of the milling by-products, showing improved technological quality in terms of dough retention capacity, loaf volume and crumb softness during storage. In addition, it decreased the anti-nutritive factors and enhanced the sensory properties.

Recently, Pontonio et al. (2020) proposed an integrated biotechnological approach, combining LAB fermentation with xylanase treatment on milling by-products (Pontonio et al., 2020). Biochemical and nutritional analysis revealed that fortified breads had higher protein digestibility and a lower glycemic index combined with a better sensory quality (Pontonio et al., 2020). Therefore, a significant improvement could be achieved in UWF breads by applying an integrated approach, suggesting new strategies for the exploitation of UWF.

The reviewed studies identified effective technological strategies for producing UWF with a high technological quality. The possibility of supplementing bread with even low amounts of milling by-products, without decreasing the bread quality, should be regarded as a technological success.

3.2 Bread formulation and improvers for UWF

In the literature the most common solution to improve the breadmaking performance of UWF and, consequently, the quality of UWF breads is to modify the bread formula; the literature results are outlined in Table 5.

3.2.1 Optimization of water amount for UFW breads

Some improvements in breadmaking with UWF can be obtained by optimizing the amount of water in the bread recipe (Table 5). Cappelli et al. (2018) examined the effect of water (70%, 76%, 82%, 88%, 94% expressed as a percentage of the dry weight of the flour) and degree of flour refinement (refined, brown and wholewheat flour) on the dough rheology. Significant differences in rheological properties were found for refined flour compared to UWF, showing that alveographic analysis cannot be extended to unrefined doughs. Addition of the optimal amount of water, modelled in function of the degree of flour refinement, could be a strategy to optimize the rheological parameters relating to product quality: flour strength “W” and the ratio between tenacity “P” and extensibility “L”, P/L (Cappelli et al., 2018). This approach could improve UWF dough quality, without introducing additional ingredients to the recipe.

Similar results were reported in a survey conducted by Guerrini, Parenti, Angeloni, & Zanoni (2019) on the breadmaking process with UWF. The creation of highly hydrated doughs improves the flour workability and bread quality (Guerrini, Parenti, Angeloni, & Zanoni, 2019). Indeed, in the literature it is known that the inclusion of bran significantly affects the water adsorption capacity of the flour and causes a competition for the water uptake with the other flour constituents (Hemdane et al., 2016). High water quantities could allow proper hydration of the gluten matrix even in the presence of bran, resulting in a better P/L balance as well as a higher W.

All these results may derive from the wide utilization of the Farinographic test as the official predictor of the water absorption of the flour: this evaluation works well for refined flour, but it is not suitable for UWF (Bruckner et al., 2001; Schmiele, Jaekel, Patricio, Steel, & Chang, 2012; Hemdane et al., 2016).

3.2.2 Modification of the flour for UWF bread

In the literature, few process strategies have tested a more “natural approach” to the use of improvers: the addition of UWF flour in a modified form, as reported in Table 5. Parenti et al. (2019) reported an improvement in breadmaking performance with the use of pre-gelatinized brown flour (6%). Pre-gelatinized UWF was obtained by heating some of the bread dough flour to 85°C in water;

the product was cooled to room temperature and tested on the dough and bread properties. The addition of the flour in a different physical form increased the water absorption capacity, improved the alveographic parameters, and increased the bread volume, crumb softness and shelf life (Parenti et al., 2019).

Hung, Maeda, & Morita (2007) tested the addition of whole waxy flour in order to improve the quality of high-fibre bread. Different levels of whole waxy flour were used to substitute refined flour (10%, 30%, 50% expressed on total flour weight); the resultant flour mixtures were tested on the breadmaking performance ~~of wholewheat flour~~ compared to refined flour. This strategy improved crumb softness during bread storage (Hung, Maeda, & Morita, 2007). It could be interesting to investigate the use of whole waxy flour compared to 100% wholewheat flour for breadmaking, in order to evaluate the impact of this ingredient on the quality of wholewheat bread.

3.2.3 Improvers for UWF bread

The use of improvers in breadmaking with UWF is summarized in Table 5. Tebben et al. (2018) reviewed the effects of common bread improvers, namely enzymes, emulsifiers, hydrocolloids, oxidants and other functional ingredients on the performance of wholewheat flour. A positive role is outlined for some enzymes: (i) by hydrolysing arabinoxylans (AX), xylanase was reported to decrease the water absorption of the flour, increase the concentration of fermentable sugars in the dough, the rate of fermentation and the dough proof height; moreover, xylanase improved the gas retention capacity, loaf volume, crumb softness and crumb staling; (ii) alfa-amylase appeared beneficial under certain conditions; (iii) G4-amylase showed promising effects on loaf volume, crumb hardness and staling (Tebben et al., 2018).

Considering hydrocolloids, a general improvement in dough rheology is reported in the literature (Tebben et al., 2018; Farbo et al., 2020). The effects of hydrocolloids change in function of their typology and level of addition. With regard to bread dough, the use of carboxymethylcellulose (CMC) decreased the final proof time and resistance to extension. Guar gum (GG) combined with an emulsifier (diacetyl tartaric esters of monoglycerides, DATEM) was reported to increase the fermentation stability and slightly increased bread volume. However, both CMC and GG reduced the elasticity of wholewheat dough. Hydroxypropyl methylcellulose (HPMC) increased dough elasticity, proof height, and decreased resistance to extension (Tebben et al., 2018).

Farbo et al. (2020) studied the effect of methylcellulose (MC), GG, psyllium gum (PG), xanthan gum (XG) and tara gum (TG) on the quality of dough made with old durum wheat. They found that 1% of PG or XG improved dough extensibility, while all hydrocolloids increased gas retention.

Considering bread quality, GG was able to increase the specific volume of wholewheat bread. Furthermore, a non-significant effect of HPMC, XG and dextran was reported on bread volume. Conversely, HPMC proved effective in increasing the specific volume of both refined and wholewheat bread, while CMC did not improve the loaf volume of either variety of bread (Tebben et al., 2018).

Oxidants are commonly added in breadmaking to increase dough strength by forming disulphide bonds through the oxidation of free sulfhydryl groups on the gluten proteins (Zhou et al., 2014). The presence of reducing compounds in wholewheat flour counteracts the effect of oxidants, which must be added at higher levels (Tebben et al., 2018). Hence, higher amounts of oxidants will also presumably be required for other UWF typologies. Potassium bromate and ascorbic acid improved the dough rheology, dough strength and gas retention ability. The addition of rosehip as a source of ascorbic acid increased the resistance to extension and reduced the extensibility of the wholewheat dough. The best effect on bread volume was reported for ascorbic acid, added at 200 ppm; accordingly, rosehip resulted effective in enhancing bread volume. This latter improver also improved the sensory score of the crumb, increasing the acceptability of the wholewheat bread. Conversely, potassium bromate showed little effect on loaf volume (Tebben et al., 2018).

Emulsifiers in breadmaking cause dough strengthening and/or crumb softening (Tebben et al., 2018). The addition of DATEM was reported by some studies to increase the fermentation stability, whereas the opposite effect was observed by others (Tebben et al., 2018). However, these studies are consistent in showing that DATEM improved dough elasticity, a valuable property for the breadmaking performance. Another emulsifier, sodium stearoyl lactylate (SSL), improved the handling properties of the wholewheat dough (Tebben et al., 2018).

The specific volume of wholewheat bread was generally improved by the addition of emulsifiers (Tebben et al., 2018). DATEM was reported to produce positive effects. Furthermore, the combined addition of DATEM and oxidants improved the gas-holding ability of the dough during the proofing and baking phases. DATEM and SSL had the greatest effect on volume increase, but ethoxylated monoglycerides, succinylated monoglycerides and lecithin significantly increased loaf volume too. On the other hand, polysorbate and monoglycerides did not affect the parameter. Similar results were reported for the inclusion of DATEM, SSL, soy lecithin, polyoxyethylene sorbitan monostearate (polysorbate-60), poly-oxyethylene sorbitan monopalmitate (polysorbate-40) and glycerol-monostearate: all these emulsifiers increased the volume of the wholewheat bread. Conversely, the addition of monoglycerides, DATEM and SSL was not effective in improving wholewheat or refined bread specific volume (Tebben et al., 2018).

DATEM and mono- and diglycerides were reported to improve the crumb structure of wholewheat bread; a similar effect was observed with SSL as well as an increase in the eatability score (Tebben et al., 2018).

The supplementation of vital gluten is effective in overcoming the multiple problems related to wholewheat bread (Tebben et al., 2018).

Parenti, Guerrini, Cavallini, Baldi, & Zanoni, (2020) tested the addition of 7 improvers (i.e., sucrose, sodium chloride, extra virgin olive oil, gelatinized flour, GG, ascorbic acid and ice) to optimize the quality of wholewheat bread. The optimized sample resulted from the combination of sucrose (2%) and extra virgin olive oil (3%), disclosing the interesting role that these improvers can play in the quality of wholewheat bread (Parenti, Guerrini, Cavallini, Baldi, & Zanoni, 2020). Furthermore, the authors proposed a two-step optimization approach for improving the use of UWF in breadmaking: (i) the Screening Design method revealed the most relevant factors affecting bread quality; (ii) the Full Factorial Design gave an in-depth evaluation of the selected variables and allowed identification of the optimized sample (Parenti, Guerrini, Cavallini, Baldi, & Zanoni, 2020).

All these results concerned the use of improvers on wholewheat flour. However, due to the very different composition of the raw materials which probably changes the effects of the improvers, they should be further tested before extending these findings to all UWF breads.

3.3 The breadmaking process with UWFs

Only a few studies have investigated the possibility of modifying the breadmaking operating conditions. The breadmaking process has been designed to maximize the quality of refined bread. Therefore, the substitution of refined flour with UWF may require an adaptation of the process to the different characteristics of the raw material. Processing conditions, such as the type of mixer, mixing time and speed, resting period etc., may require modifications from the standard procedure. This latter area of research appears poorly investigated in the literature, since the greatest efforts have been made in modifying the bread formulation, while the breadmaking variables were kept almost unchanged. Studies about modifications of the breadmaking process with UWFs are reported in Table 6.

3.3.1 Mixing

The mixing is one of the most important phases in the breadmaking process since most of the characteristics of the final product are determined during this phase (Zhou et al., 2014). Considering the different composition of UWF, modification of the mixing variables (type of mixers, mixing speed, mixing time…) could represent a good strategy to be explored, despite being poorly investigated in the current literature.

Angioloni & Rosa (2006) tested the effect of mixing time (10-15-20 s) combined with an improver (cysteine, 20 mg/kg) on the rheological properties of refined and wholewheat dough obtained at high-speed revolutions (1600 rpm). Dough viscoelastic behaviour was affected by both cysteine and kneading conditions. Cysteine significantly reduced the mixing time (optimum = 15 s) by decreasing the elastic component of the dough and aiding dough relaxation in both refined and wholewheat flour. Therefore, the use of high-speed mixing combined with cysteine could be useful to improve UWF doughs.

Parenti et al. (2013) tested different mixing times on the breadmaking of brown flour. Two trials evaluated different mixing times ((i) 12, 17, 22 min; (ii) 17, 22, 27 min). Mixing time significantly affected loaf increase during proofing: the samples mixed for 17 min showed the highest value in both trials. Furthermore, doughs obtained at the optimum mixing time (17 min) were characterized by a better water retention capacity during storage.

The control of the mixing time also proved to be extremely important in the survey by Guerrini, Parenti, Angeloni, & Zanoni (2019); short times, between 10 and 20 min, represented one of the most effective strategies for the breadmaking process with UWF.

A recent work by Cappelli, Guerrini, Cini, & Parenti (2019) investigated the delayed addition of bran and middlings during the mixing step. Three bran and middlings ~~incorporation~~ substitution levels (10%, 20%, 30% expressed on refined flour weight) and five times of addition (0, 2, 3.5, 5, 6.5 min) were tested on the dough rheology and bread quality. The addition of bran and middlings at 2 min into the mixing step improved the dough rheology and increased the bread specific volume. Furthermore, the combination of 10% bran and middlings with time of 2 min produced bread of a better quality than the control bread (i.e., without delayed addition).

A specific laboratory test, developed to predict the optimized mixing time, could boost the research on the mixing step, but, to the best of the author’s knowledge, no such test currently exists.

3.3.2 Leavening

During leavening, the bread loaf develops its final structure and several modifications of its constituents occur as a function of the different leavening agents used in the recipes. Sourdough fermentation represents one of the oldest biotechnologies in cereal food production; however, when industrial-scale baking was developed in the 19th century, baker's yeast – *Saccharomyces cerevisiae* – became the most common leavening agent (Zhou et al., 2014). In recent years, the increasing interest in healthy and functional foods has led to a rediscovery of sourdough bakery products, which are characterized by positive health benefits and unique flavours (Zhou et al., 2014). Chavan & Chavan (2011) made an exhaustive review of this ancient biotechnology. In the present review, only the issues related to the technological performance of UWF are discussed. In the literature it is largely reported that the substrate, mainly flour, used for sourdough production deeply influences its properties (Chavan & Chavan, 2011; Decock, & Cappelle, 2005). The presence of bran, increasing the ash content of wheat flour, promotes the growth of lactic acid bacteria (LAB) and increases the acidification of the sourdough system. LAB are responsible for the production of several organic acids, which are reported to improve the swelling of gluten and increase gas retention, while functioning as natural dough conditioners and reducing bread staling. Furthermore, the acid enhances the solubility of the glutenin fraction, improving the swelling power of the gluten (Chavan & Chavan, 2011). Hence, the use of UWF for sourdough production seems to improve the breadmaking performance, thanks to a better development of the gluten matrix. Studies on UWF performance are reported in Table 6.

In the survey by Guerrini, Parenti, Angeloni, & Zanoni (2019), all of the bakers use sourdough as the leavening agent for breadmaking with UWF: they perceive that this method improves the quality of the final product.

Komlenić et al. (2010) showed the positive effects of biological acidification on the quality of bread obtained with refined and wholewheat flour. They investigated the effect on dough and bread properties of three different acidifications: chemical (lactic acid) and biological (dry sourdough and *Lactobacillus brevis* pre-ferment) acidification. The bread specific volume was only significantly increased by the biological acidifiers, whereas the acidifier typologies improved the crumb hardness (Komlenić et al., 2010). Therefore, dry sourdough, characterized by a longer shelf life and better stability, could be an interesting strategy for breadmaking with UWF.

Taccari et al. (2016) reported the possibility of applying the back-slopping technique to produce type I sourdough from wholewheat flour. Wholewheat sourdough improved the quality of high fibre breads, overcoming the detrimental effect of bran on bread volume. Moreover, sourdough fermentation improved bread texture, flavour, nutritional value and shelf life. The study outlines the suitability of wholewheat flour for sourdough production, encouraging further research for its application in UWF breadmaking.

Choi, Kim, Hwang, Kim, & Yoon (2005) evaluated the application of *Leuconostoc citreum* HO12 and *Weissella koreensis* HO20 isolated from kimchi as starter cultures for sourdough wholewheat bread. The sourdoughs fermented with the selected LAB had an optimal Fermentation Quotient (FQ), a criterion for good bread quality. Although no significant improvement was observed on bread specific volume, the LAB reduced crumb hardness on both fresh and stored breads (Choi, Kim, Hwang, Kim, & Yoon, 2005). Hence, the study presented the potential application of LAB isolated from kimchi for the improvement of UWF bread quality.

Didar et al. (2011) observed positive effects on bread quality (95% extraction rate) and sensory properties upon performing sourdough fermentation with *Lactobacillus plantarum* (PTCC 1058) and *Lactobacillus reuteri* (PTCC 1655). Different dough yields (DY, 250 and 300) and different levels of sourdough addition (10%, 20%, 30%) were also tested. *Lb. plantarum* sourdough with a DY of 250 and 30% addition produced the greatest effect on the overall quality score of the breads (Didar et al., 2011).

Katina, Heiniö, Autio, & Poutanen (2006a) studied the influence of sourdough conditions on bread flavour and texture. Ash content (0.6-1.8 g/100 g), fermentation temperature (16-32°C), and fermentation time (6-20 h) were considered independent factors and different starter cultures (i.e., *Lactobacillus plantarum*, *Lactobacillus brevis*, *Saccharomyces cerevisiae* or a combination of yeast and LAB) were tested. Ash content and lactic acid fermentation were the main factors affecting the intensity of the sensory attributes. The greater the ash content, the higher the intensity of both desired and undesired flavour attributes. An optimization of the process conditions, according to the ash content and the specific LAB strain, improved the sensory quality of UWF breads. However, the improvement of bread volume and texture required different optimized conditions than those required for bread flavour. Hence, an efficient use of sourdough fermentation has to consider its end use in wheat baking (Katina, Heiniö, Autio, & Poutanen, 2006a).

The results from the use of sourdough as a leavening agent showed positive effects on UWF bread quality. The drawback of this procedure is primarily represented by the great variability of the sourdough composition, which makes the process difficult to standardize. Further research is needed to find new solutions to combine the use of this leavening agent with a standardization of bread features.

3.3.3 Baking

Baking is the final step in the breadmaking process. The phenomena occurring during this phase include gas evaporation, starch gelatinization, modification of the bread loaf from a sponge-like to a porous structure, and water evaporation. The most significant factors of the baking step are represented by temperature, time and moisture (Zanoni, Peri, & Pierucci, 1993; Zanoni, Pierucci, & Peri, 1994; Zhou et al., 2014).

In the literature there appears to be a lack of information on the baking step specifically developed for UWF breads. Guerrini, Parenti, Angeloni, & Zanoni (2019) reported that bakers create high temperatures at the beginning, followed by a temperature decrease, to improve the quality of UWF breads. Moreover, the majority of bakers check the moisture during this step, since it represents another critical factor affecting bread quality. In fact, especially in the first phase of baking, the addition of moisture improves loaf expansion. Therefore, modification of the baking conditions, such as temperature and moisture, in function of the characteristics of the raw material could represent another interesting field of exploration.

3.4 UWF bread storage

The most important phenomena limiting the shelf life of breads are bread staling and microbial growth (Fernandez, Vodovotz, Courtney, & Pascall, 2006). Bread staling is a complex phenomenon, whose mechanism has not been well established yet; however, the most important factors seem to be starch retrogradation, starch-gluten interaction and moisture redistribution (Fadda, Sanguinetti, Del Caro, Collar, & Piga 2014; Curti, Carini, Tribuzio, & Vittadini, 2015). Bread microbial spoilage is generally caused by moulds, bacteria and yeasts (Melini, & Melini, 2018). Different approaches have been developed to reduce bread staling and microbial spoilage, which generally achieve positive effects, allowing the production of breads with a shelf life of up to 4 weeks (Fadda, Sanguinetti, Del Caro, Collar, & Piga 2014; Sargent, 2008). Hence, bread flavour and aroma have become the new limiting factors for bread shelf life.

3.4.1 Improving the shelf life of UWF bread

Different strategies can be applied to extend bread shelf life: (i) direct approach on the food matrix; (ii) indirect approach through packaging systems.

Within the direct approaches, Gobbetti, Rizzello, Di Cagno, & De Angelis (2014) reviewed the importance of fermentation of the raw material for wholegrain products. Specifically, the application of this method on milling by-products before their incorporation in the bread formula was reported to improve crumb softness during bread storage.

Furthermore, the germination process also showed positive effects on bread storage, linked to the activation of alfa-amylase activity (Lemmens et al., 2019).

The supplementation of pre-gelatinized UWF in the bread formula delayed bread staling, in terms of crumb specific volume and texture parameters (Parenti et al., 2019).

With regard to improvers, different enzymes reduce the staling of UWF bread: (i) xylanase and (ii) alfa amylase result the most effective enzymes; furthermore, one study has reported that (iii) G4-amylase showed a positive outcome, but further research is necessary to confirm this result (Tebben et al., 2018).

The effects of emulsifiers on wholewheat breads were reported by Tebben et al. (2018). DATEM showed anti-staling properties. A reduction in hardness was also reported for wholewheat bread with 0.4% DATEM or 0.6% monoglycerides. Similarly, 0.5% SSL was able to decrease the staling rate of wholewheat bread over 4 days of storage. It is interesting to note that DATEM and SSL only acted as crumb softeners in wholewheat breads but not in refined breads (Tebben et al., 2018).

The use of hydrocolloids in UWF breads led to controversial results. Both CMC and GG reduced the staling rate of wholewheat bread; HPMC softened the crumb of both wholewheat bread and refined breads, while another study reported that CMC inclusion was ineffective for both bread typologies. Furthermore, the literature reported that dextran and HPMC produced a non-significant reduction in the initial loaf hardness and delay in bread staling. Hence, further research is necessary to better understand the role of emulsifiers on UWF bread staling (Tebben et al., 2018).

Malted wholewheat flour in breadmaking reduced the staling of wholewheat bread (Tebben et al., 2018).

Some efforts have been made to increase oxidative stability during the storage of UWF breads, delaying rancidity phenomena.

Jensen, Ostdal, Skibsted, & Thybo (2011b) tested three antioxidants, alfa-tocopherol and fat-soluble and water-dispersible rosemary extracts, on the sensory profile and antioxidant capacity of wholewheat bread during storage. These antioxidants did not improve the sensory quality or stability of the wholewheat bread (Jensen, Ostdal, Skibsted, & Thybo, 2011b). Furthermore, alfa-tocopherol produced fresh wholewheat bread with higher concentrations of hydroperoxides and secondary lipid oxidation products, similarly to the stored control sample (Jensen, Ostdal, Skibsted, & Thybo, 2011b). Hence, lipid oxidation is responsible for less favourable sensory notes like a rancid aroma and flavour, bitter taste and astringency, attributes most often associated with low product acceptability (Jensen, Ostdal, Skibsted, & Thybo, 2011b).

Ning, Hou, Sun, Wan, & Dubat (2017) tested green tea powder (GTP) on the quality and antioxidant activity of wholewheat dough and bread. Five levels of GTP were tested (0 g, 1 g, 2 g, 3 g, 4 g/100 g flour): the higher the amount of GTP included, the worse the bread quality, while the antioxidant activity showed a reverse trend (Ning, Hou, Sun, Wan, & Dubat, 2017). The best result was obtained with GTP 1 g/100 g, since it did not affect bread quality while enhancing the antioxidant capacity (Ning, Hou, Sun, Wan, & Dubat, 2017). Hence, 1 g/100 g GTP resulted an effective improver in reducing the rate of peroxide accumulation in wholewheat bread during storage (Ning, Hou, Sun, Wan, & Dubat, 2017).

Lu, & Norziah (2011) studied the effect of substituting shortening with different levels of microencapsulated n-3 polyunsaturated fatty acid (PUFA) powder (1%, 1.75%, 2.5% of total dough weight) on the sensory and oxidative stability of UWF bread during storage. The flour used was a blend of wholewheat and refined flour (Lu, & Norziah, 2011). Breads containing PUFA were no different to the control containing shortening, revealing that PUFA had a similar effect on bread quality (Lu, & Norziah, 2011). The lowest PUFA addition (1%) resulted in bread with the best sensory acceptability for up to 3 days of storage, suggesting that this improver could be an effective substitute for shortening (Lu, & Norziah, 2011).

With regard to the breadmaking process, the most effective variable in enhancing the shelf life of UWF bread was sourdough fermentation (Chavan & Chavan, 2011; Taccari et al., 2016; Choi, Kim, Hwang, Kim, & Yoon, 2005).

The evaluation of the sensory profile of wheat bread during shelf life has been little investigated in the literature. Significant changes in the flavour, aroma and taste of refined and wholewheat bread have been reported by Jensen, Oestdal, Skibsted, Larsen, & Thybo (2011a). The sensory characteristics of refined bread and wholewheat bread during storage were studied by measuring volatile and non-volatile compounds and performing a descriptive sensory profiling (Jensen, Oestdal, Skibsted, Larsen, & Thybo, 2011a). Refined and wholewheat bread showed distinctive flavours, revealing two different sensory profiles (Jensen, Oestdal, Skibsted, Larsen, & Thybo, 2011a). Storage time affected 8 out of 13 of the tested attributes of refined bread, while all ~~14~~ 13 attributes of wholewheat bread were significantly impacted by storage time (Jensen, Oestdal, Skibsted, Larsen, & Thybo, 2011a). The fresh wholewheat samples were characterized by higher concentrations of fermentation products; after one week of storage, dough and bran aroma were the predominant attributes, while breads stored up to 2-3 weeks were defined by rancid and fatty aromas, and a bitter taste (Jensen, Oestdal, Skibsted, Larsen, & Thybo, 2011a). The formation of off-flavours in bread could be related to the formation of secondary lipid oxidation products during storage together with a reduction in compounds from Maillard reactions (Jensen, Oestdal, Skibsted, Larsen, & Thybo, 2011a). Since UWFs are characterized by higher enzymatic activity and lipid and antioxidant contents than refined flours, the development of specific strategies for the control of oxidative reactions represents a key factor for improving bread storage (Doblado-Maldonado, Pike, Sweley, & Rose 2012).

3.4.2 Packaging of UWF breads

Several packaging strategies have been developed to preserve bread freshness. The main objectives of these methods are to prevent microbial spoilage and bread staling. Bread packaging has been studied on refined bread, while no techniques have been specifically developed to preserve UWF bread.

Therefore, here we discuss the packaging strategies that appear promising to us for extending the shelf life of UWF breads.

Packaging methods are classified as conventional and active packaging. The former includes traditional packaging methods, aimed at preserving the food from chemical, physical and biological damage without interacting with it. Conversely, active packaging is based on the interaction between the packaging material and the food matrix by absorbing or releasing specific substances (Melini, & Melini, 2018).

WG makes UWF particularly susceptible to lipid oxidation (Boukid, Folloni, Ranieri, & Vittadini, 2018), and the fibre component also impacts the product moisture during storage time (Hemdane et al., 2016). Hence, the critical aspects of UWF storage could be identified as rancidity phenomena and higher moisture retention, linked to microorganism spoilage.

Active Packaging with Antimicrobial Releasing Systems could be useful in preventing UWF bread spoilage. These methods release antimicrobial agents (organic acids, fungicides, alcohols and antibiotics) into the food surface, thus inhibiting or delaying microbial growth and spoilage (Melini, & Melini, 2018).

Active Packaging with oxygen absorbers could be even more interesting for UWF (Alhendi & Choudhary, 2013; Melini, & Melini, 2018). In fact, Nielsen, & Rios (2000) observed that oxygen absorbers combined with essential oils prevented microorganism spoilage. Furthermore, Latou, Mexis, Badeka, & Kontominas (2010), by combining oxygen absorbers with an alcohol emitter, and Tian, Decker, & Goddard (2012), using metal chelating carboxylic acids, reported effective prevention against microorganism spoilage and lipid peroxidation.

The innovative trend in Active Packaging includes the application of nanotechnology, a fusion of traditional packaging polymers with nanoparticles. These methods are able to extend a product's shelf life, while reducing the addition of preservatives in the food formulation (Melini, & Melini, 2018). Being a "natural" approach, nanotechnology could be applied to UWF bread, since it could preserve the high nutritional value of the product. Silver nanoparticles included in polypropylene food containers were reported to keep bread fresher over 3 or 4 times longer and to reduce bacterial growth by 95% compared to conventional food containers (Bumbudsanpharoke et al., 2015). Moreover, nanoencapsulation applied to essential oils, which show potent antimicrobial and/or antioxidant properties, may represent another promising technique for UWF bread. This method protects the compound against chemical reactions and undesirable interaction with the food matrix (Melini, & Melini, 2018). Nanoencapsulated essential oils extend the shelf life and maintain the sensory properties of breads (Otoni, Pontes, Medeiros, & Soares, 2014; Gutiérrez, Batlle, Andújar, Sánchez, & Nerín, 2011; Souza, Goto, Mainardi, Coelho, & Tadini, 2013). However, nanoparticles are not inert materials: they may interact with food, its surroundings and negatively impact human health. Therefore, there is an urgent need to assess the risks of this innovative method (Alhendi & Choudhary 2013; Melini, & Melini, 2018).

4. The carbon footprint of UWF bread

Technological innovations sometimes have negative environmental effects, such as the emission of greenhouse gases (GHG) and waste as a result of manufacturing activities. The Carbon Footprint (CFP) is a useful tool to quantify GHG emission during the life cycle of a product/service, allowing an estimation of its environmental impact. The food industry, including food production, preservation and distribution, consumes a considerable amount of energy which contributes to total CO_2 emission (Roy et al., 2009). Furthermore, consumers in developed countries require safe foods of a high quality, produced with a minimal impact on the environment (Boer, 2002), showing that sustainability will soon become a primary factor in making food choices a part of food quality criteria (Andersson, Ohlsson, & Olsson, 1994; Pattara, Russo, Antrodicchia, & Cichelli, 2016).

In the literature several papers have analysed the CFP associated with the life cycle of wheat bread (Holderbeke, Sanjuán, Geerken, & Vooght, 2003; Braschkat, Patyk, Quirin, & Reinhardt, 2003; Rosing & Nielsen, 2003; Roy et al., 2009; Pattara, Russo, Antrodicchia, & Cichelli, 2016; Meisterling, Samaras, & Schweizer, 2009; Notarnicola, Tassielli, Renzulli, & Monforti, 2017; Laurence, Hartono, & Christiani, 2018). These studies have shown that the main hotspots in the bread supply chain are the agricultural phase, primarily due to the use of pesticides and fertilizers, followed by the baking, mainly performed with an electric source of energy. The consumption of bread, including refrigerated storage or toasting, has an important environmental impact too (Holderbeke, Sanjuán, Geerken, & Vooght, 2003; Rosing & Nielsen, 2003; Meisterling, Samaras, & Schweizer, 2009; Espinoza-Orias, Stichnothe, & Azapagic, 2011; Notarnicola, Tassielli, Renzulli, & Monforti, 2017; Laurence, Hartono, & Christiani, 2018). Conversely, the CFP associated with the phases of packaging and transport still deserve discussion (Roy et al., 2009).

To the best of the authors' knowledge, only one paper has considered flour composition as a variable for CFP estimation (Espinoza-Orias, Stichnothe, & Azapagic, 2011). This paper reported the hot spots in the life cycle of packaged sliced breads from refined, brown and wholewheat flours produced and consumed in the UK (Espinoza-Orias, Stichnothe, & Azapagic, 2011). The key findings showed that the CFP of bread ranges from 977 to 1244 g CO_2eq per loaf of bread (defined as 800 g), and that thick-sliced wholewheat bread packaged in plastic bags has the lowest CFP while medium-sliced refined bread in a paper bag has the highest. The degree of refinement of the flour used in the bread recipe made a significant environmental impact: the higher the milling extraction rate, the lower the CFP (Espinoza-Orias, Stichnothe, & Azapagic, 2011). This means that bread with higher degrees of refinement is more ecologically sustainable. However, the reported results could be attributed to UWF breads produced with raw materials not subjected to additional processing. On the other hand, the current literature does not evaluate the environmental impact associated with those techniques designed to increase the technological quality of UWF bread. In our opinion, this topic deserves deeper investigation, considering that environmental impact has becoming an essential quality criterion for a food product (Pattara, Russo, Antrodicchia, & Cichelli, 2016). Therefore, in evaluating the best processing techniques for breadmaking with UWF, computation of the CFP should be included as a quality requirement.

5. Conclusions

The present review reported the main techniques and technologies that have been specifically developed for the use of UWF in the breadmaking process. Although the consumption of UWF breads characterized the greatest part of human history, the introduction of the roller mill in the 19th century led to the use of refined flour with a better technological performance, longer shelf life and sensory quality largely appreciated by modern consumers. Hence, refined flour has become the standard in the development of the quality tests, bread formulation and processing methods applied in each phase of the breadmaking process.

In recent years, studies about the positive effects of wholegrain consumption have led to a renewed interest in the employment of UWF in breadmaking. However, although the presence of various amounts of wheat bran and/or WG enhances the flour's nutritional value, these supplementations significantly change its composition. As a result, a different raw material, that is, UWF, can be used as a substitute for refined flour in bread production. The following points summarize the main consequences that the re-introduction of UWF have brought:

i) The standard tests to predict the breadmaking attitude of flour have remained unchanged, often giving an improper evaluation of the potentiality of UWF (i.e., water absorption capacity of the flour).

ii) The main efforts to improve the quality of UWF bread have been focused on optimizing the bread formula with the inclusion of various improvers.

iii) Little research has been conducted on modifying the processing variables of the breadmaking phases (i.e., mixing, resting, leavening and baking); practically the same methods developed for refined flours are adopted for the production of UWF bread too.

In our opinion, the different composition of UWF requires specific adaptation of the quality tests, so that this may improve both the technological evaluation and the use of UWF in bread production. Furthermore, new processing methods specifically adapted for the chemical characteristics of UWF may require further investigation as strategies to both preserve the high nutritional value and increase the technological quality of the final products, hence promoting the consumption of healthy foods.

FIGURE CAPTIONS

Fig. 1 Schematic representation of the production of unrefined wheat flours (UWFs): flour enriched with wheat germ, flour enriched with wheat bran, and flour enriched with both wheat germ and bran in the same (i.e., wholewheat flour) or in a different relative proportion to the wheat kernel.

Fig. 2 Schematic representation of the main techniques and technologies reported in the literature for the breadmaking process with unrefined wheat flours (UWFs). (i) Treatments on the raw material (i.e., wheat kernels) before the milling step; (ii) treatments on milling by-products (i.e., wheat germ and bran); (iii) modification of the bread formulation; (iv) modifications of processing variables: mixing, leavening and (v) improvement of bread storage.

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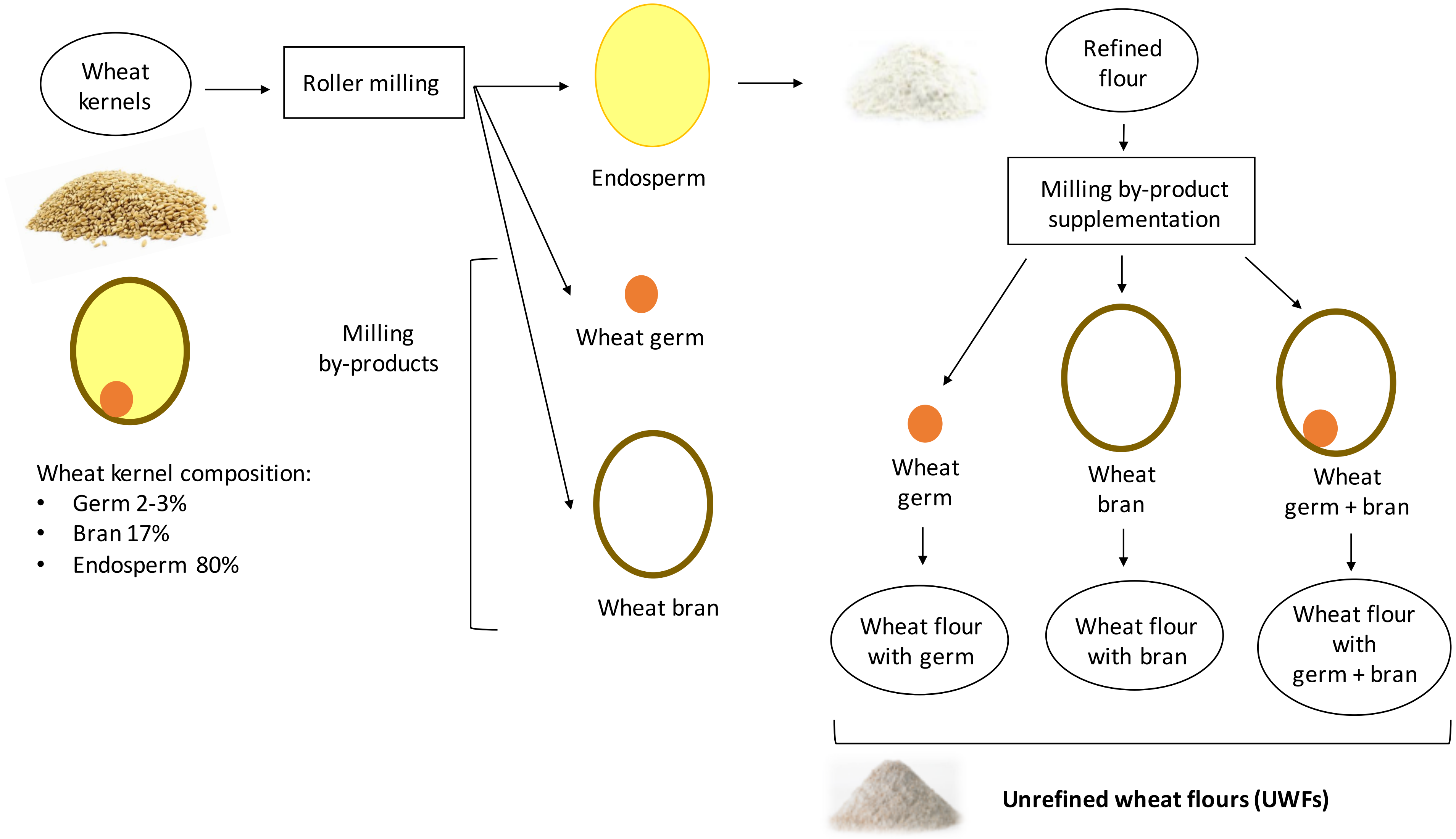
Wheat kernels
Roller milling
Endosperm
Wheat germ
Wheat bran
Milling by-products
Wheat kernel composition:
Germ 2-3%
Bran 17%
Endosperm 80%
Refined flour
Milling by-product supplementation
Wheat germ
Wheat bran
Wheat germ + bran
Wheat flour with germ
Wheat flour with bran
Wheat flour with germ + bran
Unrefined wheat flours (UWFs)

Fig.1

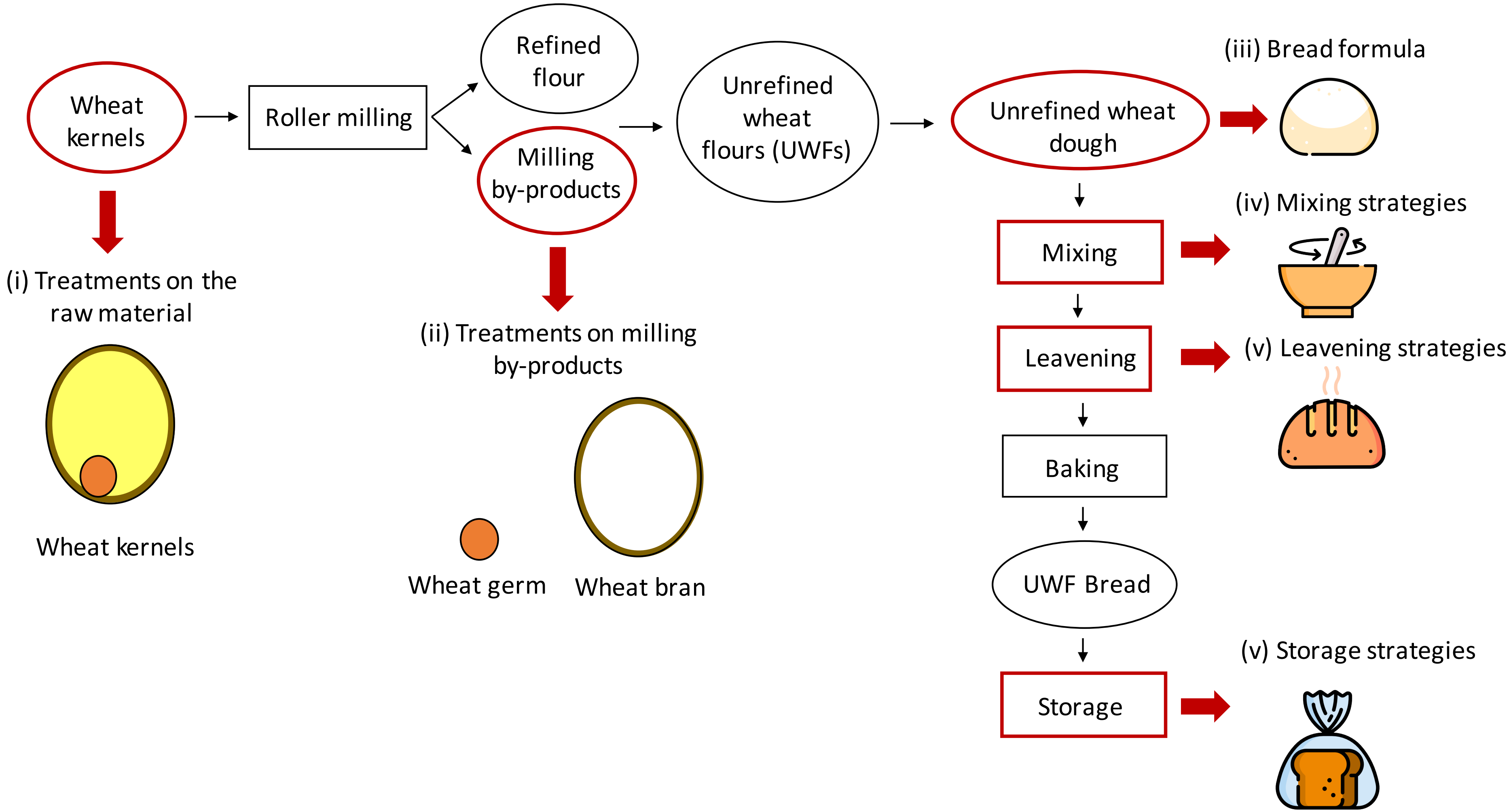
Wheat kernels
Roller milling
Refined flour
Milling by-products
Unrefined wheat flours (UWFs)
Unrefined wheat dough
(iii) Bread formula
Mixing
(iv) Mixing strategies
Leavening
(v) Leavening strategies
Baking
UWF Bread
Storage
(v) Storage strategies
(i) Treatments on the raw material
Wheat kernels
(ii) Treatments on milling by-products
Wheat germ
Wheat bran

Fig.2

Food matrix/ Process step	**Processing strategy**
Wheat kernels	Germination
Milling by-products	Bran pre-soaking
	Bran/germ fermentation
Bread dough	Bread formulation
	-Optimization of water amount
	-Addition of modified flour
	• Pre-gelatinized flour
	• Waxy wholewheat flour
	-Addition of improvers
	• Enzymes *(xylanase, alfa-amylase, G4 amylase)*
	• Hydrocolloids *(carboxymethylcellulose CMC, guar gum GG, hydroxypropyl methylcellulose HPMC, methylcellulose MC, psyllium gum PG, xanthan gum XG, tara gum TG)*
	• Oxidants *(ascorbic acid, rosehip, potassium bromate)*
	• Emulsifiers *(diacetyl tartaric esters of monoglycerides DATEM, sodium stearoyl lactylate SSL, ethoxylated monoglycerides, succinylated monoglycerides, lecithin, polyoxyethylene sorbitan monostearate, polyoxyethylene sorbitan monopalmitate, glycerol-monostearate)*
	• Vital gluten
Mixing	Mixing time
	Delayed addition of milling by-products
Leavening	Sourdough fermentation
Bread storage	Treatments on milling by-products (fermentation)
	Bread formulation
	-Addition of modified ingredients
	• Pre-gelatinized flour
	-Addition of improvers
	• Enzymes *(xylanase, alfa-amylase, G4 amylase)*
	• Emulsifiers *(diacetyl tartaric esters of monoglycerides DATEM, sodium stearoyl lactylate SSL, monoglycerides)*
	• Hydrocolloids *(carboxymethylcellulose CMC, guar gum GG, hydroxypropyl methylcellulose HPMC, dextran)*
	• Malted flour
	• Anti-oxidants *(alfa-tocopherol, rosemary extract, green tea powder, microencapsulated n-3 polyunsaturated fatty acids PUFA powder)*

Table 1. The main processing strategies for breadmaking with unrefined wheat flours (UWFs).

Literature reference	Wheat flour	Milling by-product supplement	Supplementation with good bread technological and sensory quality
Banu et al. (2012)	Refined flour	Bran streams (3%, 5%, 10%, 15%, 20%, 25%, 30% expressed on total flour weight)	25% bran stream
Blandino et al. (2013)	Refined flour	Pearled fractions (5%, 10%, 15%, 20%, 25% expressed on total flour weight)	10% pearled fraction
Bagdi et al. (2015)	Refined flour	Aleurone (40%, 75% expressed as percentages of refined flour)	40% (only on sensory profile)
Sun et al. (2015)	Refined flour	Wheat germ (0%, 3%, 6%, 9%, 12% expressed on total flour weight)	6% wheat germ
Pasqualone et al. (2017)	Refined flour (re-milled semolina)	3 fractions of durum wheat milling by-products (10%, 20% expressed as percentages of refined flour): i) bran obtained from non-debranned wheat ii) second and third debranning fractions mixed together iii) thin subfraction obtained by micronization and air classification of the second and third debranning fraction mix	10% second and third debranning step

Table 2. The use of unprocessed unrefined wheat flours (UWFs) for breadmaking. Reporting literature reference, wheat flour, type of milling by-products used for supplementation and level of supplementation that gave good bread technological and sensory quality.

Literature reference	Treatment	Tested variables	Measurements	Main results
Ding et al. (2018)	Germination	Germination time	Hagberg falling number (FN) Rapid Visco Analyser (RVA) Starch pasting properties Mixolab mixing properties Physicochemical analysis γ-aminobutyric acid (GABA) content	Controlled germination (t=5-15 h, T= 28±2°C, RH=95±3%) improved wholewheat flour functionality
Ritcher et al. (2014)	Germination	Germinated wholewheat flour + vital gluten (0%, 3%, 4%, 5%) for breadmaking	Farinographic test Proof time Loaf volume Sensory analysis	100% germinated wholewheat bread showed better technological and sensory quality than control; Vital gluten did not improve bread quality
Zilic et al. (2016)	Germination	Germination effect on wholewheat protein functionality	Total and free sulfhydryl (-SH) groups Lipoxigenase (LOX) and peroxidase (POX) activity SDS-PAGE gel electrophoresis Total antioxidant capacity of albumin+globulin proteins Gliadin and glutenin immunogenicity Analysis of pasting viscosty	Total protein content did not change with germination Intensive protein hydrolysis Increased antioxidant capacity of albumin + globulin fraction and reduced glutenin antigenicity Potential health positive effects
Johnston et al. (2019)	Germination	Germination effect on wholewheat flour functionality and flavour	Kernel hardness Hagberg falling number (FN) Sodium dodecyl sulphate sedimentation analysis (SDS) Starch content Total dietary fibre Alfa-amylase activity Metabolite analysis Mixograph analysis Sensory analysis	Controlled germination (t=24 h, T=21°C, FN=200 s, excess of water) increased wholewheat bread volume and flavour

Table 3. References concerning the use of processed unrefined wheat flours (UWFs) produced through treatments on the raw material, i.e., wheat kernels. Outlining type of treatment, tested variables, measurements made and main results.

Literature reference	Milling by-product	Treatments	Best results on bread quality	Interpretation of results
Hemdane et al. (2016)	Wheat bran	Pre-soaking Particle size reduction	14% pre-soaked bran 22% pre-soaked, fine-ground bran	Reduction of bran water uptake during mixing
Hemdane et al. (2016)	Wheat shorts	Pre-soaking	Bread specific volume	Activation of endogenous lipoxygenase
Hemdane et al. (2016)	Wheat bran	Pre-soaking (limited/excess water)	Good bread quality	A complete understanding has not been established yet. Some hypotheses proposed: -Saturating bran with water before mixing prevent the detrimental effects on dough/bread quality; -Activation of endogenous lipoxygenase oxidize components detrimental to bread quality -Washout effect when pre-soaking in excess of water
Messia et al. (2016)	Wheat bran	Pre-soaking Enzyme addition (xylanase, amylase, cellulase)	Improved dough rheology and bread physical properties	Modification of arabynoxylan solubility allowing a better redistribution of water
Zhang et al. (2019)	Arabinoxylan flour from wheat bran	Pre-soaking Enzyme addition (xylanase)	Up to 10% pre-soaked arabinoxylan flour	The positive effects associated to the pre-soaking of arabinoxylan flour was not explained
Hemdane et al. (2016)	Wheat bran (native bran and bran from peeled kernel)	Fermentation (20 h, yeast starter)	20% fermented bran from peeled kernel	Solubilization of arabinoxylans Reduction of endogenous xylanase activity
Hemdane et al. (2016)	Wheat bran	Fermentation (8 h, lactic acid bacteria and yeast strain) Particle size reduction	15% 160 um bran fermented 8 h	Lactic acid fermentation (*Lactobacillus brevis*)
Boukid et al. (2018)	Wheat germ	Sourdough fermentation (bacteria and yeast)	Up to 20% sourdough fermented wheatgerm	Reduction of enzymatic activities (lipase, lipoxygenase) Reduction of glutathione content
Boukid et al. (2018)	Wheat germ	Sourdough fermentation (*Lactobacillus plantarum* LB1, *Lactobacillus rossiae* LB5)	Better nutritional, chemical and stabilization properties	Reduction of pH Reduction of enzymatic activities (lipase, lipoxygenase) Higher total amino acids Higher protein digestibility Inactivation of anti-nutritional factors Higher antioxidant activity
Boukid et al. (2018)	Wheat germ	Sourdough fermentation (*Lactobacillus plantarum* LB1, *Lactobacillus rossiae* LB5)	4% sourdough fermented wheat germ	Reduction of enzymatic activities (lipase, lipoxygenase) Reduction of glutathione content
Boukid et al. (2018)	Wheat germ	Sourdough fermentation (*Lactobacillus plantarum* LB1, *Lactobacillus rossiae* LB5	4% sourdough fermented wheat germ bread shelf life	Antifungal activity of sourdough fermented wheat germ (phenolic acids, organic acids) Lower pH values

Table 4. References concerning the use of processed UWF produced through treatments on the raw material, i.e., milling by-products (wheat bran and wheat germ). Summarizing milling by-product, type of treatment, best results on bread quality and interpretation of the main results.

Literature reference	Process strategy	Tested variables	Wheat flour	Improvement of bread quality
Cappelli et al. (2019)	Optimization of water amount	Water amount (70%, 76%, 82%, 88%, and 94%) Flour refinement degree (refined, brown, wholewheat)	Refined, brown and wholewheat flour	Optimal water addition as a function of degree of flour refinement
Guerrini et al. (2019)	Optimization of water amount	Different variables used by bakers	Brown and wholewheat flour	Higher water amount
Parenti et al. (2019)	Modification of the flour	Water amount (59%, 70%, 80%) Pre-gelatinized flour (0%, 6%)	Brown flour	6% pre-gelatinized flour + high water amount
Hung et al. (2007)	Modification of the flour	Waxy wholewheat flour (0%, 10%, 30%, 50%)	Wholewheat flour and waxy wholewheat flour	Waxy wholewheat breads showed softer crumb during storage
Tebben et al. (2018)	Improver	Enzyme, xylanase	Wholewheat flour	Optimization of xylanase usage level
Tebben et al. (2018)	Improver	Enzyme, alfa-amylase	Wholewheat flour, blends of refined and wholewheat flours	Optimization of amylase usage level
Tebben et al. (2018)	Improver	Enzyme, G4-amylase	Wholewheat flour	Optimization of G4-amylase usage level
Tebben et al. (2018)	Improver	Hydrocolloids (carboxymethylcellulose, CMC; guar gum, GG; methylcellulose, MC; psyllium gum, PG; xanthan gum, XG; tara gum, TG)	Wholewheat flour	0.5%-1% hydrocolloids
Tebben et al. (2018)	Improver	Oxidants (potassium bromate, ascorbic acid, rosehip as a source of ascorbic acid)	Wholewheat flour	Optimum amount of antioxidants corresponds to higher quantities than refined flour; best results with 200 ppm
Tebben et al. (2018)	Improver	Emulsifiers (diacetyl tartaric esters of monoglycerides, DATEM; sodium stearoyl lactylate, SSL; ethoxylated monoglycerides, succinylated monoglycerides, lecithin, polyoxyethylene sorbitan monostearate, poly-oxyethylene sorbitan monopalmitate, glycerol-monostearate, mono- and diglycerides)	Wholewheat flour	Usage level 0.4%-0.5% Positive results emulsifiers combined with oxidants
Tebben et al. (2018)	Improver	Vital gluten	Wholewheat flour	Usage level 2%-2.5%

Table 5. Literature references about the modification of unrefined wheat flours (UWFs) bread formula to improve breadmaking performance. Reporting the main process strategies (i.e., optimization of water amount, modification of flour and addition of improvers), tested variables, type of UWF and strategies that improved bread quality. Percentages relate to flour base (ingredient/total flour %)D.

Literature reference	**Breadmaking step**	**Tested variable**	**Wheat flour**	**Processing strategy**
Angioloni et al. (2006)	Mixing	Mixing time (10, 15, 20 min) Cysteine (20 mg/kg)	Refined and wholewheat flour (*T. aestivum* L.)	Combination of high-speed mixer and cysteine addition
Parenti et al. (2013)	Mixing	Mixing time (12, 17, 22, 27 min)	Brown flour (*T. aestivum* L.)	Optimized mixing time (17 min)
Guerrini et al. (2019)	Mixing	Different variables used by bakers	Brown and wholewheat flour (*T. aestivum* L., *T. durum*)	Short mixing time (10-20 min)
Cappelli et al. (2019)	Mixing	Time for addition of bran and middlings during mixing (0, 2, 3.5, 5, 6.5 min) Levels of bran and middlings (10%, 20%, 30%)	Refined flour enriched with bran and middlings (*T. aestivum* L.)	10% bran and middlings added at t=2 min
Kolmenic et al. (2010)	Leavening	Biological acidification (dry sourdough, *Lactobacillus brevis* preferment) Chemical acidification (lactic acid)	Refined flour Wholewheat flour (commercial blends)	Biological acidification (dry form)
Taccari et al. (2016)	Leavening	Back-slopping technique for type I sourdough	Wholewheat flour (*T. aestivum* L.)	Application of back-slopping techniques for sourdough fermentation
Choi et al. (2005)	Leavening	Selected LAB isolated from kimchi as starter cultures (*Leuconostoc citreum* HO12 and *Weissella koreensis* HO20)	Wholewheat flour (*T. aestivum* L.)	Applicability of selected LAB (*Leuconostoc citreum* HO12 and *Weissella koreensis* HO20)
Didar et al. (2011)	Leavening	Sourdough fermentation with *Lactobacillus plantarum* (PTCC 1058) and *Lactobacillus reuteri* (PTCC 1655) Level of sourdough addition (10%, 20%, 30%) Dough yield (250 and 300)	Flour with 95% extraction rate (cv Alvand wheat)	30% *Lb. plantarum* sourdough with DY 250
Katina et al. (2006a)	Leavening	Sourdough time = 6-20 h Sourdough temperature = 16-32°C LAB and yeast for sourdough fermentation (*Lactobacillus plantarum*, *Lactobacillus brevis*, *Saccharomyces cerevisiae* or a combination of yeast and LAB) Flour ash content (0.6-1.8 g/100 g)	Flours with different ash content (0.6-1.8 g/100 g) (commercial flours)	Different flour ash contents required different optimization strategies

Table 6. Literature references about processing strategies for breadmaking with unrefined wheat flour (UWF). Outlining breadmaking step, tested variable, types of UWF used and process strategy.