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Assessing the effects of flour particle size distribution to improve dough rheological properties and whole wheat rusks characteristics: A case study on industrial pilot plant

Alessio Cappelli [a,*], Francesca Carlesi [b], Cristiano Paganoni [b], Sirio Cividino [a], Piernicola Masella [c], Mauro Zaninelli [a]

[a] Department of Human Science and Quality of Life Promotion, Università Telematica San Raffaele Roma, Via di Val Cannuta 247, 00166, Rome, Italy
[b] Research and development team – Barilla G. e R. Fratelli S.p.A., via Mantova, 166, 43122, Parma, Italy
[c] Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Piazzale delle cascine 16, 50144, Florence, Italy

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ABSTRACT

Rusks represent one of the most widely consumed baked goods for breakfast. Nevertheless, the use of whole wheat flour generates significant rheological problems and worsen bread and bakery products characteristics, thus motivating this work. This paper addresses the gap understanding the effects of bran, middlings, and germ addition, with different particle sizes, on flour composition, dough rheological properties, and whole-wheat rusks characteristics. Consequently, the aim of this work was to assess the effects of particle size distribution, testing three different flour mixes, on flour composition, dough rheology, and whole-wheat rusks characteristics, in an industrial pilot-scale plant. Results showed statistically significant differences, in terms of flour composition, dough rheological properties, and whole wheat rusks characteristics among the three tested mix. Mix 2 showed statistically significant differences; it was able to improve flour nutritional value, highlighting a higher insoluble (11.74) and total (13.79) fiber content, enhance dough rheology, considering the higher dough stability (11.97 min) and dough development time (8.03 min), and, finally, ameliorate the whole wheat rusks characteristics, in view of a higher crispness and friability of the product. In conclusion, based on the obtained results, mix 2 formulation could be adopted to optimize the production of whole wheat rusks.

1. Introduction

Bread and bakery products represent staple foods essential for human nutrition. As highlighted in an earlier work, bread is considered as the oldest type of baked good (10,000 years BCE). Furthermore, bread and bakery products are an important source of carbohydrates, protein, dietary fiber, vitamins, minerals, and antioxidants. Nowadays, several types of bakery products are strongly rooted in the food habits of many people from different countries (Mondal and Datta, 2008; Aglietti et al., 2022; Cappelli et al., 2023); consequently, many types of baked goods are produced in different countries, regions, or even in different municipalities (Mondal and Datta, 2008; Venturi et al., 2022; Cappelli et al., 2022). Among these products, rusks and cereal flakes are the most widely consumed baked goods worldwide for breakfast (Champilomati et al., 2020; Di Giuseppe et al., 2012).

In Italy and in Europe rusk production follows specific regulations; as established in the article 2.1 of Italian Presidential Decree No. 283 of June 23, 1993, related to regulations on the legal denominations of selected bakery products, the name “rusks” must be reserved to bakery products obtained by baking, splitting by transverse slicing, eventual drying and subsequent toasting of one or more leavened doughs, using wheat or other cereal flours, including whole grain, with water and with the possible addition of salt, sugar, oils, fats, malt, malted products, food bran, and other ingredients, as well as flavorings and additives. The moisture content of rusks cannot exceed seven percent by weight of the finished product, with an average tolerance of 2 percent in absolute value.

In the last 20 years, scientific literature and market trends highlighted a significant increase of consumer interest for bakery products able to provide health benefits by means of bioactive compounds (Van Kleef et al., 2018). Moreover, Champilomati et al. (2020) and Di Giuseppe et al. (2012) highlighted the positive effects of whole cereal inclusion in breakfast which proved to be able to significantly reduce the

* Corresponding author.
E-mail address: alessio.cappelli@uniroma5.it (A. Cappelli).

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Abbreviations

(WA)	water absorption
(DS)	degree of softening
(S)	dough stability
(DDT)	dough development time
(RVA)	Rapid Visco Analyzer
(PV)	peak viscosity
(HSV)	holding strength
(FV)	final (peak) viscosity
(BDV)	break down
(TSV)	total setback
(PT)	peak time

risk factors for cardiovascular diseases. As highlighted in earlier works, this has led to an important focus on the use of ancient wheats and whole wheat flours in the food industry. Nevertheless, the use of whole wheat flour generates significant rheological problems of dough and worsen bread and bakery products characteristics (Boita et al., 2016; Packkia-Doss et al., 2019; Tebben et al., 2018; Cappelli et al., 2019). In particular, non-endosperm components of the caryopsis (i.e. bran, middlings, and germ) significantly worsen gluten development and dough structure. This is mainly due to the negative influence of arabinoxylans, inulin, and β-glucans which bind water, increase viscosity, and disturb the formation of the gluten network during development (Boita et al., 2016; Packkia-Doss et al., 2019; Tebben et al., 2018; Cappelli et al., 2019). Furthermore, particle size distribution plays a key role in the determination of the final baked goods quality. Yin et al. (2024) highlighted that steamed bread made using whole wheat flours with smaller particle size had a larger specific volume than whole wheat flours with larger particle size. Furthermore, as highlighted by Islam et al. (2024), the particle size of whole wheat flours changes significantly according to the milling method and the milling operative parameters, affecting starch, proteins, and other nutritional components of the dough, in addition to the final product characteristics. Consequently, strategies to mitigate the negative effects of bran, middlings, and germ addition in whole wheat dough, bread, and bakery products are urgently needed.

The literature review highlighted that several authors have investigated different strategies to improve whole wheat dough rheology and bread characteristics; among these, the most interesting innovations relate to the correct dosage of water, bran, and middlings during kneading (Packkia-Doss et al., 2019), the addition of gelatinized flours, the use of enzymes such as xylanase, amylases, glucose oxidase, and phytase (Tebben et al., 2018), and, finally, delay the addition of bran and middlings during whole wheat dough kneading (Cappelli et al., 2019). Nonetheless, although whole wheat rusks are one of the most widely used baked goods for breakfast, no strategy to mitigate the negative effects of the non-endosperm components of the caryopsis has been proposed in the literature, thus motivating this work. This paper addresses the gap understanding the effects of bran, middlings, and germ addition, at different particle sizes, on flour composition, dough rheological properties, and whole-wheat rusks characteristics. Consequently, the aim of this work is to assess the effects of particle size distribution, testing three different whole wheat flour mixes, on flour composition, whole wheat dough rheology, and whole-wheat rusks final characteristics. The results could be used to optimize the whole wheat rusks formulation at industrial scale.

2. Materials and methods

2.1. Raw materials and flour preparation

27 kg of whole wheat flour were kindly provided by Molino Valente (Alessandria, Piedmont, Italy). Immediately after receiving, the whole batch of flour was sieved using a plansifter (Golfetto Sangati Industries) to separate the different fractions according to their particle size; four different sieves of 1000, 508, 308, and 212 μm were used. This allowed to collect the output from five different intervals: >1000 μm, between 1000 and 508 μm, between 508 and 308 μm, between 308 and 212 μm, and <212 μm. Successively, the different fractions were recombined to obtain the three tested whole wheat flours, named mix 1, mix 2, and mix 3, according to the percentages reported in Table 1.

2.2. Experimental design

This work assesses the effects of different particle size distribution on chemical-physical characteristics of flours, dough rheological properties, and whole wheat rusks characteristics, testing three whole wheat flour mixes recombined according to the percentages reported in Table 1. With respect to flour characteristics, differences in starch, total dietary fiber, soluble fiber, insoluble fiber, protein, total fats, ashes, and moisture content were assessed. Concerning dough rheological properties, water absorption (WA), degree of softening (DS), dough stability (S), and dough development time (DDT) were determined using a Brabender farinograph (Brabender, Duisburg, Germany) according to the standard method (AACC, 2000). Furthermore, starch pasting properties were investigated using a Rapid Visco Analyzer (RVA) to determine starch pasting temperature, peak viscosity (PV), holding strength (HSV), final (peak) viscosity (FV), break down (BDV), total setback (TSV) and peak time (PT), according to AACC method 76–21 (AACC, 2000). Finally, to obtain further information regarding starch pasting properties, a falling number test was carried out using a falling number machine (Perten falling number 1700, Perten Instruments, Inc., Springfield, IL) following the AACC Approved Method 56–81.03 (AACC, 2000). Regarding whole wheat rusk characteristics, a Texture Profile Analysis (TPA) of rusks samples was carried out by two-bite compression using a Texture Analyzer (TA-XT PLUS, SMS Stable Micro Systems, Godalming, Surrey, United Kingdom), equipped with a circular flat-plate probe of 5 Kg (diameter of 25 mm) and using a compression probe with a diameter of 35 mm. Moreover, as described in section 2.6, a friability test of the whole wheat rusks has been carried out using a mechanical sieve shaker machine (IRIS FTS-0200; Filtra Vibración Ltd, Badalona, Spain), which performed the sieving process for 5 min at a shaking amplitude of 7 mm. Finally, the final moisture content of whole wheat rusks was measured using gravimetry at 105 °C until a constant weight was reached, as highlighted in an earlier work (Cappelli et al., 2024). All the tests were carried out in three replicates.

2.3. Flour characterization and analysis

Immediately after the recombination of the different fractions to obtain the three tested whole wheat flours (i.e. mix 1, mix 2, and mix 3), 1.5 kg of flour for each mix has been sent to the laboratory to carry out

Table 1
Formulations and percentages in weight of the tested whole wheat flours (i.e. mix 1, mix 2, mix 3).

Sample	Interval 1 (<1000 μm)	Interval 2 (1000–508 μm)	Interval 3 (508–308 μm)	Interval 4 (308–212 μm)	Interval 5 (>212 μm)
Mix 1	1.8%	5.1%	3.9%	5.3%	83.9%
Mix 2	3.8%	7.3%	3.0%	2.0%	83.9%
Mix 3	1.0%	1.0%	7.0%	7.1%	83.9%

several chemical and physical analyses in three replicates. As a result, protein (AOAC 920.87 (AOAC International, 2005)), starch (AOAC 979.10 (AOAC International, 2005)), insoluble fiber, soluble fiber, total dietary fiber (AOAC 991.43 (AOAC International, 2005)), total fats (AOAC 922.06 (AOAC International, 2005)), and ash (AOAC 923.03 (AOAC International, 2005)), were determined by the Barilla sensory and analytical Laboratory (Parma, Italy) following approved, official methods. Moreover, the final moisture content of flours was measured using gravimetry at 105 °C until a constant weight was reached.

2.4. Rheological properties of dough

900 g of flour for each mix were used to investigate the rheological properties of dough with a Brabender Farinograph (Brabender, Duisburg, Germany), according to the standard method (AACC, 2000), in three replicates. Regarding farinograph tests, the ICC method ((ICC 115/1) International Association for Cereal Chemistry, 1992) was adopted: water absorption (WA), dough development time (DDT). dough stability (S), and the degree of softening (DS) were assessed in three replicates. No salt was added in farinograph trials. Furthermore, 50 g of flour for each mix were employed to assess starch pasting properties using a Rapid Visco Analyzer (RVA) to determine starch pasting temperature, peak viscosity (PV), holding strength (HSV), final (peak) viscosity (FV), break down (BDV), total setback (TSV) and peak time (PT), according to AACC method 76–21 (AACC, 2000) in three replicates. Finally, additional 50 g of flour for each mix were used to carry out a falling number test using a falling number machine (Perten falling number 1700, Perten Instruments, Inc., Springfield, IL) following the AACC Approved Method 56–81.03 (AACC, 2000) in three replicates.

2.5. Whole wheat rusk production process

1.5 kg of flour for each mix were used to create three whole wheat loaves, in the Barilla pilot scale plant at the Parma headquarters, to produce the tested whole wheat rusks in three replicates. Each loaf, of 60 cm each, has been produced mixing 500 g of whole wheat flour with 285 g of water, sunflower oil, malt, dextrose, salt, fresh brewer's yeast, in a planetary mixer with a spiral hook (Model BE5 produced by Dito Sama, Aubusson, France) kneading for 10 min at 200 RPM, following a standard recipe optimized for pilot-scale plant production. Once that the kneading process was completed, the dough was divided into three parts, to produce the three whole wheat loaves, and rested for 10 min at 25 °C. Successively, the doughs were shaped and inserted into specific molds. Consecutively, each loaf was leavened at 36 °C for 50 min in a leaving chamber (Model AVANT-GARDE, ALASKA, Rovigo, Italy) with a relative humidity of 86%. Successively, the loaves were baked at 210 °C for 30 min in an industrial forced-air convection oven (Model RMTE665, Tagliavini, Parma, Italy). Once baked, the loaves were removed from the mold and transferred to the leavening chamber to undergo a maturation period of 27 h, at 36 °C and relative humidity of 86%, which allows to create a water concentration gradient that moves water from the core of the loaf to the dried external surface, allowing the cut of the product into slices and the subsequent complete dehydration of the final product (final moisture of 8–10%).

The cut of the loaves into the slices (rusks) was carried out using an industrial cutter machine (Model S50S Samurai Line, Rollmatic, Vicenza, Italy). From each loaf, 40 slices of 15 mm were obtained. Finally, the slices were toasted in an industrial forced-air convection oven at 140 °C for 20 min. The central rusk obtained from each loaf (more precisely the number 20 of the 40 total rusks) has been selected for further analyses regarding the whole wheat rusks characterization (section 2.6). Specifically, the central rusks from each of the three loaves were employed for Texture Profile Analysis (TPA), friability test, and final moisture content assessment. All the tests were carried out in three replicates.

2.6. Whole wheat rusk characterization

The central rusk obtained from each of the three loaves, produced in the pilot scale plant, was used to carry out the whole wheat rusks characterization in three replicates. The first sample was used for a Texture Profile Analysis (TPA); the second one was employed to carry out a friability test; and the latter one to assess the final moisture content of the whole wheat rusks. With respect to the Texture Profile Analysis (TPA) of rusks samples, this was carried out by two-bite compression using a Texture Analyzer (TA-XT PLUS, SMS Stable Micro Systems, Godalming, Surrey, United Kingdom), equipped with a circular flat-plate probe of 5 Kg (diameter of 25 mm) and using a compression probe with a diameter of 35 mm. Mechanical test conditions were as follows: 50% compression rate, 50 N of automatic trigger load, 10 mm of travel distance and 3 mm s^{-1} for pre-test, test, and post-test speeds. Hardness (F max), F max/thickness ratio, and work were measured.

Moreover, a friability test of the whole wheat rusks has been carried out using a mechanical sieve shaker machine (IRIS FTS-0200; Filtra Vibración Ltd, Badalona, Spain), which performed the sieving process for 5 min at a shaking amplitude of 7 mm. in particular, the study of the particle size distribution of the rusks fragments was carried out with the mechanical sieve shaker using 3350, 2500, 1000, 500 μm sieves. This allowed to collect the output from five different intervals: >3350 μm, between 3350 and 2500 μm, between 2500 and 1000 μm, between 1000 and 500 μm, and <500 μm. The sample was placed on the first 3350 μm sieve, arranged sequentially on the other sieves, and the analysis was performed with a shaking amplitude of 7 mm for a time of 5 min. The evaluation of the rusk's fragments distribution (i.e. Friability) was made weighing the fractions collected in the various reference intervals. Finally, the final moisture content of whole wheat rusks was measured using gravimetry at 105 °C until a constant weight was reached.

2.7. Statistical analysis

The effects of the factor "flour particle size distribution" on the three whole wheat flour mixes tested in this work were assessed using a one-way ANOVA, which was applied to each parameter related to flour composition, dough rheology, and whole-wheat rusk characteristics, to establish its significance. Specifically, three levels were tested: mix 1, mix 2, and mix 3 (Table 1). Significance was set at $p < 0.05$. In cases of statistically significant results ($p < 0.05$), a Tukey HSD post hoc test was performed.

3. Results and discussion

3.1. Flour characteristics

Table 2 summarizes the results of flours characterization and analyses. Concerning moisture content, the one-way ANOVA did not find any statistically-significant differences for the investigated factor. With respect to ashes, the one-way ANOVA found a significant main effect for the factor "flour particle size distribution" ($p < 0.001$). In particular, the three tested mixes differed significantly: Mix 3 exhibited the lowest ash content, followed by Mix 1 and Mix 2. This is mainly due to the differences in flour composition and in particle size distribution within the three mixes (Table 1). As a result, the most refined and finest mix (i.e. mix 3) had the lowest ash content; an intermediate ash content was found for mix 1, and, finally, the highest ash content was found for mix 2 (i.e. the most unrefined and the coarsest). This is consistent with Dexter & Sarkar (2004), and Cappelli et al. (2019), which highlighted an extremely heterogeneous composition of the caryopsis from the external layers, richer in fiber, minerals, and polyphenols, to the internal endosperm, mainly composed by starch and gluten forming proteins. Consequently, the higher the fiber content and the particle size, the higher will be the ash content (Dexter and Sarkar, 2004; Cappelli et al., 2019).

Table 2
Results of flours characterization and analyses (based on dry weight).

Sample	Moisture (g/100g)	Ashes (g/100g)	Protein (g/100g)	Total fats (g/100g)	Starch (g/100g)	Soluble fiber (g/100g)	Insoluble fiber (g/100g)	Total fiber (g/100g)
Mix 1	13.01 ± 0.06	1.44 ± 0.01	15.74 ± 0.08	2.19 ± 0.04	58.71 ± 0.40	2.06 ± 0.08	11.23 ± 0.07	13.30 ± 0.02
Mix 2	12.96 ± 0.03	1.54 ± 0.01	15.33 ± 0.13	2.17 ± 0.04	58.47 ± 0.40	2.05 ± 0.08	11.74 ± 0.07	13.79 ± 0.01
Mix 3	13.01 ± 0.06	1.33 ± 0.01	15.81 ± 0.01	2.21 ± 0.03	58.87 ± 0.42	2.09 ± 0.07	10.73 ± 0.08	12.82 ± 0.05

Regarding protein content, the results of the one-way ANOVA found a significant main effect of the factor "flour particle size distribution" ($p < 0.001$). Mix 2 has a significantly lower protein content compared to mix 1 and mix 3. This result is consistent with ash and fiber content. As a matter of fact, the milling process leads to the separation of the inner part, which is richer in protein, from the external part, characterized by a higher fiber content (Islam et al., 2024; Gobbetti and Rizzello, 2023). As highlighted in the literature, the composition of each anatomical region of the caryopsis is different according to its biological function (Islam et al., 2024; Gobbetti and Rizzello, 2023). Furthermore, the results are supported by Noort et al. (2010), which highlighted that the bran fractions with larger particles, obtained from the outermost layers of the caryopsis, are characterized by a lower protein content (Noort et al., 2010). Finally, the higher is the content of larger bran fractions, the lower will be the protein content (Noort et al., 2010).

Regarding soluble dietary fiber, the one-way ANOVA did not highlight any statistically significant result, while this was not the case for insoluble and total dietary fiber. In particular, with respect to insoluble dietary fiber content and total dietary fiber, the one-way ANOVA found a significant main effect of the factor "flour particle size distribution" ($p < 0.001$). The tested samples differed significantly in terms of insoluble and total fiber content; in particular, mix 3 highlighted the lowest value, mix 1 a middle value, and mix 2 the highest value, respectively. Insoluble fibers are predominantly found in the external layers of the bran (Cappelli et al., 2019; Dexter and Sarkar, 2004). These parts of the kernel are rich in numerous key nutrients, including dietary fiber, antioxidants, minerals, vitamins, and phenolic compounds, which provide numerous human health benefits (Khalid et al., 2017). Coarse bran, predominant in mix 2, is obtained from the outermost layers of the pericarp which have a protective function in the seed; for this reason, is rich in cellulosic fibers (65.2%) and have a lower protein content (12.8%) (Khalid et al., 2017; Gobbetti and Rizzello, 2023). In contrast, fine bran is obtained from the part of the kernel closest to the endosperm; as a result, fine bran has a lower content in cellulosic fibers (38.0%) and higher in protein (22.0%) (Khalid et al., 2017; Gobbetti and Rizzello, 2023). Thus, the coarse bran resulted richer in fiber and poorer in protein. This is confirmed by the results of one-way ANOVA which highlighted a higher fiber content in the mix with the higher percentage of coarse bran, i.e. mix 2. Finally, with respect to starch and total fats content, the one-way ANOVA did not find any statistically-significant differences.

3.2. Rheological properties of dough

3.2.1. Farinograph results

The results of farinograph tests are reported in Table 3. With respect to water absorption (WA), the one-way ANOVA found a significant main effect for the factor "flour particle size distribution" (p = 0.046). In particular, mix 3 had a significantly lower WA compared to mix 2 and mix 1. This result can be considered as expected given the finer particle size composition of mix 3, which had a significantly lower total and insoluble dietary fiber content (Table 2). This is consistent with Cappelli et al. (2019), Boita et al. (2016) and Pavlovich-Abril et al. (2016), which highlighted that the higher the fiber content, the higher the WA. This is due to the hydrophilic nature of dietary fiber, in particular of arabinoxylans, inulin, and β-glucans, contained in bran and middlings. These elements significantly affect the dough rheology by binding water and increasing viscosity (Boita et al., 2016; Pavlovich-Abril et al., 2016; Cappelli et al., 2019). Furthermore, earlier studies highlighted a significant increase in WA when the bran content was increased from 10 g to 40 g, especially in the case of barley bran and wheat bran (Rosell et al., 2001; Ahmed et al., 2013). As a result, fiber-enriched doughs are widely known for their ability to absorb significant amounts of water, attributed to the presence of numerous hydroxyl groups that promote interactions with water through hydrogen bonds (Rosell et al., 2001; Ahmed et al., 2013). Finally, consistently with Noort et al. (2010), a decrease of wheat bran particle size decreases the water-binding capacity of fibers, thus motivating a lower WA for mix 3.

Table 3
Results of farinograph tests expressed as mean values of three replicates ± SD. Columns without letters were not significantly different.

Sample	Water Absorption (WA)	Degree of Softening (DS)	Stability (S)	Dough Development time (DDT)
Mix 1	67.40 ± 0.05a	61.33 ± 7.50	10.63 ± 0.74a	6.50 ± 0.40a
Mix 2	67.40 ± 0.17a	58.67 ± 4.62	11.97 ± 0.40b	8.03 ± 0.49b
Mix 3	67.06 ± 0.15b	55.00 ± 3.00	10.07 ± 0.75a	5.00 ± 0.26c

Regarding degree of softening (DS), the one-way ANOVA did not highlight any statistically significant result. As highlighted in Table 3, this is probably due to the high standard deviation and to a low softening of the dough in all three tested mixes. Concerning dough stability (S), the results of the one-way ANOVA highlighted a significant main effect of the factor "flour particle size distribution" ($p = 0.029$). More precisely, mix 2 showed a significantly higher stability value compared to mix 1 and 3. The higher stability of mix 2 might be explained by the greater presence of larger bran particles. As highlighted by Noort et al. (2010) and Zanoletti et al. (2017), the reduction of bran particle size has often been associated with detrimental effects on dough stability and gluten quality. This is mainly due to an increase in particle surface area and to higher chemical interactions of reactive components with gluten (Noort et al., 2010; Zanoletti et al., 2017). In particular, ferulic acid monomers bound to insoluble cell wall material could interact with gluten proteins, causing adverse effects on gluten network functionality, worsening dough stability (Noort et al., 2010; Zanoletti et al., 2017).

Regarding Dough Development Time (DDT), the one-way ANOVA found a significant main effect for the factor "flour particle size distribution" ($p < 0.001$). In particular, the three mixes were significantly different; mix 2 scored the highest value, followed by mix 1 and, finally, by mix 3. The higher DDT value of mix 2 can be explained by the presence of bran with larger particle size (Sudha et al., 2007; Liu et al., 2019; Cappelli et al., 2019); consequently, the results are directly proportional to the fiber particle size distribution. The higher DDT suggest that the dough develops more slowly due to the higher fiber content and for the larger bran particle size; this is consistent with Liu et al. (2019) and by Sudha et al. (2007) which highlighted that the increase in DDT may be related to the impairment of gluten network structure induced by the presence of fiber, requiring longer time to reach the optimal dough consistency. Moreover, as highlighted by Zanoletti et al. (2017) and Cappelli et al. (2019), in the case of whole wheat dough, the gluten network needs higher kneading time and energy to managing the structure breakage and the steric hindrance of bran and middlings through gluten rearrangement.

3.2.2. Rapid visco analyzer and falling number results

Table 4 summarizes the results of rapid visco analyzer and falling number. With respect to pasting temperature, breakdown, hold, setback, peak time, peak viscosity, and final viscosity, the one-way ANOVA did not highlight any statistically significant result. Furthermore, concerning falling number, the one-way ANOVA did not find any statistically-significant differences for the investigated factor.

3.3. Whole wheat rusk characteristics

3.3.1. Texturometer and moisture content results

The results of texturometer tests and moisture content are reported in Table 5. Concerning hardness (F – max), F – max/thickness ratio, and work, the one-way ANOVA did not find any statistically-significant differences for the investigated factor. Moreover, with respect to rusk moisture content, the one-way ANOVA did not highlight any statistically significant result.

3.3.2. Friability test

Table 6 summarizes the results of friability tests. With respect to the whole wheat rusk fragments with particle size >3350 μm, the one-way ANOVA found a significant main effect for the factor "flour particle size distribution" ($p = 0.025$). According to the results of the statistical analysis, mix 3 had a significantly higher percentage of fragments in the interval > of 3350 μm, compared to mix 1 and mix 2, highlighting the production of bigger crumbs and a lower friability of the product. Regarding to the whole wheat rusk fragments in the interval between 3350 and 2500 μm, and between 2500 and 1000 μm, the one-way ANOVA did not find any statistically-significant differences for the investigated factor. Concerning the interval between 1000 and 500 μm, the results of the one-way ANOVA highlighted a significant main effect of the factor "flour particle size distribution" ($p = 0.004$). in this case, mix 2 showed a significantly lower percentages of fragments in the interval between 1000 and 500 μm. These results are consistent with those obtained for the interval > of 3350 μm in highlighting the production of smaller crumbs and a higher friability of the whole wheat rusk in case of mix 2 employment.

The results of friability tests suggest that mix 2, the coarsest sample among the three mixes, produces finer crumbs and highlighted a higher friability when used to produce whole wheat rusks. This is due to dietary fiber–gluten interactions which lead to structural changes in the gluten network, particularly in secondary structures, aggregates, disulfide, and hydrogen bonding patterns (Zhou et al., 2021). More precisely, as highlighted by Zhou et al. (2021), this phenomenon occurs since the presence of dietary fiber leads to the weakening of the compact secondary structure of gluten (mainly a weakening due to disulfide bonds breakage). Simultaneously, the presence of dietary fiber causes an increase in less regular structure such as random coils and unfolded protein chains (Zhou et al., 2021). This mechanism, together with a lower protein content, leads to the formation of a more brittle gluten network compared to mix 1 and mix 3; this results in finer crumb formation and higher crispness of the rusk. In conclusion, these results indicate that Mix 2 provides optimal friability characteristics, as desired by whole wheat rusks consumers (Primo-Martin et al., 2008). Finally, with respect to the interval >500 μm, the one-way ANOVA did not highlight any statistically significant result.

Table 5
Results of texturometer tests and moisture content of whole wheat rusk expressed as mean values of three replicates ± SD. Columns without letters were not significantly different.

Sample	Hardness (F max) (N)	F max/thickness ratio (N/mm)	Work (J)	Rusk moisture content (g/100g)
Mix 1	614.33 ± 32.32	64.00 ± 2.65	5.63 ± 0.21	3.24 ± 0.27
Mix 2	653.33 ± 54.52	67.00 ± 5.29	6.10 ± 0.56	3.03 ± 0.34
Mix 3	636.33 ± 75.20	66.00 ± 6.56	5.73 ± 0.59	3.45 ± 0.64

4. Conclusions

The results presented in this paper demonstrate significant differences, in terms of flour composition, dough rheological properties, and whole wheat rusks characteristics among the three tested mix. Flour particle size distribution clearly indicates that flours should be carefully selected to produce essential baked goods like whole wheat rusks, to improve their nutritional value and the final product characteristics. Mix 2 showed the best performance in whole wheat rusk production since it was able to improve flour nutritional value, given the higher fiber content, enhance dough rheological properties, considering the higher value of dough stability and dough development time, and, finally, ameliorate the whole wheat rusks characteristics, in view of a higher crispness and friability. In conclusion, based on the obtained results, mix 2 formulation, based on coarser and larger bran, could be adopted to optimize the production of whole wheat rusks. Nevertheless, further studies and industrial-scale trials are needed to confirm the results of this study conducted in a pilot-scale plant, assessing additional parameters like microstructural analysis (e.g. SEM images of rusks) to deeply assess fiber-gluten interactions, reduction of defects, waste, and breakage in industrial production as well as an increased consumer preference and acceptance.

CRediT authorship contribution statement

Alessio Cappelli: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Francesca Carlesi:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Cristiano Paganoni:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Sirio Cividino:** Writing – original draft, Supervision, Software, Project administration, Investigation, Data curation, Conceptualization. **Piernicola Masella:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Data curation. **Mauro Zaninelli:** Supervision, Project administration, Methodology, Investigation, Conceptualization.

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Table 4
Results of rapid visco analyzer and falling number expressed as mean values of three replicates ± SD. Columns without letters were not significantly different.

Sample	Pasting temperature (°C)	Breakdown (cP)	Hold (cP)	Setback (cP)	Peak time (min)	Peak viscosity (cP)	Final Viscosity (cP)	Falling number
Mix 1	64.30 ± 0.05	350 ± 20	590 ± 26	657 ± 16	5.42 ± 0.04	940 ± 40	1247 ± 40	369 ± 5
Mix 2	64.63 ± 0.42	314 ± 8	605 ± 17	656 ± 22	5.52 ± 0.07	920 ± 22	1261 ± 39	370 ± 8
Mix 3	64.25 ± 0.88	335 ± 28	555 ± 21	623 ± 32	5.42 ± 0.10	890 ± 47	1178 ± 52	365 ± 5

Table 6
Results of friability tests of whole wheat rusk expressed as mean values of three replicates ± SD. Columns without letters were not significantly different.

Sample	>3350 μm (g/100g)	Between 3350 and 2500 μm (g/100g)	Between 2500 and 1000 μm (g/100g)	Between 1000 and 500 μm (g/100g)	<500 μm (g/100g)
Mix 1	19.05 ± 0.84a	13.89 ± 0.70	27.92 ± 1.56	22.60 ± 0.28a	16.50 ± 1.14
Mix 2	18.42 ± 0.51a	14.10 ± 0.22	28.73 ± 1.35	21.93 ± 0.16b	16.78 ± 0.81
Mix 3	20.98 ± 1.12b	13.52 ± 0.90	25.80 ± 0.84	23.22 ± 0.38a	16.45 ± 0.89

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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