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Hydration properties and arabinoxylans content of whole wheat flour intended for cookie production as affected by particle size and Brazilian cultivars

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ABSTRACT

The effect of particle size (PS), cultivars (C), and their interactions (PS × C) on the hydration of whole wheat flour (WWF) intended for cookie production was evaluated by different approaches. Three Brazilian wheat cultivars and three particle sizes were evaluated. Total arabinoxylans content was affected by PS, increasing up to 6.18 times with the reduction in particle size. Water-soluble arabinoxylans were more influenced by the cultivar. The water absorption capacity by farinograph indicated that the PS had a greater influence, with high absorption in fine particle size flour. Water absorption based on swelling capacity and absorption kinetics by Enslin-Neff device evidenced high water absorption for coarse particle size flour, regardless the cultivar. ORS Vintecinco cultivar demonstrated the best hydration properties and desired quality for short-dough cookies. The different methods to predict the hydration properties of the flours resulted in different behaviors, demonstrating that the presence of outer layers of the grain of WWF promotes distinct mechanisms in the water absorption capacity, which are significantly influenced by genotype and particle size factors.

1. Introduction

Whole wheat flour (WWF) is an ideal vehicle for endowing baked products with healthy properties. WWF are obtained by grinding whole grains and contains all of the anatomical components of grains in the same proportions as in the intact form, including endosperm, germ, and bran, making it an excellent source of nutritional and functional ingredients (Weaver, 2001). However, despite its health-promoting factors, there are major technological and sensory challenges regarding the use of WWF in bakery products (Sanz Penella, Collar, & Haros, 2008; Noort, Haaster, Hemery, & Hamer, 2010; Cai, Choi, Hyun, Jeong, & Baik, 2014; Hemdane et al., 2016).

Water absorption is one of the most important functional characteristics of flour (Ren, Walker, & Faubion, 2008), especially those destined for the production of cookies. Water plays a complex role since it affects the nature of interactions between ingredients, and contributes to the structure of the dough, modifying its rheological behavior. In addition, it has an influence during the baking process, in which the dry dough leads to changes that are controlled by the affinity of each component for water (Blanco Canalis, León, & Ribotta, 2019).

Flours suitable for the production of cookies, especially short-dough cookies, require a low water absorption (Kweon, Slade, & Levine, 2011). When high-affinity ingredients with water are present in the formulation, such as WWF, changes in the rheological properties of the dough

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are observed. As a result, the technological difficulties during production and changes in quality parameters can lead to reduced acceptability by consumers, thereby limiting the consumption of whole grains. Among the most frequent observations of the hydration properties of WWF, the distinctive ability of bran to absorb water has been reported. Bran is a hygroscopic material that competes for water with other flour components, such as starch and gluten, for different interaction processes (Roozendaal, Abu-hardan, & Frazier, 2012).

Wheat bran contains between 44 and 50% fiber, which consists mainly of non-starch polysaccharides (Stevenson, Phillips, O'Sullivan, & Walton, 2012). Arabinoxylans (AX) constitute the largest non-starch fraction in the bran, and their structure and solubility characteristics give them unique physicochemical properties, including high water-link capacity, which is attributed to the hydrogen bonding of water molecules to the OH groups in the polymer chain (Wang, Hamer, Van Vliet, & Oudgenoeg, 2002). In addition, the polysaccharides in the cell wall have been found to exhibit great variations in their structure and content across different cultivars (Saulnier, Guillon, & Chateigner-Boutin, 2012; Wang et al., 2019; Nishitsuji, Whitney, Nakamura, Hayakawa, & Simsek, 2020; Kaur et al., 2019). Using the genotypic factors of the bran cell wall, considerable efforts have been made to predict the interactions of the bran in the dough via changes in processing techniques, such as the variations in the particle size.

Several studies have evaluated the hydration properties of wheat bran as a function of particle size (Jacobs, Hemdane, Delcour, & Courtin, 2016; Jacobs, Hemdane, Dornez, Delcour, & Courtin, 2015; Sanz Penella et al., 2008; Wang, Hou, Kweon, & Lee, 2016). However, there are no reports of specific studies on the hydration properties of WWF elaborated by the whole milling of wheat grains intended for the production of cookies from short-dough, particularly those contemplating specific milling factors and genotypic characteristics using soft wheat. Therefore, the aim of the present study was to evaluate the simultaneous effects of particle size and cultivar, as well as their interactions, on the hydration properties and arabinoxylans content of WWF of three wheat cultivars intended for the cookies production in Brazil, since Brazilian cultivars for cookies are scarcely studied.

2. Material and methods

2.1. Materials

Three commercial wheat cultivars (*Triticum aestivum* L.), BRS 374, ORS Vintecinco, and TBIO Consistência, indicated for the production of cookies in Brazil, were kindly provided by Cooperativa Agrária Agroindustrial, Guarapuava, PR, Brazil. All of the reagents used were of analytical grade.

2.2. Whole wheat flour processing

The whole wheat flours were obtained by milling in different stages until three particle sizes were obtained, as follows. Grain processing for fine (FWWF) and medium (MWWF) particle sizes were obtained by one step of milling at a fixed speed of 20,000 rpm for 180 s and 100 s, respectively, in a laboratory impact mill with a cooled milling chamber (M20, IKA, Staufen, Germany). For coarse particle size (CWWF), grains were processed into two steps, initially broken the grain in a laboratory roll mill (CD1; Chopin, France), which were milled in the impact mill (M20, IKA, Staufen, Germany) for 4 s at 20,000 rpm (Supplementary Material Table S1). The WWF particle size was measured by a laser diffraction particle size analyzer (LV-950; Horiba, Japan) using the dry dispersion module. The mean particle sizes were approximately 194.22, 443.49, and 675.02 μm for fine, medium and coarse WWF respectively (Supplementary Material Fig. S1).

2.3. Damaged starch content of whole wheat flour

The damaged starch content in the flours was determined according to the method 76-33.01 of AACCI. American Association of Cereal Chemists International (2010) in equipment (SDmatic; Chopin, France), using 1 g of flours sample. The working solution was prepared by adding 120 mL of distilled water, 3 g of boric acid and 3 g of potassium iodide. Then, one drop of the 0.1 mol/L sodium thiosulfate was added to the mixture and transferred to the reaction vessel. Both sample and solution were placed into SDmatic device.

2.4. Total arabinoxylans (TOT-AX) and water-extractable arabinoxylans (WE-AX)

The colorimetric method based on Douglas (1981) and Finnie, Bettge, and Morris (2006) was used to determine the content of total arabinoxylans (TOT-AX) and water-extractable arabinoxylans (WE-AX). For extraction, 1 g of flours sample (fine, medium and coarse from different cultivars) was weighted in 50 mL Falcon tubes, and 25 mL of distilled water was added. The tubes were vortexed for 10 s at 2500 rpm, and 1 mL aliquots were transferred to new Pyrex tubes (for TOT-AX analysis). The rest of the suspended sample was vortexed for 30 min and then centrifuged for 10 min at 2500×*g* and the supernatant was used for WE-AX analysis. Quantification of TOT-AX and WE-AX was performed by reading on a UV-VIS spectrophotometer (Biospectrometer Kinetic, Eppendorf, Germany) at 558 and 505 nm (Kiszonas, Courtin, & Morris, 2012). The absorbance value at 558 nm was subtracted from the value at 505 nm, adopting the difference as an absolute value. The concentration of arabinoxylans (mg mL^{-1}) was calculated from the xylose standard curve ($R^2 = 0.9994$), prepared by diluting different concentrations of xylose in distilled water.

2.5. Hydration properties of whole wheat flours

2.5.1. Swelling capacity

The swelling capacity of flour samples was determined as described by Jacobs et al. (2015). In a 10 mL graduated cylinder, 500 mg of sample and 5 mL of distilled water were added. After the immersion time of 60 min, the sample expansion capacity was determined by reading the volume occupied.

2.5.2. Water absorption in farinographers

Water absorption was determined using a Farinograph Brabender (Duisburg, Germany), according to the international method of AACCI 54-21.01 (2010).

2.5.3. Solvent retention capacity (SRC)

The solvent retention capacity (SRC) profile was obtained according to method 56–11.02 by AACCI. American Association of Cereal Chemists International (2010) using sodium carbonate (Na_2CO_3) 5% (w/w), sucrose 50% (w/w), lactic acid 5% (w/w), and distilled water. The values were expressed on a moisture basis of 14.0% and calculated according to Equation (1).

$$\%\ \mathbf{SRC} = \left[\frac{\textbf{tube weight} + \textbf{gel}}{\textbf{flour weight}} - 1\right] \cdot \left[\frac{86}{100 - \ \%\ \textbf{flour moisture}}\right] .\ 100 \qquad \text{Eq. (1)}$$

2.5.4. Absorption kinetics

The absorption kinetics of the flours were determined using the Enslin-Neff device (Enslin, 1933). Fig. 1 presented the instrument used for analyzing the hydration kinetics of whole wheat flours. A Buchner funnel with a 51 mm cross-section containing filter paper was connected to a 2.0 mL graduated pipette using a rubber tube. Analysis was performed by spreading 50 mg of sample onto the filter paper with the meniscus of water in the pipette positioned at the 0 mL mark. The water

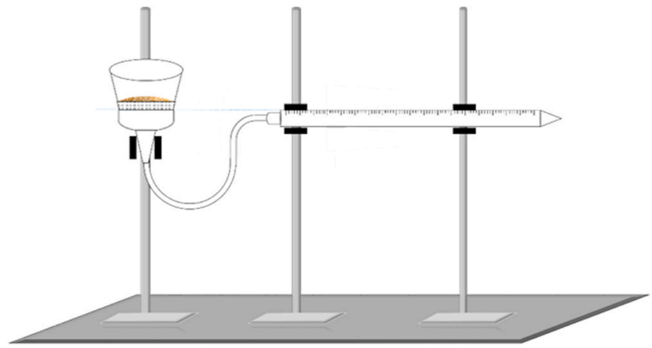

Fig. 1. Enslin-Neff instrument used to study the hydration kinetics of whole wheat flour samples.

absorption was monitored for 30 min.

2.6. Experimental design and statistical analysis

To evaluate the effects of cultivar and particle size on the hydration properties of the flours, a complete 3 × 3 (particle size × cultivar) factorial experimental design was used, with a total of nine treatments. Each treatment was performed in triplicate. Analytical tests were performed in triplicate, and the standard deviations were reported. The results were analyzed using analysis of variance (ANOVA) in a factorial design with a 99% and 95% confidence interval. The means were compared using Tukey's test ($p < 0.05$).

3. Results and discussion

3.1. Damaged starch content of whole wheat flour

The individual factors of particle size (PS), cultivar (C), and PS × C interaction had significant effects on the flours damaged starch content ($p < 0.05$) (Table 1). Based on the proportion of the middle squares (MS), PS (MS: 63.48) contributed to greater variation in the damaged starch content, with a weaker influence from the cultivars (MS: 0.77) and PS × C (MS: 0.39). For example, FWWF presented the highest content of damaged starch among the three studied wheat cultivars. The significant contribution of PS × C to the damaged starch content indicates that this parameter is not only influenced by the milling process, but also by the genotypic characteristics. These data indicate that it may be possible to control WWF-damaged starch levels by selecting the appropriate milling conditions and cultivars.

The milling process for fine WWF resulted in an increase in the damaged starch in all samples (Table 1), regardless of the cultivar. The levels of damaged starch in flours depend on the particle size because the friction severity and shear strength of the milling favor the destruction of the granular structure of the starch, thus increasing the damaged content (Angelidis, Protonotariou, Mandala, & Rosell, 2016; Protonotariou, Drakos, Evageliou, Ritzoulis, & Mandala, 2014).

A significant difference ($p < 0.05$) in damaged starch of TBIO Consistência compared to ORS Vintecinco and BRS 374 was observed in the FWWFs, presenting the highest damaged starch. Some studies have shown that the wheat genotype influences the damaged starch content due to grain hardness (Duyvejonck, Lagrain, Dornez, Delcour, & Courtin, 2012; Tsilo et al., 2011). Yu et al. (2015) reported that wheat grains with higher grain hardness presented elevated values of damaged starch under the same milling conditions, reaching an increase of 1.8%–3.4% for grains with a grain hardness of 13.6% and 57.6%, respectively. This justifies the difference ($p < 0.05$) in the FWWF since TBIO Consistência cultivar has the hardest grain texture than the ORS Vintecinco and BRS 374 cultivars (Supplementary Material, Fig. S1). In addition, there were no significant differences among cultivar for both flours, medium and coarse particle size.

Wheat grains with a higher hardness require more energy to break and reduce flour particles during processing, leading to a higher percentage of damaged starch. In addition, a high hardness may considerably affect the quality of flour and the cookie-making process by increasing water absorption, leading to changes in the viscosity of the dough, since damaged starch has the capacity to retain four times more water than native starch (Kweon et al., 2011). Although the flours evaluated had a damaged starch content in the typical range (2–4%), not only the retained water content was technologically important, but also the speed at which absorption occurs and the phenomena involved were key for the flours used in cookie production.

3.2. Total arabinoxylans (TOT-AX) and water-extractable arabinoxylans (WE-AX)

The individual factors of particle size (PS), cultivar (C), and PS × C interaction showed significant effects on the total arabinoxylans and water-extractable arabinoxylans content of the flours ($p < 0.05$) (Table 1). The variability obtained in the TOT-AX values ($p < 0.01$) was mainly influenced by the PS (MS: 41.12), followed by C (MS: 21.40), and to a lesser degree by the PS × C interaction (MS: 4.23). On the other hand, for WE-AX, the cultivar factor was the main factor responsible for the variability, while the interaction between PS and C did not show any significant influence.

The total arabinoxylans (TOT-AX) and water-extractable arabinoxylan (WE-AX) contents of the whole wheat flours are presented in Table 1. An increase in the TOT-AX content was observed with a

Table 1
Damaged starch, arabinoxylan content and statistical analysis variance of the fine, medium, and coarse whole wheat flours from different wheat cultivars.

Flours	Wheat cultivars			*Middle square*			
	ORS Vintecinco	BRS 374	TBIO Consistência	*Particle size (PS)*	*Cultivar (C)*	*PS x C*	*CV (%)*
	Damaged starch (%)						
FWWF	3.21 ± 0.04^{Ab}	3.17 ± 0.03^{Ab}	3.95 ± 0.01^{Aa}	63.48**	0.39**	0.77**	2.93
MWWF	0.28 ± 0.07^{Ba}	0.21 ± 0.04^{Ba}	0.23 ± 0.01^{Ba}				
CWWF	0.13 ± 0.01^{Ca}	0.14 ± 0.01^{Ba}	0.15 ± 0.02^{Ca}				
	Total arabinoxylans (mg. mL^{-1})						
FWWF	5.38 ± 0.18^{Ab}	11.01 ± 1.38^{Aa}	7.55 ± 1.29^{Ab}	41.13*	21.40*	4.23*	16.77
MWWF	3.53 ± 0.42^{Ba}	5.37 ± 0.75^{Ba}	4.86 ± 1.08^{Ba}				
CWWF	3.17 ± 1.15^{Bb}	4.83 ± 0.18^{Ba}	3.89 ± 0.69^{Bab}				
	Water extractable arabinoxylans (mg. mL^{-1})						
FWWF	1.59 ± 0.03^{Ab}	1.46 ± 0.05^{Ab}	2.31 ± 0.22^{Aa}	0.35*	1.09*	0.05^{ns}	10.00
MWWF	1.53 ± 0.05^{ABba}	1.19 ± 0.13^{ABb}	1.75 ± 0.23^{ABa}				
CWWF	1.41 ± 0.10^{Bab}	1.08 ± 0.17^{Bb}	1.74 ± 0.22^{Ba}				

Different uppercase letters in the same column and lowercase in the row, represent a significant difference between particle sizes and cultivars, respectively, by Tukey test ($p \leq 0.05$). Each value is presented as mean ± standard deviation ($n = 3$). FWWF: Fine Whole Wheat Flour. MWWF: Medium Whole Wheat Flour. CWWF: Coarse Whole Wheat Flour. Analysis variance: * and **. Significant at the 0.01 and 0.05 probability level, respectively.

reduction in the particle size from coarse/medium to fine WWF ($p < 0.05$) for all studied cultivars, with no difference between medium and coarse particle sizes. This can be attributed to cell disruption during the milling process, which caused a greater release of the polymers attached to it. It is known that the non-starch polysaccharides arabinoxylans (AX) are important components of dietary fiber, and are present in the endosperm of cereals (including the aleurone layer), cell walls, husk, and wheat bran (Fadel et al., 2017).

For the WE-AX the same trend as TOT-AX was observed, fine WWF presented an increase in WE-AX content ($p < 0.05$) for all cultivars, with significant difference between fine and coarse particle sizes. Similarly, the higher contents of WE-AX in FWWF were associated with an increased extraction capacity, since the greater the surface area of the flour resulted in more interactions between polysaccharides and the solvent. In other studies, evaluating the different milling conditions and particle sizes of refined flour and whole wheat flour, an increase in WE-AX content with reduction of particle size, was also observed; as suggested by Protonotariou, Batzaki, Yanniotis, and Mandala (2016), using a jet mill to produce whole wheat flours with a range of particle size from 17.02 to 84.14 μm. While, Lazaridou, Vouris, Zoumpoulakis, and Biliaderis (2018), also used a jet mill to reduce the particle size of commercial flour, by varying feed rate (2.7 and 1.5 kg/h) to achieve a particle size of 12 and 21 μm (ultrafine and fine flours), also reported an increase in WE-AX as the particle size decreased.

Water-extractable arabinoxylans are known for their human health benefits. However, in bakery products, they also perform an important role in the water balance in doughs, competing with other constituents of the dough for the water, thereby influencing the viscosity, and are able to bind to proteins to reinforce the gluten network (Courtin & Delcour, 2002; Saeed, Pasha, Anjum, & Sultan, 2011; Langó et al., 2018; Nishitsuji et al., 2020). These properties are important factors in the quality of the flour. Although it seems advantageous in the preparation of cookies, these characteristics can negatively influence the final product since low water absorption and little gluten development are desired characteristics. In addition to the technological changes in the dough, the increase of WE-AX in the flour also provides negatively changes in the cookies quality, such as the increase in dough viscosity, leading to reduced dough spreading factor and increase in the height and hardness of the cookies, hence, the reduction of the diameter (Bettge & Morris, 2007; Sozer, Cicerelli, Heinico, & Poutanen, 2014).

The literature on the arabinoxylan content of Brazilian wheat is limited. However, in our study, the TBIO Consistência cultivar presented a higher WE-AX content for the three particle sizes evaluated, followed by the ORS Vintecinco, and BRS 374 cultivar. An understanding of this parameter is extremely important since it can help, together with the techniques of milling, in the production of whole wheat flours with desirable technological characteristics for the production of short-dough cookies.

3.3. Hydration properties

3.3.1. Farinograph water absorption

The significant effects of the hydration properties are presented in Table 2. The absorption of water by farinograph was influenced significantly by particle size (PS) (MS: 58.55; $p < 0.05$). The cultivar (C) (MS: 12.22; $p < 0.01$), in a smaller proportion than the PS, also had an individual effect on these indices.

The results of the farinograph test for the water absorption of whole wheat flours are presented in Table 2. The smallest particle size flours (FWWFs) showed the highest water absorption among the three wheat cultivars studied. This can be attributed to the greater contact surface area of samples with smaller particle sizes, which provides a higher exposure of the hydroxyl groups present in the fiber structure and, consequently, increases the interactions with water through hydrogen bonds (Sanz Penella et al., 2008). Thus, relatively strong bonds with water are related to the effects at the molecular level. A similar finding was reported in a previous study, which evaluated the properties of whole grain wheat flour and performance in bakery products as a function of particle size (Bressiani et al., 2017).

While evaluating the hydration properties of wheat bran, Jacobs et al. (2015) demonstrated that bran can have a strong connection with water at the molecular level through hydrogen bonds or nanopores present in the bran matrix. The authors also affirmed that the bran can also be bound to water weakly by the micropores, and/or through the stacking phenomenon. In our study, we hypothesized that the majority of the nanopores remained intact, providing absorption actions with particle size reduced to an average of 194.22 μm, for all studied cultivars. The water absorption in the presence of mechanical action (mixing) occurs through the molecular bond, thereby the reduction particle size increases the availability of OH^- in the flour and increases water absorption by hydrogen bonds.

As reported in Table 2, water absorption was affected by flour particle size. Coarse WWF presented a water absorption increase of 7.8%, 8.9% e 6.8% compared to the fine WWF of ORS Vintecinco, BRS 374 e TBIO Consistência cultivar, respectively. Furthermore, the BRS 374 cultivar had the highest water absorption rates among the three particle sizes evaluated, followed by TBIO Consistência, and ORS Vintecinco, respectively (Table 2). These values were dependent on the amount of TOT-AX in the bran, which was directly related to the cultivar. It is important to understand the hydration properties of flour to enhance cookies quality since a lower consistency and water absorption by the flour are desired. Based on this, the ORS Vintecinco cultivar is more suitable for cookie making due to the lowest hardness gran, which led to the lowest TOT-AX content and water absorption capacity by farinograph, for all the three particle sizes evaluated. Those parameters demonstrate the importance of this cultivar for cookie making.

Table 2
Absorption properties by farinograph, swelling capacity and statistical analysis variance of the fine, medium, and coarse whole wheat flours from different wheat cultivars.

Flours	Wheat cultivars			*Middle square*			
	ORS Vintecinco	BRS 374	TBIO Consistência	*Particle size (PS)*	*Cultivar (C)*	*PS x C*	*CV (%)*
	Farinograph water absorption (%)						
FWWF	67.0 ± 0.05^{Ac}	69.2 ± 0.01^{Aa}	67.4 ± 0.10^{Ab}	58.55**	15.22**	1.81*	1.07
MWWF	62.5 ± 0.01^{Bb}	66.6 ± 0.09^{Aa}	64.1 ± 0.03^{Bab}				
CWWF	62.1 ± 0.17^{Cc}	63.5 ± 0.07^{Ba}	63.1 ± 0.14^{Cb}				
	Swelling capacity ($cm^3.g^{-1}$)						
FWWF	2.33 ± 0.12^{Cb}	2.46 ± 0.12^{Bb}	3.06 ± 0.12^{Ca}	2.51*	2.41*	0.07**	5.09
MWWF	2.73 ± 0.23^{Bb}	2.66 ± 0.23^{Bb}	3.60 ± 0.12^{Ba}				
CWWF	3.13 ± 0.12^{Ab}	3.46 ± 0.20^{Ab}	4.40 ± 0.20^{Aa}				

Different uppercase letters in the same column and lowercase in the row, represent a significant difference between particle sizes and cultivars, respectively, according to Tukey test ($p \leq 0.05$). Each value is presented as mean ± standard deviation (n = 3). FWWF: Fine Whole Wheat Flour. MWWF: Medium Whole Wheat Flour. CWWF: Coarse Whole Wheat Flour. . Analysis variance: * and **. Significant at the 0.01 and 0.05 probability level, respectively.

3.3.2. Swelling capacity

The significant effects of the hydration properties are presented in Table 2 for swelling capacity. The effects of cultivar, particle size, and the interaction between these two factors exerted an opposite effect ($p < 0.01$) observed in farinograph results, i.e., a reduction in particle size was associated with a decrease in the swelling capacity.

To evaluate the contribution of weakly bound water to whole wheat flours, the hydration properties were studied using the swelling capacity. The data are presented in Table 2. A reduction in particle size was associated with a decrease in the swelling capacity. This can be attributed to the smaller alteration in the bran matrix of the flours with a coarse particle size (CWWFs), in which the micropores are kept more intact compared with fine WWF particle sizes (Jacobs et al., 2015, 2016). The degradation of the bran tissues, by the increase in the milling intensity, leads to a reduction of the micropores, resulting in a reduced inclusion of water in the capillaries.

Regarding the cultivars, swelling capacity did no differ ($p < 0.05$) between ORS Vintecinco and BRS 374 cultivars, for all particle sizes. TBIO Consistência showed a higher swelling capacity for all three particle sizes and studied cultivars. This may be related to the higher grain hardness, which provides a more porous microstructure, and thus increases the swelling capacity through the presence of larger nanopores. ORS Vintecinco and BRS 374 cultivar, had similar grain hardness values, which contributed to similar swelling capacity. In addition, both the damaged starch and the water-extractable arabinoxylans content were higher for TBIO Consistência (Table 1), which could also contribute to the increased swelling capacity. It is important mentioning that to evaluate the weakly linked water to WWF, the hydration properties were also studied using the swelling capacity. In this technique, the hydration principle is guided by capillary, i.e., the absorption via nano and micropores prevail.

3.3.3. Solvent retention capacity (SRC) profile

The SRC parameters were significantly influenced by the individual factors PS and C, as well as by their interaction (PS × C) (Table 3). However, PS had the greatest influence on lactic acid SRC, Na_2CO_3-SRC, and sucrose SRC.

The SRC values for the four solvents are presented in Table 3. The solvent retention capacity (SRC) test aims to quantify the swelling behavior of flour polymers, that is, the ability to retain a certain solvent. For water, the values showed a significant difference ($p < 0.05$) between particle sizes. The SRC values of water (W-SRC) indicate the water retention capacity provided by the functional components of the flour, which include gluten proteins, damaged starch, and arabinoxylans (Kweon et al., 2011).

The medium WWF showed a higher water absorption, followed by coarse WWF and fine WWF, respectively, for all three cultivars. This behavior demonstrates the complexity of the interactions that occur due to the presence of grain outer layers and their influence at both molecular and physical levels. Although specific properties, such as damaged starch and WE-AX, are important in the water interaction process, the levels of these constituents were not significant for the observed water absorption behavior. Thus, water absorption by micropores may explain these results.

Regarding the cultivars, BRS 374 presented the lowest water absorption capacity, followed by ORS Vintecinco, and TBIO Consistência. In general, flours with a lower W-SRC require smaller amounts of water to prepare a dough with an ideal consistency; that is, a shorter process time is required for its removal. Thus, for ORS Vintecinco and TBIO Consistência cultivar, fine WWF is more suitable for cookie making, however, for BRS 374, the lower W-SRC of both fine and coarse particle size suggests that both flours can be suitable for the production of cookies using whole flour.

The use of lactic acid (LA) as a solvent resulted in the formation of a glutenin network and gluten strength, with a pH below 7, which favors swelling and network formation in relation to the polysaccharides (Gaines et al., 2000; Kweon et al., 2011). LA-SRC is used to indicate the functionality of flour gluten (Wang et al., 2016). The values of LA-SRC for CWWF were significantly higher compared to FWWF and MWWF, regardless of the cultivar (Table 3). The TBIO Consistência cultivar showed the highest values, regardless of particle size, indicating a greater gluten strength. The reduction of particle size from medium to fine WWF did not show a standard trend to LA-SRC values. BRS 374 had no significant difference, while ORS Vintecinco showed an increase in this value in fine WWF. However, TBIO Consistência reduced LA-SRC for fine WWF, even though the value is higher than the other cultivars.

According to Wang et al. (2016), the bran particles can interfere with the precise measurement of the LA-SRC because of the easy swelling of the bran in the presence of this solvent. However, the results of our study suggest that, as demonstrated by Wang, Oudgenoeg, Van Vliet, and Hamer (2003) and Noort et al. (2010), the fiber/protein interaction can cause greater gluten weakening, as the particles of flour were reduced. This is associated with an increased contact surface and a greater exposure of the bran compounds, increasing the protein solubility in the fine and medium flours. Reduction of LA-SRC confirmed that as particle size reduced, greater fiber/protein interactions occurred causing gluten

Table 3
Absorption properties by SRC profile and statistical analysis variance of the fine, medium, and coarse whole wheat flours from different wheat cultivars.

Flours	Wheat cultivars			*Middle square*			
	ORS Vintecinco	BRS 374	TBIO Consistência	*Particle size (PS)*	*Cultivar (C)*	*PS x C*	*CV (%)*
	SRC – Water (%)						
FWWF	68.32 ± 1.20 ^{Cb}	69.50 ± 0.15 ^{Bb}	73.51 ± 0.70 ^{Ca}	926.29*	1008.43*	154.78*	1.36
MWWF	85.76 ± 0.20 ^{Ab}	80.23 ± 1.56 ^{Ac}	105.51 ± 1.39 ^{Aa}				
CWWF	77.61 ± 0.65 ^{Bb}	70.63 ± 1.55 ^{Bc}	101.13 ± 1.57 ^{Ba}				
	SRC – Sodium Carbonate (%)						
FWWF	83.03 ± 0.60 ^{Ac}	92.28 ± 0.75 ^{Aa}	90.99 ± 0.98 ^{Bb}	393.40*	203.20*	188.21*	0.84
MWWF	77.63 ± 0.64 ^{Bb}	77.25 ± 0.11 ^{Bb}	79.75 ± 0.77 ^{Ca}				
CWWF	78.83 ± 0.46 ^{Bb}	75.08 ± 0.89 ^{Cc}	99.84 ± 0.70 ^{Aa}				
	SRC – Lactic Acid (%)						
FWWF	71.94 ± 0.70 ^{Bb}	70.14 ± 0.71 ^{Bc}	75.46 ± 0.07 ^{Ca}	1366.04*	719.21*	143.17*	0.87
MWWF	67.83 ± 0.25 ^{Cc}	70.82 ± 1.13 ^{Bb}	83.44 ± 0.32 ^{Ba}				
CWWF	84.57 ± 0.19 ^{Ab}	86.00 ± 1.57 ^{Ab}	113.14 ± 0.99 ^{Aa}				
	SRC – Sucrose (%)						
FWWF	103.81 ± 3.64 ^{Ba}	100.62 ± 2.44 ^{Ca}	100.50 ± 4.16 ^{Ba}	982.74*	152.17*	90.50*	2.44
MWWF	103.05 ± 2.89 ^{Bc}	112.05 ± 2.62 ^{Bb}	121.41 ± 1.01 ^{Aa}				
CWWF	117.50 ± 1.61 ^{Ab}	123.05 ± 1.35 ^{Aa}	127.09 ± 2.28 ^{Aa}				

Different uppercase letters in the same column and lowercase in the row, represent a significant difference between particle sizes and cultivars, respectively, according to Tukey test ($p \leq 0.05$). Each value is presented as mean ± standard deviation ($n = 3$). FWWF: Fine Whole Wheat Flour. MWWF: Medium Whole Wheat Flour. CWWF: Coarse Whole Wheat Flour. Analysis variance: * and **. Significant at the 0.01 and 0.05 probability level, respectively.

weakening. For flours intended for use in cookie production, lower functional contributions by LA-SRC are desirable, as this ensures less gluten formation during mixing and baking, which leads to a structural breakdown of cookies, resulting in cookies with the desired quality standards, larger diameters, and a lesser thickness (Slade, Levine, Craig, & Arciszewski, 1994, p. 5362502).

Sodium carbonate (SC) solvent is correlated with a damaged starch content in flours. The reduction in WWF particle size increased the SC-SRC, except for in the TBIO Consistência cultivar. In the presence of an SC solution with a high pH (Gaines et al., 2000), above the pK_a of the hydroxyl groups of the starch, the solvation of the damaged starch is facilitated (Han & Lim, 2004).

The sucrose solvent (Suc) simulates the functional environment in high-sugar dough cookies and provides an indication of the arabinoxylan content (AX) in the flour (Gaines et al., 2000). Thus, low values of Suc-SRC are desirable for flour intended for use in cookie production. Although the highest values of AX were found in flours with smaller particle sizes, the Suc-SRC of the CWWF was relatively higher than that of FWWF and MWWF (Table 2). This may be due to the difficulties presented by the SRC method when bran is present. Souza, Guttieri, and Sneller (2011) evaluated the predictive parameters of whole flour quality for cookie production and reported operational difficulties, resulting in low correlations with the results of refined flour. Among the cultivars, TBIO Consistência presented the highest Suc-SRC values, a fact that is correlated with the highest content of WE-AX.

In general, to consider the application of flour for cookie production through SRC analysis, it is necessary to consider its profile (set of all solvents). In addition, different particle sizes showed variations in the fractions of AX and damaged starch, which can significantly change the profile. Wang et al. (2016) measured the SRC of WWF from two USA wheat cultivars and demonstrated that W-SRC and sodium carbonate SRC showed considerably higher values compared with the refined flours. On the contrary, the LA-SRC values were reduced in WWF. The authors also presented an SRC profile for the whole grain flour with the smallest particle size (89.9 and 95.6 μm) composed of a W-SRC of 72.1% and 73.2%, sodium carbonate-SRC of 91.9% and 88.7%, and LA-SRC of 74.1% and 77.3%, respectively. A similar trend was observed in our study with smaller particle size flours, i.e., SRC profile of fine WWF ranged from 68.32 to 73.51 for W-SRC, 71.94–75.46 for LA-SRC, 83.03–90.99 for SC-SRC and 100.50–103.81 for Suc-SRC.

The evaluation of flour suitable for cookie production is related not only to the water absorption capacity but also to the way that each component behaves and interacts with water. In this way, traditional analyses, such as farinograph, can induce less reliable results when the final product has such complex behavior in relation to water absorption, especially when whole wheat flour is used. For this reason, it becomes relevant to use methods such as SRC to obtain more satisfactory results.

3.3.4. Absorption kinetics

The kinetic hydration profiles of WWF with different particle sizes and cultivars are shown in Fig. 2. The profiles demonstrate that changes in particle size lead to changes in water absorption rates in different proportions during the 30 min analysis. Among all the cultivars, CWWF showed the highest absorption values when compared to FWWF and MWWF, after achieving balance. After 15 min, the amount of water absorbed by CWWF increased by 5.51%, 17.11%, and 9.7% in the ORS Vintecinco, BRS 374, and TBIO Consistência cultivars, respectively. The reduction in water absorption with a decreasing particle size differed from the trend observed in farinograph and demonstrates the weaker influence of surface area on the absorption rates assessed by kinetics.

The change in the hydration behavior of the flours indicates that the connection to water in the absence of external forces can be conducted by different mechanisms, such as capillarity absorption (Chaplin, 2003; Thebaudin, Lefebvre, Harrington, & Bourgeois, 1997). With the largest reduction in particle size, the bran cell wall structure, which is represented by micro and nanopores, was also reduced. This difference most likely explains the lower values of water absorption observed in the fine WWF samples.

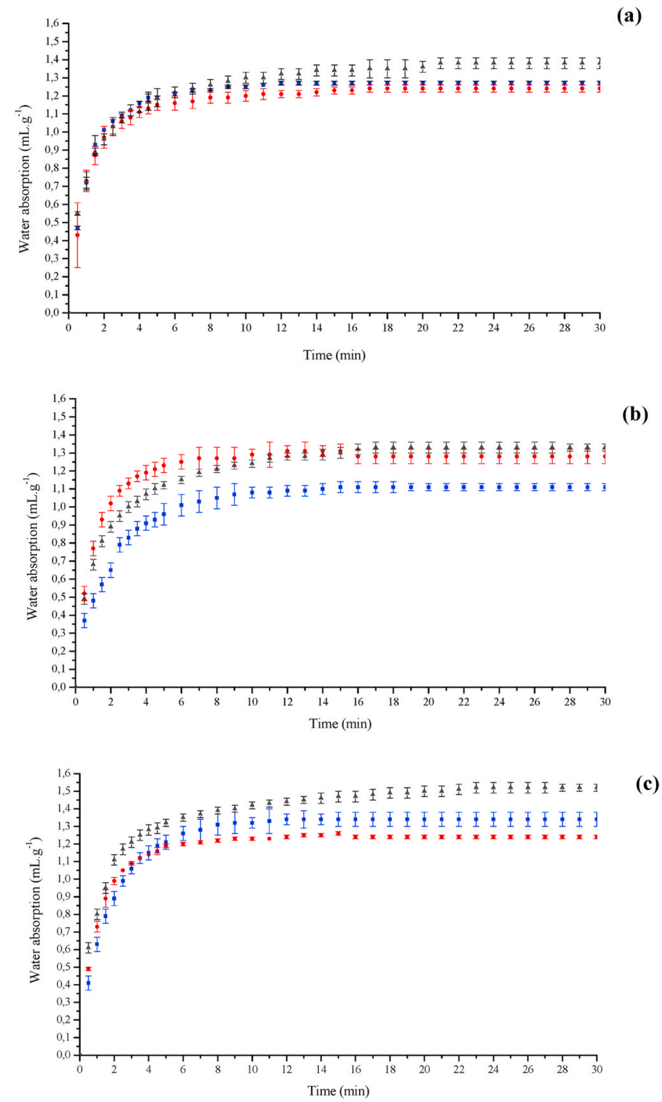

Fig. 2. Absorption kinetics of fine (■), medium (●), and coarse (▲) whole wheat flours from ORS Vintecinco (a), BRS 374 (b), and TBIO Consistência (c) wheat cultivars.

Several studies have also evaluated water absorption in the absence of external forces for wheat bran, and reported a reduction in the hydration rate using the Enslin-Neff method for smaller particles (Caprez, Arrigoni, Amado, & Neukom, 1986; Jacobs et al., 2015). However, there are no reports on the assessment of the hydration rates for whole wheat grain flours and the influence of different particle sizes and cultivars. Coarse particles also showed a long period for stabilizing and reaching a difference of 11 min until equilibrium was achieved, when comparing to flour with smaller particle sizes of the TBIO Consistência cultivar.

Comparing cultivars, the absorption kinetics demonstrated an increase in the hydration rate for TBIO Consistência during the whole test period in the three particle sizes studied (Fig. 2c). For TBIO Consistência of coarse WWF, the gains of hydration rates increased by 14.28% and 10.14% without a state of equilibrium compared to the BRS 374 and ORS Vintecinco cultivars. The strong positive correlation ($R^2 = 0.99$) between the absorption rate and WE-AX content (Table 1) in CWWF suggests that, along with the contribution to absorption by the porosity of the outer layers, a connection with water can also occur at the molecular level. This is due to the high capacity of water binding attributed to arabinoxylans, the major constituent of the insoluble fraction of dietary from wheat bran, which is related to the hydrogen bonding of water molecules to OH groups in the polymer chain (Wang et al., 2002).

Thus, two phenomena may be involved in the water absorption capacity of WWF: (i) absorption by capillarity and (ii) at the molecular level. The results also demonstrate that the intensity of the milling process can reduce the absorption rates. The evaluations carried out at equilibrium showed that porosity-related phenomena (nano and micropores) appeared to guide hydration, and were greater for flours with coarse particle sizes. Therefore, the mechanisms responsible for WWF hydration are influenced by the specific properties of each method, which allows us to develop an integrated view of the interactions between WWF and water. However, farinograph, an internationally official method, can be a suitable technique to achieve the desired results, which facilitates its reproduction. Although, it is difficult to predict the hydration properties of WWF for cookie production using only one analytical technique.

Finally, we can have observed the relation of WWF components to the analysis performed. Briefly, SRC profile is directly related to the arabinoxylans content, damaged starch and also glutenin. The increase of Suc-SRC occurs with the reduction of TOT-AX, while SC-SRC increasing can be to increased damaged starch. While LA-SRC is related to glutenin content. Water absorption by farinograph is guided by hydroxyl group, mostly from arabinoxylans structure (the major component of insoluble fiber fraction) that are exposed with reduction of particle size, justifying the highest water absorption by farinograph of BRS 374, which presented the highest TOT-AX in all flour particle size.

Properties such as larger diameter and lower height are desirable quality parameters for cookies. These characteristics may be influenced by dough behavior during the mixing phase. For cookies, the purpose of mixing is to provide a cohesive dough; however, gluten must form a minimal network, sufficient for dough handling and forming. The control of dough consistency is guided by the hydrophilic components; therefore, the lower water absorption by flour increases the water absorption by sugar, decreasing the dough viscosity. Conversely, when the flour has high water absorption, the dough viscosity increases and effects the spreading factor of the cookies, leading to cookies with smaller diameter, greater height and greater hardness.

4. Conclusion

The particle size and cultivar, and the interaction between the two, can significantly affect the hydration properties of whole wheat flour. Particle size was found to have a stronger effect on the damaged starch content, total arabinoxylan content, and water absorption according to the farinograph and SRC profile parameters. Meanwhile, the water-extractable arabinoxylans were found to be more affected by the cultivar. Differences in the hydration behavior may lead WWF to show diversity in functional properties, such as dough performance and quality attributes of the final product. Thus, the quality attributes of WWF in relation to the hydration properties may be predicted by preselecting cultivars, as well as based on particle size distribution during milling.

Whole wheat flour with the genotypic profile of the ORS Vintecinco cultivar, comprised of a lower total arabinoxylan content and damaged starch content and coarse particle size, presented the best hydration properties for the desired quality of whole grain flour for short-dough cookies. The farinograph can be a suitable technique to evaluate water absorption from whole wheat flour, although it is difficult to predict the hydration properties of WWF for cookie production using only one analytical technique. The presence of the outer layers of the grain has been shown to promote different mechanisms in the water absorption capacity. Our study established a database to evaluate the hydration properties of WWFs using different techniques. Further research will be needed to investigate the effects on the quality and functionality characteristics of whole wheat flour used for cookie production.

CRediT authorship contribution statement

Joseane Bressiani: Conceptualization, Data curation, Investigation, specifically performing the experiments, Writing – original draft, Writing – review & editing. **Gabriela Soster Santetti:** Writing – original draft, Writing – review & editing. **Tatiana Oro:** Conceptualization, Data curation. **Vanessa Esteres:** Investigation, Data curation. **Bárbara Biduski:** Writing – original draft, Writing – review & editing. **Martha Zavariz de Miranda:** Conceptualization, Supervision, Writing – review & editing. **Luiz Carlos Gutkoski:** Conceptualization, Supervision, Funding acquisition, Resources. **Juliano Luiz de Almeida:** Conceptualization, Funding acquisition, Resources. **Márcia Arocha Gularte:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2021.111918.

References

Aacci. American Association of Cereal Chemists International. (2010). *Approved methods of analysis* (11 ed.). MN, U.S.A: Saint Paul.

Angelidis, G., Protonotariou, S., Mandala, I., & Rosell, C. M. (2016). Jet milling effect on wheat flour characteristics and starch hydrolysis. *Journal of Food Science & Technology, 53*, 784–791.

Bettge, A. D., & Morris, C. F. (2007). Oxidative gelation measurement and influence on soft wheat batter viscosity and end-use quality. *Cereal Chemistry, 84*, 237–242.

Blanco Canalis, M. S., León, A. E., & Ribotta, P. D. (2019). Incorporation of dietary fiber on the cookie dough. Effects on thermal properties and water availability. *Food Chemistry, 271*, 309–317.

Bressiani, J., Oro, T., Santetti, G. S., Almeida, J. L., Bertolin, T. E., Gómez, M., et al. (2017). Properties of whole grain wheat flour and performance in bakery products as a function of particle size. *Journal of Cereal Science, 75*, 269–277.

Cai, L. M., Choi, I., Hyun, J. N., Jeong, Y. K., & Baik, B. K. (2014). Influence of bran particle size on bread-baking quality of whole grain wheat flour and starch retrogradation. *Cereal Chemistry, 91*, 65–71.

Caprez, A., Arrigoni, E., Amado, R., & Neukom, H. (1986). Influence of different types of thermal treatment on the chemical composition and physical properties of wheat bran. *Journal of Cereal Science, 4*, 233–239.

Chaplin, M. F. (2003). Fibre and water binding. *Proceedings of the Nutrition Society, 62*, 223–227.

Courtin, C. M., & Delcour, J. A. (2002). Arabinoxylans and endoxylanases in wheat flour bread-making. *Journal of Cereal Science, 35*, 225–243.

Douglas, S. G. (1981). A rapid method for the determination of pentosans in wheat flour. *Food Chemistry, 7*, 139–146.

Duyvejonck, A. E., Lagrain, B., Dornez, E., Delcour, J. A., & Courtin, C. M. (2012). Suitability of solvent retention capacity tests to assess the cookie and bread making quality of European wheat flours. *LWT-Food Science and Technology, 47*, 56–63.

Enslin, O. (1933). Über einen apparatzur messung der flüssigkeitsaufnahme von quellbaren und porösen stoffen und zur charakterisierung der benetzbarkeit. *Die Chemische Fabrik, 13*, 147–148.

Fadel, A., Plunkett, A., Li, W., Gyamfi, T., Elewosi, V., Nyaranga, R. R., et al. (2017). Modulation of innate and adaptive immune responses by arabinoxylans. *Journal of Food Biochemistry, 42*, 1–14.

Finnie, S. M., Bettge, A. D., & Morris, C. F. (2006). Influence of cultivar and environment on water-soluble and water-insoluble arabinoxylans in soft wheat. *Cereal Chemistry, 83*, 617–623.

Gaines, C. S., Raeker, M.Ö., Tilley, M., Finney, P. L., Wilson, J. D., Bechtel, D. B., et al. (2000). Associations of starch gel hardness, granule size, waxy allelic expression, thermal pasting, milling quality, and kernel texture of 12 soft wheat cultivars. *Cereal Chemistry, 77*, 163–168.

Han, J. A., & Lim, S. T. (2004). Structural changes in corn starches during alkaline dissolution by vortexing. *Carbohydrate Polymers, 55*, 193–199.

Hemdane, S., Jacobs, P. J., Dornez, E., Verspreet, J., Delcour, J. A., & Courtin, C. M. (2016). Wheat (*Triticum aestivum* L.) bran in bread making: A critical review. *Comprehensive Reviews in Food Science and Food Safety, 15*, 28–42.
Jacobs, P. J., Hemdane, S., Delcour, J. A., & Courtin, C. M. (2016). Dry heat treatment affects wheat bran surface properties and hydration kinetics. *Food Chemistry, 203*, 513–520.
Jacobs, P. J., Hemdane, S., Dornez, E., Delcour, J. A., & Courtin, C. M. (2015). Study of hydration properties of wheat bran as a function of particle size. *Food Chemistry, 179*, 296–304.
Kaur, A., Yadav, M. P., Singh, B., Bhinder, S., Simon, S., & Singh, N. (2019). Isolation and characterization of arabinoxylans from wheat bran and study of their contribution to wheat flour dough rheology. *Carbohydrate Polymers, 221*, 166–173.
Kiszonas, A. M., Courtin, C. M., & Morris, C. F. (2012). A critical assessment of the quantification of wheat grain arabinoxylans using a phloroglucinol colorimetric assay. *Cereal Chemistry, 89*, 143–150.
Kweon, M., Slade, L., & Levine, H. (2011). Solvent retention capacity (SRC) testing of wheat flour: Principles and value in predicting flour functionality in different wheat-based Food processes and in wheat breeding—a review. *Cereal Chemistry, 88*, 537–552.
Langó, B., Bóna, L., Kw Ng, P., Ács, E., Török, K., & Tömösközi, S. (2018). Evaluation of carbohydrate properties and end-use quality of hexaploidtriticale and its relationship to solvent retention capacity. *Journal of Cereal Science, 84*, 95–102.
Lazaridou, A., Vouris, D. G., Zoumpoulakis, P., & Biliaderis, C. G. (2018). Physicochemical properties of jet milled wheat flours and doughs. *Food Hydrocollloids, 80*, 111–121.
Nishitsuji, Y., Whitney, K., Nakamura, K., Hayakawa, K., & Simsek, S. (2020). Changes in structure and solubility of wheat arabinoxylan during the breadmaking process. *Food Hydrocolloids, 109*, 106129.
Noort, M. W. J., Haaster, D. V., Hemery, Y., & Hamer, R. J. (2010). The effect of particle size of wheat bran fractions on bread quality e evidence for fibre-protein interactions. *Journal of Cereal Science, 52*, 59-54.
Protonotariou, S., Batzaki, C., Yanniotis, S., & Mandala, I. (2016). Effect of jet milled whole wheat flour in biscuits properties. *LWT- Food Science and Technology, 74*, 106–113.
Protonotariou, S., Drakos, A., Evageliou, V., Ritzoulis, C., & Mandala, I. (2014). Sieving fractionation and jet mill micronization affect the functional properties of wheat flour. *Journal of Food Engineering, 134*, 24–29.
Ren, D., Walker, C. E., & Faubion, J. M. (2008). Correlating dough elastic recovery during sheeting with flour analyses and rheological properties. *Journal Of the Science Of Food and Agriculture, 88*, 2581–2588.
Roozendaal, H., Abu-hardan, M., & Frazier, R. A. (2012). Thermogravimetric analysis of water release from wheat flour and wheat bran suspensions. *Journal of Food Engineering, 111*, 606–611.
Saeed, F., Pasha, I., Anjum, F. M., & Sultan, M. T. (2011). Arabinoxylans and arabinogalactans: A comprehensive treatise. *Critical Reviews in Food Science and Nutrition, 51*, 467–476.
Sanz Penella, J. M., Collar, C., & Haros, M. (2008). Effect of wheat bran and enzyme addition on dough functional performance and phytic acid levels in bread. *Journal of Cereal Science, 48*, 715–721, 2008.
Saulnier, L., Guillon, F., & Chateigner-Boutin, A.-L. (2012). Cell wall deposition and metabolism in wheat grain. *Journal of Cereal Science, 56*, 91–108.
Slade, L., Levine, H., Craig, S., & Arciszewski, H. (1994). *Reducing checking in crackers with pentosanase*. United States Patent US.
Souza, E. J., Guttieri, M. J., & Sneller, C. (2011). Selecting soft wheat genotypes for whole grain cookies. *Crop Science, 51*, 189–197.
Sozer, N., Cicerelli, L., Heini€o, R. L., & Poutanen, K. (2014). Effect of wheat bran addition on in vitro starch digestibility, physicomechanical and sensory properties of biscuits. *Journal of Cereal Science, 60*, 105–113.
Stevenson, L., Phillips, F., O'sullivan, K., & Walton, J. (2012). Wheat bran: Its composition and benefits to health, a european perspective. *International Journal of Food Sciences & Nutrition, 63*, 1001–1013.
Thebaudin, J. Y., Lefebvre, A. C., Harrington, M., & Bourgeois, C. M. (1997). Dietary fibres: Nutritional and technological interest. *Trends in Food Science & Technology, 8*, 41–48.
Tsilo, T. J., Simsek, S., Ohm, J. B., Hareland, G. A., Chao, S., & Anderson, J. A. (2011). Quantitative trait loci influencing endosperm texture, dough-mixing strength, and bread-making properties of the hard red spring wheat breeding lines. *Genome, 54*, 460–470.
Wang, M., Hamer, R. J., Van Vliet, T., & Oudgenoeg, G. (2002). Interaction of water extractable pentosans with gluten protein: Effect on dough properties and gluten quality. *Journal of Cereal Science, 36*, 25–37.
Wang, N., Hou, G. G., Kweon, M., & Lee, B. (2016). Effects of particle size on the properties of whole-grain soft wheat flour and its cracker baking performance. *Journal of Cereal Science, 69*, 187–193.
Wang, M.-W., Oudgenoeg, G., Van Vliet, T., & Hamer, R. J. (2003). Interaction of water unextractable solids with gluten protein: Effect on dough properties and gluten quality. *Journal of Cereal Science, 38*, 95–104.
Wang, L., Zhang, L., Qiu, S., Liu, C., Zhang, P., Yin, L., et al. (2019). Rheological properties and structural characteristics of arabinoxylan hydrogels prepared from three wheat bran sources. *Journal of Cereal Science, 88*, 79–86.
Weaver, G. L. (2001). A miller's perspective on the impact of health claims. *Nutrition Today, 36*, 115–118.
Yu, J., Wang, S., Wang, J., Li, C., Xin, Q., Huang, W., et al. (2015). Effect of laboratory milling on properties of starches isolated from different flour millstreams of hard and soft wheat. *Food Chemistry, 172*, 504–514.