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Abstract: In Western countries, the use of waxy wheat in bread-making is gaining interest in view of extending the shelf-life of bread, avoiding the use of additives. Considering the high impact of the environment on wheat properties, selection of waxy autochthonous lines is highly recommended. In this frame, the behavior of three new Italian waxy lines (IW) were compared with that of two waxy lines breeded in United States (USW). Compared to USW, two out of three IW lines exhibited better mixing properties in terms of higher tolerance to mechanical stress (stability and softness index). IW dough showed similar water absorption, stickiness values and visco-elasticity (G' and G'') compared to USW samples. On the other hand, the waxy wheat lines adapted to the Italian environmental conditions showed a more developed loaf volume with respect to USW lines. The difficulties in dough handling that is typical of waxy wheat when used alone could be partially solved using waxy wheat in combination with non-waxy flours.

Highlights

- Italian (IW) and American (USW) waxy lines were compared
- Dough and bread performance of waxy wheat lines of different origin were studied
- IW lines showed good performance in terms of dough stability and mixing tolerance
- IW lines assured a good dough development during leavening and high bread volume
- USW lines performed better in terms of dough stickiness

Rheological properties and baking performance of new waxy lines: strengths and weaknesses

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Abstract

In Western countries, the use of waxy wheat in bread-making is gaining interest in view of extending the shelf-life of bread, avoiding the use of additives. Considering the high impact of the environment on wheat properties, selection of waxy autochthonous lines is highly recommended. In this frame, the behavior of three new Italian waxy lines (IW) were compared with that of two waxy lines breeded in United States (USW). Compared to USW, two out of three IW lines exhibited better mixing properties in terms of higher tolerance to mechanical stress (stability and softness index). IW dough showed similar water absorption, stickiness values and visco-elasticity (G' and G'') compared to USW samples. On the other hand, the waxy wheat lines adapted to the Italian environmental conditions showed a more developed loaf volume with respect to USW lines. The difficulties in dough handling that is typical of waxy wheat when used alone could be partially solved using waxy wheat in combination with non-waxy flours.

Keywords: waxy wheat; stickiness; dough rheology; bread-making

1. Introduction

Waxy (or amylose-free) wheat is characterized by low amylose content - generally < 3% (Van Hung, Maeda, & Morita, 2007) - due to the absence of all the three isoforms of the granule-bound starch synthase (GBSS-I), which are responsible for the biosynthesis of amylose (Sivak & Preiss, 1995).

Starch retrogradation is believed to be one of the major players of the increase in bread crumb firmness during storage, commonly referred to as bread staling, and amylose is assumed to be the main contributor to this phenomenon (Van Hung, Maeda, & Morita, 2007). Thus, food industry is increasingly interested in waxy starch and in its low susceptibility to retrogradation (Šárka & Dvořáček, 2017). Indeed, the use of waxy wheat in the formulation would avoid the addition of the additives commonly used in bread-making (e.g. enzymes, emulsifiers, etc.) to extend the shelf-life of baked products (Šárka & Dvořáček, 2017). The unique properties and uses of waxy wheat in noodles, bread, cakes, tortillas, refrigerate and frozen food products have been widely reviewed (Graybosh, 1998; Hayakawa, Tanaka, Nakamura, Endo, & Hoshino, 2004; Van Hung, Maeda, & Morita, 2006; Yi, Kerr, & Johnson, 2009; Šárka & Dvořáček, 2017).

Japanese researchers were the first to produce completely waxy wheat by using traditional hybridization approach (Nakamura, Yamamori, Hirano, Hidaka, & Nagamine, 1995). Since then, numerous efforts to develop waxy wheat cultivars are underway in Europe, United States, and Australia (Graybosh, 1998). Considering the high influence of the environment on wheat productivity and quality (Graybosch, Souza, Berzonsky, Baenziger, & Chung, 2003), it is unlikely that waxy wheat lines produced in United States or Japan could be successfully cultivated in other Countries. Moreover, consumer resistance and existing regulations do not allow employing genetically engineered foods in Europe. For these reasons, waxy wheat obtained from traditional crossing starting from partial waxy autochthonous landraces have to be taken into consideration (Boggini, Cattaneo, Paganoni, & Vaccino, 2001).

Italy and other Countries in the Mediterranean area occupy a distinct position within the framework of wheat products in Europe, by producing bread with particular sensory traits compared with common leavened breads consumed in most of the Western Countries (Iametti, Marti, Pagani, & Bonomi 2015). In the perspective of developing waxy wheat lines suitable for being cultivated in the Mediterranean area, various research activities have been accomplished in the past decade (Boggini, Cattaneo, Paganoni, & Vaccino, 2001; Urbano, Margiotta, Colaprico, & Lafiandra, 2002; Monari, Simeone, Urbano, Margiotta, & Lafiandra, 2005). In particular, a breeding program involved partial-waxy cultivars previously identified in the germplasm collection, leading to the release of 18 waxy lines (Boggini, Cattaneo, Paganoni, & Vaccino, 2001; Caramanico, Vaccino, & Pagani, 2011). Out of these lines, three were worthy of consideration for being proposed for registration based on their agronomic performance (Caramanico, Vaccino, & Pagani, 2011). In this context, the aims of the present work were to: i) evaluate dough rheological properties and bread-making performance of the three Italian waxy lines and ii) compare our waxy lines with two waxy lines from United States with similar compositional traits.

2. Materials and Methods

2.1 Materials

Five waxy wheat lines were used in this study (Table 1): three Italian waxy wheat lines (henceforth IW), and two US waxy lines (henceforth USW; Morris & Konzak, 2001). All the samples were grown in S. Angelo Lodigiano (Italy) during the 2009-10 growing season. Wheat kernels were milled into flour (particle size less than 220nm) in a Bona Quadrumat Labor mill (Bona, Monza, Italy).

A non-waxy wheat flour (Aubusson cv.; henceforth NWW; protein: 10.8%; alveographic W: 155 $*10^{-4}$ J; alveographic P/L: 0.56) was used as reference.

The chemical composition of all the samples is reported in Table -1. Moisture, starch, protein, fat, and ash content was determined according to the approved methods AACC 44-15A, 76-13, 39-10 and 46-12, 30-10, 08-12, respectively (AACC, 2000). In particular, protein content was determined by using the NIR System Model 6500 (Foss NIR Systems, Laurel, MD). Amylose content was measured by enzymatic kit Megazyme International (Megazyme International Ireland Ltd., Wicklow, Ireland).

2.2 Pasting properties

The pasting properties of flours were determined by using the Rapid Visco Analyzer test (RVA-4 model, Newport Scientific, Sidney, Australia), according to the approved method ICC 162 (ICC; 1995). An aliquot of flour (3.5 g) was dispersed in distilled water (25 mL), scaling both sample and water weight on a 14% (w/w) sample moisture basis. The suspension was subjected to the following temperature profile: holding at 50°C for 1 min; heating from 50 to 95°C; holding at 95°C for 3.5 min; cooling from 95°C to 50°C; holding at 50°C for 2 min. A heating/cooling rate of 12°C/min was applied. Data were elaborated by using the software provided with the instrument (Thermocline for Windows, rev. 3.6). Measurements were performed in triplicate and the average value was used.

2.3 Viscoelastic properties

The fundamental rheological behavior of dough samples was studied by dynamic oscillatory measurements performed on a Physica MCR300 Rheometer (Anton Paar GmbH, Graz, Austria), supported by the Universal Software US200 (version 2.5) (Anton Paar, Ostfildern, Germany).
Dough sample was prepared by mixing flour (10g) and water (according to the water absorption calculated by the farinograph test) for 1 min in the Glutomatic 2200 (Perten Instruments, Stockholm, Sweden). Measurements were carried out at 25°C, using a corrugated plate system (diameter: 2.5 cm) at a gap of 1 mm. After loading the sample between the parallel plates, the excess was trimmed off and a thin layer of paraffin oil was applied to the edge of the exposed sample to prevent moisture loss during measurements Sample was allowed to rest at 25 °C for 30 min to relax stresses, before starting the test.
Dynamic shear data were measured within the linear viscoelastic region, as determined by preliminary amplitude sweep tests performed in the range of 0.01–200% strain, at a constant

frequency of 1 Hz. Frequency sweep tests were performed over the range 0.1–10 Hz at 0.03% strain. From each trial, storage modulus (G', Pa) loss modulus (G'', Pa), and tanδ (ratio between G'' and G') were computed by using US200/32 v.2.50 rheometer software (Physica Messtechnic GmbH, Ostfildern, Germany). All the measurements were performed in triplicate.

2.4 Mixing properties and stickiness

Mixing properties were evaluated in triplicate using the Brabender Farinograph-E Brabender OHG, Duisburg, Germany) according to the standard ICC Method 115D (ICC, 1992), using a 50g-mixing bowl.

A rounded portion of dough (15 g) was collected after 6 min mixing in the farinograph hand placed in a round plastic container (diameter 40 mm). Dough stickiness was evaluated using a TA-HDplus Texture Analyzer (Stable Micro Systems, Surrey, UK), equipped with a 10 N load cell. After five min, each sample was submitted to compression with a plate probe (diameter: 35 mm) at a crosshead speed of 1 mm/s. The sample was compressed up to 30% deformation, and maintained at this deformation for 5 s, before releasing the force pulling the probe off the sample at a speed of 1 mm/s. Data were collected and elaborated using the Texture Exponent TEE32 V 3.0.4.0 Software (Stable Micro System, UK). Stickiness was evaluated as the negative area of the force-time curve measured during force removal. The time of plate detachment from the sample was also considered. Four replicates were performed for each sample.

2.5 Leavening properties

Just after bread dough preparation (see section below), six aliquots (10 g each) were collected, molded in a spherical shape, put into six Petri dishes, and leavened in a climatic chamber up to 4 h at 30 °C and 80% of relative humidity. At the beginning of the test, and then every 30 min, the images of the Petri dishes were scanned full scale in 256 grey level at 300 dpi with a flatbed scanner (Epson Perfection 3170 Photo, Saiko-Epson Corporation, Japan). Images were processed using a dedicated software (Image Pro-Plus 4.5.1.29, Media Cybernetics Inc, MD, USA). The dough area (mm^2) increase was measured and the relative increase was considered (A_t/A_{t0}).

2.6 Bread preparation

Bread loaves were prepared according to the official method AACC 10-10.03(AACCI, 2000) with some modifications. Flour (50.0g) was mixed with sugar (2.0 g), salt (1.0 g), shortening (1.5 g), yeast (1.75 g), and ascorbic acid (0.4 mg). Water was added based on the farinographic water absorption index. All the ingredients were mixed in a mixer (Model 325 Gram Swanson Mixer, National Manufacturing, Lincoln, US) for 3 min. Dough was divided into portions of 45 g and fermented in cabinet at 30°C at 80% relative humidity for 150 min. Punching was performed after 50 min and after 75 min. All dough samples were placed in aluminum steel baking pans (4.2 x 7.0 cm in top, 3.1 x 6.0 cm in bottom, and 4.0 cm in depth) and fermented in a fermentation cabinet (Model 505-SS 2/3National Manufacturing, Lincoln, NE U.S.A) for 70 min. Dough pieces were baked at 220°C for 20 min (Reel Type Ovens Model 8/16, National Manufacturing, Lincoln, US.). Bread loaves were allowed to cool for 60 min before further tests.

2.7 Bread characteristics

Fresh breads were characterized for weight (g), height (mm), volume (mL), and specific volume (mL/g). Loaf volume was determined by Micro Volumeter (National Manufacturing, Lincoln, NE U.S.A.). Results are the average of four replicates.

2.8 Statistical analysis

The data were processed by Statgraphics XV version 15.1.02 (StatPoint Inc., Warrenton, VA, USA).One-way analysis of variance (ANOVA) was performed and samples were used as factors. When a factor effect was found significant ($P < 0.05$), significant differences among the mean values were determined by Fisher's Least Significant Difference (LSD) test.

3. Results and Discussion

3.1 Pasting properties

Waxy wheat flours exhibited quicker gelatinization (lower peak temperature/time) and lower retrogradation (lower final viscosity and setback) tendency compared to non-waxy flour (Table 2), in agreement with literature (Yoo & Jane, 2002; Van Hung, Maeda, & Morita, 2006; Van Hung, Maeda, & Morita, 2007; Lan et al., 2008). Peak viscosity values of waxy samples were significantly ($P<0.05$) lower than that shown by NWW sample, likely due differences in amylose content (Table 1). Furthermore, during the holding period at 95°C, viscosity decreased for all the samples due to the starch granule breaking.

Among the waxy lines, even if their amylose content is comparable (Table 1), in general, the Italian lines evidenced the lowest peak temperatures to indicate that they are able to interact with water and swell more rapidly than USW lines (Table 2). This pasting behavior can be explained by many factors such as the starch content and amylose: amylopectin ratio, the percentage of smaller size granules and damaged granules that favor a faster hydration and swelling of the starch (Abdel-Aal, Hucl, Chibbar, Han, & Demeke, 2002). Differences among samples could be also related to damaged starch content and α-amylase activity, which play a role in the granule swelling ability.

3.2 Viscoelastic properties

The frequency sweep curves of waxy and non-waxy dough samples are shown in Figure 1. For all flours in the whole range of frequency G' was greater than G'', which is typical of a highly structured material. Both moduli increased with frequency, following an exponential equation (power law equation: $y = a \cdot x^b$). The results of the fitting are reported in Table 3 where "a" is a consistency index and "b" is related to dependence of the measure on the strain rate and mainly depends on the nature of the interactions in the dough. NWW dough presented the highest G' and G" consistency indices, with values that resulted very far from the ones found for the waxy dough samples. On the contrary, "b" values changed in a narrow interval. The different amount of water used for preparing the dough (see Table 4) certainly contributed to create a more diluted protein network in waxy wheat dough, accounting for low G' and G'' values.

Among waxy wheat samples, IW_70 and IW_123 showed the highest G' values, despite the high amount of water added. On the contrary, both IW_118 and USW_546 presented the lowest "a" value (Table 3). Similar trends were also found for the power law coefficients of G" curves. As regard the tang δ values (ratio between the viscous and elastic components), NWW and IW_123 dough presented very similar viscoelastic characteristics, even at high strain rates, which is in agreement with the farinographic stability (Table 4). On the contrary, USW_546 exhibited the highest tan δ, highlighting more viscous behavior compared to the other samples. In agreement with previous results (Morita, Meada, Myazaki, & Yamamori, 2002; Van Hung, Maeda, & Morita, 2007), the highest water absorption of waxy flour – which could mainly due to the different structural organization of the starchy fraction (Zhang, Zhang, Xu, & Zhou, 2014; Šárka & Dvořáček, 2017)– determined a soft and more viscous dough.

3.3 Mixing properties

Dough mixing properties are shown in Table 4. The water absorption values of waxy flours ranged from 69.5% to 74.3%, for USW_545 and IW_123, respectively. Regardless the geographical origin, these values were significantly higher compared to common wheat (52.5%). Differences in water absorption may be attributed to the amylopectin structure of waxy wheat (Zhang, Zhang, Xu, & Zhou, 2014). Highly branched macromolecules quicker absorb water that will not be available for protein solvation. Consequently, waxy wheat required higher water amount and longer mixing times for assuring protein solvation and gluten formation. Dough made with waxy wheat exhibited lower mixing stability and higher softening index (ranging from 87 to 206 UB for IW_123 and USW_545) than NWW. This trend suggested that the gluten network from waxy wheat was weaker compared to the matrix developed in NWW despite the higher protein content .The mixing profiles of IW and USW lines were similar to literature data (Morita, Meada, Myazaki, & Yamamori, 2002;

Van Hung, Maeda, & Morita, 2006; Van Hung, Maeda, & Morita, 2007; Zhang, Zhang, Xu, & Zhou, 2014). Interestingly, the IW_70 and IW_123 samples presented higher stability and lower degree of softening than USW lines, making them more suitable for bread-making. These features could reduce difficulties during the preparation of waxy wheat dough and its handling during processing.

3.4 Dough stickiness

Dough samples from waxy wheat exhibited a higher energy value and longer time for plate detachment than regular wheat dough, indicating high stickiness (Table 4). IW lines generally exhibited slightly but not always significant higher stickiness than USW. This characteristic is an important textural property of wheat dough as sticky dough adheres to machine surface, giving troubles during bread preparation (Armero & Collar, 1997). In addition, dough stickiness might result in a chewy bread that adheres to the mouth, or/and seems to be under-baked, decreasing consumer acceptance (Yi et al., 2009). Some studies (Morita, Meada, Myazaki, & Yamamori, 2002; Van Hung, Maeda, & Morita, 2006) reported the relation between high stickiness and the high water content of waxy wheat dough. Recently, Caramanico et al. (2017) found that waxy starch is characterized by a high water retention capacity, accounting for the higher level of flour hydration to reach the optimum protein solvation.

Moreover, the same Authors suggested that differences in protein-protein interactions might also account for the differences in dough properties during mixing, with hydrophobic interactions playing a more significant role than covalent ones in imparting the stickiness trait to dough.

3.5 Leavening properties

The relative increase of dough area is reported in Figure 2.This analysis allows predicting the dough leavening properties during bread-making (Cappa, Lucisano, & Mariotti, 2013).

Up to 90 min of leavening, all the waxy samples showed a major relative increment of dough surface with respect to the control (NWW), with IW_70 and USW_546 flours having a faster and greater development compared to the others (Figure 2), suggesting a potential good leavening properties and likely bread-making performance in terms of bread volume. In particular, IW_70 achieved a maximum value of dough development equal to 4.6 after 120 min, whereas the maximum development for USW_546 was 4.0 after 180 min of leavening. In all cases, the maximum At/At0 values were reached between 120 and 180 min (Figure 2). After this point, dough development reached a plateau.

3.6 Bread characteristics

The bread-making performances of samples are reported in Table 5. All the IW lines resulted in a higher bread height and larger volume than USW samples, confirming the importance of the environment on starch and protein properties and, therefore, on bread-making performance (Peterson, Graybosch, Beanzinger, & Grombacher, 1992; Peterson, Graybosch, Shelton, Beanzinger Graybosch, Souza, Berzonsky, Baenziger, & Chung, 2003). In fact, results indicated that waxy samples with Italian germplasm were characterized by a better technological quality in comparison to the USW lines. Among the Italian lines, IW_123 showed the best bread-making aptitude (Table 5), likely related to the higher dough elasticity and lower stickiness shown during dough mixing and handling (Table 4). At the same time, the crumb of waxy wheat samples appeared typically more porous than in non-waxy wheat, with the presence of big gas cell (Caramanico, Vaccino, & Pagani, 2011). Indeed, amylopectin seems to be more susceptible to α-amylase hydrolysis during fermentation, assuring higher sugar content and, therefore, a higher gas production in waxy wheat systems (Van Hung, Maeda, & Morita, 2006).

Our data are in agreement with those of previous studies (Lee, Swanson, & Baik, 2001; Morita, Meada, Myazaki, & Yamamori, 2002), showing that bread made from waxy wheat had usually slightly larger volume than bread from non waxy wheat flour. It has also been reported that, although bread made from waxy wheat flour produced loaves of very high volume, some structural collapse during the first 24 h out of the oven may happen (Hayakawa, Tanaka, Nakamura, Endo, & Hoshino, 2004).

4. Conclusions

The Italian breeding program allowed selecting some waxy lines with interesting technological performance, in terms of dough stability and tolerance to mechanical stress. In addition, protein network assured a good dough development during leavening resulting in bread with very high specific volume. Despite that, the relevant amount of water necessary to reach the optimal farinographic consistency could be responsible for the high stickiness. Therefore, the weakness of waxy dough could be skipped by mixing waxy wheat flours at high percentage with non-waxy wheat, and the potential antistaling effects of this mixture could be of interest for bakeries.

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References

AACC International. (2001). Approved methods of analysis (11th ed.). St Paul: AACC International.

Abdel-Aal, E. M., Hucl, P., Chibbar, R. N., Han, H. L., & Demeke, T. (2002). Physicochemical and structural characteristics of flours and starches from waxy and non waxy wheats. *Cereal Chemistry, 79*, 458-464.

Armero, E., & Collar, C. (1997). Texture properties of formulated wheat doughs. Relationships with dough and bread technological quality. E*uropean Food Research & Technology, 204*, 136-145.

Boggini, G., Cattaneo, M., Paganoni, C., & Vaccino, P. (2001). Genetic variation for waxy proteins and starch properties in Italian wheat germplasm. In □Z. Bedö, L. Láng (Eds.) *Wheat in a Global Environment* (pp. 249-253). Springer Netherlands.

Cappa, C., Lucisano, M., Mariotti, M. (2013). Influence of Psyllium, sugar beet fibre and water on gluten-free dough properties and bread quality. *Carbohydrate Polymers*, *98*, 1657-1666.

Caramanico, R., Barbiroli, A., Marengo, M., Fessas, D., Bonomi, F., Lucisano, M., Pagani, M. A., Iametti, S., Marti, A. (2017). Interplay between starch and proteins in waxy wheat. *Journal of Cereal Science, 75,* 198–204.

Caramanico, R., Vaccino, P. & Pagani, M.A. (2011). Caratteristiche qualitative e attitudine panificatoria di linee di frumento tenero waxy. *Tecnica Molitoria, 2,* 102-110.

Graybosch, R. A. (1998). Waxy wheats: Origin, properties, and prospects. *Trends in Food Science & Technology, 9,* 135-142.

Graybosch, R. A., Souza, E., Berzonsky, W., Baenziger, P. S., & Chung, O. (2003). Functional properties of waxy wheat flours: genotypic and environmental effects. *Journal of Cereal Science, 38,* 69-76.

Hayakawa, K., Tanaka, K., Nakamura, T., Endo, S., & Hoshino, T. (2004). End use quality of waxy wheat flour in various grain-based foods. *Cereal Chemistry, 81,* 666-672.

Iametti, S., Marti, A., Pagani, M.A., & Bonomi, F. (2015). Future of Grain Science Series: Italy. *Cereal Foods World, 60,* 27-31.

ICC International. (1992). Standard methods of analysis. Vienne: ICC.

Lan, H., Hoover, R., Jayakody, L., Liu, Q., Donner, E., Baga, M., Asare E.K., Hurt P., & Chibbar, R. N. (2008). Impact of annealing on the molecular structure and physicochemical properties of normal, waxy and high amylose bread wheat starches. *Food Chemistry, 111,* 663-675.

Lee, M. R., Swanson, B. G., & Baik, B. K. (2001). Influence of amylose content on properties of wheat starch and breadmaking quality of starch and gluten blends. *Cereal Chemistry, 78,* 701-706.

Monari, A. M., Simeone, M. C., Urbano, M., Margiotta, B., & Lafiandra, D. (2005). Molecular characterization of new waxy mutants identified in bread and durum wheat. *Theoretical and Applied Genetics, 110,* 1481-1489.

Morita, N., Meada, T., Myazaki, M., & Yamamori, M. (2002). Dough and baking properties of high-amylose and waxy wheat flours. *Cereal Chemistry, 79,* 491-495.

Morris, C. F., & Konzak, C. F. (2001). Registration of hard and soft homozygous waxy wheat germplasm. *Crop Science, 41,* 934-934.

Nakamura, T., Yamamori, M., Hirano, H., Hidaka, S., & Nagamine, T. (1995). Production of waxy (amylose-free) wheats. *Molecular and General Genetics, 248,* 253-259.

Peterson, C.J., Graybosch, R.A., Beanzinger, P.S., & Grombacher, A.W. (1992). Genotype and environment effects on quality characteristics of hard red winter wheat. *Crop Science*, *32,* 98-103.

Peterson, C.J., Graybosch, R.A., Shelton, D.R., &Beanzinger, P.S. (1998). Baking quality and hard winter wheat: response of cultivars to environment in the Great Plant. *Euphytica*, *100,* 157-162.

Šárka, E. & Dvořáček, V. (2017). Waxy starch as a perspective raw material: A review. *Food Hydrocolloids, 69,* 402-409.

Sivak, M.N. & Preiss, J. (1995). Starch Synthesis in Food. In J. Kigel, & G. Galili (Eds.), *Seed Development and Germination* (pp. 139-168). New York: Marcel Dekker.

Urbano, M., Margiotta, B., Colaprico, G., & Lafiandra, D. (2002). Waxy proteins in diploid, tetraploid and hexaploid wheats. *Plant Breeding*, *121*, 465-469.

Van Hung, P., Maeda, T., & Morita, N. (2006). Waxy and high-amylose wheat starches and flours—characteristics, functionality and application. *Trends in Food Science & Technology, 17,* 448-456.

Van Hung, P., Maeda, T., & Morita, N. (2007). Dough and bread qualities of flours with whole waxy wheat flour substitution. *Food Research International*, *40*, 273-279.

Yi, J., Kerr, W. L., & Johnson, J. W. (2009). Effects of waxy wheat flour and water on frozen dough and bread properties. *Journal of Food Science, 74,* E278-E284.

Yoo, S. H., & Jane, J. L. (2002). Structural and physical characteristics of waxy and other wheat starches. *Carbohydrate Polymers, 49,* 297-305.

Zhang, H., Zhang, W., Xu, C., & Zhou, X. (2014). Studies on the rheological and gelatinization characteristics of waxy wheat flour. *International Journal of Biological Macromolecules, 64,* 123-129.

Figure captions

Figure 1. Frequency sweep curves. A: storage modulus (G'); B: loss modulus (G''); C: damping factor (tangδ).

Figure 2. Relative increase of dough surface (At/At0) during leavening.

Table

Table 1. Chemical composition of Italian waxy wheat lines (IW), USwaxy wheat lines (USW), and non-waxy wheat flour (NWW). All data are expressed as g/100g flour dry basis, except for Amylose which is expressed as g/100g starch.

Name	Abbreviation	Starch	Amylose	Protein	Lipid	Ash
Wx70	IW_70	79.4[bc]	1.4[a]	12.0[b]	1.8[b]	0.66 [c]
Wx 118	IW_118	79.5[c]	1.5[a]	12.9[d]	1.8[b]	0.38[a]
Wx 123	IW_123	79.2[bc]	1.4[a]	13.2[e]	1.7[ab]	0.55[b]
WQL6K107-BHWX2-2a PI 612545	USW_545	77.0[ab]	1.7[a]	12.2[c]	1.5[a]	0.38[a]
WQL6K107-BHWX14-7 PI 612546	USW_546	76.4[a]	1.6[a]	13.3[e]	1.9[b]	0.59[bc]
Aubusson	NWW	80.6[c]	23.9[b]	10.8[a]	1.4[a]	0.60[bc]

Mean values followed by different letters in a column are significantly different (LSD; P <0.05).

Table 2. Pasting properties of flour from Italian waxy wheat lines (IW), USwaxy wheat lines (USW), and non-waxy wheat (NWW).

	Pasting Temperature (°C)	Peak Viscosity (10^{-3}Pa*s)	Peak Temperature (°C)	Breakdown (10^{-3}Pa*s)	Final Viscosity (°C)	Setback (10^{-3}Pa*s)
IW_70	66.2^{ab}	2390^{c}	79.0^{b}	1435^{b}	1281^{b}	326^{b}
IW_118	66.7^{abc}	2377^{c}	78.3^{a}	1419^{b}	1341^{c}	383^{c}
IW_123	66.7^{bc}	2077^{a}	79.9^{c}	1238^{a}	1111^{a}	272^{a}
USW_545	67.0^{bc}	2398^{c}	81.2^{d}	1384^{b}	1383^{c}	369^{c}
USW_546	65.4^{a}	2310^{b}	82.0^{e}	1283^{a}	1364^{c}	337^{b}
NWW	67.6^{c}	3119^{d}	95.0^{f}	1237^{a}	3227^{d}	1371^{d}

Mean values followed by different letters in a column are significantly different (LSD; $P < 0.05$).

Table 3. Application of the power law equation ($y = a \cdot x^b$)to the frequency sweep test of G′ (storage

modulus) and G″ (loss modulus) for dough samples.

	G’		G’’	
	a	b	a	b
IW_70	6996^{b}	0.258^{b}	3130^{c}	0.302^{bc}
IW_118	5604^{a}	0.266^{bc}	2482^{ab}	0.306^{c}
IW_123	7004^{b}	0.235^{a}	2788^{bc}	0.282^{b}
USW_545	6899^{a}	0.264^{c}	3012^{a}	0.305^{c}
USW_546	4814^{b}	0.278^{bc}	2297^{c}	0.310^{bc}
NWW	12811^{c}	0.237^{a}	5247^{d}	0.252^{a}

Mean values followed by different letters in a column are significantly different

(LSD; $p<0.05$).

Table 4. Mixing properties and stickiness of dough from Italian waxy wheat lines (IW), US waxy wheat lines (USW), and non-waxy wheat flour (NWW).

	Mixing Properties				Stickiness	
	Water Absorption (g/100g)	Development Time (min)	Stability (min)	Softening Value (BU)	Stickiness (N*mm)	Time of Plate Detachment (s)
IW_70	72.0^{cd}	4.3^{d}	3.0^{b}	106^{c}	130.9^{c}	19.6^{bc}
IW_118	70.6^{bc}	2.9^{bc}	2.4^{a}	136^{d}	114.9^{bc}	21.3^{c}
IW_123	74.3^{e}	4.8^{e}	4.1^{c}	87^{b}	115.1^{bc}	16.4^{b}
USW_545	69.5^{b}	2.6^{b}	2.2^{a}	206^{f}	88.2^{b}	21.7^{c}
USW_546	73.2^{de}	3.2^{c}	2.1^{a}	158^{e}	95.0^{b}	20.7^{c}
NWW	52.5^{a}	1.8^{a}	4.3^{c}	63^{a}	43.7^{a}	4.0^{a}

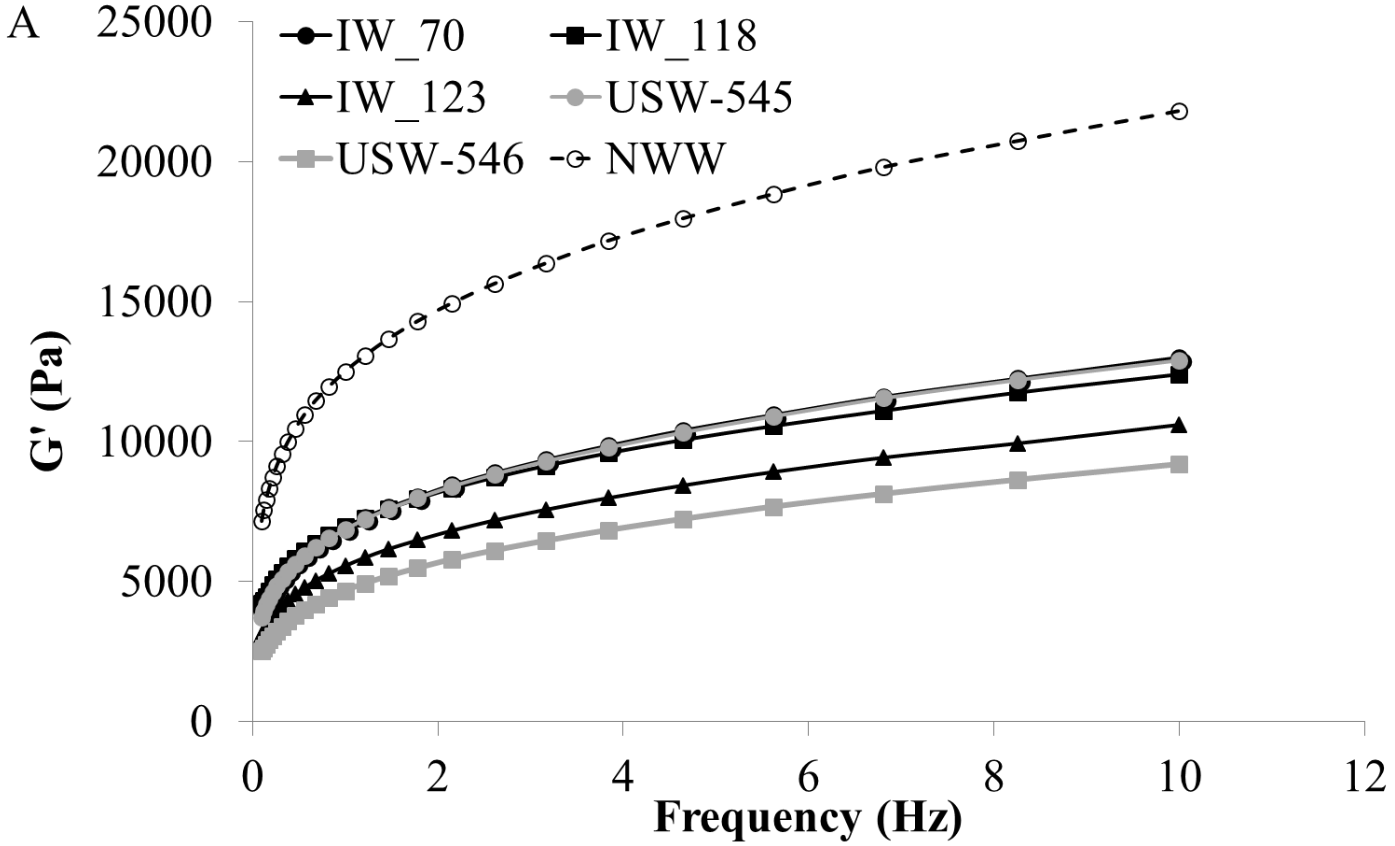
Mean values followed by different letters in a column are significantly different (LSD; $p < 0.05$).

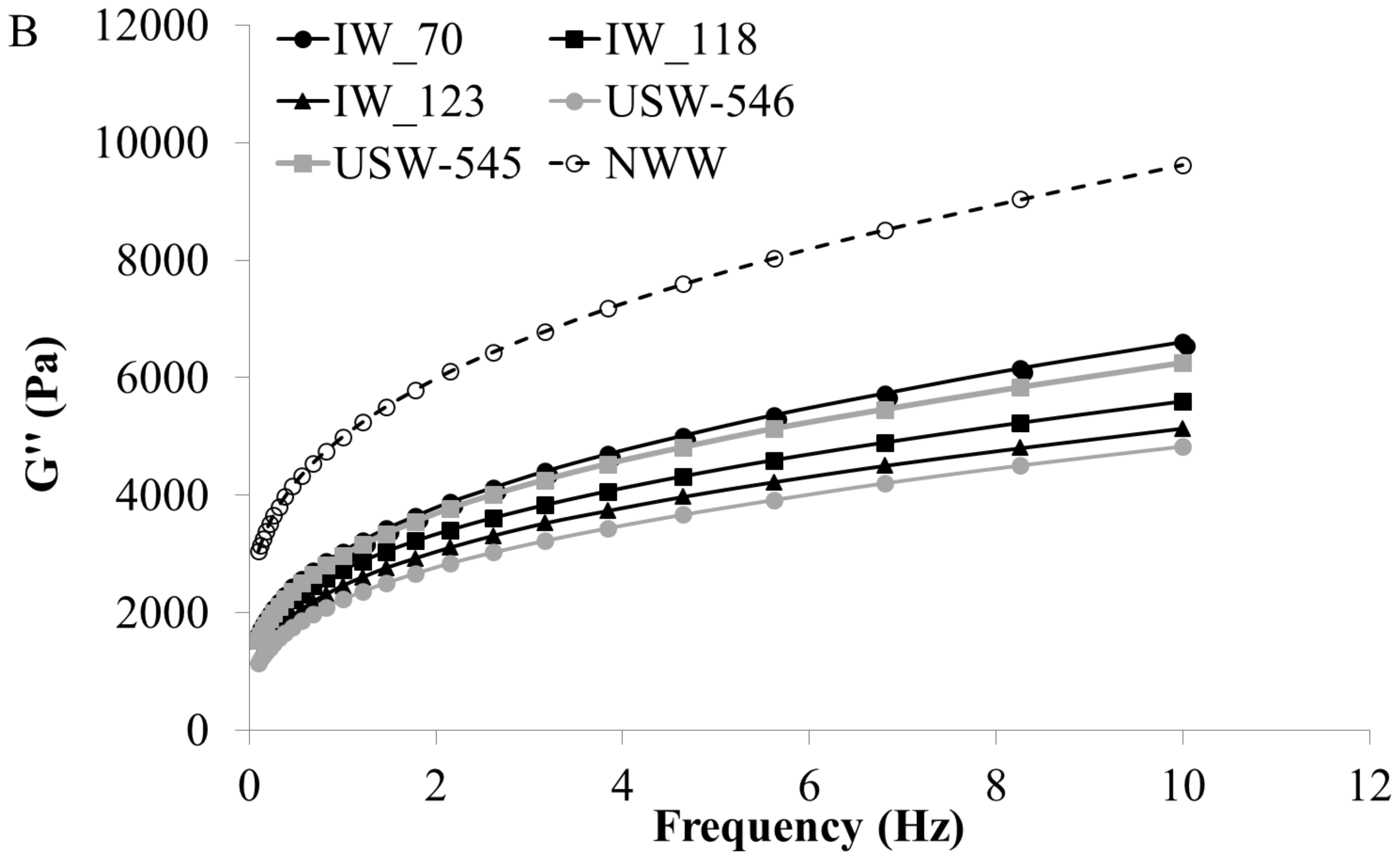
Table 5. Bread-making performance of Italian waxy wheat lines (IW), US waxy wheat lines (USW), and non-waxy wheat (NWW).

	Height (mm)	Weight (g)	Volume (mL)	Specific Volume (mL/g)
IW_70	73.6^{c}	32.7^{ab}	208^{d}	6.37^{d}
IW_118	77.7^{d}	33.0^{b}	219^{e}	6.62^{e}
IW_123	81.1^{e}	33.0^{b}	226^{f}	6.89^{f}
USW_545	63.6^{a}	32.4^{a}	163^{b}	5.08^{b}
USW_546	76.4^{cd}	32.8^{ab}	185^{c}	5.66^{c}
NWW	66.8^{b}	32.6^{ab}	131^{a}	4.05^{a}

Mean values followed by different letters in a column are significantly different (LSD; $p<0.05$).

Figure


A
IW_70
IW_118
IW_123
USW-545
USW-546
NWW
G' (Pa)
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
Frequency (Hz)


B
IW_70
IW_118
IW_123
USW-546
USW-545
NWW
G'' (Pa)
12000
10000
8000
6000
4000
2000
0
0
2
4
6
8
10
12
Frequency (Hz)

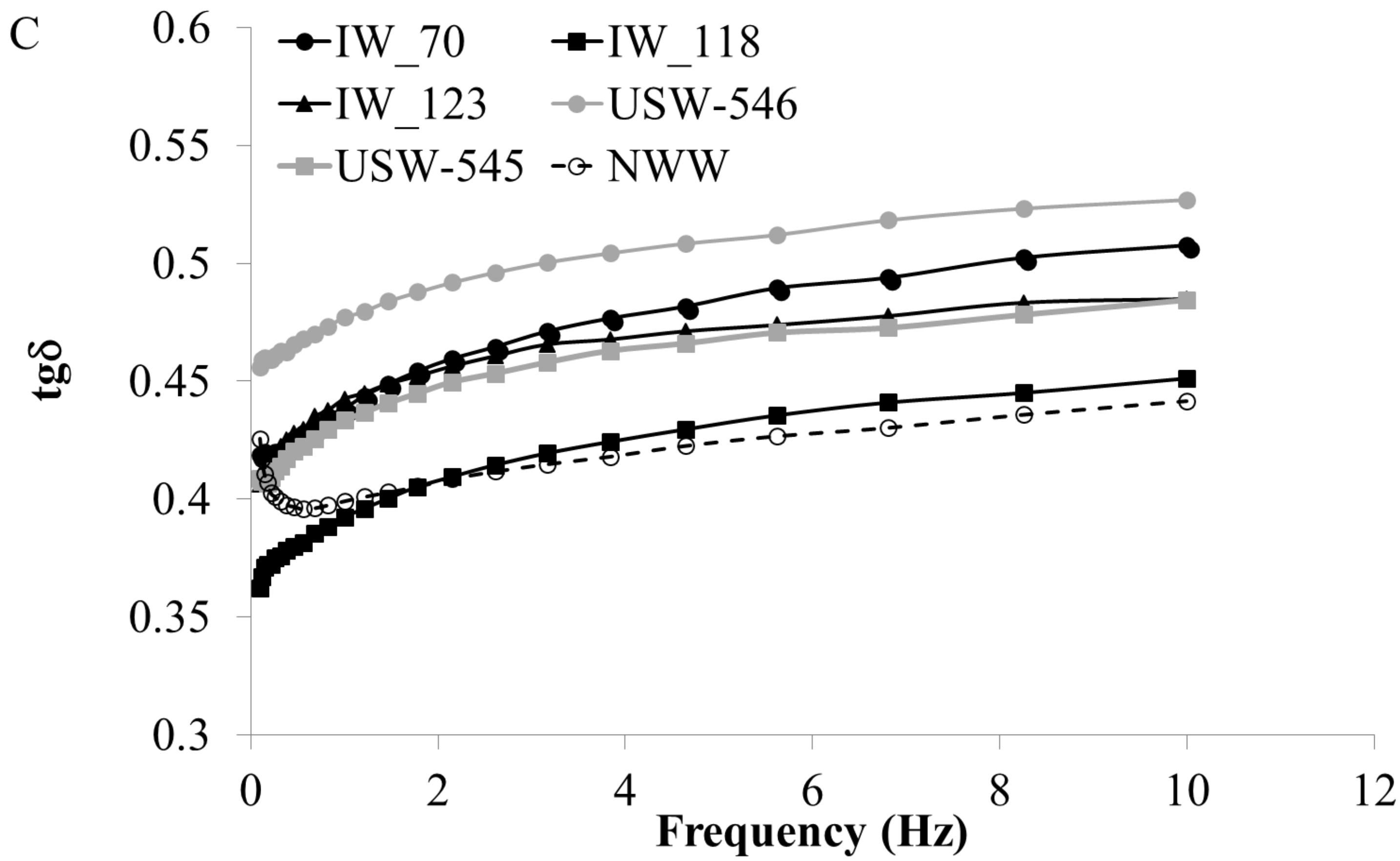
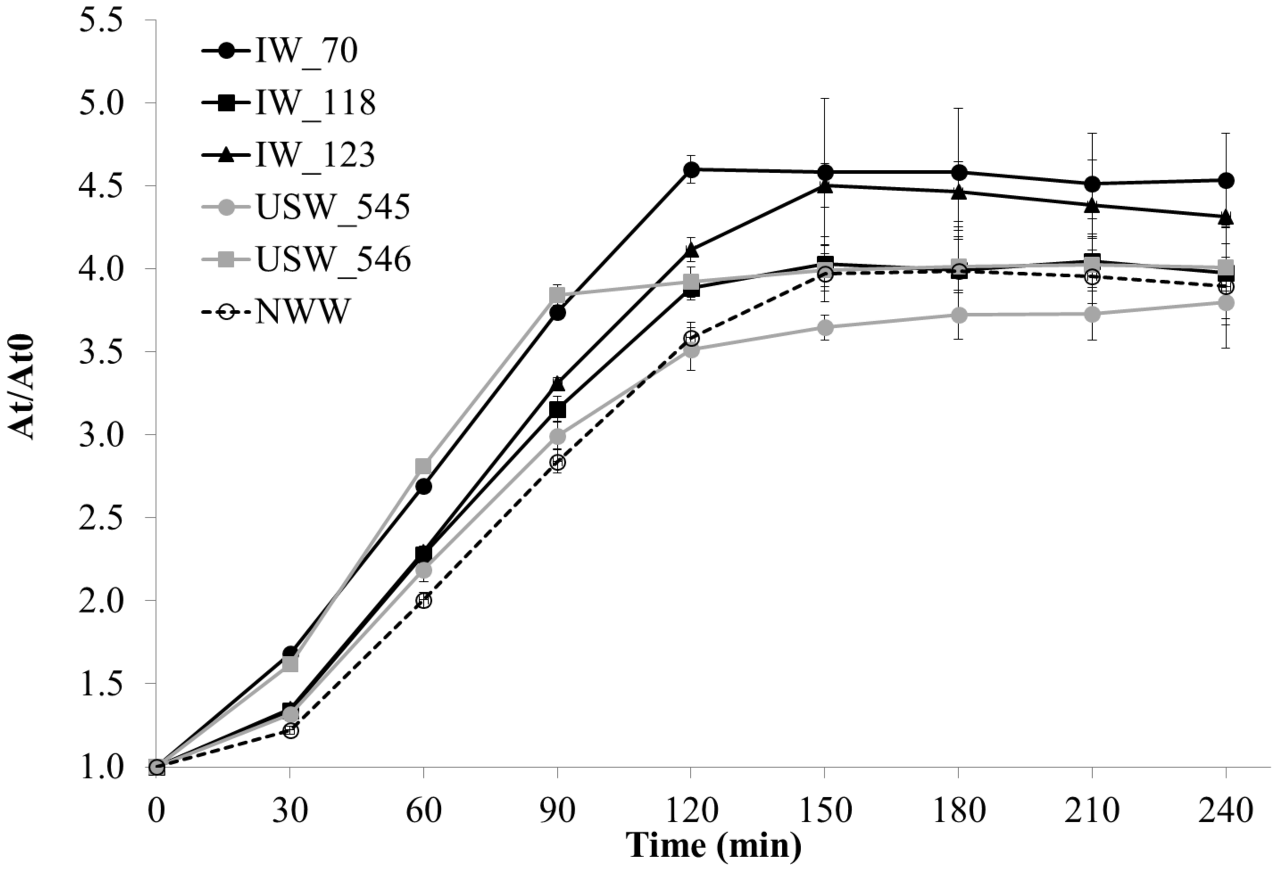

C
0.6
0.55
0.5
0.45
0.4
0.35
0.3
tgδ
IW_70
IW_118
IW_123
USW-546
USW-545
NWW
0
2
4
6
8
10
12
Frequency (Hz)

Fig. 1



5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
At/At0
IW_70
IW_118
IW_123
USW_545
USW_546
NWW
0
30
60
90
120
150
180
210
240
Time (min)

Fig. 2