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Short communication

The effect of gradual flour addition during kneading on wholewheat dough properties and bread quality

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ABSTRACT

The increasing interest in unrefined flour-based products demands innovative strategies to improve dough properties and bread quality. This study investigated the effect of an empirical practice used by bakers – gradual flour addition during kneading – on wholewheat flour dough properties and bread quality. After optimizing the kneading operating conditions to perform gradual flour addition during kneading, a full factorial design tested gradual flour addition in the optimized dough samples as a function of total water content. Although gradual flour addition did not affect bread quality, the dough extensibility – *L* and swelling index – *G* improved significantly independently of the total water content. Significant interaction was observed between gradual flour addition and dough water amount; a reduction of dough tenacity – *P* and tenacity-to-extensibility ratio – *P/L* at Farinograph water absorption, and an increase of dough tenacity – *P* and flour strength – *W* at the highest water level were observed. Furthermore, the ^{1}H NMR results revealed different water redistribution and dynamics which could be interpreted as molecular phenomena associated with the macroscopic parameters. Gradually adding flour during kneading improved the rheology and workability of unrefined dough.

1. Introduction

Consumers' increasing interest in high nutritional value foods has led to a greater demand for unrefined wheat flour to make bread~~s~~ (Parenti, Guerrini, & Zanoni, 2020; Gómez, Gutkoski, & Bravo-Núñez, 2020). In the past, sensory features, convenience and price of food products were the main factors driving consumer choices, whereas today nutritional quality has become equally as important (Schaffer-Lequart et al., 2017). Although unrefined wheat flours have a better nutritional profile than refined wheat flours (Boukid, Folloni, Ranieri, & Vittadini, 2018; Hemdane et al., 2016), they are characterised by lower technological quality, giving ~~and sensory profile of~~ baked products with poor sensory profile (Heinio et al., 2016; Boukid et al., 2018; Hemdane et al., 2016), and making the use of unrefined flour in the bread-making process a challenge. Moreover, several studies have reported the detrimental impact of ~~milling by-products~~ using unrefined wheat flours on dough rheology. Indeed, unrefined dough has shown a higher rate of water absorption and hydration, greater tenacity and lower extensibility, resulting in poor bread quality (Messia et al., 2016; Gómez, Ronda, Blanco, Caballero, & Apesteguía, 2003; Banu, Stoenescu, Ionescu, & Aprodu, 2012; Gómez, Jiménez, Ruiz, & Oliete, 2011; Srivastava, Sudha, Baskaran, & Leelavathi, 2007; Gómez, González, & Oliete, 2012). The literature has mainly tried to improve the technological performances of unrefined wheat flours by pre-treating the raw materials, using sourdough fermentation and adding improvers to the formulation (Tebben, Shen, & Li, 2018; Parenti, Guerrini, & Zanoni, 2020; Parenti, Guerrini, Cavallini, Baldi, & Zanoni, 2020). Instead of adding improvers, bakers have developed empirical strategies adapted to the features of unrefined wheat flour to improve dough handling properties and bread quality (Guerrini, Parenti, Angeloni, &). A common bakers' practice is to gradually add part of bread ingredients (i.e., water and flour) during kneading, which would seem to improve the bread-making performance of unrefined wheat flours (Guerrini et al., 2019). Scant information is reported in the literature about the effect of gradually dosing bread ingredients during the kneading phase of the bread-making process (Parenti, Carini, et al., 2021; Yang, Guan, Zhang, Li, & Bian, 2019).

Given the above, the aim of the present study was to investigate the effect of the gradual addition of wholewheat flour (WWF) during kneading to understand the reasons for its widespread use among bakers. Two experimental trials were performed: (i) optimization of the

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kneading operating conditions, to properly test the gradual addition of flour; (ii) an in-depth investigation of the dough's molecular and macroscopic properties and bread quality as a function of flour addition and total water content.

2. Material and methods

2.1. Materials

The trials were performed with one batch of sp. *Triticum aestivum* L., cv. Verna. The wheat was stone milled and sieved (using a 1100–1200 μm sieve) at the Molino Paciscopi (Montespertoli, Florence, Italy) to obtain a wholewheat flour according to the Italian classification (i.e., extraction rate 98 g/100 g dry kernel, ash content 1.3–1.7 g/100 g dm) (Zhou, Therdthai, & Hui, 2014). The mineral water (Sant'Anna, Vinadio, Italy) and fresh brewer's yeast (Lievital, Trecasali, Italy) were purchased at a local market.

2.2. The experimental design

Two trials were performed to investigate the effect of gradual WWF addition:

(i) An optimization trial to determine the kneading operating conditions
(ii) A full factorial trial for in-depth evaluation of the effects of gradual WWF addition as a function of total water content.

2.2.1. The optimization trial

The optimization trial (*OT*) was performed using a Box-Behnken design (BBD) and Response Surface Methodology (RSM) to find the combination of variables for specific bread volume maximization. Three different levels of four independent variables were selected according to some preliminary trials: (i) total water content – W_a (i.e., 56%, 58% and 60% w/flour w); (ii) gradual WWF addition during kneading – F (i.e., 5%, 15%, 25% w/flour w); (iii) total kneading time – T (i.e., 14 min, 18 min, 22 min); (iv) WWF addition kneading time – t (i.e., 4 min, 7 min, 10 min). Farinograph water absorption, namely, the lowest water level, resulted 56%. The experimental conditions at the centre point were $W_a = 58\%$, $F = 15\%$, $T = 18$ min and $t = 7$ min.

The dough samples were identified by alphanumeric codes; for example, the *OT56:5:10:4* code identified the dough sample in the optimization trial with $W_a = 56\%$, $F = 5\%$, $T = 10$ min, $t = 4$ min.

2.2.2. The full factorial trial

The full factorial trial was performed to test the effects of the following two variables on the dough and bread quality: (i) gradual WWF addition during kneading – F; (ii) total water content – W_a.

The two variables were tested at two levels:

- $F = 5\%$ *vs* $F = 0\%$;
- $W_a = 56\%$ (i.e., Farinograph water absorption) *vs* $W_a = 60\%$ (i.e., optimized water amount from the RSM trial).

The above percentages are expressed as w/flour w. The WWF addition kneading time and the total kneading time were chosen according to the *OT* results.

The dough samples were labelled using an alphanumeric code; for example, the code *FFT56:5* identified the dough sample in the full factorial trial with $W_a = 56\%$ and $F = 5\%$.

2.3. Bread-making

The dough samples were prepared in 500 g batches; the bread formula and bread-making process followed the indications in Parenti, Carini, et al., 2021. Three replicates were performed.

2.4. Measurement methods

2.4.1. ^{1}H NMR measurements

The ^{1}H NMR Relaxometry technique was used to investigate the molecular mobility and dynamics of the WWF doughs at the optimum kneading time, in order to show the effect of variable F and its interactions with the total water content – W_a (F*W_a). A low-resolution (20 MHz) ^{1}H NMR spectrometer (the MiniSpec, Bruker Biospin, Milan, Italy) operating at 25.0 ± 0.1 °C and ^{1}H T_2 Carr-Purcell-Meiboom-Gill (CPMG) experiment were used. The measurements and experimental conditions were performed following Parenti, Carini, et al. (2021). Each replicate corresponded to a different dough batch for a total of four replications. Pop"X″ was the abbreviation for the relative abundance of population X, and $T_{2''X''}$ for the relaxation time of population X.

2.4.2. Dough rheology

Dough rheology was measured using the Brabender Farinograph (AACC 54-21.02) and the Chopin Alveograph (AACC 54-30.02) with the same modifications as reported in Parenti, Carini, et al. (2021). Three replicates were performed.

2.4.3. Bread quality

Bread specific volume (L/kg), crumb specific volume (L/kg), crumb and crust moisture contents (g/100 g), and Texture Profile Analysis (TPA) of the bread samples were performed according to Parenti, Carini, et al. (2021). Three replicates were performed.

2.5. Data processing

In the *OT*, bread quality in terms of bread specific volume was estimated using RSM based on the Box-Behnken design (BBD). The second-order model proved to be the most appropriate. The results were examined using R software; the RSM was estimated by partial least square (PLS) for the 28 runs of the BBD design. From the response variable, model summary and lack-of-fit tests were performed considering linear and quadratic models. The bread-making conditions maximizing the bread specific volume were considered optimal.

In the *FFT*, data were analysed with two-way ANOVA to assess significant differences ($p < 0.05$) resulting from the tested variables (i.e., gradual WWF addition – F, total water content – W_a and their interaction – F*W_a).

3. Results

3.1. The optimization trial

The optimization trial investigated the operating conditions to optimize bread quality when performing gradual WWF addition during kneading. The model considered first order, second order and interaction terms to fit the data. The p value of the effectiveness of the model was 0.011 and the lack-of-fit was above the 5% significance level, showing that the RSM model accurately predicts the bread specific volume.

The data showed that W_a, W_a^2 and F*T interaction greatly affected the bread specific volume. We found a maximum specific volume in the considered water range at 60% W_a. Considering F*T interaction, a significant improvement in the bread specific volume can be obtained by combining $F = 5\%$ (w/flour w) with T of approx. 18 min.

Specifically, the combinations $W_a = 60\%$ with $F = 5\%$, $W_a = 60\%$ with $T = 18$ min and $W_a = 60\%$ with $t = 5$ min gave the highest bread specific volume. Therefore, the bread specific volume was found to be optimized in the *OT60:5:18:5* dough samples, that is, with $W_a = 60\%$, $F = 5\%$, $T = 18$ min and $t = 5$ min.

Thus, the above operating conditions were used in the full factorial

Table 1
^{1}H NMR characterization at optimum kneading time (18 min) of *FFT* dough samples.

^{1}H NMR parameters	Samples				*SE*	*p W_a*	*p F*	*p W_a*F*
	FFT60:5	FFT60:0	FFT56:5	FFT56:0				
popC (%)	9.06^a	9.60^a	9.90^b	9.39^b	0.17	*	ns	*
T_{2C} (ms)	0.35	0.27	0.26	0.32	$2.61\ 10^{-3}$	ns	ns	**
popD (%)	27.63^a	27.57^a	28.34^b	28.32^b	0.42	**	ns	ns
T_{2D} (ms)	3.54	3.41	3.33	3.40	0.02	ns	ns	ns
popE (%)	56.25	55.56	55.07	55.31	5.83	ns	ns	ns
T_{2E} (ms)	13.69	13.26	12.63	13.13	1.93	ns	ns	ns
popF (%)	7.06	7.27	6.69	6.98	2.65	ns	ns	ns
T_{2F} (ms)	48.95	49.02	47.70	49.27	5.81	ns	ns	ns

^{1}H NMR parameters: relative abundance of population C (popC, %), population D (popD, %), population E (popE, %) and population F (popF, %); relaxation time of population C (T_{2C}, ms), population D (T_{2D}, ms), population E (T_{2E}, ms) and population F (T_F, ms). Data are expressed as mean ± SE. *p W_a*, *p F* and *p W_a*F* represent the effects of the tested factors: W_a refers to total dough water, *F* to the addition of 5% of WWF (w/flour w) after 5 min of kneading, and W_a**F* represents the interaction between these factors. *, and ** indicate significant differences at $p < 0.05$, and $p < 0.01$ respectively. "ns" indicates no significant differences at $p < 0.05$. Means in a raw with different superscripts are significantly different ($p < 0.05$); specifically, "a" and "b" refer to W_a main effect.

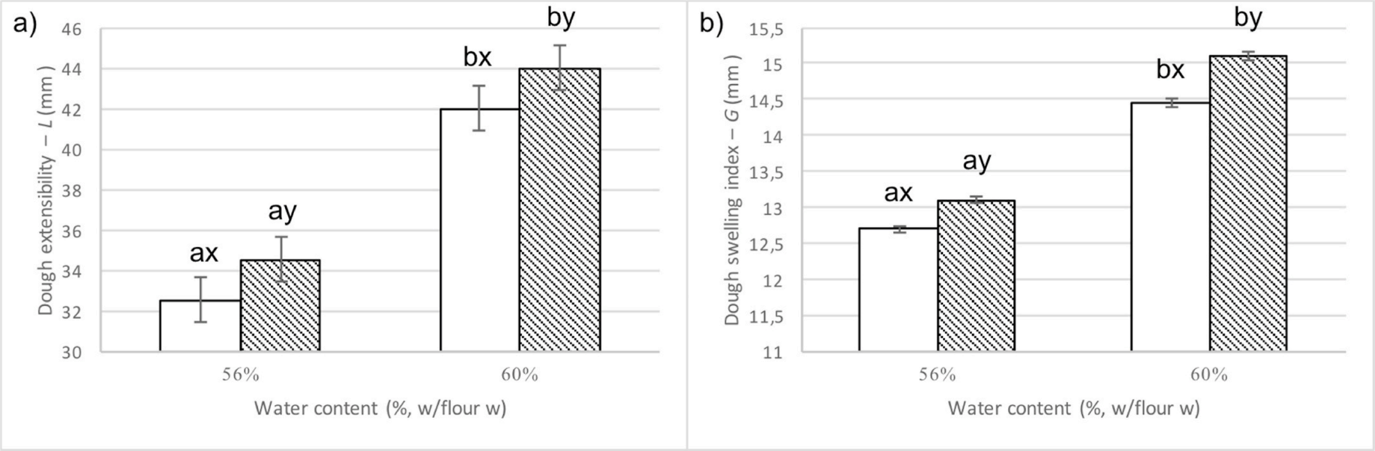

Fig. 1. Alveograph parameters: (a) Dough extensibility – *L* (mm) and (b) Dough swelling index – *G* (mm) as affected by the main effect of the gradual flour addition – *F* (0% *vs* 5%, w/flour w), and the main effect of total water content – W_a (Farinograph water absorption = 56% *vs* optimized water amount from RSM trial 60%, w/flour w). White bars represent *CTR* samples = 0% flour addition (w/flour w), whereas striped bars correspond to *F* samples = 5% flour addition (w/flour w). Bars marked with different letters are significantly different ($p < 0.05$) specifically, "a" and "b" refer to W_a main effect, whereas "x" and "y" refer to *F* main effect.

trial since they were optimal for performing the gradual WWF addition. Then, $T = 18$ min was fixed as the optimal kneading time, and the effect of gradual WWF addition, *F* (i.e., 5% *vs* 0%, w/flour w) tested as a function of total water content, W_a (i.e., optimized 60% *vs* Farinograph 56%).

3.2. *Full factorial trial*

3.2.1. *^{1}H NMR molecular mobility at the optimal kneading time*

The ^{1}H NMR data of unrefined dough showed the presence of four protons populations, identified as popC, popD, popE and popF, from the least to the most mobile proton population, respectively. According to the ^{1}H T_2 relaxation times ranges of the four populations observed ($T_{2C} = 0.22$–0.44 ms, $T_{2D} = 3.32$–3.66 ms, $T_{2E} = 12.47$–13.99 ms, and $T_{2F} = 47.39$–50.00 ms) and to the literature (Bosmans et al., 2012; Parenti, Guerrini, et al., 2021), they were related to specific wheat flour biopolymers - water interactions. PopE, the most abundant population (54.85–56.57%), was assigned to the overlapped populations of starch extra-granular water and water in the gluten matrix; popD (27.19–28.59%) corresponded to hydroxyl protons of intra-granular water and starch, and some CH protons of gluten and exchanging protons of confined water and gluten; popC (8.87–10.23%) was attributed to CH protons of amorphous starch and CH protons of gluten in the sheets with little contact with the confined water (Bosmans et al., 2012), and popF (6.48–7.20%) to weakly bound protons of water (Li, Deng, Li, Liu, & Bian, 2015; Lu & Seetharaman, 2013; Wang et al., 2017).

The effect of *F* and its interaction with variable W_a (*F**W_a) on ^{1}H NMR mobility and dynamics was tested on the dough samples kneaded for the optimum kneading time (Table 1). Although *F* did not show any significant main effects, W_a**F* interaction significantly affected popC ($p < 0.01$) and T_{2C} ($p < 0.01$). A significant increase in popC was observed in *FFT56:5* compared to *FFT56:0* (9.90% vs 9.39%). Conversely, *F* significantly reduced popC in *FFT60:5* compared to *FFT60:0* (9.06% vs 9.38%). T_{2C} was significantly reduced by variable *F* in *FFT56:5* compared to *FFT56:0* (0.26 ms vs 0.32 ms), whereas *F* increased the parameter in *FFT60:5* compared to *FFT60:0* (0.35 ms vs 0.25 ms).

W_a significantly affected popC ($p < 0.05$) and popD ($p < 0.01$); both parameters increased in doughs with the highest water content *FFT60:0-FFT60:5* compared to doughs with the lowest water content *FFT56:0-FFT56:5* (9.64% vs 9.22%, and 28.33% vs 27.18%, respectively) consistently with Parenti, Guerrini, et al. (2021).

3.2.2. *Dough rheology*

The Alveograph results are shown in Figs. 1 and 2. Consistently with the literature, W_a affected all the rheological parameters (Cappelli et al., 2018; Parenti, Carini, et al., 2021). Variable *F* significantly affected the dough extensibility – *L* ($p < 0.05$) and swelling index – *G* ($p < 0.01$), and W_a**F* interaction significantly impacted the dough tenacity – *P* ($p < 0.01$), flour strength – *W* ($p < 0.01$) and *P/L* ($p < 0.01$).

The *FFT56:5-FFT60:5* dough samples were characterised by a

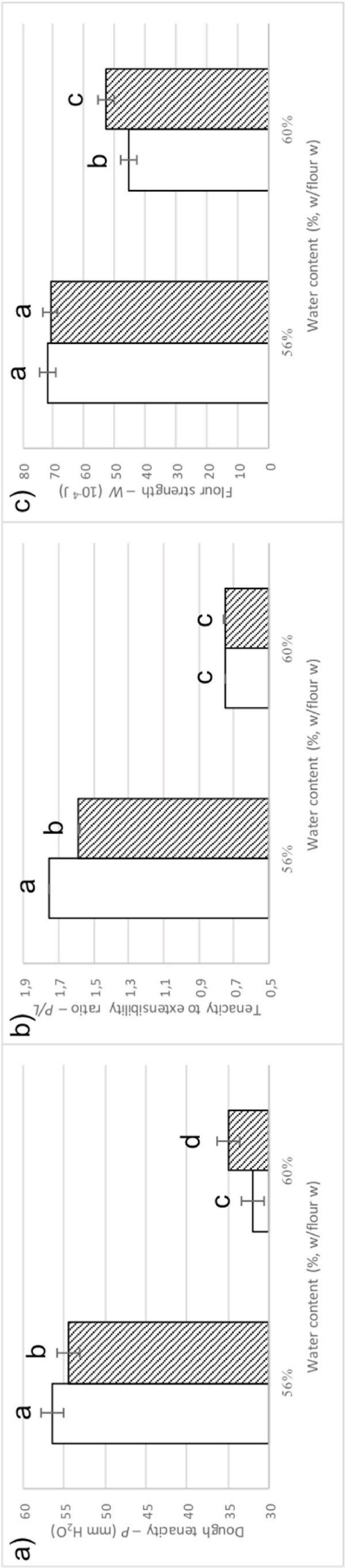

Fig. 2. Alveograph parameters: (a) Dough tenacity – P (mm H_2O), (b) Tenacity to extensibility ratio – P/L and c) Flour strength – W (10^{-4} J) as affected by the interaction between the gradual flour addition (0% *vs* 5%, w/flour w) and the total water content (Farinograph water absorption = 56% *vs* optimized water amount from RSM trial 60%, w/flour w) – F^*W_a. White bars represent *CTR* samples = 0% flour addition (w/flour w), whereas striped bars correspond to *F* samples = 5% flour addition (w/flour w). Bars marked with different letters are significantly different as a function of the interaction F^*W ($p < 0.05$).

significantly higher L (approx. 5.4%), and G (approx. 4%), compared to the *FFT56:0-FFT60:0* dough samples (Fig. 1).

$W_a{}^*F$ interaction revealed that F showed different effects on P, W and P/L as a function of the level of W_a. The most relevant effects are reported in Fig. 2. In the dough samples with the lowest water content (*FFT56:0-FFT56:5*), F caused a significant decrease in P (approx. 3.5%) and P/L (9.7%). Conversely, in the dough samples with the highest water content (*FFT60:0-FFT60:5*), F produced a significant increase in P (approx. 9.4%) and W (approx. 16.5%).

3.2.3. Bread quality

The *FFT* bread quality results are shown in Table 2. W_a significantly affected bread quality, whereas F and $W_a{}^*F$ did not significantly impact the bread properties. Particularly, the *FFT60:5-FFT60:0* samples showed a higher bread-specific volume than the *FFT56:5-FFT56:0* samples ($p <$ 0.05), with values of 3.22 ± 0.07 L/kg and 3.01 ± 0.07 L/kg, respectively. Crumb specific volume was not affected by W_a, but this factor significantly impacted the crumb texture: the higher the water amount, the better the bread texture. Hardness was significantly reduced ($p <$ 0.01) in the *FFT60:5-FFT60:0* samples compared to the *FFT56:5-FFT56:0* samples (3.293 ± 0.526 N and 4.252 ± 0.255 N, respectively). Cohesiveness exhibited the opposite trend ($p < 0.05$), growing from 0.260 ± 0.026 in the *FFT56:5-FFT56:0* samples to 0.302 ± 0.045 in the *FFT60:5-FFT60:0* samples.

4. Discussion

The literature has mainly proposed the use of improvers to enhance the technological performance of unrefined flours (Parenti, Guerrini, & Zanoni, 2020; Gómez et al., 2020), whereas bakers have attempted to adapt the bread-making conditions to the flour's requirements (Guerrini et al., 2019; Parenti, Carini, et al., 2021). In order to understand the reasons for the shared bakers' practice (Guerrini et al., 2019) of gradually adding bread ingredients (i.e., water and flour) during kneading, we investigated the effect of the gradual addition of WWF as a function of two water levels: the water amount optimized in the RSM trial and the Farinograph water absorption, a standard parameter used in both the literature and baking industry.

The present discussion focuses on the effect of gradual WWF addition and its interaction with the total water content, since the main effect of total water content has already been discussed elsewhere (Parenti, Guerrini, et al., 2021).

The gradual flour addition significantly affected dough extensibility – L and swelling index – G in a similar way to the results of Parenti, Carini, et al. (2021), showing that the gradual addition of bread ingredients enhanced dough extensibility properties independently of the total water content (Fig. 1). Since dough from unrefined wheat flours are generally characterised by significantly reduced extensibility (Gómez et al., 2003; Banu et al., 2012; Gómez et al., 2011; Srivastava et al., 2007; Gómez et al., 2012), and a negative correlation between dough extensibility and flour ash content has been reported in the literature (Indrani, Manohar, Rajiv, & Rao, 2007), practices able to enhance this parameter are important for improving the bread-making performances of unrefined flours.

The other Alveograph parameters were significantly affected by F^*W_a (Fig. 2), whereas the gradual water addition only showed one main effect (Parenti, Carini, et al., 2021). In doughs prepared at Farinograph water absorption, the gradual flour addition caused a significant decrease in P (3.5%), leading to a similar reduction in P/L to that observed with gradual water addition (9.7% *vs* 10%) (Parenti, Carini, et al., 2021). These rheological effects are particularly relevant for unrefined flours since, besides less dough extensibility, unrefined doughs are generally characterised by increased P and P/L, which causes poor dough handling properties and low-quality breads (Messia et al., 2016; Gómez et al., 2003; Banu et al., 2012; Gómez et al., 2011; Srivastava et al., 2007).

Table 2
Quality characteristics of *FFT* bread samples.

Parameter	Samples				*SE*	$p\ W_a$	$p\ F$	$p\ W_a{*}F$
	FFT60:5	FFT60:0	FFT56:5	FFT56:0				
Bread specific volume (L/kg)	3.25^a	3.20^a	3.05^b	2.98^b	0.11	*	ns	ns
Crumb specific volume (L/kg)	3.33	3.23	3.07	2.98	0.16	ns	ns	ns
Crumb moisture/dough moisture	95.50	95.53	95.50	94.37	0.55	ns	ns	ns
Crust moisture/dough moisture	53.99	53.55	53.09	53.05	1.16	ns	ns	ns
Hardness (N)	2.775^a	3.373^a	4.087^b	4.417^b	0.434	**	ns	ns
Cohesiveness	0.325^a	0.279^a	0.248^b	0.271^b	0.034	*	ns	ns
Springiness (mm)	0.773	0.771	0.759	0.759	0.040	ns	ns	ns
Chewiness (N mm)	0.837	0.727	0.775	0.912	0.216	ns	ns	ns

Data are expressed as mean ± SE. $p\ W_a$, $p\ F$ and $p\ W_a{*}F$ represent the effects of the tested factors: W_a refers to total dough water, F to the addition of 5% of WWF (w/flour w) after 5 min of kneading, and $W_a{*}F$ represents the interaction between these factors. *, and ** indicate significant differences at $p < 0.05$, and $p < 0.01$, respectively. "ns" indicate no significant differences at $p < 0.05$. Means in a raw with different superscripts are significantly different ($p < 0.05$) specifically, "a" and "b" refer to W_a main effect.

At the water level optimized in the RSM trial, the gradual flour addition determined a significant increase of P (approx. 9.4%) and W (approx. 16.5%). Since dough prepared at the optimal water level (i.e., the highest level) were characterised by the lowest P and W values resulting from the water main effect, the gradual addition of flour significantly improved dough rheological and handling properties.

The ^{1}H NMR data may be tentatively related to the Alveograph results: Indeed, PopC, T_{2C} and P were significantly affected by the interaction between gradual flour addition and dough water amount ($W_a{*}F$). This result may reveal that the changes in popC and T_{2C} parameters as a function of the $W_a{*}F$ interaction may account for the changes in dough tenacity – P Hemdane et al. (2017) showed that wheat dough with added bran had less resolved proton populations and a higher relative abundance of popC, popE and popF compared to refined wheat dough. Hence, the significant increase of the relative abundance of popC in doughs at the lowest water level may be interpreted as a better hydration of the bran constituents which may account for the lower dough tenacity and improved tenacity-extensibility ratio. On the other hand, the observed rheological effect might be also related to the overall different water redistribution and dynamics among all the protons populations. Anyway, these findings are worth of interest and further investigation is required to better investigate the correlation between ^{1}H NMR and Alveograph parameters.

Neither F nor $F{*}W_a$ significantly affected bread quality, consistently with Parenti, Carini, et al. (2021).

Therefore, adding flour during kneading significantly enhanced dough extensibility. At the Farinograph water absorption the gradual flour addition improved the dough tenacity and tenacity-to-extensibility ratio, whereas at the optimal water level an increase of dough tenacity and flour strength was obtained. As a result, gradually adding flour during kneading produced an improvement of the rheological parameters and handling properties of unrefined dough. These reasons could account for the widespread use of this technique among bakers working unrefined flours.

5. Conclusions

Gradual flour addition during kneading is an empirical strategy commonly adopted by bakers working unrefined wheat flours. The present study showed that gradual flour addition significantly improved Alveographic parameters of WWF dough: a significant increase of dough extensibility (L) and swelling index (G) was observed independently of total dough water amount. Furthermore, the gradual flour addition significantly interacted with total dough water amount; WWF doughs at Farinograph water absorption had significantly lower tenacity (P) and an improved tenacity-to-extensibility ratio (P/L), whereas dough at the optimal water amount showed an increase of dough tenacity (P) and flour strength (W). The ^{1}H NMR data showed changes of water redistributions and dynamics as a function of the interaction between the gradual flour addition and water level, which were tentatively ~~cor~~related to the rheological effects. Bread quality was not significantly affected by the gradual WWF addition.

Overall, gradually adding flour during the kneading operation of unrefined dough could partially counteract the low value of dough extensibility that characterised unrefined wheat dough. Moreover, this strategy allowed to obtain further improvements of the dough rheology as a function of the water amounts, improving the rheological and handling properties of unrefined dough.

CRediT authorship contribution statement

Ottavia Parenti: Conceptualization, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing. **Lorenzo Guerrini:** Conceptualization, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Eleonora Carini:** Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Bruno Zanoni:** Conceptualization, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

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

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