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Stone milling versus roller milling: A systematic review of the effects on wheat flour quality, dough rheology, and bread characteristics

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ABSTRACT

Background: Grain milling might be the oldest manufacturing process in the world, and many techniques are currently used in the food industry. The two predominant methods used in wheat milling are stone milling and roller milling. The selected technique significantly influences flour quality, dough rheological properties, and bread characteristics. Choosing the most suitable method is essential; therefore, here we summarise the advantages and disadvantages of each technique and suggest specific improvement strategies.
Scope and approach: The first aim is to summarise current knowledge regarding the effects of stone milling and roller milling on wheat flour quality, dough rheology, and bread characteristics. The second aim is to propose specific strategies to improve the two techniques.
Key Findings and Conclusions: This review highlights the importance of selecting the most suitable technique. Stone milling has a few, clear advantages. These include: ease of use and the simplicity of the system; higher concentrations of macroelements, microelements, and polyphenols in flour; increased whole wheat bread volume; and popularity with consumers. Roller milling, on the other hand, also has advantages. These include: greater efficiency and flexibility; less heat generation; and better dough rheological performance. This review has not declared a "winner", as both techniques have advantages and disadvantages. The optimal milling system is a function of the aim to be achieved, bearing in mind business needs and product demand.

1. Introduction

Grain milling might be the oldest manufacturing process in the world. Archaeologists have found drawings, dating back to 2600 BC, of the basic process of rubbing or grinding using two stones on the walls of Egyptian tombs (Walker & Eustace, 2016). Grinding (milling) of cereal grains is the fundamental operation currently used to produce flour, which is an ingredient in many food products (Liu, He, Wang, & Wang, 2018). Milling consists of breaking down wheat kernels, followed by the separation of the endosperm from the bran and germ (Campbell, 2007). The forerunner of the stone mill (SM) is the *quern*, which was made up of two horizontal (circular or conical) stones placed one on top of the other. A tool called a *rind* supported the upper stone, creating a slight gap between the two grinding surfaces. The upper stone was able to turn, while the lower one remained stationary (Walker & Eustace, 2016).

With the passage of time and the growth of knowledge, a new method was introduced: roller milling (RM). Giovanni Torriano is credited with its design, in 1558, in Spain. The process consisted of a hand-powered corrugated cone working inside a curved, corrugated shell. There are no other references to RM until 1774, when a patent was granted in England for a RM to grind corn (Walker & Eustace, 2016); however, since then, the technique has evolved remarkably. Nowadays, RM has become the most utilized method in the food industry. It involves the separation of the endosperm from the bran and germ, followed by a gradual reduction in endosperm particle size (Campbell, 2007), using a series of corrugated and smooth rollers, with sifting between each stage (Doblado-Maldonado, Pike, Sweley, & Rose, 2012; Liu et al., 2018). The traditional SM method has also been optimized over the years, and, despite the popularity of RM, it is still preferred by many bakers and organic food producers because of its effect on the texture of the product and the sweet, nutty flavour it produces (Cappelli et al., 2018; Di Silvestro et al., 2014).

Although there are many other milling techniques that use mechanical force to break grain into smaller fragments or fine particles (Liu et al., 2018), SM and RM continue to dominate in the food industry

Abbreviations: SM, stone mill; RM, roller mill; SMF, stone-milled flour; RMF, roller-milled flour; P, dough tenacity; L, dough extensibility; W, deformation energy; P/L, curve configuration ratio; PLC, Programmable Logic Controller; PA, Programmable Automation

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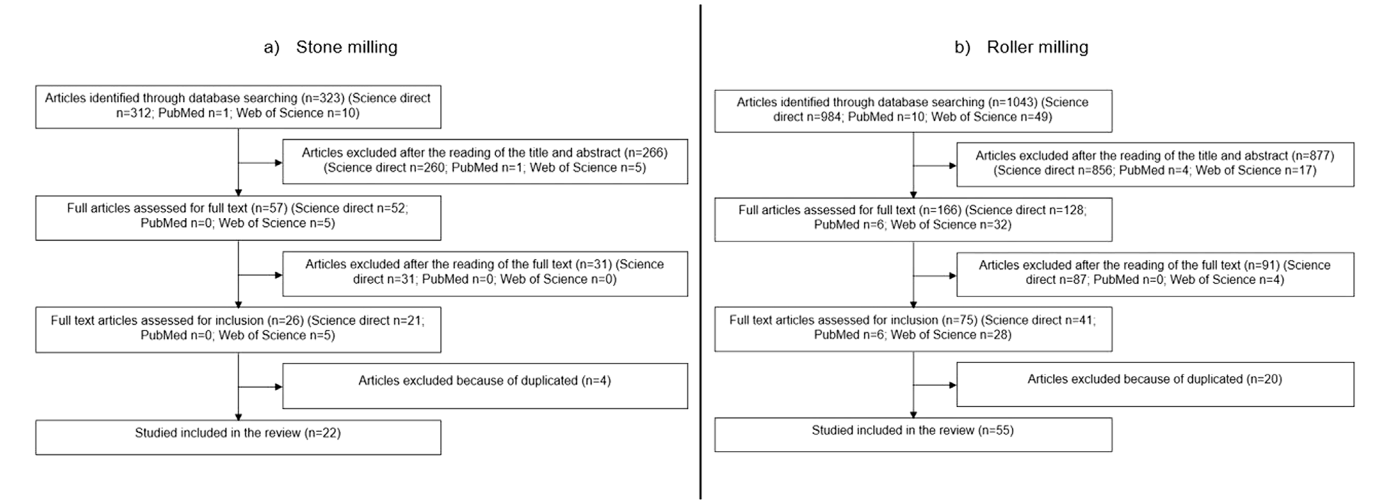

Fig. 1. Flow charts pertaining to the selection of papers on stone milling (a) and roller milling (b), obtained according to the results of the systematic literature review.

(Doblado-Maldonado et al., 2012; Liu et al., 2018). Selecting the optimal milling process is a key consideration in production, because the physicochemical and functional properties of wheat flour, dough and bread are significantly affected by different methods (Doblado-Maldonado et al., 2012; Li, Dhital, & Hasjim, 2014). The first consideration is the wheat itself, since the milling technique influences the quality of the final product. Posner (2003) notes that there are three main kinds of wheat: hard, soft, and durum. Hard wheats tend to be higher in protein content (10–15%), usually have more resistant and structured endosperm, and find their principal use in bread flour. Flours produced from softer wheats, which are often characterized by lower protein content (8–11%), are used in bread, cake, and cookie production (Kweon, Slade, Levine, & Gannon, 2014). Finally, durum wheat processing produces a granular or floury endosperm product (semolina), which is used in pasta production (Posner, 2003; Recchia, Cappelli, Cini, Garbati Pegna, & Boncinelli, 2019).

Many studies have shown that when different cereal grains (e.g. wheat, rice, sorghum, barley, rye) are milled, the selected milling method affects the colour, particle size, surface area, bulk density, damaged starch, and the structure and functional properties of the flour, leading to flours with different physicochemical properties (Albergamo et al., 2018; Cubadda, Aureli, Raggi, & Carcea, 2009; Ficco et al., 2016; Kihlberg, Johansson, Kohler, & Risvik, 2004; Liu et al., 2018; Palpacelli, Beco, & Ciani, 2007; Yu et al., 2018). Yu et al. (2018) noted that these differences are mainly due to milling conditions, notably mechanical forces, intensity, etc., and that the milling process is an important factor in determining the quality, performance, and suitability of end products. Nonetheless, in the literature there are no articles that compare SM and RM from a usability point of view, which is becoming a key element in the development and design of machines and plants for the food industry (Cappelli, Parretti, Cini, & Citti, 2019b). Furthermore, not only the milling process influence the dough rheology and the bread-making process. Type of flour, correct dosage of water, room and dough temperature, type of kneading machine, duration of kneading process, use of wheat flour improvers, operator variability, selected yeast and lactic acid bacterial strains, are only a few possible influencer of the final result. Despite this, according to the literature, the selected milling method seems to have greater effects on wheat flour quality, dough rheology, and bread characteristics, thus motivating this review (Albergamo et al., 2018; Cappelli, Guerrini, Parenti, Palladino, & Cini, 2020; Cubadda et al., 2009; Ficco et al., 2016; Kihlberg et al., 2004; Liu et al., 2018; Palpacelli et al., 2007; Yu et al., 2018).

The food industry is continuously seeking strategies and techniques that can improve milling operations. Therefore, the first aim of this review is to summarise current knowledge regarding the effects of SM and RM on wheat flour quality, dough rheology, and bread characteristics. The second aim is to suggest specific strategies to improve SM and RM by increasing efficacy, efficiency, and the quality of the final product, with positive impacts on production, profitability, and the environment.

2. Search strategy

The literature review used two search strings (one for RM and one for SM) to explore three databases: Science Direct, PubMed, and the Web of Science. The search strings used were as follows:

- Wheat AND (“stone milling” OR “stone grinding”)
- Wheat AND (“roller milling” OR “roller grinding”)

No language, time, or publication status restrictions were imposed, and duplicates were excluded. The initial results were screened by reading the title and abstract (articles that only consisted of an abstract and/or index were excluded at this point), and then by a full text reading. All articles concerning any aspect of SM or RM of cereals were included, while those that were not relevant to their effects on flour quality, dough rheology, or bread characteristics were discarded. For each type of milling, a flow chart was produced to summarise the obtained results (Fig. 1).

3. Wheat milling

Nowadays, the two most widely-used wheat processing techniques in the food industry are SM and RM (Doblado-Maldonado et al., 2012; Liu et al., 2018). The following paragraphs describe their functioning (3.1 and 3.2), effects on wheat flour, dough, and bread (4.2 and 4.3), and improvement strategies (5.1 and 5.2).

3.1. Stone milling

SMs are the oldest form of attrition mill used to produce flour. They simultaneously use several physical forces, such as shear, compression and abrasion, to mill wheat kernels between two stones, with a theoretical extraction rate of 100% (Kihlberg et al., 2004). Contemporary systems use composite millstones attached to metal plates (Doblado-Maldonado et al., 2012). Wheat is crushed between the two stones, and the output is a whole wheat flour containing all kernel fractions (endosperm, bran, middlings, and germ). SM is very simple and quick, and is the easiest way to produce whole wheat flour (Zhang, Wang, Cao, & Wang, 2018). If the aim is to produce whole wheat flour, the process ends here. If, however, the aim is to produce refined white flour, the output is sifted in centrifugal sifters (in small and medium-sized plants) or in plansifters (in larger plants). The centrifugal sifter consists of a rotating cylindrical sieve and a counter-rotating internal paddle that throws the product against the sieve, forcing the fine fraction through, while the coarse fraction tails over (Posner, 2003). At the end of the process, three distinct fractions are collected: refined white flour, bran, and middlings.

The literature notes that SM generates considerable heat due to friction and other physical forces, which can result in considerable damage to starch, protein, and unsaturated fatty acids, compared to other milling techniques (Prabhasankar & Rao, 2001). The latter study found slight protein degradation in samples milled at 55 and 85 °C using stone and plate mills. However, data regarding amounts of nutrients such as protein and fat were not supported by appropriate statistical analyses, and no information was given on other nutritional/nutraceutical properties. Nevertheless, it is clear that heat is a process parameter that should be controlled and kept as low as possible.

Interestingly, there appears to be a marketing advantage in using the term “stone ground” with consumers, as evidenced by the prevalence of whole wheat flour products in both retail and commercial markets. The main benefit of SM is that the endosperm, bran, and germ fractions remain in their natural proportions in whole wheat flour, which is perceived by the consumer as a “natural” product. Vendors can guarantee that all of the valuable nutritional/nutraceutical compounds are present, as most phytochemicals are concentrated in the germ and the outer bran layer of the wheat kernel (Di Silvestro et al., 2014). The SM claim has become so important to consumers that some mills have started to “crack” the grain using a SM, before the cracked wheat is reduced to flour via RM (Doblado-Maldonado et al., 2012).

3.2. Roller milling

Roller milling involves the separation of the endosperm from the bran and germ, followed by a gradual reduction in endosperm particle size (Campbell, 2007). Wheat passes through a series of rollers (rolls), accompanied by sifting between stages (Doblado-Maldonado et al., 2012). Rolls may be smooth or fluted, according to the stage of the process. Corrugations on fluted rolls do not run parallel to the long axis, but instead are arranged in a spiral pattern to obtain a scissor action. Fluting has either a steep (sharp) or shallow (dull) profile, and rolls can be arranged in a dull-to-dull, sharp-to-sharp, dull-to-sharp, or sharp-to-dull sequence (Rosentrater & Evers, 2017). This sequence can significantly impact particle size distribution of the flour (Fang & Campbell, 2003).

Rolls are driven by flat belts. Their speeds are controlled by a cogwheel or chain drive. Chains or stepped gears enable the distance between axes of pairs of rollers to be adjusted, without changing the transmission wheels. The material to be ground is fed into the machine by two feed rolls (Meuser, 2003). Wheat is ground between two rolls that rotate against each other and are positioned horizontally. Commercial rolls range from 180 to 350 mm in diameter and can be up to 1500 mm in length. In terms of performance, smaller-diameter rollers are more suited to shearing actions that aim to separate endosperm and bran. On the other hand, larger-diameter rolls create a longer grinding path that acts on the material mainly through compression. Most modern RM are equipped with rollers that have the same length and diameter, in order to achieve maximum uniformity and avoid maintaining a large inventory of spare rollers (Posner, 2003).

RM is characterized by high pressures that, like SM, inevitably lead to increases in temperature. In RM, the problem is managed by passing cooling water through the hollow centre of the rollers. Another issue arising from the continuous, high-pressure process is adhesion of the processed material to the roller surface, which can block the flutes of corrugated rolls and create an irregular increase in the effective diameter of smooth rollers. Surface adhesions can be removed by scrapers mounted below smooth rollers; unfortunately, they are not appropriate for corrugated rollers, where strong-bristled brushes are employed (Rosentrater & Evers, 2017).

RM efficiency depends on the amount of material fed into the rollers, the type of corrugation, and their differential speed. The amount of material that is processed is limited by the air cushion formed over the rollers, which is, therefore, frequently reduced by means of feed mechanisms that aim to increase efficiency (i.e. by drawing off the air above the gap and compacting the material to be ground). The differential speed can be as high as 1:15, depending on the flour product. At this ratio, the fixed, driven roller is reduced to the circumferential speed of the movable roller. The upper limit of the circumferential speed is around 6 ms^{-1}. Typically, corrugated and smooth rollers with a standard diameter have a circumferential speed of 3.3–4.4 ms^{-1} during wheat and rye milling (at 250–360 rpm) (Meuser, 2003).

RM is characterized by four distinct phases (Sakhare & Inamdar, 2014):

i. The break system

The first stage is known as the break, and the aim is to separate the endosperm from the bran and germ (Rosentrater & Evers, 2017). The idea is to open the kernel and scrape the endosperm off the bran (Campbell, Webb, Owens, & Scanlon, 2012b; Posner, 2003); this is when most of the endosperm separation is achieved (Campbell et al., 2012b). Rosentrater and Evers (2017) noted that although some flour is produced, that is not the purpose of this stage. Instead, the intention is to produce large fragments of endosperm that are fed into the reduction system and purifiers. The system consists of four break rolls that are typically followed by sieving (although this step may be omitted when an eight RM system is used). The flutes on the first break rolls are the largest (3.5–1 cm). They shear open the wheat kernel, ideally along the crease, and unroll the bran coat to form an irregular, relatively thick layer of endosperm that is pressed onto a thin sheet of bran. Overtails are conveyed to the second break RM, in which the rolls are less coarsely fluted (5.5–1 cm), and the gap between rolls is narrower. The largest particles from the following sieving stage pass to the third break, where they are ground by finer-fluted rolls with a narrower gap, and so on to the fourth and, potentially, a fifth break. The details of the system vary significantly among mills, and the applicable wheat type is determined by the number of break stages and grist.

ii. The sizing system

Next, smooth, sizing, and reduction rollers are employed to reduce the endosperm to fine flour (Posner, 2003). In some milling systems, the largest endosperm particles may be ground by finely fluted rollers, called sizing rollers. The purpose is to scrape bran particles from chunks of endosperm, so that the two components can be easily separated by purifiers, before further endosperm reduction (Rosentrater & Evers, 2017).

iii. The reduction system

The reduction system consists of 6–12 milling stages, interspersed with sifting that removes the flour produced by the preceding grind (Campbell et al., 2012b; Rosentrater & Evers, 2017). Milling is carried out with rollers that differ in two significant ways compared to break rollers: their surface is smooth or, more often, slightly matt; and the speed differential between them is lower (usually 1.25:1), although the fast roll still runs at 500–550 rpm. The purpose of the system is to crush and shear the grain, while the balance between the two forces is controlled by the smoothness of the rolls' surface (Rosentrater & Evers, 2017).

iv. The tailings system

Heterogeneous materials left over from each stage are sent to a sieving machine, called a plansifter (Campbell et al., 2012b; Posner, 2003). This is an enclosed unit that contains up to 10 stacks (compartments) of up to 32 sieve frames. The exact number of frames varies according to the sieved material and the manufacturer. Sieves are arranged in groups that differ in terms of their aperture size. Sieve aperture (measured in microns) is established by the miller. The mill designer assigns a certain surface area to each sieving stack. Overtails are directed to the next stage in the process for further milling or purification (Posner, 2003).

4. Main findings

4.1. Results of the systematic literature review

A total of 1366 initial items were obtained. Following the application of the selection criteria described in section 2 (removal of duplicates and screening), 77 texts were selected. Duplicates that had been included twice, because they referred to both RM and SM, were also removed, leaving a final total of 66 items: 11 book chapters, 6 reviews, and 49 research papers. 19 of these were published in the last five years. Fig. 1 summarises, in the form of flow charts, the selection process, which is consistent with the PRISMA statement (Moher, Liberati, Tetzlaff, & Altman, 2009). Fig. 1(a) and (b) show the results for SM and RM, respectively.

4.2. Effects of stone milling on wheat flour, dough, and bread

For consumers, millers, and bakers, one of the most important aspects of wheat flour quality is its nutritional profile. Recently, interest has grown in the use of SM, due to the widespread opinion that stone-milled flours (SMF) have a better nutritional profile than roller-milled flours (RMF). The marketing advantage is evidenced by the recent preponderance of SM products in both retail and commercial markets. SM has been found to have very little effect on macroelement losses (sodium, magnesium, potassium, calcium, and phosphorus) and no effect on microelement losses (manganese, iron, copper, zinc, and selenium), reinforcing the idea that it produces flours with high nutritional value (Albergamo et al., 2018). Moreover, trace element loss has been confirmed to be much less severe than in conventional RM. Cubadda, Raggi, Zanasi, and Carcea (2003) found average losses of iron, copper, zinc, and selenium ranging from 33 to 81% in white durum wheat flour. These findings are consistent with those by Ficco et al. (2016), who showed that SM preserves more compounds with high value for health, such as total fibre, carotenoids, and, in the purple wheat genotype, anthocyanins.

Albergamo et al. (2018) reported that SM, like RM, cannot reduce mycotoxins. However, the latter paper contradicts a comparative study reported by Palpacelli et al. (2007), who showed that SM reduces the vomitoxin and zearalenone content in flour, unlike RM. Specifically, the mean vomitoxin content in SMF was found to be 170 ppb, compared to 360 ppb for RMF, while the zearalenone content showed a similar difference (6 ppb *vs* 13 ppb). These results were confirmed by the analysis of commercial flours, which found that vomitoxin in SMF was 245 ppb, compared to 945 ppb in RMF, and the zearalenone content was 1.7 ppb and 6.0 ppb, respectively. SM therefore appeared to result in a reduction of about 40–50% in the vomitoxin and zearalenone contents. The authors argued that these results were related to the SM trimming machine they used. This machine was equipped with an aspirator that was able to, at least partially, eliminate the outermost layer of the wheat kernel, where most of the mycotoxins are located. Furthermore, their RM system used a series of reduction rollers to extract residual flour from the bran, which, the authors argued, was likely to increase mycotoxin extraction.

Crude fat content has been found to be significantly higher in SMF (2.1%) than RMF (0.9%) (Liu et al., 2018). The same study also found a significant difference for protein content; amounts were highest in SMF (11.4%), and significantly lower for RMF (7.3%). SMF contained higher amounts of crude fibre, ash, potassium, calcium, magnesium, iron, manganese, copper, and zinc than RMF. However, Liu et al. (2018) emphasized that these results were obtained at low stone rotational speed, which limits heating. Regarding phenolic compounds, the same study found that SMF contained higher amounts of protocatechuic acid, vanillic acid, epicatechin, ferulic acid, rutin, and ellagic acid, compared to RMF. This finding was confirmed by total phenolic content, total flavonoids content, and antioxidant activity, which were significantly higher for SMF. Di Silvestro et al. (2014) observed that heat stress, caused by SM, might lead to an increase in amylose content. Lin and Czuchajowska (1996) noted that this damage should be taken into account during baking, as damaged starch must be minimised in wheat flour used to make sourdough bread, to ensure adequate gassing during fermentation, while excessive damage can lead to a sticky dough and an undesirable red crust colour. Finally, Liu et al. (2018) emphasized that the moisture content of SMF (12.7%) was significantly higher than in RMF (12.0%), and that it had higher water holding capacity.

Regarding the effects of SM on wheat flour characteristics, Liu et al. (2018) found that SM produced flour with a narrower particle size distribution and more uniform particle size, compared to RM, while Kihlberg et al. (2004) found that SMF had a wider particle size distribution in the central range ($> 400 - \leq 800$ μ), compared to RMF. Bayram and Öner (2005) emphasized that the particle surface of SM bulgur was smoother and the shape was more regular, due to the abrasion effect. SM smooths the surface and improves the appearance of the particles; in particular, they are not split or glassy, and their surface is opaque. Furthermore, in the case of coarse bulgur (Pilaf) obtained from SM, the yield was highest (83.1%). Bayram and Öner (2005) concluded that, although alternative milling techniques and systems for bulgur processing were needed, SM still seemed to be the best current method.

With respect to dough, Kihlberg et al. (2004) found that doughs made with whole wheat SMF had a more homogenous particle size than those made with RMF. This was because the majority of the SMF flour fractions had the smallest size distribution, and the endosperm was separated from the bran to a lesser degree. Regarding rheological properties, Kihlberg et al. (2004) found higher values of falling number for whole wheat SMF compared to RMF, while SM samples showed lower water absorption compared to RM samples. The opposite trend was observed for conventional wheat milling. Image analyses of bread showed that the milling technique was also able to influence loaf volume (measured as slice area) and had the greatest impact on baking performance, measured as the area of the middle slice of the loaf, which was larger for SM than RM samples in whole wheat bread. The slice area of breads baked with SMF was larger than for breads baked with RMF. Furthermore, when the bran particle size was smaller, and still partly connected with endosperm, as in SMF, deformity increased.

Kihlberg et al. (2004) also found that the milling technique had a significant impact on the sensory qualities of whole wheat flour products. Their study showed that whole wheat breads baked with RMF and SMF differed in their sensory attributes, due to differences in the physical processing of the wheat. Whole wheat bread produced with SMF was characterized by the crispiness of the crust, its roasted cereal aroma, saltiness, and crumb deformity. Crust crispiness may have been related to the heat produced during flour grinding. Furthermore, the starch in the dough that formed the crust of the bread baked with SMF was less damaged and more directly exposed to heat, despite the standardized baking process used. SM influenced not only the crust, but also the crumb, thereby affecting both texture and flavour, with consequences for the saltiness attribute. This was not unexpected, as the bran contains a rich combination of compounds. Phenolic compounds are mostly derivatives of benzoic acid, and include ferulic acid, resorcinol, aromatic amines, phytates, folates, and sterols. At the same time, the smaller size of the bran particles in SMF facilitated reactivity, thus affecting the intensity of taste perceptions.

4.3. Effects of roller milling on wheat flour, dough, and bread

Regarding wheat flour characteristics, Kihlberg et al. (2004) reported that RMF had more damaged starch than did SMF. Liu et al. (2018) found that total starch content was significantly higher in RMF (77%) compared to SMF (70%). RM produced flour that had a wider particle size distribution than SM (Kihlberg et al., 2004; Liu et al., 2018). Notably, distributions were widest in the ranges > 1120 μ and ≤ 250 μ (Kihlberg et al., 2004). RM had negative effects on the mineral content of flour and semolina (Cubadda et al., 2009). The latter study found that RM had the most influence on the mineral content of semolina. At least six groups could be distinguished: selenium had the highest decrease (77–85%) (dry weight basis), followed by calcium (54–60%), copper (49–53%), potassium and phosphorous (42–47%), iron (36–38%), magnesium and zinc (32–36%). Furthermore, in RM, wheat germ was subject to more pronounced oxidation and rancidity phenomena (Boukid, Folloni, Ranieri, & Vittadini, 2018).

With respect to dough rheological properties, the falling number for whole wheat RMF was found to be lower compared to SMF (Kihlberg et al., 2004), and juiciness was reported to be greater in breads produced with RMF. Furthermore, the latter authors found that breads made with RMF had higher maximum consistency, water absorption, dough development time, and stability. RM also affected bread characteristics: the image analysis described in Kihlberg et al. (2004) showed that the milling technique had a great impact on loaf volume, measured as the area of the middle slice of the loaf, in whole wheat breads. Volumes were larger for whole wheat breads made with SMF compared to RMF. Dough rheology and the baking performances of RMF could be improved with a slight extension of kneading time, while this was not the case for SMF. Cappelli, Guerrini, Cini, and Parenti (2019a) proposed another strategy to improve whole wheat dough and bread. As the RM process separates white flour, bran, and middlings, the authors suggested delaying the addition of the bran and middlings during kneading. They found that a delay of 2 min (25% of the total kneading time) improved the dough rheology (reduced tenacity and tenacity/extensibility ratio, and increased extensibility) and bread characteristics (greater specific volume).

Kihlberg et al. (2004) found that wheat flour characteristics and specifically the amount of damaged starch produced by milling were enough to influence the sensory qualities of whole wheat bread, and to distinguish breads obtained from RMF and SMF. Furthermore, the impact was greater than that of the farming system or of the amount of flour in the formulation. In fact, their study found that the milling technique had the greatest impact on baking performance. The sensory attributes of whole wheat breads differed significantly, due to the mechanical and physical processing of the wheat. Sweetness, juiciness, compactness, and the raw streak of the crumb were the main sensory attributes noted for the whole wheat bread produced with RMF, and samples were generally characterized by a higher intensity of wheat aroma.

5. Discussion

The milling technique significantly influences wheat flour quality, the rheological properties of dough, and bread characteristics. Several authors have highlighted the importance of choosing the most suitable technique, given the desired effects on flour, dough, and bread (Albergamo et al., 2018; Cubadda et al., 2009; Ficco et al., 2016; Kihlberg et al., 2004; Liu et al., 2018; Palpacelli et al., 2007; Yu et al., 2018). Since the food industry is always seeking improvements and innovations, several strategies to improve the efficacy and efficiency of both SM and RM are suggested in the following paragraphs.

5.1. Strategies for improving stone milling

5.1.1. Keep the milling temperature as low as possible and avoid heating

Prabhasankar and Rao (2001) found that the key disadvantage of SM was that it generated considerable heat (due to friction), which damaged starch, protein, and unsaturated fatty acids. Their study found a slight degradation in protein, in samples milled at 55 and 85 °C using stone and plate mills. However, data regarding the effects on other nutrients were not supported by appropriate statistical analyses, and no information was given about other nutraceutical components. Nevertheless, it is clearly important to keep temperatures low during SM, in order to avoid heating that could lead to nutrient loss. This observation is supported by the findings described in section 4.2, which highlighted the fact that SM has less severe effects on macronutrients and micronutrients than does RM (at low temperatures and low stone rotational speed). Given that SM maintains the natural proportions of bran, middlings, and germ in whole wheat flour, and the consequent marketing advantages (Di Silvestro et al., 2014), systems need to be developed that can cool down the stones used in SM, following the model of existing systems used for cooling in RM.

5.1.2. Correct management of wheat feed rate and the distance between stones

Ghodke, Ananthanarayan, and Rodrigues (2009) emphasized the importance of correct regulation in SM. The authors tested feed rates of 0.21, 0.63, and 1.05 min for 200 g of wheat grain, with apertures (distance between the stones) of 2, 3, and 4 mm. Increasing the feed rate and aperture decreased the damaged starch content in the resulting flour, and vice versa. Aperture had the largest effect on damaged starch formation, while dough stickiness was dependent on feed rate. Highest stickiness was found at the slowest feed rate. Tear was lowest and moisture content was highest with the smallest aperture. The smaller aperture resulted in increased damage to flour starch and, hence, increased water absorption and softening of the dough. The study showed that feed rate and aperture were important process parameters that needed to be correctly set as a function of the desired flour characteristics.

5.1.3. Wheat conditioning

Wheat conditioning (also known as tempering) consists of the addition and absorption of water by the kernel (Posner, 2003). The aim is to ensure that the pericarp and germ are tough and plastic, and do not splinter during milling. At the same time, the endosperm should be as friable as possible, in order to optimize milling. Various studies have investigated conditioning, which has been found to have five purposes: (i) to toughen the bran, thus reducing the formation of bran powder and contamination (Boukid et al., 2018; Dexter & Sarkar, 2004; Doblado-Maldonado, Flores, & Rose, 2013; El-Porai, Salama, Sharaf, Hegazy, & Gadallah, 2013; Kweon, Martin, & Souza, 2009; Posner, 2003); (ii) to soften the endosperm, thereby enhancing its milling ability (Boukid et al., 2018; Dexter & Sarkar, 2004; El-Porai et al., 2013; Kweon et al., 2009; Posner, 2003); (iii) to facilitate the separation of bran from endosperm, reducing evaporative losses (Dexter & Sarkar, 2004; El-Porai et al., 2013); (iv) to ensure easy and accurate sifting of stocks (El-Porai et al., 2013); and (v) to ensure that endosperm moisture content is sufficient to result in a final moisture content of flour of between 14 and 15% (El-Porai et al., 2013; Kweon et al., 2009). However, the amount of water to be added and the correct tempering time vary widely, and there is no one regime that is universally appropriate for all wheat types and milling systems. Typically, soft wheat is conditioned to 15–15.5% (Kweon et al., 2009) and hard wheat to 16–16.5% (Posner, 2003).

Conditioning time is very important. El-Porai et al. (2013) studied three times (12, 24, and 36 h). The results showed that 12 h increased flour yield, 24 h increased dough tenacity and extensibility, and 36 h increased dough deformation energy. Although mill type and speed have greater effects on dough rheological properties and bread characteristics, conditioning time seems to be an interesting avenue for further investigation. Tempering time, temperature, and final moisture content should be carefully considered, as these three variables affect the milling process (Kweon et al., 2009; Posner, 2003). Achieving optimum wheat moisture content before milling is critical (Dexter & Sarkar, 2004; Kweon et al., 2009). The latter authors found that too much tempering reduces flour yield, because it becomes more difficult to completely separate bran from endosperm, and sieving efficiency is reduced. Too little tempering results in bran powdering, which contaminates the flour. Nozzles are used to spray water onto the wheat as it moves along an enclosed screw conveyor, and modern systems include an electronic unit that controls the precise and uniform addition of moisture.

Regarding energy consumption, Warechowska, Markowska, Warechowski, Miś, and Nawrocka (2016) and Dziki (2008) highlighted the fact that conditioning significantly increased the specific grinding energy and the grinding efficiency index. Furthermore, increasing moisture content significantly increased the average size of ground wheat particles, notably the bran fraction (Warechowska et al., 2016). The latter authors found that flour yield decreased by 12–18% regardless of genotype, and ash, protein, and gluten content decreased as moisture increased. The decreased ash content was considered to be an improvement in flour quality. An opposite trend was observed for the gluten index and water absorption; here, increased moistening contributed to the mechanical strengthening of the gluten network, thus enhancing sorption capacity. Finally, an increase in water absorption and better stability of the dough was noted for *Astoria* and *Cytra* cultivars.

Dziki (2008) proposed an interesting strategy to reduce the specific grinding energy, based on wheat crushing before milling. The paper suggested that crushing considerably decreased grinding energy requirements, for both soft and hard cultivars, with a reduction in average particle size distribution of ground material (in particular, an increase in the fraction < 200 μm) in soft wheat. Cappelli et al. (2020), assessed the effects of wheat conditioning on refined white flour quality, dough rheological properties, and bread characteristics. The authors highlighted the fact that wheat conditioning at 13% increased the farinograph dough stability, which successively decreased as the conditioning moisture increased (i.e. 15 and 17%) (Cappelli et al., 2020). Furthermore, regarding Chopin alveograph results, Cappelli et al. (2020) reported that the dough tenacity (P) and the curve configuration ratio (P/L) decreased as the conditioning moisture increased, for the softening of the doughs. An inverse trend was observed for dough extensibility (L), which instead, increased with the increase in conditioning moisture (Cappelli et al., 2020). Finally, regarding the results of wheat conditioning on bread characteristics, Cappelli et al. (2020) highlighted that the higher bread specific volumes and the lower crumb densities were obtained with a wheat conditioning of 15% and 17%. Despite the latter article examined in depth the topic, further studies are necessary. In conclusion, the correct management of tempering could significantly affect the milling process, and could improve dough rheological properties and bread characteristics.

5.1.4. Rediscover and modernize traditional stone watermills

The traditional watermill, described by Aristotle in 400 BC, uses water fed through a gear mechanism (Walker & Eustace, 2016). Di Silvestro et al. (2014) emphasized the fact that SMF obtained using a traditional watermill (at temperatures of around 30 °C) is different is several ways, compared to modern SMF (obtained at 60 °C). Their study found that lower total starch was obtained using a modern SM (61.6 g) compared to a watermill (68.1 g), and the higher temperature led to an average loss of 6.5 g of starch per 100 g of flour. Although flours obtained with the modern SM had higher amounts of insoluble dietary fibre, watermill SMF contained more polyphenols and flavonoids, making the latter technique a very interesting way to increase nutraceutical content. Not only does the lower milling temperature have positive effects on flour quality, but traditional stone watermills could have other advantages: lower environmental impacts (due to the use of green energy); improvements to the landscape and attractiveness of rural areas; opportunities to produce flour with higher polyphenols; and a potential marketing advantage related to the promotion of tradition and craftsmanship.

5.2. Strategies for improving roller milling

Both the literature and the evolution in milling techniques confirm the advantages of RM compared to SM. The first advantage relates to better efficiency and flexibility. As reported by Doblado-Maldonado et al. (2012), efficiency was improved by narrowing the gap and using smooth, rather than corrugated, rollers during reduction. Flexibility is another important advantage. The diameter, surface structure, rotational and differential speeds of rollers can all be configured (Meuser, 2003). Moreover, milling and reduction can be varied for each roller and for different raw materials (Doblado-Maldonado et al., 2012). This wide range of adjustable operating parameters is not possible in SM. The second advantage is lower heat generation compared to SM (and the ability to install cooling systems). The last (but not least) advantage is linked to the ability to separate bran and middlings. Unlike SM, which can only output whole wheat flour, RM can separate the bran, middlings, and germ from the endosperm fraction for further processing (Chun-feng, Xian-qing, & Yu-rong, 2006; Gili, Palavecino, Cecilia Penci, Martinez, & Ribotta, 2017; Srivastava, Sudha, Baskaran, & Leelavathi, 2006). These strategies can result in inhibited lipase activity, which is concentrated in the bran, thus extending the shelf life of whole wheat flours (through enzyme inhibition), without influencing the flour's functional properties (Doblado-Maldonado et al., 2012).

Wheat conditioning is an improvement strategy that is also applicable to RM. Strategies specific to RM are described in the following subsections.

5.2.1. Wheat debranning combined with the processing of bran, middlings, and germ

Nowadays, many industrial mills include debranning in *aestivum* and *durum* milling, as it increases capacity, enhances yield (De Brier et al., 2015), and improves semolina quality (Bottega et al., 2009; Campbell et al., 2012b; Rosentrater & Evers, 2017). Debranning removes a portion of the bran before the first break, through the application of friction and abrasion forces, without nicking the endosperm, but which limit the number of broken kernels. This facilitates the separation of the germ after the first break, thus enhancing flour quality (Bottega et al., 2009), although this strategy seems to be most suited to *triticum durum* (Dexter & Wood, 1996). It also appears to increase refinement, and the nutritional content of by-products that hold great promise as novel food ingredients (Dexter & Wood, 1996). Moreover, the process improves milling performance and can simplify flows in mill plants (Dexter & Wood, 1996).

Lijuan, Guiying, Guoan, and Zaigui (2007) reported that debranning had several positive aspects, such as a decrease in the gluten index, reduced starch damage, optimal falling number, and increase in the maximum resistance of dough. In addition, debranned flour was whiter than non-debranned flour and had higher peak viscosity. Furthermore, Dexter and Wood (1996) reported increases in deformation energy, flour yield, pasta brightness, and mineral, vitamin, and polyphenol content in debranned fractions. Positive effects were observed on bread quality scores, such as volume, vol/wt, height and structure of steamed bread, increased ash and pericarp content, and particle size distribution (Lijuan et al., 2007). Debranning was an effective way to obtain wheat bran fractions that were enriched in phenolic compounds and antioxidants, with reduced α-amylase activity (debranning from 3 to 6% of kernel weight) (De Brier et al., 2015). This could increase the health benefits associated with whole wheat products (Beta, Nam, Dexter, & Sapirstein, 2005). However, debranning has very different effects on soft and hard wheats, and further studies are needed to understand the performance of doughs made from flours obtained using different milling and debranning methods.

Debranning is even more interesting in the context of whole wheat flour production and storage. Studies have found that significant enzyme inactivation is achieved if the debranned fraction is stabilized, using light steam treatments (Srivastava et al., 2006), microwaves (Chun-feng et al., 2006), or infrared radiation (Gili et al., 2017), before its reinsertion into the refined flour, thus increasing whole wheat flour storage time and improving the nutritional characteristics of whole wheat bread. Infrared radiation is another heating method for bran processing. That method reduces processing time, lowers energy consumption, only requires simple equipment, and has no toxicological or environmental effects. It also reduces phytic acid content, but does not affect the content of crude fat, protein, and phenolic compounds. Another interesting strategy to stabilize bran, middlings, and germ involves the use of microwaves. Microwave heating at 900 W for 120 s has been found to decrease lipase activity and the moisture content of the wheat bran, thus extending its storage period (Zhang et al., 2018). Lipase activity is the first step in lipid degradation, and enzyme activity is concentrated in the bran; consequently, this fraction can be treated separately, before being added back to refined wheat flour to make whole wheat flour. This method extends the shelf life of whole wheat flours (by the inhibition of enzymes), without influencing their functional properties (Doblado-Maldonado et al., 2012).

Furthermore, laboratory and industrial debranning techniques have proved effective in reducing the mycotoxin content of wheat, although their efficiency is extremely variable; for example, the reduction of deoxynivalenol in debranned wheat was found to range from 15 to 78% (Cheli, Pinotti, Rossi, & Dell'Orto, 2013). Rosentrater and Evers (2017) and Posner (2003) highlighted several other advantages of debranning: a reduction in bacterial, fungal, and other contamination associated with the outer layers of the kernel that are removed in the early stages of the milling process. Zhang et al. (2018) and Rosentrater and Evers (2017) noted a reduction in the enzyme activity concentrated in the external bran layers. The aleurone layer can be reintroduced, after being processed and stabilized, into the resulting flours, thus improving their nutritional value (Rosentrater & Evers, 2017). The RM process can be shortened for grains that have been decorticated – coarsely fluted rolls used in the conventional first break are not required and can be substituted with sizing rolls (Posner, 2003). Finally, extraction rates for flour and semolina are higher, while bran contamination may be reduced, when grains are decorticated before milling (Posner, 2003; Rosentrater & Evers, 2017).

5.2.2. Cooling down the rollers

Rollers are often called 'chills', as they can be cooled (Posner, 2003; Rosentrater & Evers, 2017). Fast cooling after casting ensures that the carbon is mixed with steel, creating a hard roller surface, while slow cooling allows the carbon present in the steel to crystallize, resulting in a softer surface (Posner, 2003). Rollers can heat up considerably during grinding, due to friction; this makes it difficult to maintain the aperture, particularly when the rollers are subject to a high degree of wear. To remedy this problem, hollow, water-cooled rollers have been developed – rollers are cooled by pumping water over the shaft. This has been found to improve milling performance, leading to a more uniform result (Meuser, 2003).

5.2.3. Correct setting of differential ratios

Posner (2003) studied the differential ratio between rollers, which ranged from 1.2:1 to 1.5:1. Lower differentials have a larger compression effect on the wheat kernel. Smooth rollers are placed closer together, in order to reduce endosperm chunks in the flour and, as a result, require considerably more power than corrugated rollers. The miller must control compression to avoid damage to the flour and prevent excessive flaking of endosperm particles. Flaked endosperm can reduce flour yield, because overtails from the top sieves during reduction ends up in the mill's overtails streams and, subsequently, the bran stream (stock that has gone over a sieve is known as 'overs').

5.2.4. Development and improvement of automatic and adaptive mill plants

From a long-term perspective, in particular regarding industrial-scale RM, the development and use of Programmable Logic Controllers and Programmable Automation units will make it possible to set, on a case-by-case basis, the correct amount of water provided during conditioning, the distance between rollers, differential ratios, wheat feed rate and other fundamental milling parameters that can reduce consumption and waste, and enhance final flour product quality. These systems could be based on data-driven systems, such as model-based predictive controls (Dal-Pastro, Facco, Zamprogna, Bezzo, & Barolo, 2017, 2016; Owens, 2001), compositional breakage equations and functions (Galindez-Najera, Choomjaihan, Barron, Lullien-Pellerin, & Campbell, 2016; Mateos-Salvador, Sadhukhan, & Campbell, 2013; Campbell, Bunn, Webb, & Hook, 2001, 2012a), and the discrete element method (Patwa, Ambrose, & Casada, 2016). The aim is to develop an intelligent grain processing system that is able to automatically manage milling by, for example, the optimal selection of processing conditions, the early detection of faults in real-time, and real-time product quality prediction (Campbell et al., 2012a; Dal-Pastro et al., 2017, 2016; Owens, 2001). Although further investigations are necessary, we are not so far from making all this possible.

5.2.5. Purification of by-products

Purification is one of the three major steps in the RM process (Posner, 2003). A purifier consists of a long, oscillating sieve with a slight descending slope, which is divided into four or more sections. The material to be purified becomes progressively coarser from the head to the tail. Air currents are drawn through one to three layered sieves that move simultaneously with alternating motion. Individually controlled air currents rise through the cover, aspirating the stock as it moves over the oscillating sieve cover, and heavier particles tend to fall through. Purification relies on materials of different sizes, density, and air resistance (Posner, 2003; Rosentrater & Evers, 2017). Controlled air currents separate heavier particles (relatively pure endosperm), which flow through the sieves, and lighter ones (with higher bran content), which tail over the sieves (Posner, 2003). This process of stratification results in, from top to bottom: light bran, heavy bran, large composites, large pure endosperm particles, and small pure endosperm particles (Rosentrater & Evers, 2017). Relatively pure endosperm particles are sent to reduction rollers to increase flour production, while overtails is directed to sizing rollers or tail-end fine breaks. Grinding, sifting, separation, and regrinding are repeated, until the endosperm is reduced to an acceptable degree, and, in particular, no more flour can be separated from the bran. Each flour stream differs in quality, due to its origin within the wheat kernel, equipment adjustment, stage of the milling process, etc. The collected flours are mixed, and then transferred by screw conveyors to storage bins (Posner, 2003).

6. Conclusions & future trends

This review has highlighted the importance of selecting the optimal milling technique, as a function of the desired flour quality, dough rheology, and bread characteristics (Albergamo et al., 2018; Cubadda et al., 2009; Ficco et al., 2016; Kihlberg et al., 2004; Liu et al., 2018; Palpacelli et al., 2007; Yu et al., 2018). We have noted that only a few studies have specifically compared SM and RM techniques, which have pointed up the need for extensive comparative studies of their different effects. Nevertheless, this review has revealed several important observations regarding the effects of the two milling techniques.

The benefits of SM are: its simplicity (Zhang et al., 2018); the higher concentration of macroelements, microelements, and polyphenols in flours milled at low temperature and at low stone rotational speed (Albergamo et al., 2018; Cubadda et al., 2003; Ficco et al., 2016; Liu et al., 2018); and a marketing advantage (Di Silvestro et al., 2014). Other, potentially positive effects are its ability to reduce mycotoxins (Palpacelli et al., 2007), the higher protein and fibre contents of the flour (Liu et al., 2018), and higher whole wheat bread volume (Kihlberg et al., 2004). However, these results need to be validated by further comparative studies. On the other hand, it is difficult to manage milling parameters, and there are other negative effects, notably, heat generation (Prabhasankar & Rao, 2001), not optimal falling number, and poorer dough rheological properties (Kihlberg et al., 2004), indicating that there is significant room for technological improvement.

On the other hand, RM also has clear advantages in terms of efficiency and flexibility (Doblado-Maldonado et al., 2012; Meuser, 2003). Positive effects include lower heat generation, optimal falling number, and better dough rheological performance (Kihlberg et al., 2004; Posner, 2003). Although this technique has already been significantly improved at the technological level, much can still be done to improve performance. Section 5.2 highlighted the fact that particular attention should be paid to wheat debranning and the stabilization of bran, middlings, and germ (a combined strategy that is not yet widely applied). The application of this solution could lead to enzyme and microorganism inactivation, the stabilization and extension of whole wheat flour shelf life, and, for millers, a simplified strategy to manage whole wheat flour storage and orders.

In our opinion, this review has not declared a “winner”, because both SM and RM techniques have advantages and disadvantages. The optimal milling system is a function of the aim of the process, keeping in mind business needs and flour product demand. For example, SM is the best option if the aim is to produce flour with high nutritional content (macroelements, microelements, polyphenols, and fibre) and market appeal. On the other hand, RM is best if the miller has to provide large quantities of refined white flour with more preferred dough rheological properties and higher kneading resistance. To support these different aims, many modern mills are equipped with both SM and RM. Finally, it is important to emphasize that the milling technique is only one of many factors that affect flour quality, dough rheological properties, and bread characteristics. Agronomic practices, the selection of the right cultivar, and optimal wheat moisture content are just some of the other parameters that need to be considered. A final consideration is the choice of improvement strategies for both SM and RM (sections 5.1 and 5.2), which should also be based on the goal of the milling process. The rational and optimized development of innovations and improvements will have positive effects, not only on flour product quality, but also on the productivity and profitability of the entire production/supply chain.

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