



Valorization of Buckwheat (*Fagopyrum esculentum*) in Baked Goods Through Sprouting Process

Alessio Sergiacomo¹ · Andrea Bresciani¹ · Matteo Miele¹ · Alessandra Marti¹

Received: 11 November 2024 / Accepted: 25 February 2025 / Published online: 15 March 2025
© The Author(s) 2025

Abstract

Increasing the use of minor crops, such as buckwheat, can enhance biodiversity. Thanks to its composition (e.g., protein, fiber, flavonoids), buckwheat is a valuable raw material for food production. However, its application is limited also by its astringency and bitterness. Despite the sensory challenges have been already solved by applying sprouting, its impact on technological aspects has not been yet addressed. Thus, this study aimed at evaluating the impact of sprouted buckwheat on the rheological properties of dough for bread and cracker production. Buckwheat was sprouted for 48 and 72 h and mixed at 10%, 20%, and 30% with two types of wheat flour: one for bread (flour B) and one for crackers (flour C). The pasting properties of unsprouted and sprouted buckwheat were analyzed, while gluten aggregation, mixing, and extensibility properties were evaluated in the mixtures of wheat and buckwheat. The addition of buckwheat, particularly at higher substitution levels and with longer sprouting times, primarily weakened gluten aggregation and extensional properties. Mixing properties, such as dough development time and stability, were influenced more by the sprouting time. This weakening effect was less pronounced when using mixtures for crackers compared to those for bread. Suitable substitution levels were found to be 30% for crackers and 10% for bread. Specifically, bread made with sprouted buckwheat showed a higher volume and lower hardness compared to bread made with unsprouted buckwheat.

Keywords Bread · Cracker · Dough rheology · Pseudocereal · Sprouted buckwheat

Introduction

The consumption of minor (or less common) grains promotes biodiversity by enhancing genetic diversity and supporting more resilient agricultural ecosystems. These crops improve soil health, offer a diversified diet, and reduce dependence on major cereals like wheat, rice, and corn. Although the consumption of cereals is highly recommended for their provision of energy, carbohydrates, proteins, fiber, B-complex vitamins, E vitamins, and iron (Rosell & Garzon, 2015), it is important to ensure variety in grain consumption. The combination of wheat with other grains supports a diverse intake of macronutrients and micronutrients and promotes biodiversity. Additionally, minor crops preserve local traditions and strengthen rural economies, contributing

to more sustainable and resilient agriculture. One way to increase the consumption of minor grains is to include them in widely consumed food products such as bread and other baked goods. However, to be successful, the resulting products must be sensorially acceptable to the consumer and maintain the overall quality to avoid compromising consumer choice.

Among minor grains, buckwheat (*Fagopyrum esculentum*) is a pseudocereal belonging to the *Polygonaceae* family. Its cultivation declined in the last 30 years from 4.9 million tons to 2.2 million tons in 2022, as well as the harvested area from 4.9 million ha in 1992 to 2.2 million ha, mainly in Russia and China (FAOSTAT, 2022). However, interest in buckwheat has grown in recent decades due to its nutritional benefits and positive health effects (Christa & Soral-Śmietana, 2008). Indeed, buckwheat seeds are characterized by a high fiber content (around 11%, mainly composed of insoluble fiber) and a well-balanced amino acid profile with high biological value (Neacsu et al., 2022; Mota et al., 2016). In terms of micronutrients, buckwheat is an excellent source of B vitamins (especially

✉ Alessandra Marti
alessandra.marti@unimi.it

¹ Department of Food, Environmental and Nutritional Sciences (DeFENS), Università Degli Studi Di Milano, Via G. Celoria 2, Milan 20133, Italy

vitamin B1), vitamin C, and vitamin E (Lebiedzińska & Szefer, 2006; Giménez-Bastida et al., 2015a). It also contains minerals (Mg, Zn, K, P, Cu, and Mn) (Steadman et al., 2001) and various antioxidant compounds such as quercetin, rutin, catechins, and other polyphenols (Wijngaard & Arendt, 2006). Rutin and quercetin are the main polyphenols found in buckwheat. Specifically, buckwheat is one of the primary dietary sources of rutin and this has led to increasing interest in this pseudocereal from a nutritional perspective (Sofi et al., 2023). The beneficial effects of rutin on the human body include anti-inflammatory, antimutagenic, antitumor, and anticancer activities (Giménez-Bastida & Zielinski, 2015b). However, the presence of antinutritional compounds limits its use in widely consumed food products. Despite buckwheat's well-balanced amino acid profile, its protein digestibility is low due to the presence of tannins, phytic acid, and protease inhibitors (Mattila et al., 2018; Wijngaard & Arendt, 2006). Additionally, the lack of gluten-forming proteins and its sensory profile limit its use. Indeed, while the presence of flavonoids makes the use of this pseudocereal attractive, on the other hand sensory aspects of buckwheat are influenced by its phenolic content, particularly rutin, impacting bitterness and astringency (Buratti et al., 2022). In fact, when developing buckwheat-based products, it is crucial to consider the level of integration to better manage the intensity of bitter and astringent flavors (Rabitti et al., 2022).

The application of biotechnological processes such as fermentation, enzymatic treatments, and sprouting (or germination) can potentially address some of these issues, improving the nutritional, sensory, and technological properties of raw materials (Garrido-Galand et al., 2021; Ikram et al., 2021; Poutanen, 1997). The sprouting of buckwheat can enhance its nutritional value, leading to an increase in γ -aminobutyric acid (GABA) and total phenolic content (especially quercetin, orientin, and vitexin) (Alvarez-Jubet et al., 2010; Bhinder et al., 2022). The sprouting duration plays a key role in these changes. By identifying the optimal degree of sprouting, it is possible to achieve a greater release of free peptides/amino acids, phenolic compounds, and an increase in antioxidant activity while reducing antinutritional factors (Borgonovi et al., 2023).

While numerous studies have evaluated the compositional and nutritional changes resulting from sprouting, few have investigated the effects of germination on the technological properties of sprouted buckwheat in food formulation. Among the least published paper, Giovanelli et al. (2023) reformulated 100% buckwheat cous-cous using 25% or 50% of buckwheat that was sprouted for 48 h and 72 h. The reformulation with 50% of buckwheat that was sprouted for 72 h resulted in a product richer in phenolic compounds and characterized by improved textural characteristics (in terms

of cohesiveness, gumminess, and resilience) and enhanced sensory attributes (with particular reference to reduced astringency, bitter taste, and aftertaste).

As regards baked goods, Sturza et al. (2020) assessed the bread-making performance of buckwheat used as such (20%) or as sprouts (10%). Although they are valuable raw materials for their positive impact on the nutritional enrichment, in terms of total flavonoids and total phenols, of the final baked products, their uses in buns manufacturing are limited due to their negative influence on the sensorial and rheological features. The authors proposed the use of other ingredients, such as guar gum, to improve sensory and textural properties of the final product (Sturza et al., 2020).

The impact of sprouting was also investigated on tartary buckwheat (*Fagopyrum tataricum*) used for the production of steamed bread (Xu et al., 2014). Also in the case of tartary buckwheat, the sprouted sample has been proposed as a feasible gluten-free material to enhance the nutritive properties in steamed bread making; however, although it had a positive effect on crumb softness, the use of 8–12% sprouted buckwheat negatively affected crumb structure and resilience that is an important criterion of consumers' preference (Xu et al., 2014).

However, none of the previous studies has emphasized the rheological properties of dough, assessing the influence of adding sprouted buckwheat. This leads to main objectives of the present study that aims at investigating the impact of sprouting on the rheological properties and baking aptitude of buckwheat-enriched wheat dough. In particular, crackers and bread were used as a case study, analyzing the behavior of the dough during mixing, shaping, and baking phases. Furthermore, this study aims at assessing the relation between sprouting duration, enrichment level and dough properties, with the final goal of valorizing buckwheat in baked goods.

Materials and Methods

Materials

Commercial dehulled buckwheat (*Fagopyrum esculentum*) was sprouted in a climate chamber (Memmert GmbH Co. KG, Schwabach, Germany) as described in Sergiacomo et al. (2024). Briefly, the seeds were sprouted in batches of 1.5 kg for each sprouting time and were divided into three aliquots and soaked in distilled water (1:2) for 8 h at 22 °C. After removing the excess water, the seeds were sprouted for 48 and 72 h under conditions of relative humidity greater than 90%. Following sprouting, the seeds were dried at 50 °C for 16 h (Self Cooking Center, Rational International AG, Landsberg am Lech, Germany) and ground to a particle size of less than 250 μ m in a laboratory mill M20 Universal

Mill (IKA, Werke Staufen, Germany). Three batches of sprouted seeds were carried out and combined together. Unsprouted buckwheat was milled as the sprouted samples and used as control. After milling, unsprouted and 48 h- and 72 h-sprouted buckwheat were mixed with two commercial wheat flours, one suitable for cracker production (CWF, cracker wheat flour; alveograph $W = 150 \times 10^{-4}$ J, protein content = 9 g/100 g flour) and the other one suitable for bread production (BWF, bread wheat flour; alveograph $W = 295 \times 10^{-4}$ J, protein content = 14 g/100 g flour). The substitution levels tested for both wheat bases were 10, 20 and 30%. Thus, two wheat flours (CWF and BWF), two sprouting times (48 h and 72 h) and three enrichment levels (10, 20, and 30%) were considered.

Rheological Properties

Pasting Properties of Buckwheat Flours

Pasting properties of unsprouted and sprouted buckwheat were measured using a Micro-Visco-Amylograph device (MVAG, Brabender by Anton Paar Group GmbH, Graz, Austria) as reported by Suárez-Estrella et al. (2020a) using silver nitrate solution (AgNO_3) to inactivate amylase activity. An aliquot of sample (12 g) was dispersed in 100 mL of distilled water and stirred at 250 rpm. The following temperature profile was applied: heating from 30 °C to 95 °C at a rate of 3 °C/min, holding at 95 °C for 20 min, cooling from 95 °C to 30 °C at a cooling rate of 3 °C/min, and holding at 30 °C for 1 min. The test was carried out in duplicate and a representative curve of each sample was reported.

Gluten Aggregation Properties of Buckwheat-wheat Blends

Gluten aggregation properties were measured using the GlutoPeak device (Brabender by Anton Paar Group GmbH, Graz, Austria). The test was conducted using the same method reported by Sergiacomo et al. (2024). The test was carried out in triplicate and the following indices were considered: i) Peak Maximum Time (PMT, expressed in s), corresponding to the time before torque falling off when gluten breaks down; ii) Maximum Torque (expressed in GlutoPeak Units, GPU), corresponding to the peak occurring due to gluten aggregation; iii) Aggregation Energy (expressed in GPU) represents the area under the curve.

Mixing Properties of Buckwheat-wheat Blends

The mixing properties were performed by means of the Farinograph-E (Brabender by Anton Paar Group GmbH, Graz, Austria) equipped with a 50 g mixing bowl, following the ICC method n. 115/1. The test was carried out in

duplicate and the following indices were considered: water absorption, development time, and stability.

Extensibility Properties of Buckwheat-wheat Blends

Uniaxial extensibility properties were evaluated on a 25 g dough by means of the micro-Extensograph® (Brabender by Anton Paar Group GmbH, Graz, Austria), at three resting times (45, 90, and 135 min) following the AACC standard method 54–10.01. Dough samples were prepared by following the standard method (AACC 54–10.01) in the 50 g kneading bowl of the Farinograph-E®. The dough was prepared in duplicate and the test was carried out on two sub-samples taken from each dough. The following indices were considered: resistance to extension at 5 cm (i.e., torque after 5 cm of extension), maximum resistance (i.e., maximum torque during the extension), extensibility (i.e., maximum length before dough rupture), and extensional energy (i.e., the area under the curve) were considered.

Product Development

Cracker Preparation

For the production of the crackers, sprouted and unsprouted buckwheat were used at a replacement level of 30%. This enrichment level was selected based on the rheological tests. The recipe used was as follows: CWF (300 g), distilled water (170 g), sunflower oil (21 g), dry yeast (4 g), salt (3.5 g) and sugar (3 g).

The snack production began by pre-mixing flour, yeast, salt, and sugar in a Kitchen Aid Artisan mixer (Kitchen Aid, Whirlpool, St. Paul, USA) using a wire whisk for 1 min. Subsequently, the wire whisk was replaced with a dough hook, and liquid ingredients (i.e., water and oil) were added. Mixing continued until a smooth and homogeneous dough was obtained (approximately 5 min). The dough then underwent initial proofing at room temperature for 20 min before being portioned and laminated using a specific sheeter set at thickness 3, with a gap between the rollers of 0.2 cm, and undergoing 3 passes. Subsequently, snacks measuring 100 mm in length, 50 mm in width, and 2 mm in thickness were obtained from the dough sheet. After shaping, the snacks underwent a second proofing phase in an oven (Self-Cooking Center, Rational AG, Landsberg Lech, Germany) at 35 °C for 30 min with a relative humidity of 75%. Following proofing, samples were pierced with a toothpick to prevent puffing during baking and then baked in a static oven mode at 180 °C for 14 min on a tray. After the first 7 min of baking, samples were properly rotated to ensure even baking. Two production batches were prepared for each formulation, and 15 pieces were obtained per batch.

Bread Preparation

Based on the results on dough, bread was made using buckwheat (sprouted and unsprouted) at 10%. The recipe used was: BWF (350 g), distilled water (195 g), dry yeast (5.25 g), salt (3.5 g).

The bread was prepared using the bread machine "La Forneria" (IMETEC, Azzano San Paolo, Italy). Water and yeast were mixed for 2 min; after that, salt and flour were added and mixed for 15 min of intermittent mixing (3 s of stop every 27 s of mixing) and for 7 min of regular mixing. After that, dough was leavened for 1 h and 30 min of rising (at 30 °C and 80% relative humidity), manually divided into 6 portions of 80 g each and transferred to special baking pans ($5.7 \times 10.3 \times 2.5$ cm), previously oiled. A second rising of 15 min (at 30 °C and 80% relative humidity) was carried out; after that bread was baked for 45 min at 160 °C. Two production batches were made for each formulation, and 6 buns were obtained for each batch. Bread was stored in air-tight plastic bags at room temperature (20 °C) for 2 days.

Product Characterization

Cracker Characterization

Cracker characterization was conducted two hours after production. Using a ruler and a thickness gauge, the three dimensions (height, width, and thickness) of 10 pieces for each formulation were measured and the weight was measured on 15 pieces. The volume was measured in duplicate on 5 pieces using the sesame seed displacement method (AACC 10–05.01, AACC, 2001). The moisture content of two pieces of crackers for each batch was determined by using the MA 50.R Radwag thermobalance (Radom, Poland). The evaluation of cracker texture was carried out on 10 pieces per batch using the Texture Analyzer TA.XTplus (Stable Micro Systems Ltd., Godalming, UK), equipped with a 100 N load cell. A three-point bending test was conducted utilizing a 3-point bending rig (A/3 PB, Stable Micro Systems, UK). The test parameters were set as follows: pre-test speed: 1.0 mm/s; test speed: 1 mm/s; post-test speed: 10.0 mm/s; and distance: 10 mm to make contact with the sample. The downward movement continued until the product broke. The maximum force (expressed in N) recorded represented the cracker 'hardness', while the area under the curve (expressed in N/cm) was indicative of its 'toughness'.

Bread Characterization

All analyses were conducted two hours after bread production. The weight was measured on six loaves. The volume was measured on six loaves for each batch using the sesame seed displacement method (AACC 10–05.01, AACC, 2001).

Specific volume was calculated as the ratio of volume to weight. The moisture content of the crumb was determined on two samples from each batch by using the MA 50.R Radwag thermobalance (Radom, Poland). Bread texture analysis was measured through the Texture Analyzer TA.XTplus (Stable Micro Systems Ltd., Godalming, UK). Two central slices (thickness: 2.5 cm) were obtained from each bread loaf and subjected to texture analysis. For each production batch, three loaves were analyzed 2 h after baking and three loaves were analyzed after 2 days of storage.

The Texture Analyzer was equipped with a 100 N load cell and the Texture Profile Analysis (TPA) test was conducted utilizing a SMS P/36R probe. The parameters used were as follows: contact force: 9.8×10^{-3} N; compression piston diameter: 36 mm. The following indices were considered: 'hardness' (expressed in N; the maximum height of the first compression peak); 'cohesiveness' (dimensionless index; the ratio of the areas of the second to the first compression peak); 'chewiness' (adimensional index; calculated as the product of hardness, cohesiveness, and elasticity, the latter defined as the width of the second compression curve from start of rise to point of maximum height). Crumb porosity was assessed through image analysis on two slides taken by two loaves for each formulation. Images were captured at a resolution of 300 dpi (dots per inch) using a flatbed scanner (Epson Perfection 3170 Photo, Seiko Epson Corp., Japan). Images were converted to 8-bit grayscale and spatially calibrated prior to analysis. Images were then calibrated, standardized, and optimized by applying specific filters to assess the morphological characteristics of the bubble area (mm^2) and porosity (%) using the Image-Pro Plus 6.0 software (Media Cybernetics Inc., USA). Additionally, bubbles were classified into three size categories based on their surface area: class 1 for bubbles between 0.01 and 0.99 mm^2 ; class 2 for bubbles between 1.00 and 4.99 mm^2 ; and class 3 for bubbles greater than 5.00 mm^2 . The number of pores and the area occupied by each class (expressed as a percentage of the total number of pores and the total pore area, respectively) were also calculated.

Statistical Analysis

Pasting properties were analyzed only on 100% unsprouted and 100% sprouted buckwheat (both 48 h and 72 h), whereas a total number of 20 formulations were considered for gluten aggregation properties, mixing, and extensional properties; four formulations were considered for cracker preparation and characterization and other four formulation were considered in the case of bread. All data underwent one-way analysis of variance (ANOVA) with a significance level of 0.05, conducted using Statgraphics Plus 5.1 (StatPoint Inc., Warrenton, VA, USA). Significantly different factors were further assessed using the Tukey HSD test. Rheological data

were also processed by principal component analysis (PCA) by using Unscramble software 9.7 (Camo Software, Nedre Vollgate, Oslo, Norway).

Results and Discussion

Pasting Properties of Buckwheat Flours

The MVAG test was carried out on buckwheat flours to provide information on the impact of the sprouting process and its duration on starch hydrolysis and thus on its ability to gelatinize and retrograde in controlled conditions. The pasting properties of buckwheat flours, before and after sprouting of seeds, are reported in Fig. 1. AgNO_3 was used for its ability to inhibit α -amylases; amylase activity developed during sprouting promotes the degradation of starch granules into sugars which are necessary for sprout growth, resulting in the decrease of starch gelatinization and thus the retrogradation properties (Grassi et al., 2018).

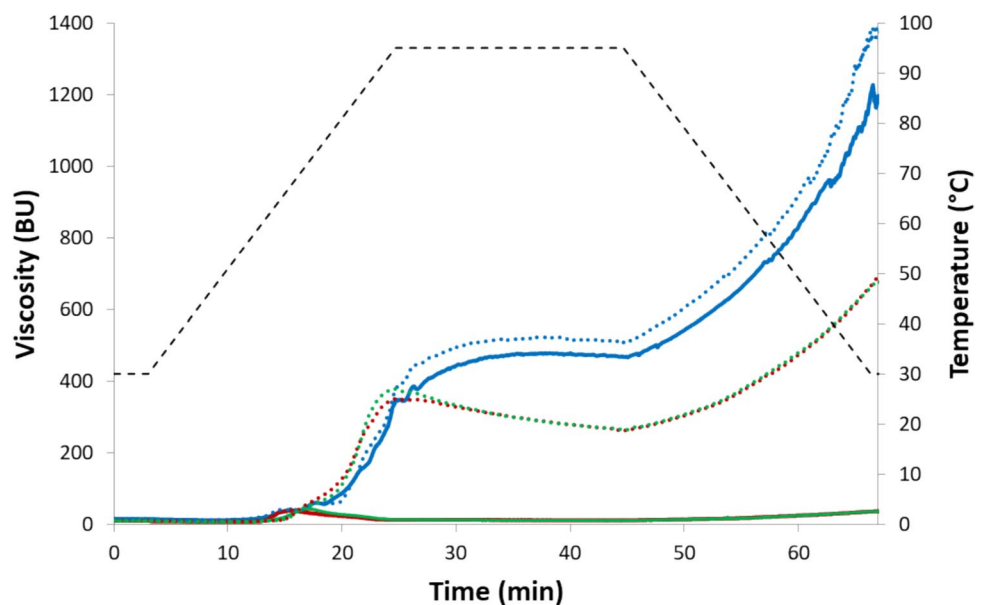
In presence of water, unsprouted buckwheat showed a gelatinization and retrogradation profile (Fig. 1), in agreement with previous studies (Di Cairano et al., 2020; Mariotti et al., 2006). Unsprouted buckwheat – as other pseudocereals such as quinoa (Suárez-Estrella et al., 2020a)—did not exhibit the typical viscosity peak of cereals, due to both the high amylose and starch compactness, which limit the swelling of starch granules.

In contrast, sprouted buckwheat, regardless of the sprouting time (48 h or 72 h), does not exhibit gelatinization and retrogradation properties, as an effect of amylases. By inhibiting enzymatic activity through the use of AgNO_3 , gelatinization and retrogradation capacity was also observed for

sprouted buckwheat although the values were lower than that of the control (unsprouted buckwheat flour). Specifically, the onset temperature of gelatinization increased (from 61.3 ± 1.6 to 66.2 ± 0.1 and 65.3 ± 1.1 °C for unsprouted buckwheat, 48 h- and 72 h-sprouted samples, respectively), while the peak viscosity (which represents the point of maximum swelling of the starch granules) decreased with sprouting (from 520 ± 4 to 352 ± 3 and 378.5 ± 1 BU for unsprouted, 48 h and 72 h-sprouted samples, respectively). This result indicates a partial degradation of starch granules during the sprouting process; however, there was no significant difference between the two sprouting times considered (48 and 72 h). Finally, a decrease in thermal and mechanical stability following sprouting was observed since breakdown values increased from 10.5 ± 6 BU (unsprouted sample) to 87.5 ± 1 and 114 ± 0.1 BU (for 48 h- and 72 h-sprouted buckwheat, respectively). Consequently to the changes in gelatinization properties, retrogradation tendency also decreased upon sprouting, with sprouted samples showing a lower final viscosity (691 ± 4 and 679 ± 7 BU for 48 h- and 72 h-sprouted samples, respectively) compared to unsprouted buckwheat (1369 ± 5 BU). Furthermore, the setback value (i.e., the difference in viscosity between the value at the end of cooling and the minimum value after gelatinization), which provides indications of starch retrogradation, decreased with sprouting (from 851 ± 22 BU of unsprouted buckwheat to 403 ± 5 and 398 ± 1 BU after 48 h and 72 h sprouting, respectively).

Similar results were found by Hara et al. (2007) who evaluated the effects of natural and artificial pre-harvest sprouting on the pasting properties of buckwheat. The peak viscosity decreased in sprouted buckwheat, whether the pre-harvest sprouting was natural or induced, and it had been

Fig. 1 Pasting profile of flours from unsprouted (blue line) and sprouted buckwheat for 48 h (red line) and 72 h (green line), by using water (full line) or AgNO_3 as solvent (dotted line)



shown to affect the behavior of buckwheat noodles during cooking: specifically, the hardness decreased when sprouted buckwheat was used (Hara et al., 2009). Slightly contrasting results were found by Yang et al. (2021), who reported a higher pasting profile in buckwheat sprouted for 24 and 48 h compared to unsprouted buckwheat, which then decreased after 72 h of sprouting. A similar behavior has also been observed in sorghum (Cardone et al., 2021) and yellow pea and faba bean (Setia et al., 2019). The increase in viscosity profile at the beginning of sprouting was attributed to changes in the matrix due to the hydrolysis of proteins that surrounds starch granules, whereas the decrease in viscosity upon longer germination was likely due to intense starch hydrolysis (Cardone et al., 2021; Setia et al., 2019; Yang et al., 2021).

As regards sprouting time, the present study showed no differences in parting profiles for the samples sprouted for 48 h and 72 h, confirming previous findings on wheat (Grassi et al., 2018). On the contrary, sprouting time (48 h versus 72 h) had a significant effect on the pasting properties of other grains, such as oats and quinoa (Suárez et al., 2020a; Sergiacomo et al., 2024). These results would suggest the importance of studying the effect of sprouting on each individual grain, as extending the results obtained on one raw material to another could lead to misleading results. It can be assumed that the structure of the caryopsis or seed, its chemical composition, and the structure of the macromolecules (mainly starch and protein) have an effect on the development of enzymes and their mobilization within the caryopsis/seed and thus on their hydrolytic action.

Rheological Properties of Buckwheat-wheat Blends

Flours from unsprouted and sprouted buckwheat were used in mixture with two wheat flours that were characterized by a different gluten strength, evaluated as the W alveographic index (BWF > CWF) to elucidate the role of wheat properties in defining the potential application of sprouted buckwheat. The rheological properties of BWF and CWF are summarized in Supplementary Table 1. Blends were prepared by substituting wheat flour with unsprouted and sprouted buckwheat at 10, 20, 30%; the substitution levels were chosen based on a previous studies. Indeed, Gavurníková et al. (2011), designated 10–20% as the favourable ratio of buckwheat in composite flour without a markedly negative impact of buckwheat on technological parameters of dough. Also, Mariotti et al. (2008) suggested that the use of buckwheat at high percentage (> 40%) should be avoided for the production of bread.

The impact of the enrichment of sprouted buckwheat on dough rheological properties was assessed by evaluating the gluten aggregation, mixing, and extensional properties of the blends, to provide information on the behavior of blends

during the production of baked goods (e.g., crackers and bread).

Gluten Aggregation Properties

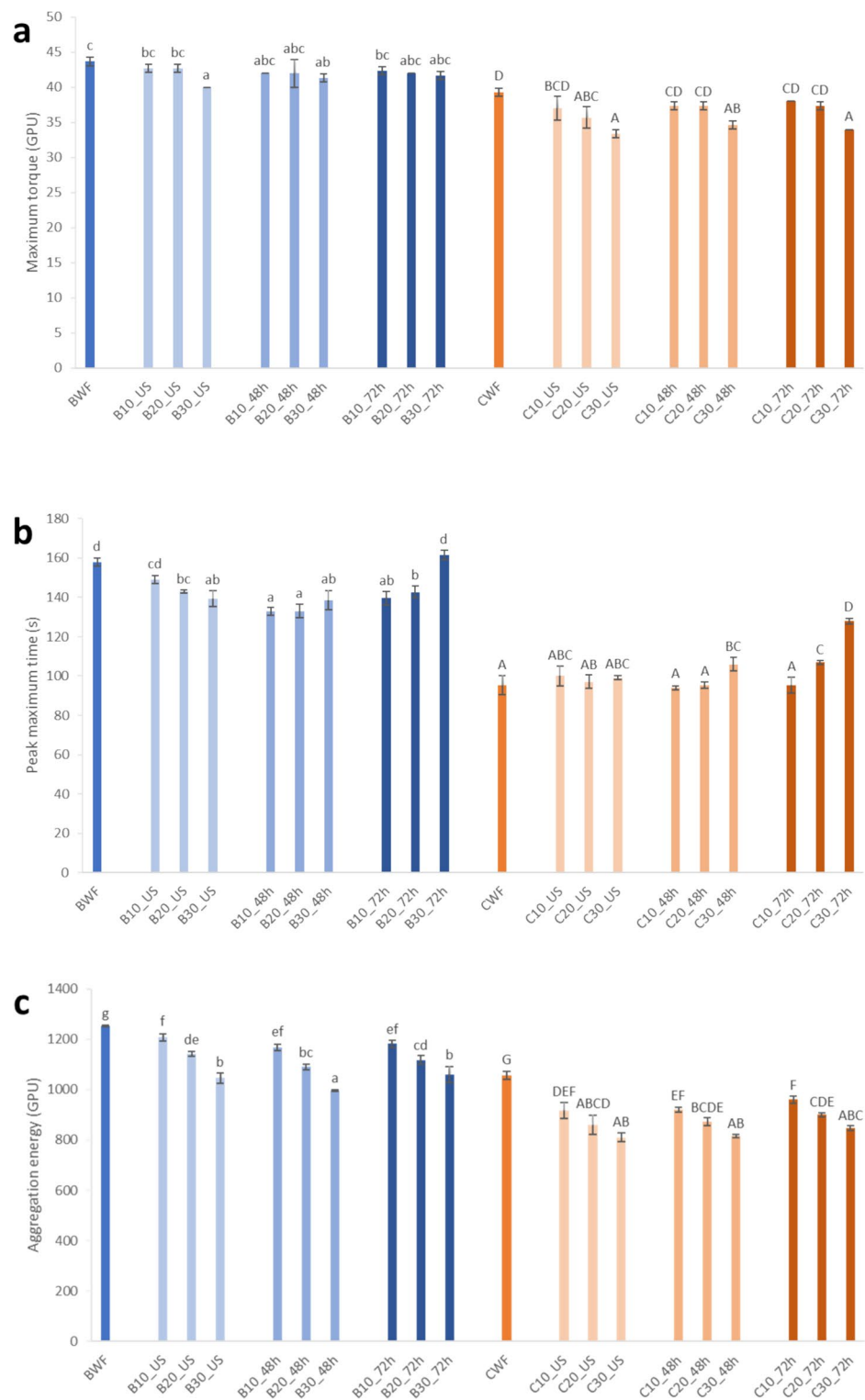
The gluten aggregation properties of wheat flours alone or in combination with sprouted and unsprouted buckwheat at different enrichment levels are shown in Fig. 2.

The two wheat flours used as the base for the mixtures with buckwheat had markedly different gluten aggregation properties: specifically, CWF was characterized by a lower maximum torque and lower aggregation energy compared to BWF. This aligns with recent findings of Karaduman et al. (2020), which attribute higher values of aggregation energy to flours characterized by high gluten strength and their suitability for bread making, while lower values indicate a weaker gluten and thus the suitability of such flours, for example, for biscuit production. However, the peak maximum time is higher for BWF, suggesting that more time is needed to develop the gluten network. Also, this behavior would suggest low gluten strength; similarly, hard wheat flours usually exhibit longer peak maximum time and higher maximum torque than soft wheat flours (Lu & Seetharaman, 2014).

The addition of unsprouted buckwheat to CWF caused a decrease in maximum torque (that was significant only at 20 and 30% enrichment level), and aggregation energy (that was significant and proportional to the enrichment levels considered in this study) with no change in peak maximum time. Overall, results suggest a worsening of gluten aggregation capacity in presence of buckwheat, likely due to the lack of gluten-forming proteins and high fiber and phenolic compounds in buckwheat that interfere with gluten formation (Marti et al., 2015).

Overall, 48 h-sprouted buckwheat had the same impact on gluten aggregation properties as unsprouted buckwheat. Indeed, no significant differences were measured among the samples, at any of the enrichment levels considered. As regards 72 h-sprouted buckwheat, its impact on delaying the gluten aggregation was mainly evident at high enrichment level (30%). The prolonged aggregation time in this sample could be explained by structural changes in buckwheat proteins following sprouting. It has been shown that proteins in buckwheat were prone to establish hydrophobic interactions (Mariotti et al., 2008) and that proteolytic activity developed during sprouting resulted in an increase in small peptides and amino acids (Kim et al., 2004; Phiarias et al., 2008; Borgonovi et al., 2023). Such modifications could alter buckwheat-buckwheat and wheat-buckwheat protein interactions, resulting in longer aggregation time as both the enrichment level and sprouting time increased. Further studies on protein organization are needed to confirm this hypothesis.

Fig. 2 Gluten aggregation properties of wheat flours for bread (BWF) and cracker (CWF) production, with added unsprouted and sprouted buckwheat. **(a)** Maximum torque; **(b)** Peak maximum time; **(c)** Energy. Blends were prepared replacing BWF and CWF with 10, 20 and 30% of unsprouted buckwheat (US) and sprouted buckwheat for 48 h and 72 h. Different letters indicate significant differences among samples. Specifically, lowercase letters refer to differences among samples prepared with BWF, while uppercase letters denote differences among samples prepared with CWF (one-way ANOVA; Tukey HSD test; $p \leq 0.05$). GPU, GlutoPeak Units



Overall, longer sprouting time might result in molecular changes that would further compromise the gluten aggregation properties of buckwheat-wheat mixture only at high ($\geq 20\%$) enrichment level.

Using a strong flour (i.e., BWF) made the addition of buckwheat (either in the unsprouted and sprouted form) less

impactful on maximum torque, except for 30% unsprouted buckwheat. Overall, peak maximum time decreased upon buckwheat addition, with the exception of B10_US and B30_72h samples, which did not differ from BWF. Finally, buckwheat negatively impacted gluten aggregation energy (by decreasing it), suggesting an overall gluten weakening,

as reported for CWF-based mixtures. In the case of BWF blends, the decrease in aggregation energy was proportional to the enrichment level, with an impact of sprouting and its duration only at high enrichment levels (i.e., 20–30%). Overall, it seems that using 10% of 72 h-sprouted buckwheat might represent a good compromise between using buckwheat with enhanced sensory properties, as reported in previous studies (Giovannelli et al., 2023), without extremely compromising the gluten aggregation properties of the blend.

It has been reported that the addition of sprouted grains different from buckwheat (i.e., oats, sorghum, and quinoa) to wheat flour was responsible for decreased maximum torque and energy, but not necessarily the peak maximum time (Cardone et al., 2021; Sergiacomo et al., 2024; Suárez-Estrella et al., 2020a). The authors related such changes in gluten aggregation properties to gluten weakening due to several aspects, including gluten dilution, fiber interference with proteins, and structural changes in components that results in different wheat gluten-non gluten component interactions.

Mixing Properties

The mixing properties of wheat flours alone and with the addition of sprouted and unsprouted buckwheat at different substitution levels are shown in Table 1. Besides the water absorption value (i.e., the amount of water added to make a dough with constant consistency, 500 FU), CWF and BWF exhibited different mixing profiles: CWF was characterized by a lower development time and lower stability than BWF.

The addition of buckwheat affected the mixing properties differently depending on the wheat flour in which it was included. In the case of CWF, the water absorption varied from 54.6 and 56.9% for 10_US and 30_72h samples, respectively, with only samples 20_72h and 30_72h showing a significantly higher water absorption than CFW and all the other samples.

Several factors might affect water absorption: damaged starch (which increased upon sprouting; Borgonovi et al., 2023), protein and fiber content (which are generally higher in buckwheat compared to cereals; Mir et al., 2018). Moreover, structural changes occurring during sprouting could be responsible for the increase in the water-soluble albumins and thus water absorption (Nikolić et al., 2011), as well as the exposure of more hydrophilic components which are able to bind more water (Yang et al., 2021).

In the case of BWF used as a base for the blends, the addition of either unsprouted and sprouted buckwheat did not affect the water absorption, suggesting that the higher protein content (14% vs 9%) of higher quality (W alveographic: 295 vs 150×10^{-4} J) had a bigger impact on this index rather than the addition of buckwheat.

The impact of both unsprouted and sprouted buckwheat addition on the decrease in dough development time was significant only in the case of BWF, with sprouted samples having the greatest effect. Low development time is associated with gluten weakening. However, neither the sprouting time nor the enrichment level affected the time required to form a dough with optimal consistency (500 FU).

Finally, buckwheat addition significantly decreased dough stability of both CWF and BWF, with the latter being mostly

Table 1 Mixing properties of wheat flours for bread (BWF) and cracker (CWF) production, with the addition of unsprouted and sprouted buckwheat

	Water absorption (%)	Development time (min)	Stability (min)	Water absorption (%)	Development time (min)	Stability (min)
	CWF			BWF		
WF	55.4 ± 0.2 ^{abc}	1.5 ± 0.1 ^{ab}	2.6 ± 0.3 ^b	56.3 ± 0.8 ^{ab}	11.3 ± 0.1 ^c	19.9 ± 0.1 ^e
10_US	54.6 ± 0.3 ^a	1.7 ± 0.01 ^b	3.3 ± 0.01 ^c	56.6 ± 0.1 ^{ab}	5.4 ± 0.1 ^b	9.4 ± 0.2 ^d
20_US	55.0 ± 0.1 ^{ab}	1.5 ± 0.01 ^{ab}	2.9 ± 0.01 ^{bc}	57.0 ± 0.1 ^{ab}	4.3 ± 0.01 ^b	5.2 ± 0.1 ^c
30_US	55.0 ± 0.1 ^{ab}	1.6 ± 0.1 ^b	2.8 ± 0.01 ^{bc}	56.9 ± 0.4 ^{ab}	4.4 ± 0.2 ^b	3.9 ± 0.1 ^{ab}
10_48h	55.2 ± 0.1 ^{abc}	1.6 ± 0.1 ^b	1.9 ± 0.3 ^a	55.7 ± 0.3 ^a	1.7 ± 0.3 ^a	5.3 ± 0.2 ^c
20_48h	55.2 ± 0.01 ^{abc}	1.6 ± 0.1 ^b	1.6 ± 0.3 ^a	56.2 ± 0.4 ^{ab}	1.7 ± 0.1 ^a	3.5 ± 0.7 ^{ab}
30_48h	55.7 ± 0.1 ^{bc}	1.4 ± 0.01 ^{ab}	1.8 ± 0.01 ^a	57.1 ± 0.5 ^{ab}	1.3 ± 0.01 ^a	3.2 ± 0.1 ^a
10_72h	54.9 ± 0.4 ^{ab}	1.5 ± 0.01 ^{ab}	1.8 ± 0.1 ^a	56.5 ± 0.1 ^{ab}	1.5 ± 0.4 ^a	4.4 ± 0.6 ^{bc}
20_72h	56.0 ± 0.4	1.4 ± 0.2 ^{ab}	1.8 ± 0.1 ^a	56.6 ± 0.4 ^{ab}	1.4 ± 0.3 ^a	3.3 ± 0.1 ^{ab}
30_72h	56.9 ± 0.01 ^d	1.1 ± 0.1 ^a	1.6 ± 0.1 ^a	57.6 ± 0.3 ^b	1.5 ± 0.1 ^a	3.1 ± 0.1 ^a

Data are expressed as mean ± standard deviation of two measurements. Different letters in the same column indicate significant differences among samples (one-way ANOVA; Tukey HSD test; $p \leq 0.05$)

The mixtures were prepared replacing wheat flours with 10, 20, and 30% of unsprouted buckwheat (US) and sprouted buckwheat for 48 h and 72 h

affected by gluten dilution and the disruption of the continuity of gluten network by adding a source of fiber and non-gluten proteins. Once again, in the case of CWF, neither the sprouting duration nor the enrichment level significantly affected dough resistance to mixing. On the contrary, in BWF-samples, only the enrichment level affected dough stability, with 10% showing the highest values, regardless of the sprouting time considered.

Overall, a substantial worsening in mixing properties was observed with the use of sprouted buckwheat, with the changes being more pronounced when BWF was used as the base. Conversely, the use of CWF partially masked the effect of adding sprouted buckwheat. This finding is an important consideration that could better identify the most suitable applications of this sprouted raw material concerning the type of product to be produced.

Buckwheat enrichment in wheat dough was investigated up to 40%. In agreement with our findings, Gavurníková et al. (2011) found minor changes in water absorption (at buckwheat levels between 5 and 30%), reduced dough development time (at buckwheat levels between 20 and 30%) and increased dough stability (at buckwheat levels of already 5%). However, Mariotti et al. (2008), using a wheat flour with a higher protein content (and greater water absorption, development time, and stability) than the previously cited study, reported no significant differences in water absorption when using up to 30% dehulled buckwheat, while a decrease in dough development time and stability was observed even at the 20% enrichment level. Differences between the previous studies might be due to differences in wheat flour characteristics (with the study of Mariotti et al. (2008) using a wheat flour with a higher protein content, water absorption, and dough development time than the flour used by Gavurníková et al. (2011)), as shown by the present study.

As regards the impact of sprouting, Xu et al. (2014) tested the addition of tartaric buckwheat, sprouted and unsprouted up to 12% in wheat bread dough. It was observed that the addition of buckwheat negatively affected farinographic indices; specifically, (i) water absorption decreased with both the addition of unsprouted and sprouted buckwheat; (ii) dough development time decreased proportionally with increasing supplementation level (4%, 8% or 12%), with a more pronounced effect due to sprouting; (iii) stability decreased based on both sprouting and enrichment level; (iv) the degree of softening increased, but it did not depend on the level of buckwheat enrichment, but solely on the effect of sprouting.

As regards the effect of sprouted grains other than buckwheat, an increase in water absorption and a decrease in development time was seen upon the use of sprouted quinoa (Suárez et al., 2020b); whereas this index was not affected by the addition of sprouted oat (Sergiacomo et al., 2024) and sorghum (Cardone et al., 2021). On the other hand,

regardless of the botanical origin, adding sprouted grain to wheat caused a decrease in dough stability (Suárez et al., 2020b; Cardone et al., 2021; Sergiacomo et al., 2024). Residual enzymatic activity present in the sprouted buckwheat fraction might have acted on wheat during analysis, worsening the mixing indices. Not only proteases but also amylases could play a key role during this analysis. This was partly observed by Kim et al. (2006), as the addition of fungal α -amylase to wheat flour before the farinograph test substantially worsened all the kneading properties due to the formation of low molecular weight dextrins produced from damaged starches by amylase hydrolysis. These low molecular weight dextrins contribute to the weakening of mixed doughs by disrupting the gluten network, leading to reduced dough strength and stability. In fact, high enzymatic activity, particularly of endogenous α -amylase, was observed in buckwheat after 72 h of sprouting (Borgonovi et al., 2023).

Extensional Properties

The evaluation of the extensional properties of dough provides information on dough ability to withstand unidirectional stretching performed by a hook. CWF was characterized by a lower resistance to extension and extensibility than BWF (Fig. 3), in agreement with previous studies that compared hard and soft wheat flours (Lu & Seetharaman, 2014; Huen et al., 2018).

The addition of buckwheat caused a significant reduction of all the indices, i.e. resistance to extension (both maximum and after 5 cm), extensibility, and extension energy (Fig. 3).

The negative impact of unsprouted buckwheat on dough extensional properties was observed using both CWF and BWF as base for the blends and generally seemed to depend on the integration level, with a more pronounced effect at the highest integration level (30%). The decrease in extensibility and energy were consistent across both flour types. However, notable differences emerged in other parameters: adding buckwheat to CWF resulted in a greater decrease in resistance to short deformation (i.e., resistance at 50 mm), while BWF dough exhibited a more significant decline in maximum resistance, particularly at incorporation levels of 20% and 30%. The decrease in both dough resistance to extension and extensibility upon buckwheat addition was due to a decreased ability of the dough to withstand the mechanical stresses. This information could be valuable during the design phase of the production process, particularly concerning the shaping stage of baked goods.

The decrease in extensibility, attributed solely to the addition of buckwheat (and not to sprouting time), may be due to the absence of gluten-forming proteins in buckwheat, whose prolamin content is insufficient to develop doughs with good viscosity and plasticity (Wei et al., 1995). The decrease in dough extensibility due to the addition of buckwheat, even

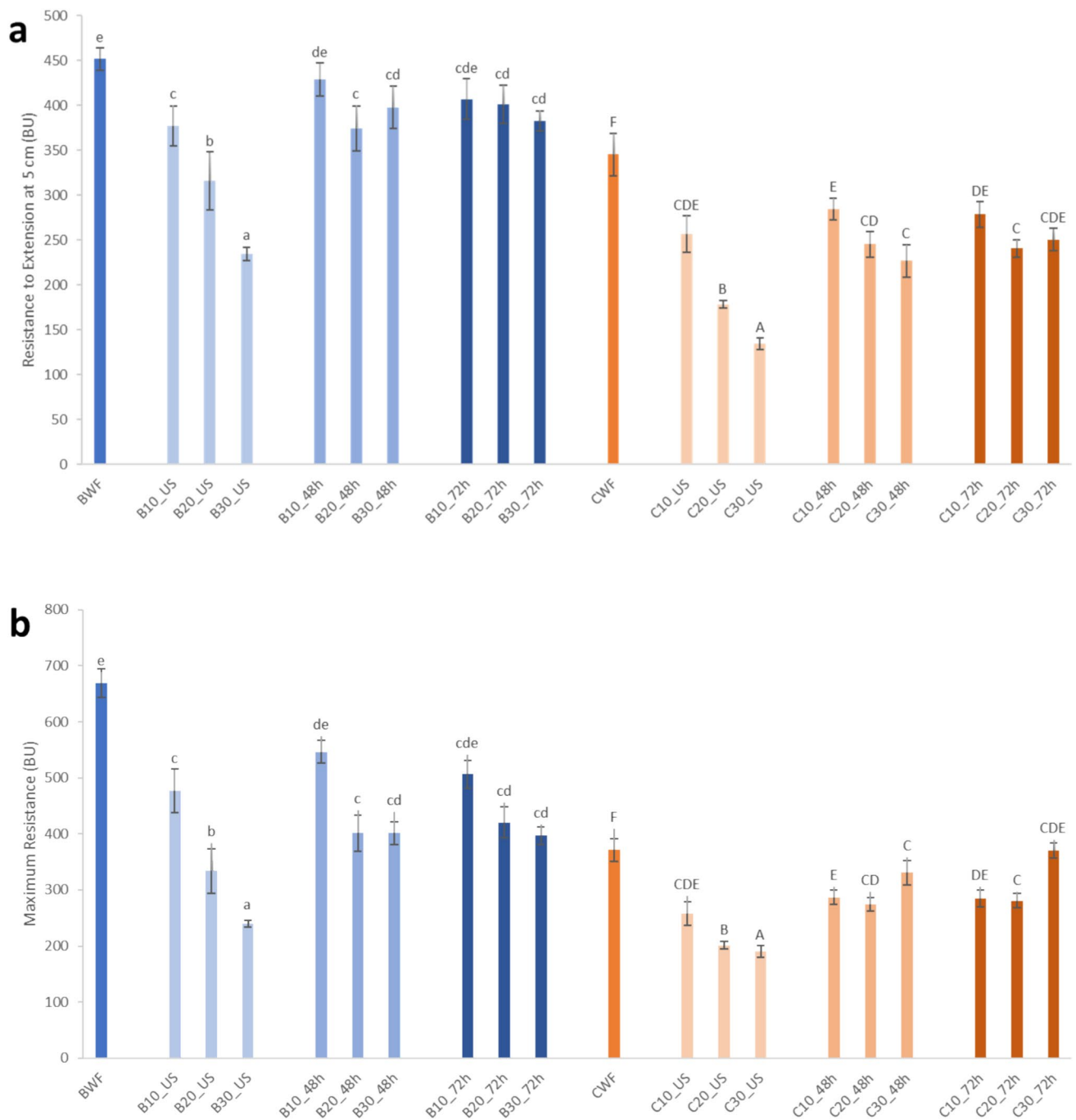


Fig. 3 Extensibility properties of wheat flours for bread (BWF) and cracker (CWF) production, with added unsprouted and sprouted buckwheat. **a** Resistance to extension at 5 cm; **b** Maximum resistance; **c** Extensibility; **d** extensional energy. Blends were prepared replacing BWF and CWF with 10, 20 and 30% of unsprouted buckwheat (US) and sprouted buckwheat for 48 h and 72 h. Different

letters indicate significant differences among samples (one-way ANOVA; Tukey HSD test; $p \leq 0.05$). Specifically, lowercase letters refer to differences among samples prepared with BWF, while uppercase letters denote differences among samples prepared with CWF (one-way ANOVA; Tukey HSD test; $p \leq 0.05$). BU, Brabender Unit

at a 10% substitution level, has been previously observed using a Kieffer rig (Liu et al., 2017). The decrease in extensibility was also observed when using sprouted lentils and soybeans in wheat doughs, compared to doughs made solely

from wheat (Hernandez-Aguilar et al., 2020; Ungureanu-Iuga et al., 2021).

As regards the effect of sprouting, the addition of sprouted buckwheat at 20% and 30% levels to both CWF

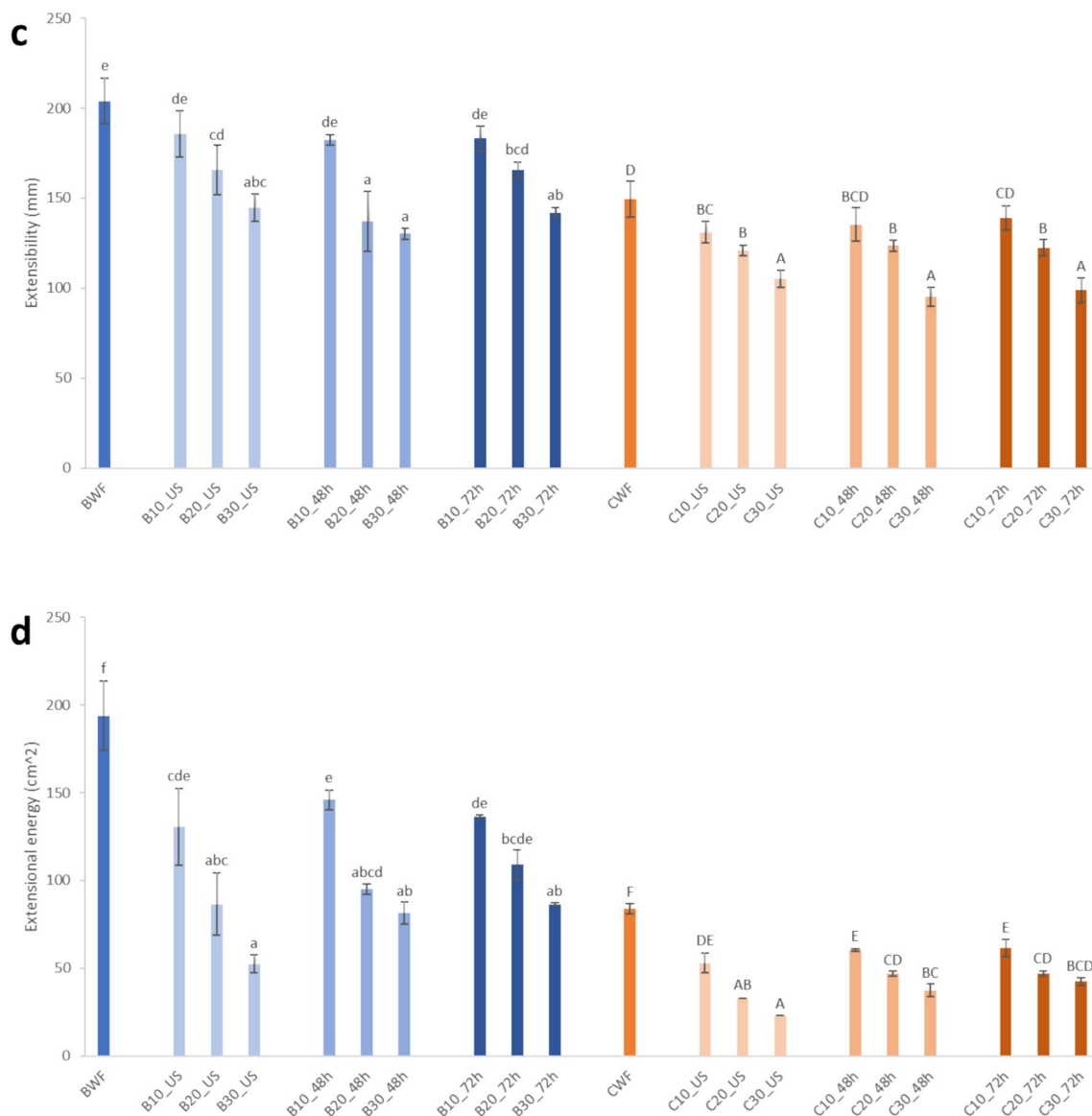


Fig. 3 (continued)

and BWF resulted in a higher resistance to extension (both maximum and at 50 cm) compared to unsprouted buckwheat. Sprouting did not affect extensibility, but the observed decrease was solely due to the wheat substitution levels. As the resistance to extension increased, also the extensional energy increased using sprouted buckwheat. This could be due not only to the action of proteases but also to the action of enzymes acting on non-starch polysaccharides. Indeed, laccase and xylanase can modify the rheological characteristics of wheat dough by increasing resistance and decreasing extensibility due to their action (as secondary substrates) on gluten and probably on proteins other than gluten, such as albumins and globulins (Selinheimo et al., 2006).

The extensional properties were evaluated at a different resting time (i.e., 45, 90, and 135 min) to evaluate the effect of endogenous enzymatic activity on dough rheology, as well as to mimic the phases of the production of baked goods. In the case of unsprouted buckwheat-enriched doughs, the same behavior was observed at all the resting times considered, regardless of the type of wheat flour used and the enrichment level) (Supplementary Table S2). Indeed, when buckwheat was added to both BWF and CWF, a decrease in resistance to extension (both maximum and at 50 mm) was observed, depending on the resting time, which led to a reduction in energy. This effect varied based on the time points at which the analysis was conducted (i.e., 45, 90, and 135 min), highlighting the influence of resting

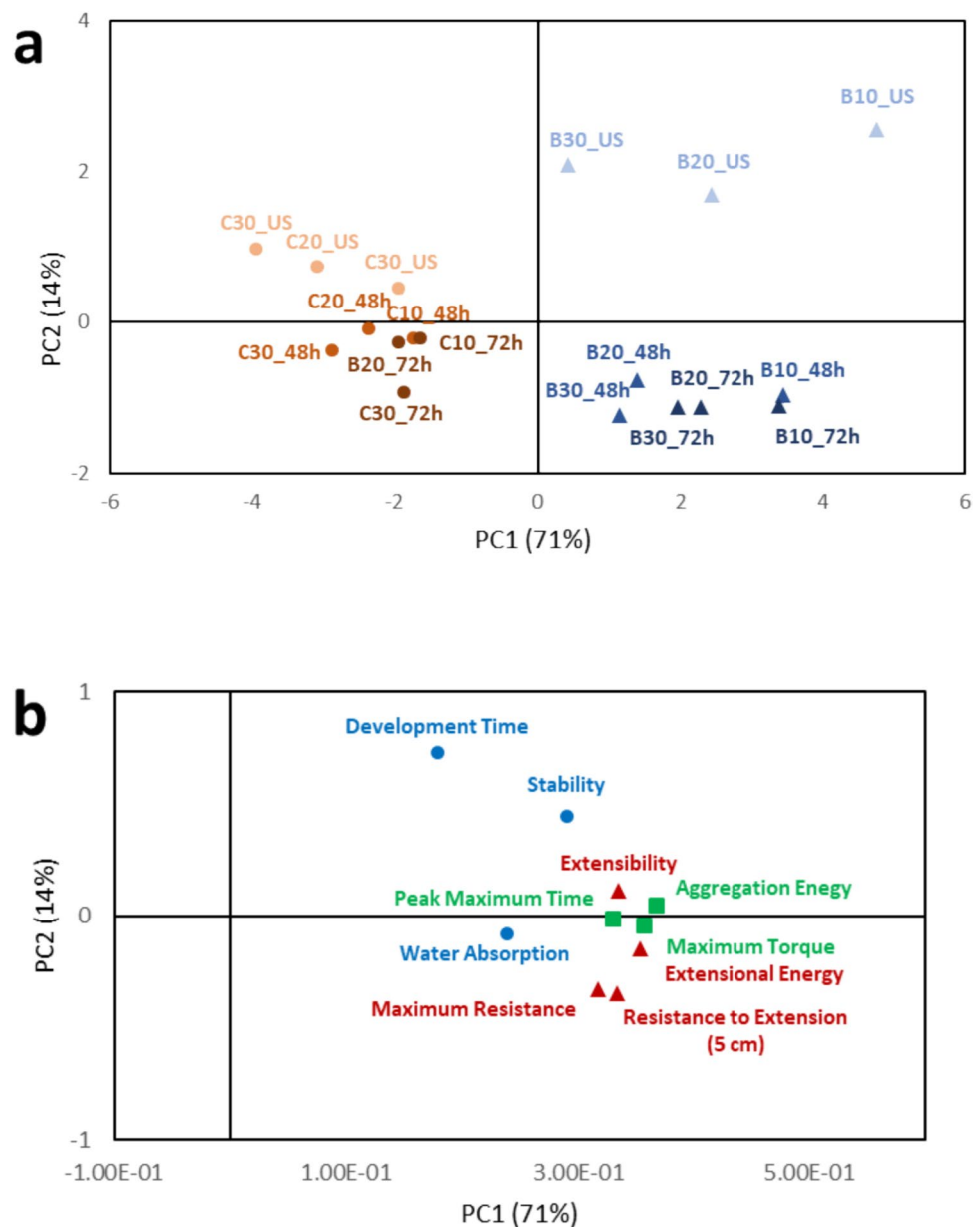
time on the dough's properties. Sprouting caused an increase in resistance to extension for both wheat bases when using 48 h sprouted buckwheat. However, with 72 h sprouted buckwheat, an increase was observed only at 10% inclusion level; at 20% and above, a decrease was noted. Extensibility decreased over time only when buckwheat was added to BWF. The proteolytic activity of sprouted buckwheat, which varied with the sprouting time as reported by Borgonovi et al. (2023), may have acted on wheat proteins during the resting period of the analysis, enhancing certain interactions and making the dough more resistant to extension. However, the lack of studies on the extensibility of dough enriched with sprouted raw materials makes the explanation of these results difficult, suggesting the need of further studies to

elucidate the effect of proteases developed during sprouting on dough rheological properties in composite fours.

Principal Component Analysis (PCA) of Rheological Data

All the rheological indices discussed in the previous sections were analyzed using PCA to enhance discriminatory power and simplify the dataset comprising 20 different samples. Note that the two controls consisting of 100% wheat (BWF and CWF) were excluded to make the differences between the buckwheat-containing blends more clear. The PCA results presented in Fig. 4 illustrate the distribution of samples, i.e. blends made with sprouted and unsprouted buckwheat across two different wheat bases,

Fig. 4 Distribution of the mixtures prepared from the two different wheat flours for bread (BWF) and cracker (CWF) production, with added 10, 20 and 30% of unsprouted buckwheat (USB) and sprouted (SB) for 48 and 72 h (loadings plot, Fig. 4a) for PC1-PC2, generated from a correlation-matrix PCA. Score plot of the samples on PC1-PC2, generated from a correlation-matrix PCA (Fig. 4b). Gluten aggregation properties were evaluated by GlutoPeak, indices in green (peak maximum time; maximum torque and aggregation energy), mixing properties by Farinograph, indices in blue (water absorption, development time, stability and degree of softening), extensibility properties by Estensograph, indices in red (energy, maximum resistance, resistance at 50 mm, extensibility, resistance/extensibility ratio and maximum resistance/extensibility ratio)



based on the described indices. The first two principal components effectively summarize the data, accounting for 85% of the total variance (PC1 = 71%; PC2 = 14%).

Specifically, in the loading plot of Fig. 4a, the first principal component (PC1) distinguishes samples based on enrichment level, while the second principal component (PC2) differentiates samples according to the sprouting time. Additionally, samples are distributed along the PC1 depending on the wheat flour used. Specifically, the blends prepared with BWF occupy the two quadrants on the right side of the plot, while the mixtures prepared with CWF wheat flour are located in the quadrants on the left side. Furthermore, in the case of the BWF blends, unsprouted samples are separated along the PC1 as a function of buckwheat enrichment level, and along the PC2 they are separated by the sprouted samples. As regards the sprouted samples, at the lowest enrichment level, the effect of sprouting time (48 or 72 h) was not evident, whereas as the enrichment level increased, the effect of sprouting time became more pronounced.

In the case of CWF mixtures, the distance between the mixtures with the addition of unsprouted buckwheat and those with sprouted buckwheat is smaller, with the C30_US mixture being very close to the C10_48h and C20_48h mixtures. The mixtures prepared with sprouted buckwheat in this case are grouped within a confined area, showing little differentiation based on the two factors, sprouting time and integration level.

The loading plot (Fig. 4b) identifies the variables most influential in differentiating the samples, particularly those furthest from the origin. The indices that most significantly differentiate the mixtures along PC2, and thus according to sprouting time, are the development time and dough stability recorded by the Farinograph, which tend to decrease with sprouting time (unsprouted buckwheat > 48 h sprouted buckwheat > 72 h sprouted buckwheat; Table 1). Along PC1, the indices that primarily differentiate the samples according to the enrichment level are those derived from the GlutoPeak test (Maximum Torque, Peak Maximum Time, and Aggregation energy; Fig. 2) and the indices from the Extensograph (especially Extensibility, and Energy; Fig. 3). All these parameters generally decrease as the enrichment level increases, with the exception of the Peak Maximum Time, which shows different trends depending on the use of unsprouted versus sprouted buckwheat.

Overall, elaborating the data by a multivariate approach would allow to select the most valuable indices that might guide the reformulation of baked goods with sprouted buckwheat.

In consideration of the distribution of samples in Fig. 4, 10% enrichment level was used for bread production and 30% enrichment level was selected for cracker production.

Product Characterization

BWF and CWF were selected for their different rheological properties and thus their potential application: bread and crackers, respectively. These products were selected since they are widely consumed and characterized by different structures and textures: the porous structure of bread makes softness one of the most appreciated features for this product, whereas the laminated structure of crackers makes crunchiness and friability the key quality attributes sought by consumers.

Based on the rheological properties described in the previous paragraphs, mixtures of CWF containing 30% buckwheat were used for crackers production. According to the PCA results described, the differences in rheology between the various levels of integration were not as obvious using CWF as a basis. Therefore, given the equivalent rheological properties, the mixture containing the highest percentage of buckwheat was chosen to take advantage of its unique nutritional properties.

In contrast, when BWF flour was used as a base, the rheological differences among the various enrichment levels were more pronounced, as indicated by the greater distance between the points related to the mixtures containing 10%, 20%, and 30% in the PCA. For this reason, the lowest percentage of buckwheat enrichment was selected for bread production.

Cracker Characteristics

All tested formulations produced crackers that closely resembled the control, as illustrated in Fig. 5. The physical characteristics of the cracker are summarized in Table 2. No differences in cracker length and width were found; only the thickness was influenced by the addition of buckwheat, making the crackers thinner compared to the control (i.e., wheat cracker). The addition of buckwheat (whether sprouted or not) resulted in a reduction in weight and moisture and in an increase in the specific volume of the cracker. Likely, the greater water loss during the cooking phase resulted in lower weight and consequently a higher specific volume, despite the decrease in volume. The lower moisture content would suggest a greater stability over time and therefore a longer shelf life of buckwheat-enriched crackers compared to those made with only wheat.

Texture is particularly important for crackers, as their hardness is a strong indicator of freshness and quality, both highly desirable properties (Giannoutsos et al., 2023).

The substitution of wheat with buckwheat affected the hardness of the crackers, causing a decrease in value; however, neither sprouting or sprouting time had an effect on this index. As regards toughness (i.e., the work required to break the sample), adding either unsprouted

Fig. 5 Image acquisition of crackers produced with wheat flour (CWF) and 30% of unsprouted buckwheat (C30_US) and buckwheat that was sprouted for 48 h (C30_48h) and 72 h (C30_72h)

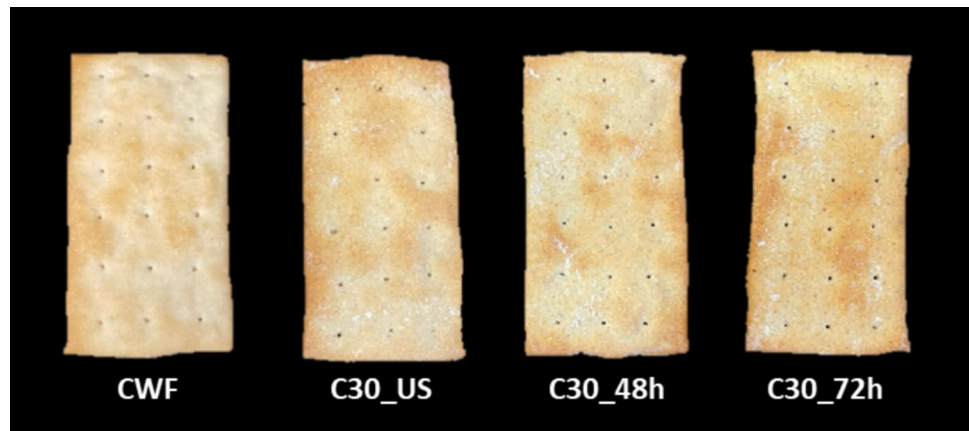


Table 2 Quality parameters of cracker prepared from wheat flours for cracker (CWF) production and buckwheat blends

	Length (cm)	Width (cm)	Thickness (mm)	Weight (g)	Volume (mL)	Specific volume (mL/g)	Moisture (%)	Hardness (N)	Toughness (N/cm)
CWF	9.1 ± 0.3 ^a	4.6 ± 0.2 ^a	4.9 ± 0.2 ^c	10.0 ± 1.0 ^c	113.7 ± 7.5 ^a	2.3 ± 0.2 ^a	10.0 ± 1.0 ^b	41.9 ± 6.1 ^c	336.6 ± 41.5 ^b
C30_US	9.1 ± 0.2 ^a	4.6 ± 0.2 ^a	3.6 ± 0.1 ^a	6.8 ± 0.8 ^a	101.2 ± 8.5 ^a	3.0 ± 0.3 ^b	7.0 ± 1.0 ^a	25.7 ± 2.8 ^{ab}	228.2 ± 36.0 ^a
C30_48h	9.1 ± 0.2 ^a	4.5 ± 0.1 ^{ab}	4.0 ± 0.1 ^b	8.2 ± 0.5 ^b	112.5 ± 6.4 ^a	2.8 ± 0.2 ^b	8.0 ± 2.1 ^{ab}	31.9 ± 4.4 ^b	265.0 ± 43.7 ^a
C30_72h	9.2 ± 0.2 ^a	4.6 ± 0.2 ^a	4.1 ± 0.1 ^b	8.1 ± 0.6 ^b	108.7 ± 4.8 ^a	2.7 ± 0.1 ^b	6.3 ± 0.5 ^a	31.8 ± 4.3 ^{ab}	342.0 ± 57.5 ^b

Data are expressed as mean ± standard deviation of 10 measurements for length, width, thickness, hardness, and toughness, 6 measurements for weight, volume, and specific volume, and four replicates for moisture. Different letters in the same column indicate significant differences among samples (one-way ANOVA; Tukey HSD test; $p \leq 0.05$)

Blends were prepared replacing CWF with 30% of unsprouted buckwheat (C30_US) and sprouted buckwheat for 48 h (C30_48h) and 72 h (C30_72h)

or 48 h-sprouted buckwheat resulted in a decrease in this index, suggesting a matrix weakening due to gluten dilution and/or fiber inclusion. On the other hand, adding 72 h-sprouted buckwheat resulted in an increase in toughness that reached the same value as the control. It could be hypothesized that the molecular changes occurring upon prolonged sprouting had favored the formation of a cohesive matrix, also through protein–protein interactions (Sergiacomo et al., 2024).

Giannoutsos et al. (2023) evaluated the texture and toughness of crackers made from wheat flour with the addition of gluten-free grains, such as barley, and legumes, such as chickpeas, up to 50%. Their findings indicated that texture and toughness values were higher in crackers with greater amounts of wheat, and thus gluten. Similarly, Wójtowicz et al. (2013) assessed the hardness of corn-based snacks with added buckwheat, highlighting a proportional decrease with increasing levels of buckwheat. This reduction in hardness could be due to the proteins present in buckwheat flour (Ikeda et al., 1999), as the replacement of wheat proteins with those from buckwheat dilutes the gluten-forming proteins, leading to a less developed gluten network that affects the hardness of the final product.

Bread Characteristics

The qualitative indices of the bread measured two hours after baking (day 0) and after two days (day 2) are summarized in Table 3.

Replacing wheat flour with sprouted buckwheat resulted in a higher specific volume compared to bread made with only wheat and with the addition of unsprouted buckwheat (Fig. 6). The increase in the specific volume as an effect of sprouting had already been observed in wheat breads enriched in 5% sprouted amaranth (Guardianelli et al., 2022) and 20% sprouted quinoa (Suárez-Estrella et al., 2020b). As regards sprouted buckwheat, Xu et al. (2014) also reported an increase in the volume of steamed bread when sprouted buckwheat for 96 h was incorporated at low percentages (i.e., 4% and 8%). It is already known that the volume increase of baked goods containing sprouted grains is generally associated with a higher amount of fermentable sugars released by the activity of α -amylase, which allows yeasts to produce more CO_2 during the leavening phase (Marti et al., 2018).

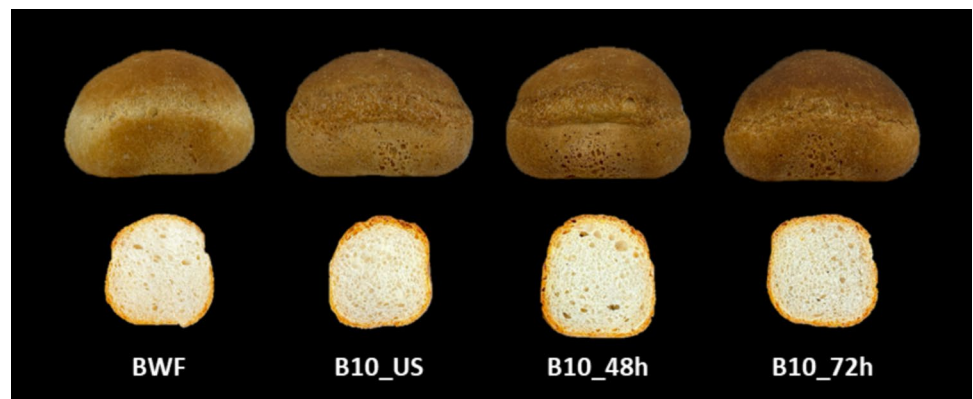
The addition of buckwheat, both sprouted and unsprouted, to wheat also resulted in changes in crumb texture. Specifically, the hardness decreased with the use of sprouted

Table 3 Properties of bread on the day of production (*Day 0*) and after two days of storage (*Day 2*) prepared from wheat flours for bread (BWF) production, and buckwheat blends

	Specific Volume (mL/g)	Hardness (N)		Cohesiveness		Chewiness		Moisture (%)	
		<i>Day 0</i>	<i>Day 2</i>	<i>Day 0</i>	<i>Day 2</i>	<i>Day 0</i>	<i>Day 2</i>	<i>Day 0</i>	<i>Day 2</i>
BWF	3.2±0.1 ^a	14.7±1.3 ^{bc}	55.3±3.3 ^a	0.80±0.02 ^b	0.64±0.05 ^b	13.3±2.3 ^b	33.5±3.9 ^b	42.3±0.7 ^a	33.5±0.7 ^b
B10_US	3.3±0.1 ^a	15.2±2.6 ^c	57.4±2.5 ^a	0.76±0.03 ^a	0.58±0.04 ^a	11.5±1.7 ^{ab}	32.4±1.8 ^b	42.4±0.7 ^a	33.0±0.3 ^b
B10_48h	3.7±0.2 ^b	12.2±1.2 ^a	52.8±2.5 ^a	0.75±0.02 ^a	0.56±0.03 ^a	9.3±0.7 ^a	28.2±3.1 ^a	42.4±0.5 ^a	29.9±1.8 ^a
B10_72h	3.6±0.1 ^b	12.4±0.8 ^a	52.3±4.5 ^a	0.75±0.02 ^a	0.56±0.02 ^a	9.3±0.9 ^a	28.2±2.9 ^a	42.6±0.8 ^a	31.2±0.9 ^{ab}

Data are expressed as mean±standard deviation of six replicates for specific volume, twelve replicates for hardness, cohesiveness, and chewiness, and four replicates for moisture. Different letters in the same column indicate a significant difference among samples (one-way ANOVA; Tukey HSD test; $p \leq 0.05$)

Blends were prepared replacing BWF with 10% of unsprouted buckwheat (B10_US) and sprouted buckwheat for 48 h (B10_48h) and 72 h (B10_72h)

Fig. 6 Image acquisition of breads produced with wheat flour (BWF) and 10% of unsprouted buckwheat (B10_US) and buckwheat that was sprouted for 48 h (B10_48h) and 72 h (B10_72h)

buckwheat (whether 48 or 72 h) compared to both wheat and bread made with unsprouted buckwheat. The high specific volume of the bread could explain the softness of the crumb in bread enriched with sprouted buckwheat (Scanlon & Zghal, 2001). The effect was observed only at day 0, as these differences were no longer pronounced after two days of storage. This was probably due to the greater moisture loss observed after two days in bread made with the addition of sprouted buckwheat. The effect could be due not only to gluten dilution, as explained in the cracker section, but also to modifications induced by sprouting in the soluble macromolecules present in greater quantities (starch and proteins). These aspects are currently under evaluation to better understand their contribution to the observed effects.

Springiness and resilience did not show differences due to the addition of either unsprouted or sprouted buckwheat (data not shown), but cohesiveness was lower in (sprouted and unsprouted) buckwheat-enriched bread. Bread with high cohesiveness is preferred as it forms a cohesive mass rather than breaking apart during chewing, while low cohesiveness suggests that the bread is more likely to break or crumble (Carocho et al., 2020).

Chewiness, obtained by multiplying gumminess by springiness, is more closely related to hardness than to other parameters (Armero & Collar, 1997). At day 0, it followed the trend of hardness, with differences remaining even after two days of storage, suggesting that less energy was needed to chew the bread containing sprouted buckwheat. Similar results were found by Sturza et al. (2020), who, after producing rolls 10% containing 120 h-sprouted buckwheat, observed a decrease in hardness, cohesiveness, and chewiness.

The crumb porosity data are presented in Table 4. The porosity, calculated as the total pore area on the slice surface, differed between the bread made solely with wheat flour (34.3%) and the bread produced with the addition of unsprouted buckwheat (42.8%). Bread containing sprouted buckwheat at both sprouting times showed intermediate porosity values, without significant differences compared to either wheat and unsprouted buckwheat-enriched samples. Regarding pore size distribution across classes, significant differences were observed between wheat bread and the other samples in both class 1 and class 2. Specifically, buckwheat-enriched bread showed a lower amount of small

Table 4 Porosity of crumb surface and percentage of individual class area relative to total porosity of bread made from wheat flour (BWF) and buckwheat blends

	Porosity (%)	Class 1 (%)	Class 2 (%)	Class 3 (%)
BWF	34.3 ± 1.8 ^a	91.8 ± 1.2 ^b	7.5 ± 1.1 ^a	0.6 ± 0.1 ^a
B10_US	42.8 ± 4.0 ^b	86.5 ± 1.4 ^a	12.1 ± 1.1 ^b	1.4 ± 0.4 ^a
B10_48h	38.0 ± 1.6 ^{ab}	88.4 ± 1.2 ^a	10.4 ± 0.6 ^b	1.1 ± 0.6 ^a
B10_72h	38.7 ± 1.0 ^{ab}	87.5 ± 0.7 ^a	11.5 ± 0.6 ^b	0.9 ± 0.5 ^a

Data are expressed as mean ± standard deviation of four measurements. Different letters in the same column indicate a significant difference among samples (one-way ANOVA; Tukey HSD test; $p \leq 0.05$). Class 1: 0.01–0.99 mm²; Class 2: 1.00–4.99 mm²; Class 3: ≥ 5.00 mm²

Blends were prepared by substituting 10% of BWF with unsprouted buckwheat (B10_US) and buckwheat sprouted for 48 h (B10_48h) and 72 h (B10_72h)

pores (0.01–0.99 mm²) and a higher amount of medium pores (1.00–4.99 mm²), regardless the type of buckwheat (i.e., unsprouted or sprouted buckwheat). On the other hand, formulation did not affect the amount of large pores (> 5.00 mm²). Similar results were observed by Coțovanu and Mironnea (2022), who reported a decrease in crumb porosity with increasing levels of buckwheat flour in a wheat-based formulation. Notably, their reported porosity values were higher, ranging from 65 to 75%, calculated based on the volume of a cylindrical sample.

Conclusion

The findings of this study highlight that both sprouting time (0, 48 and 72 h) and substitution level (10, 20, and 30%) affected the rheological properties of buckwheat-enriched dough, although at a different extent. Specifically, buckwheat enrichment mainly affected gluten aggregation and extensional properties, whereas the mixing properties (particularly dough development time and stability) were mainly affected by the sprouting time. Moreover, the impact of buckwheat enrichment and sprouting time was more pronounced in mixtures for bread production compared to those for cracker production.

Our results also suggest that studying the effect of sprouting time on dough rheological properties provides useful information for selecting the enrichment levels to be used in product development. In the case of sprouted buckwheat, 10% enrichment level was used for bread production, while 30% for cracker production. In the case of crackers, using sprouted buckwheat for 72 h it was possible to produce baked goods with qualities comparable to the control (100% wheat), while offering a significant nutritional benefit due to the high enrichment percentage. On the other hand, the

technological properties of bread (specific volume and crumb softness) were improved compared to the control, when sprouted buckwheat (for 48 or 72 h) was used.

Although preliminary tests have proved the repeatability of the sprouting process in terms of enzymatic activities and functional properties (data not shown), further studies are necessary to test the reproducibility of the process and its scaling-up at industrial scale.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11947-025-03796-8>.

Acknowledgements A.S.'s scholarship is funded under PON: "National Research and Innovation Operational Program 2014–2020". M. M.'s fellowship is funded under CROPDIVA "European Union's Horizon 2020 research and innovation programme". The contribution of (i) "One Health Action Hub: University Task Force for the resilience of territorial ecosystems" project, funded by Università degli Studi di Milano (PSR 2021-GSA-Linea 6) and (ii) the Horizon 2020 UE programme through the project "CROPDIVA" [grant number 101000847] is also acknowledged. The authors express their gratitude to Dr. Francesca Gallio and Dr. Paolo Varetto (Soremartec S.r.l.) for their partial support of this research.

Author Contributions A.S. contributed to Formal analysis, Investigation, Writing—Original Draft Preparation, Visualization. A.B. contributed to Methodology, Validation, Resources, Writing—Original Draft Preparation. M.M. contributed to Formal analysis. A.M. contributed to Conceptualization, Writing—Review & Editing, Supervision, Project administration, Funding acquisition.

Funding Open access funding provided by Università degli Studi di Milano within the CRUI-CARE Agreement. This research was funded by the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3—Call for proposals No. 341 of 15 March 2022 of the Italian Ministry of University and Research, funded by the European Union—NextGenerationEU, Award Number: Project code PE000000003, Concession Decree No. 1550 of 11 October 2022 adopted by the Italian Ministry of University and Research, CUP D93C22000890001, Project title "ON Foods—Research and innovation network on food and nutrition Sustainability, Safety, and Security—Working ON Foods".

Data Availability Data is provided within the manuscript.

Declarations

Competing Interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- AACC. (2001). Approved methods of analysis (eleventh). Cereals & Grains Association.
- Alvarez-Jubete, L., Wijngaard, H., Arendt, E. K., & Gallagher, E. (2010). Polyphenol composition and in vitro antioxidant activity of amaranth, quinoa buckwheat and wheat as affected by sprouting and baking. *Food Chemistry*, 119(2), 770–778. <https://doi.org/10.1016/j.foodchem.2009.07.032>
- Armero, E., & Collar, C. (1997). Texture properties of formulated wheat doughs relationships with dough and bread technological quality: Relationships with dough and bread technological quality. *Zeitschrift Für Lebensmitteluntersuchung und-Forschung A*, 204, 136–145. <https://doi.org/10.1007/S002170050050>
- Bhinder, S., Singh, N., & Kaur, A. (2022). Impact of germination on nutraceutical, functional and gluten free muffin making properties of Tartary buckwheat (*Fagopyrum tataricum*). *Food Hydrocolloids*, 124, 107268-. <https://doi.org/10.1016/j.foodhyd.2021.107268>
- Borgonovi, S. M., Chiarello, E., Pasini, F., Picone, G., Marzocchi, S., Capozzi, F., Bordoni, A., Barbiroli, A., Marti, A., Iametti, S., & Di Nunzio, M. (2023). Effect of sprouting on biomolecular and antioxidant features of common buckwheat (*Fagopyrum esculentum*). *Foods*, 12(10), 2047. <https://doi.org/10.3390/foods12102047>
- Buratti, S., Giovanelli, G., Benedetti, S., & Marti, A. (2022). Impact of gelatinization on common (*Fagopyrum esculentum*) and Tartary (*Fagopyrum tataricum*) buckwheat: Effect on taste and flavor assessed by e-senses in relation to phenolic compounds. *European Food Research & Technology*, 248(10), 2521–2530. <https://doi.org/10.1007/s00217-022-04066-z>
- Cardone, G., Rumler, R., Speranza, S., Marti, A., & Schönlechner, R. (2021). Sprouting time affects sorghum (*Sorghum bicolor* [L.] Moench) functionality and bread-baking performance. *Foods*, 10(10), 2285. <https://doi.org/10.3390/foods10102285>
- Carocho, M., Morales, P., Ciudad-Mulero, M., Fernández-Ruiz, V., Ferreira, E., Heleno, S., Rodrigues, P., Barros, L., & Ferreira, I. C. F. R. (2020). Comparison of different bread types: Chemical and physical parameters. *Food Chemistry*, 310, 125954–125954. <https://doi.org/10.1016/j.foodchem.2019.125954>
- Christa, K., & Soral-Šmietana, M. (2008). Buckwheat grains and buckwheat products—nutritional and prophylactic value of their components—a review. *Czech J. Food Sci*, 26(3), 153–162. <https://doi.org/10.17221/1602-CJFS>
- Coțovanu, I., & Mironeasa, S. (2022). Influence of buckwheat seed fractions on dough and baking performance of wheat bread. *Agronomy (Basel)*, 12(1), 137-. <https://doi.org/10.3390/agronomy12010137>
- Di Cairano, M., Condelli, N., Caruso, M. C., Marti, A., Cela, N., & Galgano, F. (2020). Functional properties and predicted glycemic index of gluten free cereal, pseudocereal and legume flours. *Food Science & Technology*, 133, 109860-. <https://doi.org/10.1016/j.lwt.2020.109860>
- FAOSTAT. (2022). <https://www.fao.org/faostat/en/#data/QCL>
- Garrido-Galand, S., Asensio-Grau, A., Calvo-Lerma, J., Heredia, A., & Andrés, A. (2021). The potential of fermentation on nutritional and technological improvement of cereal and legume flours: A review. *Food Research International*, 145, 110398–110398. <https://doi.org/10.1016/j.foodres.2021.110398>
- Gavurníková, S., Havrlentová, M., Mendel, L., Čičová, I., Bieliková, M., & Kraic, J. (2011). Parameters of wheat flour, dough, and bread fortified by buckwheat and millet flours. *Agriculture*, 57(4), 144–153. <https://doi.org/10.2478/v10207-011-0015-y>
- Giannoutsos, K., Zalidis, A. P., Koukoumaki, D. I., Menexes, G., Mourtzinis, I., Sarris, D., & Gkatzionis, K. (2023). Production of functional crackers based on non-conventional flours. Study of the physicochemical and sensory properties. *Food Chemistry Advances*, 2, 100194. <https://doi.org/10.17113/ftb.60.04.22.7655>
- Giménez-Bastida, J. A., Piskula, M., & Zieliński, H. (2015). Recent advances in development of gluten-free buckwheat products. *Trends in Food Science & Technology*, 44(1), 58–65. <https://doi.org/10.1016/j.tifs.2015.02.013>
- Giménez-Bastida, J. A., & Zieliński, H. (2015). Buckwheat as a functional food and its effects on health. *Journal of Agricultural and Food Chemistry*, 63(36), 7896–7913. <https://doi.org/10.1021/acs.jafc.5b02498>
- Giovanelli, G., Bresciani, A., Benedetti, S., Chiodaroli, G., Ratti, S., Buratti, S., & Marti, A. (2023). Reformulating couscous with sprouted buckwheat: Physico-chemical properties and sensory characteristics assessed by E-senses. *Foods*, 12(19), 3578. <https://doi.org/10.3390/foods12193578>
- Grassi, S., Cardone, G., Bigagnoli, D., & Marti, A. (2018). Monitoring the sprouting process of wheat by non-conventional approaches. *Journal of Cereal Science*, 83, 180–187. <https://doi.org/10.1016/j.jcs.2018.08.007>
- Guardianelli, L. M., Salinas, M. V., & Puppo, M. C. (2022). Quality of wheat breads enriched with flour from germinated amaranth seeds. *Food Science and Technology International*, 28(5), 388–396. <https://doi.org/10.1177/10820132211016577>
- Hara, T., Matsui, K., Noda, T., & Tetsuka, T. (2007). Effects of preharvest sprouting on flour pasting viscosity in common buckwheat (*Fagopyrum esculentum* Moench). *Plant production science*, 10(3), 361–366. <https://doi.org/10.1626/pps.10.361>
- Hara, T., & National A. R. C. for K. O. R., Sasaki, T., Tetsuka, T., Ikoma, H., & Kohyama, K. (2009). Effects of sprouting on texture of cooked buckwheat (*Fagopyrum esculentum* Moench) noodles. *Plant Production Science*, 12(4), 492–496. <https://doi.org/10.1626/pps.12.492>
- Hernandez-Aguilar, C., Dominguez-Pacheco, A., Palma Tenango, M., Valderrama-Bravo, C., Soto Hernández, M., Cruz-Orea, A., & Ordóñez-Miranda, J. (2020). Lentil sprouts: A nutraceutical alternative for the elaboration of bread. *Journal of Food Science and Technology*, 57(5), 1817–1829. <https://doi.org/10.1007/s13197-019-04215-5>
- Huen, J., Börsmann, J., Matullat, I., Böhm, L., Stukenborg, F., Heitmann, M., Zannini, E., & Arendt, E. K. (2018). Wheat flour quality evaluation from the baker's perspective: Comparative assessment of 18 analytical methods. *European Food Research & Technology*, 244(3), 535–545. <https://doi.org/10.1007/s00217-017-2974-3>
- Ikeda, K., Fujiwara, J., Asami, Y., Arai, R., Bonafaccia, G., Kreft, I., & Yasumoto, K. (1999). Relationship of protein to the textural characteristics of buckwheat products: Analysis with various buckwheat flour fractions. *Fagopyrum*, 16(1), 79–83. <https://doi.org/10.1016/j.plaphy.2005.08.002>
- Ikram, A., Saeed, F., Afzaal, M., Imran, A., Niaz, B., Tufail, T., Hussain, M., & Anjum, F. M. (2021). Nutritional and end-use perspectives of sprouted grains: A comprehensive review. *Food Science & Nutrition*, 9(8), 4617–4628. <https://doi.org/10.1002/fsn3.2408>
- Karaduman, Y., Sayaslan, A., & Akın, A. (2020). GlutoPeak parameters of whole wheat flours for gluten quality evaluation in soft wheat breeding programs. *Journal of Cereal Science*, 95, 103031-. <https://doi.org/10.1016/j.jcs.2020.103031>
- Kim, J. H., Maeda, T., & Morita, N. (2006). Effect of fungal α -amylase on the dough properties and bread quality of wheat flour substituted with polished flours. *Food Research International*, 39(1), 117–126. <https://doi.org/10.1016/j.foodres.2005.06.008>
- Kim, S.-L., Kim, S.-K., & Park, C.-H. (2004). Introduction and nutritional evaluation of buckwheat sprouts as a new vegetable. *Food Research International*, 37(4), 319–327. <https://doi.org/10.1016/j.foodres.2003.12.008>
- Lebiedzinska, A., & Szefer, P. (2006). Vitamins B in grain and cereal-grain food, soy-products and seeds. *Food Chemistry*, 95(1), 116–122. <https://doi.org/10.1016/j.foodchem.2004.12.024>
- Liu, W., Brennan, M., Serventi, L., & Brennan, C. (2017). Buckwheat flour inclusion in Chinese steamed bread: Potential reduction in

- glycemic response and effects on dough quality. *European Food Research & Technology*, 243(5), 727–734. <https://doi.org/10.1007/s00217-016-2786-x>
- Lu, Z., & Seetharaman, K. (2014). Suitability of ontario-grown hard and soft wheat flour blends for noodle making. *Cereal Chemistry*, 91(5), 482–488. <https://doi.org/10.1094/CCHEM-10-13-0218-R>
- Mariotti, M., Alamprese, C., Pagani, M. A., & Lucisano, M. (2006). Effect of puffing on ultrastructure and physical characteristics of cereal grains and flours. *Journal of Cereal Science*, 43(1), 47–56. <https://doi.org/10.1016/j.jcs.2005.06.007>
- Mariotti, M., Lucisano, M., Pagani, M. A., & Iametti, S. (2008). Macromolecular interactions and rheological properties of buckwheat-based dough obtained from differently processed grains. *Journal of Agricultural and Food Chemistry*, 56(11), 4258–4267. <https://doi.org/10.1021/jf800009e>
- Marti, A., Augst, E., Cox, S., & Koehler, P. (2015). Correlations between gluten aggregation properties defined by the GlutoPeak test and content of quality-related protein fractions of winter wheat flour. *Journal of Cereal Science*, 66, 89–95. <https://doi.org/10.1016/j.jcs.2015.10.010>
- Marti, A., Cardone, G., Pagani, M. A., & Casiraghi, M. C. (2018). Flour from sprouted wheat as a new ingredient in bread-making. *Food Science & Technology*, 89, 237–243. <https://doi.org/10.1016/j.lwt.2017.10.052>
- Mattila, P. H., Pihlala, J.-M., Hellström, J., Nurmi, M., Eurola, M., Mäkinen, S., Jalava, T., & Pihlanto, A. (2018). Contents of phytochemicals and antinutritional factors in commercial protein-rich plant products. *Food Quality and Safety*. <https://doi.org/10.1093/fqsafe/fyy021>
- Mir, N. A., Riar, C. S., & Singh, S. (2018). Nutritional constituents of pseudo cereals and their potential use in food systems: A review. *Trends in Food Science & Technology*, 75, 170–180. <https://doi.org/10.1016/j.tifs.2018.03.016>
- Mota, C., Santos, M., Mauro, R., Samman, N., Matos, A. S., Torres, D., & Castanheira, I. (2016). Protein content and amino acids profile of pseudocereals. *Food Chemistry*, 193, 55–61. <https://doi.org/10.1016/j.foodchem.2014.11.043>
- Neacsu, M., De Lima Sampaio, S., Hayes, H. E., Duncan, G. J., Vaughan, N. J., Russell, W. R., & Raikos, V. (2022). Nutritional content, phytochemical profiling, and physical properties of bBuckwheat (*Fagopyrum esculentum*) seeds for promotion of dietary and food ingredient biodiversity. *Crops*, 2(3), 287–305. <https://doi.org/10.3390/crops2030021>
- Nikolić, N., Sakač, M., & Mastilović, J. (2011). Effect of buckwheat flour addition to wheat flour on acylglycerols and fatty acids composition and rheology properties. *Food Science & Technology*, 44(3), 650–655. <https://doi.org/10.1016/j.lwt.2010.08.017>
- Phiarais, B. N., Schehl, B. D., & Arendt, E. K. (2008). Protein changes during malting of buckwheat. *Journal of the American Society of Brewing Chemists*, 66(2), 127–135. <https://doi.org/10.1094/asbcj-2008-0102-01>
- Poutanen, K. (1997). Enzymes: An important tool in the improvement of the quality of cereal foods. *Trends in Food Science & Technology*, 8(9), 300–306. [https://doi.org/10.1016/S0924-2244\(97\)01063-7](https://doi.org/10.1016/S0924-2244(97)01063-7)
- Rabitti, N. S., Appiani, M., Marti, A., Buratti, S., Benedetti, S., Chiodaroli, G., Proserpio, C., & Laureati, M. (2022). Valorization of common (*Fagopyrum esculentum* Moench.) and tartary (*Fagopyrum tataricum* Gaertn.) Buckwheat in gluten-free polenta samples: Chemical-physical and sensory characterization. *Foods*, 11(21), 3442. <https://doi.org/10.3390/foods11213442>
- Rosell, C. M., & Garzon, R. (2015). Chemical composition of bakery products. *Handbook of Food Chemistry*, 191–224. https://doi.org/10.1007/978-3-642-41609-5_22-2
- Scanlon, M. G., & Zghal, M. C. (2001). Bread properties and crumb structure. *Food Research International*, 34(10), 841–864. [https://doi.org/10.1016/S0963-9969\(01\)00109-0](https://doi.org/10.1016/S0963-9969(01)00109-0)
- Selinheimo, E., Kruus, K., Buchert, J., Hopia, A., & Autio, K. (2006). Effects of laccase, xylanase and their combination on the rheological properties of wheat doughs. *Journal of Cereal Science*, 43(2), 152–159. <https://doi.org/10.1016/j.jcs.2005.08.007>
- Sergiacomo, A., Bresciani, A., Gallio, F., Varetto, P., & Marti, A. (2024). Sprouted oats (*Avena sativa* L.) in baked goods: from the rheological properties of dough to the physical properties of biscuits. *Food and Bioprocess Technology*. <https://doi.org/10.1007/s11947-024-03362-8>
- Setia, R., Dai, Z., Nickerson, M. T., Sopiwnyk, E., Malcolmson, L., & Ai, Y. (2019). Impacts of short-term germination on the chemical compositions, technological characteristics and nutritional quality of yellow pea and faba bean flours. *Food Research International*, 122, 263–272. <https://doi.org/10.1016/j.foodres.2019.04.021>
- Sofi, S. A., Ahmed, N., Farooq, A., Rafiq, S., Zargar, S. M., Kamran, F., Dar, T. A., Mir, S. A., Dar, B. N., & Mousavi Khaneghah, A. (2023). Nutritional and bioactive characteristics of buckwheat, and its potential for developing gluten-free products: An updated overview. *Food Science & Nutrition*, 11(5), 2256–2276. <https://doi.org/10.1002/fsn3.3166>
- Steadman, K. J., Burgoon, M. S., Lewis, B. A., Edwardson, S. E., & Obendorf, R. L. (2001). Minerals, phytic acid, tannin and rutin in buckwheat seed milling fractions. *Journal of the Science of Food and Agriculture*, 81(11), 1094–1100. <https://doi.org/10.1002/jsfa.914>
- Sturza, A., Paucean, A., Chis, M. S., Muresan, V., Vodnar, D. C., Man, S. M., Urcan, A. C., Rusu, I. E., Fostoc, G., & Sevastita, M. (2020). Influence of buckwheat and buckwheat sprouts flours on the nutritional and textural parameters of wheat Buns. *Applied Sciences*, 10(22), 7969-. <https://doi.org/10.3390/app10227969>
- Suárez-Estrella, D., Bresciani, A., Iametti, S., Marengo, M., Pagani, M. A., & Marti, A. (2020a). Effect of sprouting on proteins and starch in quinoa (*Chenopodium quinoa* Willd.). *Plant Foods for Human Nutrition (Dordrecht)*, 75(4), 635–641. <https://doi.org/10.1007/s11130-020-00864-6>
- Suárez-Estrella, D., Cardone, G., Buratti, S., Pagani, M. A., & Marti, A. (2020b). Sprouting as a pre-processing for producing quinoa-enriched bread. *Journal of Cereal Science*, 96, 103111-. <https://doi.org/10.1016/j.jcs.2020.103111>
- Ungureanu-Iuga, M., Atudorei, D., Codină, G. G., & Mironeasa, S. (2021). Rheological approaches of wheat flour dough enriched with germinated soybean and lentil. *Applied Sciences*, 11(24), 11706-. <https://doi.org/10.3390/app112411706>
- Wei, Y. M., Zhang, G. Q., & Li, Z. X. (1995). Study on nutritive and physico-chemical properties of buckwheat flour. *Food/nahrung*, 39(1), 48–54. <https://doi.org/10.1002/food.19950390106>
- Wijngaard, H. H., & Arendt, E. K. (2006). Buckwheat. *Cereal Chemistry*, 83(4), 391–401. <https://doi.org/10.1094/CC-83-0391>
- Wójtowicz, A., Kolasa, A., & Mościcki, L. (2013). Influence of buckwheat addition on physical properties, texture and sensory characteristics of extruded corn snacks. *Polish Journal of Food and Nutrition Sciences*, 63(4), 239–244. <https://doi.org/10.2478/v10222-012-0076-2>
- Xu, F., Gao, Q., Ma, Y., Guo, X., & Wang, M. (2014). Comparison of tartary buckwheat flour and sprouts steamed bread in quality and antioxidant property. *Journal of Food Quality*, 37(5), 318–328. <https://doi.org/10.1111/jfq.12101>
- Yang, Q., Luo, Y., Wang, H., Li, J., Gao, X., Gao, J., & Feng, B. (2021). Effects of germination on the physicochemical, nutritional and in vitro digestion characteristics of flours from waxy and nonwaxy proso millet, common buckwheat and pea. *Innovative Food Science & Emerging Technologies*, 67, 102586-. <https://doi.org/10.1016/j.ifset.2020.102586>