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Original article

A study on relationships between durum wheat semolina properties, technological mixing parameters and the properties of dough after mixing

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Summary Partial least square regression analysis was used to study the correlation between X variables (semolina quality, hydration level and mixing time) and Y variables, which were, in a first model, dough consistency during mixing, and, in a second model, dough properties after mixing (strength, elasticity, density) and leavening (maximum volume). The first model showed a predictive residual sum of squares (PRESS) of 2.98 and a predictive R^2 (Q^2) of 0.92, and highlighted the key role of hydration and mixing time on dough consistency. The second model had the best PRESS (8.25) and Q^2 (0.94) values for dough volume and indicated that the volume increased with increasing mixing time until the dough consistency decreased of 20–30%. Dough volume was primarily affected by hydration. The model indicated that maximum volume after leavening, corresponding to optimum mixing time, was obtained with a soft and elastic dough, with a low-density value.

Keywords Chopin Consistograph, dough mixing, partial least square regression, semolina.

Introduction

Although semolina from durum wheat (*Triticum turgidum ssp. durum*) is the raw material of preference for making high-quality pasta and cous cous, its protein characteristics make it suitable for production of hearth and flat breads with unique sensorial and textural characteristics. Various types of regional baked products are consumed particularly in Middle East and Mediterranean countries, where durum wheat is traditionally grown. Durum wheat market demand for baked product is increasing (Palumbo *et al*., 2000), due to a renewed interest in market channels for specialty and traditional bread. Mixing is the first step in bread-making process and consists in combining the ingredients in order to develop a dough with suitable visco-elastic properties (Sluimer, 2005). During mixing, the mechanical energy is transferred to the gluten proteins that become hydrated, forming a network entrapping starch granules. In order to obtain a good bread product, the mixing step should develop an appropriate dough structure, with an optimum capacity for retaining the carbon dioxide produced during the fermentation step, and supporting all the manipulations (dividing, rounding, moulding) of the process. The mixing process is influenced by a number of factors, as raw material characteristics, type of mixer, the temperature, the amount of water, the addition of other ingredients and the mixing time (Cauvain & Young, 2006b). During the mixing process, the dough goes from 'underdeveloped', with a poor gluten structure, to 'properly developed', with an appropriate gluten network and finally 'overdeveloped', a soft, extensible and sticky dough that is undesired because of reduced machinability. On the other hand, extended mixing time is considered favourable for the loaf volume and softness of the crumb (Sluimer, 2005). Dubois *et al*. (2008) reported that a modification of the mixing time, using the Alveograph, can modify the dough extensibility (L) and strength (W), whereas dough tenacity (P) was unaffected.

The formation of the dough during mixing has been studied by a number of instruments, as the Brabender® Farinograph, the Mixograph, the Rheomixer and the Chopin Alveograph (Hajšelová & Alldrick, 2003). The Chopin Consistograph measures the hydration potential of a flour or semolina. The pressure applied by the dough to a sensor during mixing is registered as a curve, plotting the pressure in ordinate and the mixing time in

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abscissa. The dough consistency and relative measured pressure are the functions of the dough hydration rate, and the water absorption needed to reach target consistency, named PrMax, is calculated. Too little water gives a stiff dough with a high viscosity, but too much water gives a soft dough, which may not maintain the shape during manipulation (Cauvain & Young, 2000).

Dough properties and the resulting bread quality are influenced by several factors, and numerous scientific papers have described the effect of different types of mixers, mixing speed, temperature and ingredients, on the properties of wheat doughs (Chin & Campbell, 2005a,b; Connelly & McIntier, 2008; Ktenioudaki *et al.*, 2010). To our knowledge, only a few researches have been carried out on the behaviour of doughs made with semolina of different extraction rate, during the mixing process (Rao *et al.*, 2001). Moreover, the dough samples have been prepared by means of the Chopin Consistograph mixer, and the Chopin Consistograph has never been used to measure key mixing variables and to correlate them with dough properties and leavening performances.

In this work, the relationships between the properties of durum wheat semolina, the technological parameters taken into account during the mixing phase (i.e. hydration level and mixing time) and the properties of dough after mixing were studied, with the purpose of building an empirical model. Such a model should be able to predict the baking performances via the properties of a leavened dough (namely maximum dough height), by combining the chemical and rheological properties of semolina, which are easily available at industrial level (i.e. ash and protein content, Alveograph indexes), and two technological parameters of process, *that is,* hydration level of the dough and mixing time, which are under the control of the baker's hand.

Materials and methods

Raw materials

Three commercial durum wheat blends, named L, G2 and New, were conditioned to 15% moisture and milled in an Industrial mill, in Sardinia (Italy), to produce semolina (S) and low-grade semolina (LGS), which differ in particle size distribution and extraction rate. Ashes (%), protein content (% N $\times$ 5.7), calculated on dry basis (d.b.), granularity (% as is basis) as well as gluten index (GI; %) and dry gluten content (%d.b.) were measured using AACC Approved Method 08-12, 46-12, 66-20, 38-12A, respectively (AACC, 2000). SDMatic analyzer (Chopin, France) was used to measure the amount of absorbed iodine (AI%) from damaged starch in semolina and LGS samples, according to the AACC Approved Method 76-33 (AACC, 2000). Alveograph (AACC Approved Method 54-30A, adapted to durum wheat as per Dubois *et al.*, 2008) was used to measure overpressure (P), average abscissa to rupture (L), configuration ratio (P to L ratio) and deformation energy (W). Five dough pieces were analysed per sample and data were averaged. A Consistograph (Chopin, France) was used to determine water absorption capacity (Hydha%, 15% moisture basis, m.b.) and the time required to reach target consistency (TPrMax, s), following the AACC Approved Method 54-50 (AACC, 2000). The properties of the S and LGS samples used in this work are described in Table 1.

Dough mixing

The doughs were prepared in the Consistograph mixer, set at 25 °C, by mixing 250 g of semolina or LGS, 1.8% (w/w) of sodium chloride (Sigma-Aldrich, Milano, Italy), 1% of baker's yeast (AB Mauri Group, Italy) and the amount of water (v/w) required to obtain a dough at optimal or at suboptimal hydration (Table 1). The optimal hydration (Table 1) was based on the Hydha value determined with the Consistograph; the suboptimal was arbitrarily set to 80% of the optimal hydration (Table 1). Three different mixing time were established: T1-time required for reaching maximum dough consistency (i.e. TPrMax in the Consistograph curve); T2-7,5 min of mixing, which is the time required to complete a Consistograph cycle; T3-an extra mixing time of 7 min after T2. At the end of mixing, the dough was removed from the mixer and divided in pieces. Two of them (88 g each) were used for a leavening trial, 100 g for a stress relaxation test, and the remaining was used to study the dough density (20 g) and glutenin macropolymer (50 g). The experiment was carried out in duplicate.

The leavening trial was performed by transferring 88 g of dough into graduated glass cylinders. The dough was left at 25 °C, for at least 3 h. The increase in volume (mL) was monitored every 30 min until the maximum volume was reached.

The stress relaxation test was carried out as described by Singh *et al.* (2006). A TA.XT2i Texture Analyzer (Stable Micro Systems Ltd., Godalming, Surrey, UK) equipped with a 25-kg load cell and a S/P 35 probe, was used, and data were processed with the Texture Expert Exceed software version 2.64. After mixing, 100 g of dough were removed from the mixer and sheeted on the sheeting system of the Alveograph (AACC Approved Method 54-30A). Three dough discs obtained from each dough sample were analysed. The dough disc was compressed to a 20% strain, and the modification in force vs. time was measured. A pretest speed of 5 mm s^{-1} and test speed of 0.5 mm s^{-1} were

Table 1 Properties of durum wheat samples and hydration levels used in the dough mixing

Blend	Extraction rate	Granules <180 μm (% as is basis)	Ashes (%d.b.)[a]	Protein content (%d.b.)	Dry Gluten content (%d.b.)	Gluten index (%)	AI[b] (%)	Optimal hydration[c] (%, v/w)	Suboptimal hydration[d] (%, v/w)	Alveograph indexes P (mm)	L (mm)	W ($J \times 10^{-4}$)	P/L
G2	Semolina	0.07 ± 0.01	0.82 ± 0.01	11 ± 0.1	7.6 ± 0.1	92 ± 0.2	61 ± 0.3	44.9	35.9	58	38	92	1.52
	Low-grade semolina	21.40 ± 0.09	1.04 ± 0.01	11 ± 0.1	8.7 ± 0.1	96 ± 0.6	92 ± 0.3	44.3	35.4	85	39	132	2.17
L	Semolina	0.14 ± 0.04	0.64 ± 0.01	12 ± 0.1	9.8 ± 0.5	71 ± 1.5	61 ± 0.6	45.8	36.6	58	55	110	1.1
	Low-grade semolina	42.72 ± 0.13	1.02 ± 0.01	13 ± 0.1	12 ± 0.04	70 ± 1.4	92 ± 0.3	50.7	40.6	83	46	133	1.8
New	Semolina	0.06 ± 0.02	0.64 ± 0.02	10 ± 0.1	7 ± 0.7	91 ± 1.3	55 ± 0.2	42.7	34.2	47	37	69	1.27
	Low-grade semolina	48.45 ± 0.15	0.99 ± 0.01	13 ± 0.1	11 ± 0.1	80 ± 1.6	93 ± 0.2	46.0	36.8	74	42	114	1.76

[a]d.b. = dry basis.
[b]Absorbed iodine from damaged starch.
[c]2200-mbar equivalent hydration rate based on 15% water.
[d]80% of the optimal hydration.

used. The dough strength (Fmax; N) and the elasticity (ratio between force at 30 s and maximum force;%) for each dough were calculated.

Dough density (g cm^{-3}) was determined using the analytical balance Sartorius ME235S (Sartorius AG, Goettingen, Germany) equipped with the Sartorius YDK01 density determination kit. For glutenin macropolymer (GMP, g) determination, 5 g of freeze-dried dough samples was dispersed into 75 mL of hexane (Sigma-Aldrich Srl, Milano, Italy), mixed for 15 min, and centrifuged for 10 min at 4150 ***g*** at room temperature. Residual hexane was removed by overnight evaporation in a chemical fume hood. Distilled water and 12% (w/v) sodium dodecyl sulphate (SDS) solution were added to obtain a final SDS concentration of 1.5%. After centrifugation for 30 min at 80 000 ***g*** and 20 °C, the supernatant was removed and according to Primo-Martin *et al.* (2005), the GMP was measured as wet weight.

Statistical analysis

Statistical analysis was carried out with Systat 13 (Systat Software Inc., Chicago, IL, USA). Partial least square regression models (PLS1 and PLS2; Wold *et al.*, 2001) were estimated using the SIMPLS algorithm.

Results and discussion

Effect of semolina quality and mixing parameters on dough consistency (pressure at the Consistograph)

The pressure value recorded in the Consistograph is a function of hydration and dough properties, and can be considered a measure of dough consistency (Dubois *et al.*, 2008). In this work, the relationship between mixing time and pressure measured at the Chopin Consistograph was nonlinear, but a log transformation of both values resulted in a satisfactory linear relationship for almost all combinations (data not shown). The pressure showed a decrease in all samples as the mixing time increased. All the variables (type of blend, extraction rate and hydration) affected both the slope and the intercept of the line.

In a typical Consistograph curve, after the maximum pressure has been reached, a decay in dough pressure is shown (Dubois *et al.*, 2008). In this work, the first mixing time considered (T1) corresponds to the maximum pressure, and then further measurements were carried out after the maximum pressure has been reached, as the pressure decayed.

In order to predict the effect of mixing time, hydration and the chemical–physical properties of S and LGS samples on the consistency of the dough, a partial least square (PLS) regression model was developed using log(pressure) as dependent variable and log(mixing time), hydration, and the quality parameters reported in Table 1 (ashes, damaged starch, protein content, dry gluten content, gluten index and Alveograph indexes) as independent variables. All variables were centred (by subtracting the mean) and scaled (by dividing by standard deviation) prior to the analysis. Because only thirty-six data points were available, cross-validation was performed using the jackknife procedure.

A model with four components had a good predictive value, and explained 94 and 94.2% of the X and Y variance, respectively. Predictive R^2 (Q^2) and predictive residual sum of squares (PRESS) (Wold *et al.*, 2001) were 0.92 and 2.98, respectively. 90% of the predicted values departed from the experimental values of 1.6% or less. The coefficients of the model and their standard errors are shown in Table 2. The two most important variables were hydration and mixing time, both of which negatively affected the consistency of the dough, while all the other variables had a smaller influence, indicating the prevailing role of technological parameter on dough consistency with respect to the characteristic of the raw materials. In addition to providing a predictive model, partial least square models allow to explore the structure of the data: the relationship among groups of observations can be explored in the score plot and interpreted using X-loadings and Y-loadings. An X-score and X-loading plot for the first two components are shown in Fig. 1a, b, respectively. The Y-loadings for log(pressure) are oriented from lower left corner to upper right corner (not shown). The points corresponding to the different blends/extraction rate/hydration combinations are distributed from the lower left corner to the upper left corner as a function of increasing mixing time (log mixing time), which is inversely related to log(pressure). Dough hydration loads on component 1 only, while variables related to composition influence the position of the pressure vs. mixing time lines rather than their slope. For each variety, S and LGS are clearly separated around the diagonal of the graph. As expected, the separation is affected by compositional parameters all of which are strongly correlated (as shown by the direction of the loading vectors).

Table 2 Regression coefficients for a PLS model relating log(pressure) to log(mixing time), hydration and properties of semolina

	Estimate	Standard error
Constant	0.000	0.047
Hydration (%)	−0.658	0.056
Ashes (%)	0.021	0.039
Damaged starch (AI%)	−0.019	0.033
Gluten index (%)	−0.014	0.054
Dry gluten (%)	−0.008	0.018
Protein content(%)	−0.011	0.040
Alveograph Indexes		
P (mm)	0.002	0.025
L (mm)	−0.016	0.055
W (J 10^{-4})	0.003	0.037
P/L	0.004	0.017
log(mixing time) (s)	−0.827	0.061

Effect of semolina quality and mixing parameters on dough properties after mixing and leavening

The relationships between properties of Ss and LGSs, technological parameters, and properties of dough after mixing were studied. The properties of dough after mixing were: density, strength, elasticity and GMP, measured immediately after dough preparation, and the volume of dough after a leavening process performed by baker's yeast. The last was considered as a key dough parameter, since it is fundamental in bread-making process to obtain a well-textured bread.

Neither pressure nor mixing time had a linear, monotonic relationship with dough properties, as volume after leavening. Fig. 2a, b show the relationship between mixing time and the increase of dough volume after leavening for the two extraction rates. A quadratic smoother suggested that, at least in the experimental interval used in this study, a quadratic relationship could empirically be used to predict dough volume from mixing time. Similar quadratic trends were also found for the other variables (strength and elasticity, density and GMP, data not shown).

For most combinations, dough volume after leavening apparently increased with increasing mixing time, with a maximum which corresponded the time needed to obtain 70–80% of the maximum pressure measured at the Consistograph (Fig. 3).

In order to explore the relationships between X variables describing flours (ashes, damaged starch, protein, dry gluten, gluten index and Alveograph indexes) and technological properties (hydration, mixing time), and dependent Y variables describing dough properties after mixing (density, strength, elasticity, glutenin macropolymer and volume after leavening), a PLS2 (Wold *et al.*, 2001) model was built. Because independent replicates were used for different Y measurements, and because leavened dough volume was the variable that was of more interest, raw data were used for leavened dough volumes while average values were used for strength, elasticity, glutenin macropolymer and dough density. A quadratic transformation was used for mixing time, and all variables were centred and scaled as described in the previous section. Cross-validation was carried out by resampling (a random subsample of 20% of the cases was used for cross-validation).

A model with six components explained 99.5% of the X variance and 79.1% of Y variance. The model had

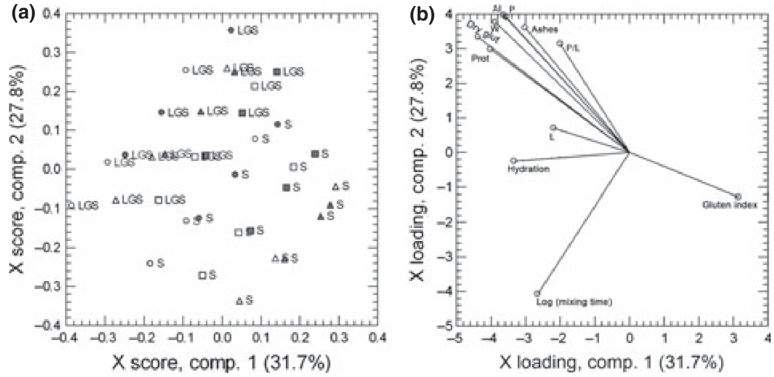

Figure 1 X-score (a) and X-loading (b) plot for a PLS regression model developed using log(pressure) as dependent variable and log (mixing time), hydration, semolina properties, as independent variables. Durum wheat blends: o = G2, △ = L, □ = New. Empty symbols = optimal hydration, closed symbols = suboptimal hydration. S = semolina, LGS = low-grade semolina.

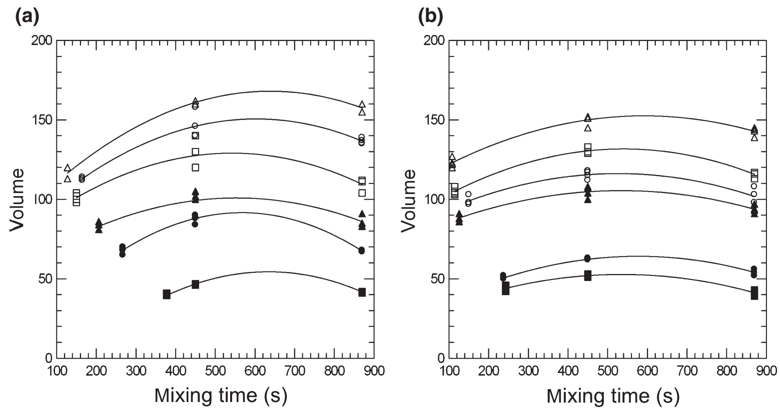

Figure 2 Leavened dough volume (mL) as a function of mixing time for semolina (graph a) and low-grade semolina (graph b). Durum wheat blends: o = G2, △ = L, □ = New). Empty symbols = optimal hydration, closed symbols = suboptimal hydration. Estimated quadratic regression lines are shown on the graph.

good predictive ability for volume (PRESS = 8.25, $Q^2 = 0.94$), while predictive ability for Fmax (PRESS = 12.30, $Q^2 = 0.91$), elasticity (PRESS = 12.11, $Q^2 = 0.91$), glutenin macropolymer (PRESS = 20.79, $Q^2 = 0.85$) and dough density (PRESS = 27.05, $Q^2 = 0.80$) was lower, although the F test for model vs. error variance was highly significant for all variables. The residuals (expressed as % of the untransformed experimental values for the entire data set, including both training and validation data) were lower for volume (for 90% of the data predicted values for volume were within 25% of the experimental values, with a median of 10%), density (90° percentile 1.9%, median 0.7%), elasticity (90° percentile 8%, median 4%) and higher for Fmax (90° percentile 72%, median 16%; the high value for the 90° percentile was mostly due to G2 samples at optimum hydration and to semolina samples of New), and GMP (90° percentile 40%, median 13%).

X-score and loading plots for the first four components, which explained 91% of the X variance, are shown in Fig. 4a–d. The first two components isolate variables related to S and LGS samples composition and hydration, which load on both components. Therefore, in the score plot (Fig. 4a), the samples are clearly separated in two groups, semolinas (bottom right corner) and LGSs (top left corner), according to the extraction rate and points corresponding to the same wheat blend/extraction rate/hydration nearly overlap. The fourth component in Fig. 4c is dominated by mixing time while the third component is dominated by gluten index and some alveographic parameters such as L and P/L. As a consequence, different samples are distributed over the *y*-axis in Fig. 4b as a function of mixing time and over the *x*-axis as a function of alveographic parameters. By comparing the position of symbols with the same size (similar mixing time) and shape (same wheat blend), the effect of hydration and milling on alveographic variables becomes evident.

The Y-loading plots in the first four components (which explained 65.7% of the Y variance) are shown in Fig. 5a, b. By comparing the orientation of the vectors corresponding to the X- and Y variables in the loading plots, it is clear that in the space defined by the first two components, leavened dough volume is inversely proportional to Fmax (strength), elasticity and dough density; in turn it is proportional to hydration and alveographic L and inversely related to gluten index, while P/L, W, damaged starch, ashes, protein and gluten affect the relative position of the points corresponding to the different cultivars and milling sizes, but not the slope of the relationship with dough volume. In the space defined by components 3 and 4, average density is inversely related to mixing time,

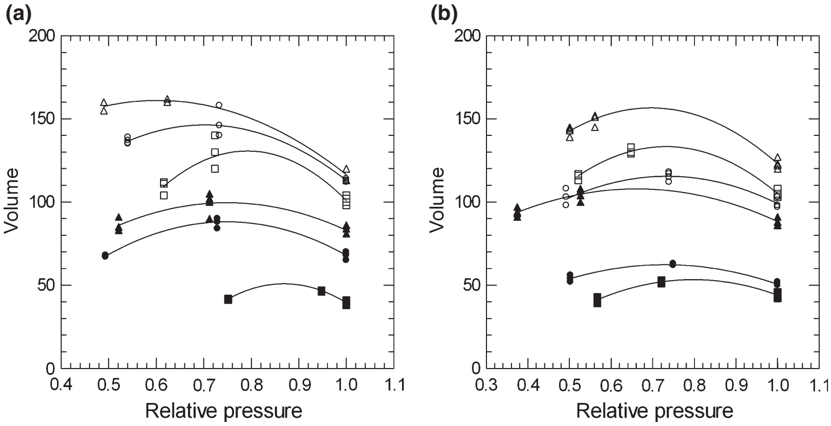

Figure 3 Leavened dough volume (mL) as a function of relative pressure (ratio between the pressure value and the maximum pressure value) for semolina (graph a) and low-grade semolina (graph b). Durum wheat blends: o = G2, △ = L, □ = New). Empty symbols = optimal hydration, closed symbols = suboptimal hydration. Estimated quadratic regression lines are shown on the graph.

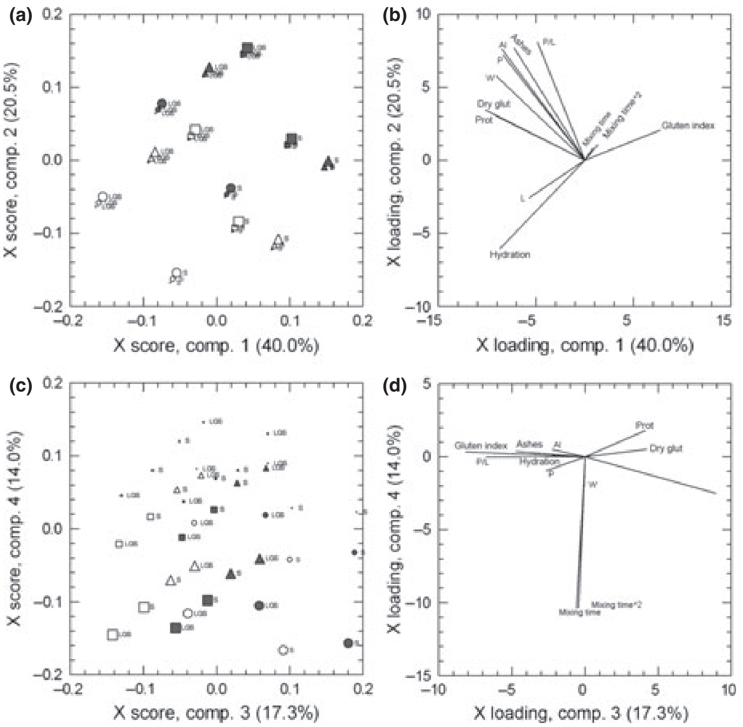

Figure 4 X-scores and loading plots for a PLS2 model relating semolina properties and mixing time (X variables), and variables describing dough properties after mixing and volume after leavening (Y). Durum wheat blends: o = G2, △ = L, □ = New. Empty symbols = optimal hydration, closed symbols = suboptimal hydration. S = semolina, LGS = low-grade semolina. The size of the symbols indicates the three mixing times.

while dough volume is affected by both mixing time, gluten index, P/L, and, to a lesser extent, by hydration and ashes.

Estimated regression coefficients for the PLS2 model and their standard errors are shown in Table 3. As judged by the size of the coefficients, all X variables (with the exception of P and L Alveograph indexes) affected one or more of the Y variables to some degree. Leavened dough volume was primarily affected, in decreasing order of importance, by hydration (increasing hydration increased volume) and damaged starch (decreasing damaged starch increased volume). This result points out the key role of hydration properties of the semolina to improve the dough leavening. We did not evaluate the effect of an overhydration, and the model indicates only the positive effect of optimal vs. suboptimal hydration level. A certain level of damaged starch is sought after because of the increase of water absorption and gassing power of the dough. However, excessive starch damage can overhydrate the dough and lead to inferior baking performance (Lijuan *et al.*, 2007). In our case, damaged starch was the main factor affecting all the Y variables. If we look at the correlation coefficient between damaged starch and the dough properties after mixing, we can see that it had a strong and positive effect on dough hardness and density, and a negative one on elasticity and GMP quantity, thus being responsible for a denser, stiffer and less elastic dough in samples with higher starch damage (LGSs), confirming previous findings (Lindahl & Eliasson, 1992) that by varying the water content, particle size distribution and level of damaged starch, it is possible to influence the rheological values obtained as a result of mixing, and that dough stiffness depends on available water and the level of damaged starch. Surprisingly the effects of ash content and damaged starch were opposite on all the Y dough properties. The increase in the extraction rate during milling is expected to cause higher levels of both damaged starch and ashes. These properties are undesirable in semolina for pasta production, due to their negative effect on both firmness and optimum cooking time, as pointed out by Samaan *et al.* (2006). The higher extraction rate, obtained when durum wheat is milled into LGS, is accompanied by a higher fibre content. The effect of the fibre on the Y variables could be indirect (i.e. related to variation of water-flour ratio) or direct (i.e. a contribution to dough elasticity), as commented by Peressini & Sensidoni (2009). They found a more elastic and solid-like behaviour in dough after addition of fibre. The positive effect of fibre addition on the elastic resistance and extensibility balance (P to L ratio) of the dough was already detected (Wang *et al.*, 2002) and was also observed in our LGS samples, which showed higher P to L ratio than semolinas (Table 1). Fibres have a high water-adsorption capacity (Wang *et al.*, 2002), due to hydroxyl groups in the fibre structure, which allow more water interaction through hydrogen bonding, and can absorb the excess of water eventually released by swollen granules of starch. In this way, fibres oppose to the negative effects of excessive damaged starch in LGS and contribute to make the dough less stiff and more elastic (see the negative effect of ashes on Fmax and the positive one on elasticity in Table 3), through their negative effect on the dough density, and at the end showed a positive effect on the leavening height.

A good dough density, deriving from the incorporation of air during mixing, is a prerequisite for a good dough expansion during leavening and cooking. In fact, the air bubbles serve as nuclei for the expansion of carbon dioxide produced during fermentation. The amount of air incorporated into the dough during the mixing phase has been found to be related to water addition, speed of mixing and flour strength, that is, doughs from strong flours incorporate less air during mixing than dough from weak flours (Campbell *et al.*, 1993, 2001; Bellido *et al.*, 2006). In agreement with this, dough density is strongly and positively affected by gluten index (Table 3), which is an indicator of gluten strength. In the model, the dough density also appears to be affected by alveographic W, another indicator of gluten strength, but in a negative way. That is, gluten index and alveographic W had opposite correlations with all the Y variables, although both indicate gluten quality. This is probably because W is a property of the whole dough and is dependent on both flour properties and the conditions under which the dough is prepared. Alveographic W was obtained according to AACC method 50-30A (AACC, 2000), which is a physical dough test, whereas gluten index is evaluated after extraction of gluten and is a strict gluten properties rather than a dough properties. Mixing time can be considered a critical parameter to obtain a good loaf bread. It is considered to affect the dough development more than water addition, mixing equipment or mixing speed (Zounis & Quail, 1997; Zheng *et al.*, 2000; Ktenioudaki *et al.*, 2010). In Table 3 both mixing time and square mixing time are indicated, because the model used an empirical quadratic relationship between mixing time and dough leavening, and the other dough properties, which may suggest the existence of an optimum value of mixing time. These results must be taken with some caution because a higher number of mixing times would have been needed to identify the true non-linear model describing the relationships between mixing time and the other variables. Nonetheless, we feel that some interesting preliminary conclusions can be drawn from the analysis. If we look at the coefficient between square mixing time and the Y variables, we can argue that the optimum mixing time, that is, the

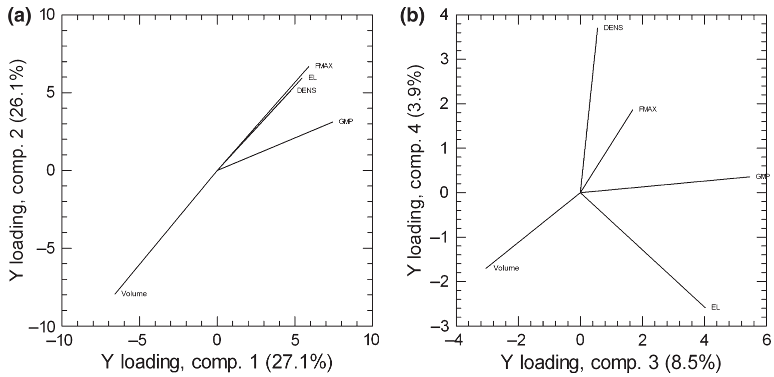

Figure 5 Y- loading plots for a PLS2 model relating semolina properties and mixing time (X variables), and variables describing dough properties after mixing and volume after leavening (Y).

Table 3 Estimated regression coefficients and standard errors for a PLS regression model relating X and Y variables

Y variables	Leavened dough volume	Dough strength	Dough elasticity	Glutenin macropolymer	Dough density
X variables					
Constant	0.058 ± 0.031	−0.002 ± 0.036	−0.019 ± 0.038	0.027 ± 0.042	−0.011 ± 0.054
Hydration (%)	0.906 ± 0.035	−0.677 ± 0.043	−0.897 ± 0.043	−0.836 ± 0.047	−0.473 ± 0.060
Mixing time (s)	0.229 ± 0.068	−0.355 ± 0.071	0.753 ± 0.140	0.293 ± 0.096	−0.610 ± 0.136
Square mixing time (s^2)	−0.176 ± 0.070	0.418 ± 0.082	−0.541 ± 0.142	−0.399 ± 0.096	0.471 ± 0.146
Ashes%	0.374 ± 0.106	−0.703 ± 0.156	1.193 ± 0.179	0.553 ± 0.105	−0.988 ± 0.195
Damaged starch (%)	−0.487 ± 0.083	0.825 ± 0.113	−1.008 ± 0.128	−0.589 ± 0.092	1.046 ± 0.145
Gluten index (%)	−0.301 ± 0.057	0.501 ± 0.090	−0.723 ± 0.139	−0.394 ± 0.114	0.688 ± 0.136
Dry gluten (%)	−0.121 ± 0.014	0.218 ± 0.017	−0.105 ± 0.023	−0.095 ± 0.023	0.212 ± 0.020
Crude protein (%)	−0.221 ± 0.028	0.437 ± 0.040	−0.157 ± 0.065	−0.163 ± 0.049	0.410 ± 0.052
Alveograph Indexes					
P (mBar)	−0.015 ± 0.026	−0.050 ± 0.048	−0.049 ± 0.067	−0.041 ± 0.033	−0.014 ± 0.057
L (mm)	0.044 ± 0.046	−0.137 ± 0.057	−0.314 ± 0.088	−0.051 ± 0.080	−0.020 ± 0.098
W (J)	0.184 ± 0.030	−0.424 ± 0.039	0.283 ± 0.040	0.178 ± 0.040	−0.445 ± 0.058
P/L	−0.096 ± 0.023	0.107 ± 0.042	−0.111 ± 0.055	−0.111 ± 0.028	0.146 ± 0.049

one able to guarantee the highest leavened dough volume, is the mixing time that leads to a soft and elastic dough, with low density and a high quantity of glutenin macropolymer. In this work, the effect of mixing time on the leavened dough volume was lower than the effect of other X variables, mainly hydration. The results we obtained with the Consistograph confirm what found by Ktenioudaki *et al.* (2010) with the use of the Farinograph. Those authors observed that mixing past the dough development time (DDT) as indicated from the Farinograph had positive results on dough development during proofing, which was increased by energy input levels, and therefore by the mixing time. In our work, the doughs obtained at the T1, which is the time required to reach the maximum consistency (TPrMax), are 'under-developed', because lower dough volumes after leavening were obtained than the doughs mixed until T2. Stauffer (2007) suggested the term 'dough breakdown' referred to a dough that becomes softer and less resistant during mixing, observing that this dough loses its ability to retain gases produced in the fermentation process. It is of note that the Consistograph equipment is part of the Chopin Alveograph instrument, then, because it was found to produce data that are consistent with those from the wider used Farinograph and that are reliable in the model, the Alveo-Consistograph could be better exploited at industrial level than now.

Glutenin macropolymer refers to the glutenin macropolymer that is insoluble in 1.5% of SDS. The glutenin fraction is considered responsible for the elastic properties of gluten (Cauvain & Young, 2006a), and GMP in flour was found to correlate strongly with physical dough properties and loaf volume (Weegels *et al.*, 1996). As abovementioned, the analysis reported in Table 3 showed a nonlinear correlation between the GMP and the mixing time, indicating a maximum value of GMP corresponding to a maximum value of dough volume. Commonly, the literature describes a decrease in GMP during mixing (Don *et al.*, 2005). Accordingly, Wang *et al.* (2007) observed that during dough mixing, the amount of GMP tends to decrease, with respect to the GMP content in the flour, before the dough development time is reached, and after that the amount of GMP increased. In our work, the GMP increased after the TPrMax in all the doughs. GMP was negatively affected by hydration (Table 3), in fact in low hydrated doughs, the amount of GMP was higher than optimal hydrated doughs (data not shown). Because a decrease of GMP content is associated with dough development (Wang *et al.*, 2007), we suggest that low hydrated doughs were less developed than the optimum hydrated ones.

Conclusion

In this paper, the relationships among the properties of durum wheat doughs after mixing, the properties of raw material and technological parameters of process, as hydration and mixing time, were studied in order to predict their effect on the leavening process. The use of the partial least square regression allowed us to predict and explain the variation in the leavening performance of the doughs, at least in the range of conditions explored in the study. In fact, the key role of hydration in improving the dough leavening was pointed out, but only the positive effect of optimal vs. suboptimal hydration level can be considered, because the effect of an overhydration was not evaluated.

Analyses of data revealed that technological parameter (hydration and mixing time) had a prevailing role on dough consistency with respect to the characteristic of the raw material. In all the experiments performed, an increase in mixing time resulted in a decrease of dough consistency. Dough at maximum consistency (as registered in the Consistograph) was not ideal for baking purpose, but a further mixing was necessary to obtain a well-developed dough in order to obtain the maximum volume after leavening. The maximum dough volume after leavening can be obtained when the dough pressure value is 70–80% of the maximum pressure measured at the Consistograph.

Damaged starch was the most important factor among semolina quality characteristics, affecting negatively dough volume. This means that semolina, obtained at lower extraction rate than LGS, *ceteris paribus*, gives doughs with a higher volume respect to LGS.

The mixing time is considered a key parameter to obtain a good dough volume, but in this work, the effect of mixing time on the leavened dough was not superior to the effect of other X variables, mainly hydration. From the data obtained, it can be asserted that the optimum mixing time is the one leading to a soft and elastic dough, with low density and a high quantity of glutenin macropolymer.

In order to build a model that might be introduced in an industrial situation, a study of the application of a multivariate analysis to other bread quality traits (i.e. crumb textural and sensorial properties), as outputs of the model, and over a wider range of process conditions (i.e. over hydration levels and more mixing times), with semolina of different origin (cultivar) and different extraction rates, as inputs of the model, should be carried out. The application of this model in the bakery would allow to profitably suggest the correct hydration level and mixing time to guarantee the best quality of bread *a priori*, by loading into the model easily available inputs, as the chemical and rheological tests that are routinely used for semolina and flour.

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