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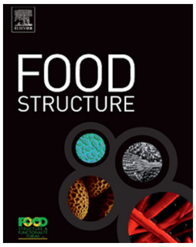

Fibre enrichment of wheat bread with Jerusalem artichoke inulin: Effect on dough rheology and bread quality

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ABSTRACT

Dietary fibre enrichment of white bread with inulin-rich carbohydrate (IRC) powder extracted from Jerusalem artichoke tubers (IRC-J) was studied. Previously, it was shown that this IRC-J powder had higher prebiotic activity score than a commercial chicory inulin (IRC-C) powder, used for comparison. For bread making, 2.5 and 5.0 g of either IRC-J or IRC-C were added to 100 g of wheat flour, and the effects on dough viscoelastic properties and bread quality properties were analyzed, relative to a Control sample (no IRC added). The lowest IRC concentration of both fibres had no significant effect on the elastic modulus (G') of the dough, but the highest IRC level decreased G', with a stronger effect of IRC-J. This was attributed to disruption of the starch–gluten matrix due to fibre replacement of flour. In turn, this was thought to impair gas retention (known as diluting effect), resulting in the observed decrease of bread specific volume and cell/total area ratio, and the increase in crumb hardness and chewiness. IRC addition also had a significant effect on crumb and crust colour, and other crumb grain features. These effects were more significant at the highest IRC concentration of both fibres. Breads with 5.0 g of IRC-J were significantly darker, flatter, and more humid. All the sensory attributes of breads with 0 (Control sample), 2.5 g IRC-J, and 2.5 g IRC-C were acceptable, and no significant differences were found between the three samples, in any of the attributes.

1. Introduction

Bread is considered to be of global importance in nutrition, because it is a source of carbohydrates, proteins, dietary fibre, vitamins, micronutrients and antioxidants. Whole bread is relatively high in fibre content (7–8% of dry matter). However, white bread contains only 2–3% fibre on a dry matter basis (Poinot et al., 2010). Fibres, and more particularly the soluble ones, like inulin and fructooligosaccharides (FOS), are known to provide health benefits like stimulation of beneficial colonic bacteria (prebiotic capacity), reduction in bowel transit time, increase mineral absorption, improve immune response, and prevent diseases like intestinal infections, colorectal cancers,

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obesity, cardiovascular diseases and type II diabetes. Nevertheless, fibre intake is commonly lower than recommended (Mandala, Polaki, & Yanniotis, 2009). Therefore, being white bread low in fibre and at the same time the most consumed type of bread, it is of great interest to improve its nutritional quality by enriching its formulation with soluble fibres like inulin (Hager et al., 2011; Mandala et al., 2009; Morris & Morris, 2012; Peressini & Sensidoni, 2009; Poinot et al., 2010). However, the addition of these fibres may cause a significant effect on the final bread quality (Wang, Rosell, & Benedito de Barber, 2002). Consequently, it is necessary to analyze the physical and sensory properties of fibre-enriched white bread.

Inulin is a linear fructan, a biopolymer chain constituted by fructose molecules linked by $\beta(2\rightarrow1)$ bonds, with a terminal glucose unit linked by a $\alpha(1\rightarrow2)$ bond. Its degree of polymerization (DP) typically ranges from 2 to 60 units, with number average values (DP_n) of 10–12 units (Franck & De Leenheer, 2005; Kays & Nottingham, 2007). Commercial inulin preparations are mainly made from chicory (*Cichorium intybus* L.). However, products of other fructans-containing plants such as Jerusalem artichoke (*Helianthus tuberosus* L.) become increasingly interesting for application in food as they do not contain bitter taste compounds and therefore constitute a palatable functional ingredient, which may be applied as substitute of cereal flour in bakery products (Praznik, Cieślik, & Filipiak-Florkiewicz, 2002). A number of studies have looked at the effect of FOS and/or inulin addition on the rheological properties of doughs and the final quality of the resulting breads (Collar, Santos, & Rosell, 2007; Hager et al., 2011; Mandala et al., 2009; Morris & Morris, 2012; O'Brien, Mueller, Scannell, & Arendt, 2003; Peressini & Sensidoni, 2009; Poinot et al., 2010; Praznik et al., 2002; Wang et al., 2002). Most of these works used commercial chicory inulin as a fibre source. We only found one work (Praznik et al., 2002) which studied the application of Jerusalem artichoke powder in wheat/rye bread, and some physical and organoleptic properties of the resulting breads. However, the rheological properties of the dough, and some important physical properties of the bread (like mechanical properties, colour, and crumb grain) were not studied.

Dough is known to have a foam structure, consisting of a dispersion of discrete gas cells in a continuous starch–protein matrix. The gas cell nuclei are incorporated by the occlusion of air during mixing, and later expand as carbon dioxide (CO_2) is produced by yeast fermentation. Under normal baking conditions, the loss of gas is slow at the beginning, but increases sharply towards the end of baking at high temperatures. The later has been attributed to the rupture of the starch–protein matrix, resulting in the interconnection of adjacent gas cells, yielding an open sponge structure of crumb bread. To produce a loaf of bread with a light and even crumb structure, the dough must be able to retain the gases for a sufficiently long period (Gan, Ellis, & Schofield, 1995).

Bread doughs show viscoelastic behaviour, which is mainly attributed to gluten, the major protein source in wheat flour (Dobraszczyk & Morgenstern, 2003; Mirsaeedghazi, Emam-Djomeh, & Mousavi, 2008). Dynamic oscillatory measurements with small amplitudes are useful to obtain information on dough structure from its viscoelastic properties. It is worth mentioning that these tests are often inappropriate to predict the behaviour of doughs during processing, where the deformation conditions (rate and extension) are very different (Dobraszczyk & Morgenstern, 2003). The addition of fibres can have a significant effect on the rheological behaviour of doughs, which is likely due to interactions between the fibre structure and wheat proteins (Bonnand-Ducasse, Della Valle, Lefebvre, & Saulnier, 2010; Collar et al., 2007; Hager et al., 2011; Mirsaeedghazi et al., 2008; Morris & Morris, 2012; Peressini & Sensidoni, 2009; Wang et al., 2002).

In a recent work (Rubel, Pérez, Genovese, & Manrique, 2014), we studied the properties of inulin-rich carbohydrates (IRCs) extracted from Jerusalem artichoke tubers after different cold-storage times, and determined that the IRC powder extracted after 4 months (here called IRC-J) had the highest prebiotic activity score (PAS), which was even higher than the PAS value obtained for a commercial chicory inulin (IRC-C). The PAS value reflects the growth index of a probiotic benefic bacteria (in this case *Lactobacillus paracasei*) relative to an enteric pathogenic bacteria (in this case *Escherichia coli*), using the prebiotic (in this case inulin) as source of carbon, relative to glucose. The higher PAS value obtained for IRC-J indicates a more selective use of this prebiotic by the benefic microorganism, compared to the pathogen. This was attributed to the particular characteristics of this sample, including polymerization degree (~9), and purity (~90%). Since prebiotic capacity is a desired property of dietary fibre, those IRC-J and IRC-C samples were used in the present work for fibre enrichment of white bread. Therefore, the objective of this work was to study the addition of IRC-J powder to wheat flour for bread making (compared to IRC-C), and to determine the effect on the rheological properties of the dough and bread quality, evaluated in terms of physical and sensory properties.

2. Materials and methods

2.1. Materials

Inulin-rich carbohydrates (IRCs) were extracted from Jerusalem artichoke tubers after different cold-storage times, and their prebiotic capacity was determined as described in a previous work (Rubel et al., 2014). The powder with the best prebiotic capacity, from now on called IRC-J, was selected and used in the present work for fibre enrichment of wheat bread, as well as commercial food grade chicory inulin Orafti®GR (Beneo-Orafti, Belgium), hereinafter called IRC-C, kindly donated by Saporiti SA (Argentina). Average degree of polymerization of IRC-J and IRC-C was 9.2 and 12.1, respectively. Inulin content (purity) of IRC-J was 90.8 g/100 g, while purity of IRC-C was 94.2 g/100 g. The prebiotic activity score of IRC-J and IRC-C was 0.30 and 0.17, respectively, as determined by Rubel et al. (2014).

2.2. Dough preparation and baking procedure

The bread formula contained flour (100 g), dried yeast (2 g), sodium chloride (2 g), sucrose (0.8 g), sunflower oil (2 mL), IRC-J or IRC-C (0, 2.5, or 5.0 g), and deionized water (58.8 mL) on the basis of farinograph water absorption. We used the same water content for all samples, a criterion that has been applied in several works on fibre enriched breads (Poinot et al., 2010; Praznik et al., 2002; Sangnark & Noomhorm, 2004). Sample without IRC was called Control. Samples with 2.5 and 5.0 g IRC-J/100 g flour were called J-2.5 and J-5.0, respectively. In the same way, samples with 2.5 and 5.0 g IRC-C/100 g flour were called C-2.5 and C-5.0, respectively. The choice of these IRC levels (2.5 and 5.0 g/100 g flour) was based on the most common values used in many studies of inulin enriched breads (Collar et al., 2007; Hager et al., 2011; Mandala et al., 2009; O'Brien et al., 2003; Peressini & Sensidoni, 2009; Poinot et al., 2010; Wang et al., 2002). Additionally, the Control sample was also prepared without yeast for comparative rheological measurements of the dough.

The flour was sieved three times (sieve no. 70, 212 mm). Dry ingredients were added into the mixer (HP4030, ATMA, Argentina), except inulin that was previously dissolved in distilled water and incorporated into the mixer together with the oil. The program consisted of a kneading step for 20 min, then resting for 5 min prior to rounding and fermentation for 30 min at 25 °C, followed by degassing and fermentation for another 40 min at 25 °C. Then the mass was removed from the mixer. Three dough pieces of 150 g were punched, reshaped and placed into steel moulds, which in turn were placed in an oven (MCH, Argentina) for fermentation during 70 min at 38 °C, RH 90%. An aliquot of dough was withdrawn for rheological measurements. The fermented rolls were baked for 35 min at 200 ± 5 °C in a thermostatically controlled oven (ORL-SD 755 PID/T, ORL Electric Ovens SA, Argentina). A tray of water was placed inside the oven to keep air humidity. After baking, bread was cooled down at room temperature during 1 h before measurements.

2.3. Dough rheology

Viscoelastic properties of the dough samples were determined by small deformation dynamic oscillatory measurements performed in a Paar Physica rheometer model MCR301 (Anton Paar GmbH, Austria), using a geometry of parallel plates (50 mm diameter, 2 mm gap), with peltier temperature control. Immediately after kneading, an aliquot of the dough was placed on the rheometer's lower plate, previously conditioned at 25 °C. The upper plate was lowered to the sample, excess sample was removed, and the exposed surface was covered with silicon oil to avoid sample dehydration during measurement. Sample was allowed to rest for at least 5 min to attain thermal equilibrium and dough relaxation. Then, a frequency (ω) sweep test was performed from 100 to 0.1 rad/s at 0.05% strain. Data obtained were elastic modulus (G'), viscous modulus (G''), and loss tangent ($\tan\delta = G''/G'$). Immediately after the first measurement, a strain amplitude (γ) sweep (from 0.01 to 100%, at 10 rad/s) was performed to verify that the measurement was within the linear viscoelastic range (LVR). Each dough sample was measured at least in triplicate, using a fresh sample each time. Additional measurements (under the same conditions) were performed in Control doughs without yeast, in order to determine whether dough leavening during measurement had a significant effect on rheological results.

2.4. Bread quality

2.4.1. Specific volume measurement

To determine the bread specific volume, each loaf was weighed and its volume was determined by the rapeseed displacement method (AACC, 2000). Data were reported as the mean of three measurements, each one performed on a fresh-made loaf.

2.4.2. Moisture content measurement

Moisture content of the breadcrumb was determined by oven drying for 12 h at 80 °C, under vacuum. For each measurement, approximately 5 g of crumb were taken from central slices of the loaf. Data are reported as the mean of three measurements, each one performed on a fresh-made loaf.

2.4.3. Texture analysis

Mechanical properties of the breadcrumbs were obtained from a texture profile analysis (TPA) test using a TA-Plus texture analyzer (Lloyds Instruments, UK). Two slices of 20 mm thickness were cut from each loaf of bread for testing. Then, six measurements were performed for each breadcrumb sample (3 loaves × 2 slices). The TPA test consists of two cycles of compression. In each measurement, a slice of bread was compressed twice in its centre with a cylinder probe (25 mm diameter), to an extension of 10 mm (50% strain), using a crosshead speed of 1 mm/s. Strictly speaking, since the bread slice was bigger than the probe cylinder, this was not a compression experiment, but an indentation experiment (Liu & Scanlon, 2004).

From each force–time curve of the TPA test a number of textural parameters can be extracted, which are considered to correlate well with sensory evaluation of those same parameters (Bourne, 2002). Hardness was obtained as the maximum peak force during the first compression cycle ($H = f_{max}$). It has been defined as the force necessary to attain a given deformation (sometimes called firmness). In sensory analysis, it is the force required to compress a food between molars in the first bite. Fracturability was obtained as the force at the first significant break in the first compression cycle ($F = f_{break}$). It has been defined as a measure of the ease with which a material fractures (sometimes called brittleness). Adhesiveness was calculated as the negative area under the force curve after the first compression cycle ($A = a_3$). It represents the work required to pull the compressive probe away from the sample. In sensory analyses, it represents the work necessary to overcome the attractive forces between the surface of the food and the surface of the material with which the food comes into contact (e.g. tongue, teeth, palate). Cohesiveness was calculated as the ratio of the positive force area during the second compression cycle to that during the first compression ($C = a_2/a_1$). It represents the strength of the internal bonds making up the body of the product. It is expected to be inversely proportional to the rate at which the material fractures under mechanical action. In other words, the lower the cohesiveness of a material, the more brittle it will be. Springiness was calculated as the ratio of the time elapsed during positive forces at the second compression, to that of the first compression ($S = t_2/t_1$). It is related to the height that the food recovers during the time that elapses between the end of the first bite and the start of the second bite. It represents the rate at which a deformed material goes back to its undeformed condition after deforming force is removed (originally it was called elasticity). And chewiness was calculated as the product of hardness × cohesiveness × springiness ($Ch = H \times C \times S$). It represents the energy required to chew a solid food product to a state ready for swallowing.

2.4.4. *Colour measurement*

Colour of breads crumb and crust was measured in a HunterLab UltraScan XE tristimulus colorimeter (Hunter Associates Laboratory, Inc., Reston, VA). Reflected colour (specular component excluded) was measured at 10° observer angle with D65 illuminant. Three loaves of each bread sample were used for measurements and for each loaf, the colour of the crust and the crumb was measured five and eight times, respectively. Results were expressed as the CIE $L^*a^*b^*$ scale parameters, namely L^* [lightness: 0 = black, 100 = white], a^* [greenness(−), redness(+)] and b^* [blueness(−), yellowness(+)].

2.4.5. *Digital image analysis of crumb structure*

Two vertical and central slices (12 mm thickness) were cut from each loaf and placed in a light-box. Colour images were captured using a Nikon D3100 digital camera (35 mm, 1/8, f/5, ISO 100), with a resolution of 300 pixels per inch. Digital images of the crumbs were analyzed with the software ImageJ 1.47 v (National Institutes of Health, Bethesda, MD, USA). The centre of each image (slice) was cropped to a square field of view of 40 mm × 40 mm of the slice area and converted to 8-bits with grey levels ranging from 0 to 255. The images were binarized (converted from grey-level to black and white) using an automated fuzzy measure thresholding method to differentiate gas cells from non-cells. Several crumb grain features were extracted, and the following were selected for analysis: cell density (cells/cm^2), mean cell area (mm^2), polydispersity of cell area, and cell/total area ratio or void fraction (%). Cell area polydispersity was calculated as the ratio of standard deviation to mean value of the cell area distribution of each sample ($P_A = \sigma_A/\bar{A}$), and considered to be inversely proportional to crumb grain uniformity: the lower the value of P_A, the more uniform the cell size. It should be noted that when measuring cell area from bread slices, it must be taken into consideration that only a very small proportion of cells in the slice are actually bisected, and that larger cells are more likely to be cut rather than smaller ones (Crowley, Grau, & Arendt, 2000).

2.4.6. *Sensory evaluation*

Based on the experimental results and overall quality of the breads obtained, sensory evaluation was performed only on breads enriched with 2.5 g IRC of both fibres (samples J-2.5 and C-2.5), and without inulin (Control sample). A total of 138 untrained panellists (males and females) participated in the study. Three slices of bread (one of each sample) coded and in random order, were served to each panellist. Drinking water was offered to the panellists to cleanse their palates between sample tasting. Panellists were asked to evaluate each sample for quality attributes: smell, taste, sponginess (defined as porosity), crumb colour, and crumb texture. They were asked to score each attribute on a 9-point Hedonic scale (1 = dislike extremely, 5 = neither like or dislike, 9 = like extremely). A randomized complete block was the statistic design to analyze sensory results, where each panellist was considered a block.

2.5. *Statistical analysis*

All experiments were performed in a completely randomized design. Statistical differences in bread properties were determined by analysis of variance (ANOVA) and Tukey test, at a significance level of 5% (Infostat software, version 2011 I, Argentina).

3. Results and discussion

3.1. *Dough rheology*

In this work, the effect of IRC addition to wheat flour, on the viscoelastic properties of doughs was analyzed. Analysis of all results indicated that elastic modulus (G') was better than viscous modulus (G'') and phase angle ($\tan\delta$) to represent dough rheological behaviour during fermentation and baking, because G' showed a higher correlation with bread properties, as will be described in next sections. In all cases, G' (Fig. 1) and G'' (not shown) increased with angular frequency (ω), and $G' > G''$, indicating a predominant solid behaviour of the doughs. Measurements of the Control sample dough without yeast showed (Fig. 1) a power law increase of G' with ω (linear increase in a log–log plot) in all the range of frequencies, while all the other samples of doughs with yeast showed negative deviations of this behaviour at $\omega < 4$ rad/s, which were attributed to dough leavening during measurements. It is worth noting that frequency sweeps were performed from 100 to 0.1 rad/s, so that deviations occurred in the later stages of measurement. These negative deviations have been attributed to the decrease in dough density due to the evolving gas

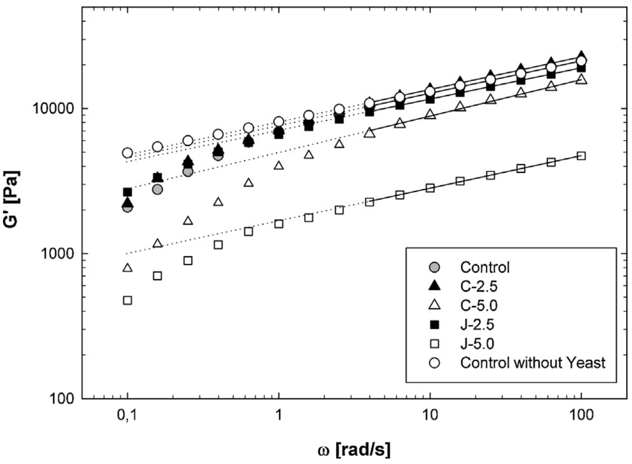

Fig. 1 – Storage modulus vs. angular frequency of wheat doughs enriched with different types and concentrations of inulin. Experimental data at $\omega \geq 4$ rad/s were fitted with power law curves (solid lines), which were extrapolated at lower frequencies (dotted lines).

volume from fermentation, with the effect of decreasing modulus and viscosity (Dobraszczyk & Morgenstern, 2003). Nevertheless, G' values of Control sample with and without yeast exhibited similar values at frequencies higher than 3–4 rad/s. Consequently, results obtained for doughs with yeast (Fig. 1) were considered valid for $\omega \geq 4$ rad/s, where $\log G'$ increased linearly with $\log \omega$. In this region (4–100 rad/s), experimental data of the five samples with yeast were fitted with a power law model (solid lines). These fittings were extrapolated to the non-linear region (0.1–4 rad/s, dotted lines) to show the deviations due to dough leavening.

Values of G' at $\omega = 10$ rad/s (within the linear region) were taken into consideration in order to compare samples. Generally, higher G' values indicate a more solid character of the material; in this case it means more tenacious or stronger dough. It can be observed (Fig. 1) that G' (dough strength) decreased in the following order: C-2.5, Control, J-2.5 > C-5.0 > J-5.0. This means that: (a) addition of 2.5 g of either IRC to 100 g of flour had no significant effect on dough rheology; (b) addition of 5.0 g of either IRC had a weakening effect on wheat dough, and this effect was stronger in the case of IRC-J. This weakening effect of inulin on dough strength may be attributed to the fact that fibre replacement of flour disrupts the starch–gluten matrix due to inulin–gluten or inulin–inulin interactions, affecting dough viscoelastic behaviour and constraining dough machinability and gassing power (Collar et al., 2007; Morris & Morris, 2012).

However, other studies about the effect of inulin on the rheological properties of wheat doughs have shown different trends, and their results are inconclusive. Peressini and Sensidoni (2009) found that G' increased and $\tan\delta$ decreased with increasing levels of inulin, and that this effect was stronger at higher polymerization degrees of the inulin. Hager et al. (2011) reported that the addition of 6.8% inulin had no significant effect on the loss tangent of the doughs, which in all cases was $\tan\delta < 1$. Wang et al. (2002) reported a decrease in dough elasticity, determined by a farinograph test, upon addition of 3% chicory inulin. The addition of chicory inulin Fibruline (1–5%) did not have an impact on extensibility, stickiness, and adhesiveness of the dough, determined by TPA tests (Collar et al., 2007).

3.2. *Bread properties*

3.2.1. *Volume and moisture*

Final moisture content of bread depends on water absorption during dough preparation and water loss during baking. In turn, it has been suggested that crumb morphology strongly affects the rate of water transport (Krupa-Kozak, Altamirano-Fortoul, Wronkowska, & Rosell, 2012). Table 1 shows that addition of IRC had no significant effect on moisture content (M) compared to the Control sample. However, sample J-5.0 showed the highest moisture content, and it was evident by simple observation that this bread was the most humid. As shown in Section 3.2.4, this sample showed the lowest cell/total area ratio (void fraction) (Table 3). This probably slowed down moisture migration and reduced bake loss.

Final bread volume depends on dough expansion during fermentation and baking, and ability of the matrix to stabilize the retained gas. Table 1 shows that addition of IRC produced a decrease in the specific volume ($\hat{V}$) of breads in the following order: Control, C-2.5, J-2.5, C-5.0 > J-5.0. This means that $\hat{V}$ decreased at increasing IRC concentrations, with IRC-J having a stronger effect than IRC-C. According to the Tukey test, the only significantly different sample was bread J-5.0, which was remarkably flat (Fig. 3f). The decrease in bread volume with inulin addition has been attributed to the dilution or diluting effect: soluble fibres impair gas retention (due to the interaction with the gluten network), while do not increase gas production, resulting in a disrupted structure (Mandala et al., 2009; Morris & Morris, 2012). Furthermore, these results seem to be correlated with rheological data of the doughs (Fig. 1), since the decrease in the specific volume of the breads was coincident with the decrease in the elastic modulus of the doughs, at the highest IRC concentration of both fibres, while there was no significant effect on both parameters at the lowest IRC concentration of both fibres.

The effect of the addition of inulin powder to wheat flour on bread volume and moisture, have been studied in several works. In general, it was found that the addition of inulin produced a decrease in bread moisture (Hager et al., 2011; Peressini & Sensidoni, 2009; Wang et al., 2002), while one study reported no significant effect (Praznik et al., 2002). In agreement with our results, most works (Mandala et al., 2009; Meyer & Peters, 2009; O'Brien et al., 2003; Poinot et al., 2010; Wang et al., 2002) found a decrease in bread volume with inulin addition. However, some works showed different trends. Praznik et al. (2002) reported an increase in bread volume, while Hager et al. (2011) found no significant changes upon inulin addition. On the other hand, Peressini and Sensidoni (2009) reported that the addition of inulin ST ($DP_n = 10$) resulted in a decrease or increase in specific volume depending on the type of flour.

Table 1 – Effect of inulin powder addition (0, 2.5 and 5.0 g/100 g of wheat flour) on physical and mechanical properties of bread.

Sample	Moisture (%)	Specific volume (cm^3/g)	Hardness (N)	Springiness	Cohesiveness	Chewiness (N)
Control	39.55 ± 1.43 ab	5.20 ± 0.10 b	2.50 ± 0.25 a	0.85 ± 0.02 a	0.72 ± 0.01 b	1.53 ± 0.16 a
J-2.5	38.13 ± 2.41 a	4.75 ± 0.26 b	3.45 ± 0.16 a	0.90 ± 0.01 b	0.75 ± 0.02 bc	2.31 ± 0.11 ab
C-2.5	40.91 ± 2.14 ab	4.79 ± 0.30 b	5.02 ± 0.51 b	0.90 ± 0.01 b	0.67 ± 0.03 a	3.00 ± 0.13 b
J-5.0	43.34 ± 0.12 b	3.19 ± 0.15 a	6.00 ± 0.71 b	0.88 ± 0.02 ab	0.79 ± 0.01 c	4.16 ± 0.59 c
C-5.0	40.22 ± 2.45 ab	4.66 ± 0.25 b	7.62 ± 0.89 c	0.90 ± 0.01 b	0.64 ± 0.02 a	4.35 ± 0.41 c

Means with a common letter within a column are not significantly different ($p \leq 0.05$).

Regarding the effect of inulin chain length on bread volume, our results showed that IRC-J (*DP* = 9.2) had stronger (negative) effect than IRC-C (*DP* = 12.1). On the contrary, Meyer and Peters (2009) found that higher inulin DP had greatest impact in reducing bread volume.

3.2.2. *Mechanical properties*

Texture profile analysis (TPA) consists of compressing a food sample twice, in a reciprocating motion that imitates the action of the jaw. Fig. 2 shows the resulting force–time curves obtained for the breadcrumb samples. It can be observed that the curves were shifted-up at increasing IRC concentrations, and that IRC-C had a stronger effect than IRC-J.

Calculated textural parameters are listed in Table 1. ANOVA results showed that addition of IRC had a significant effect on all the textural parameters of the breadcrumbs. In first place, hardness (*H*) decreased in the following order: C-5.0 > J-5.0, C-2.5 > J-2.5, Control. These results show a clear trend: *H* values increased at increasing IRC concentrations, with IRC-C having a stronger effect than IRC-J. Secondly, the Control breadcrumb had a springiness (*S*) significantly lower than all the breads with IRC, with no significant differences among them. In third place, cohesiveness (*C*) decreased in the following order: J-5.0 ≥ J-2.5 ≥ Control > C-2.5, C-5.0. This suggests that IRC-J addition had a positive effect on *C* of the breadcrumbs, while IRC-C had a negative effect on *C*. Finally, chewiness (*Ch*) decreased in the following order: C-5.0, J-5.0 > C-2.5 ≥ J-2.5 ≥ Control. These results showed the same trend as *H*: *Ch* values increased at increasing IRC concentrations, with IRC-C having a stronger effect than IRC-J. It is worth to remind that *Ch* is directly proportional to *H*.

The effect of the addition of inulin powder to wheat flour, on breadcrumb mechanical properties (mainly hardness) have been studied in several works. In agreement with our results, most of these works (O'Brien et al., 2003; Poinot et al., 2010; Wang et al., 2002) reported an increase in breadcrumb hardness with inulin addition. However, Hager et al. (2011) found no significant effect of inulin addition on *H* (day 0), and the results of Peressini and Sensidoni (2009) with inulin ST ($DP_n = 10$) did not show a clear trend. Wang et al. (2002) also found an increase in breadcrumb chewiness with inulin addition (in agreement with our results), and no significant effect on cohesiveness and springiness.

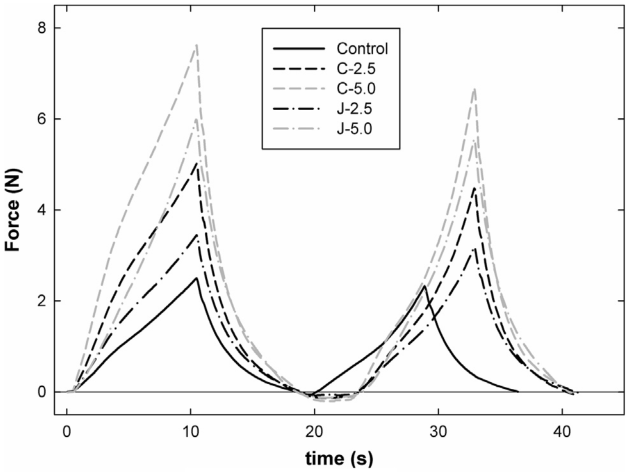

Fig. 2 – Force vs. time curves obtained from the TPA test on wheat breads enriched with different types and concentrations of inulin.

The reported increased crumb hardness (or firmness) has been attributed to the diluting effect (discussed in Section 3.2.1), which impairs gas retention resulting in a lower bread volume (Mandala et al., 2009; Meyer & Peters, 2009; Morris & Morris, 2012). This is in agreement with our results, which showed a coincidence between the increase in crumb hardness and the decrease in bread specific volume at the highest IRC concentration of both fibres (Table 1), which in turn was associated with the decrease in the elastic modulus of the dough.

Regarding the effect of inulin chain length on crumb hardness, our results showed that IRC-C (*DP* = 12.1) had stronger hardening effect than IRC-J (*DP* = 9.2). This is in agreement with Peressini and Sensidoni (2009), who also observed greater hardness increase with higher inulin DP. However, there is some contradiction among our own results because the longer chain inulin produced the higher effect on crumb hardness (*H*), but it was the shorter chain inulin which most affected bread volume ($\hat{V}$). One possible reason is that the difference in DP between IRC-J and IRC-C was not big enough to determine a consistent effect of DP on *H* and $\hat{V}$. Consequently, it was not possible to establish a clear conclusion about the effect of inulin chain length on baking, and bread properties.

3.2.3. *Colour*

Colour of breadcrumb and crust was measured in the CIE $L^*a^*b^*$ colour scale, and the values are listed in Table 2. IRC addition had a significant effect on the colour of both crumb and crust. Colour parameters did not show a clear trend,

Table 2 – Effect of inulin powder addition (0, 2.5 and 5.0 g/100 g of wheat flour) on the colour of breadcrumb and crust.

Sample	Crumb			Crust		
	L^*	a^*	b^*	L^*	a^*	b^*
Control	71.22 ± 1.59 c	0.06 ± 0.37 a	19.35 ± 1.88 a	78.85 ± 0.60 b	2.56 ± 0.39 c	25.45 ± 1.33 c
J-2.5	70.79 ± 1.05 bc	0.44 ± 0.21 b	20.87 ± 0.56 b	80.49 ± 0.53 c	1.64 ± 0.17 b	21.74 ± 0.75 b
C-2.5	71.49 ± 1.15 c	0.45 ± 0.19 b	20.83 ± 0.41 b	81.22 ± 0.79 c	1.90 ± 0.53 b	22.45 ± 1.80 b
J-5.0	61.51 ± 2.05 a	1.47 ± 0.20 d	21.81 ± 0.85 c	69.53 ± 1.61 a	0.62 ± 0.12 a	16.92 ± 0.70 a
C-5.0	69.94 ± 1.09 b	0.88 ± 0.25 c	20.45 ± 0.47 b	79.50 ± 1.05 b	2.89 ± 0.96 c	24.92 ± 1.24 c

Means with a common letter within a column are not significantly different ($p \leq 0.05$).

except crumb redness that increased at increasing IRC concentrations. For all parameters, colour of sample J-5.0 was significantly different from the rest. Crumb of bread J-5.0 was the darkest, most red and most yellow (in opposition to Control sample), while its crust was the darkest, less red, and less yellow.

Some works have studied the effect of inulin addition to wheat flour, on the colour of bread crust, but no one was found on the colour of breadcrumb. Hager et al. (2011) found that inulin darkened the crust (lower L^* values), and attributed this to the partial breakdown of inulin mono and polysaccharides, leading to a stronger Maillard reaction. Peressini and Sensidoni (2009) found that crust browning (colour difference ΔE^*) increased with the increase in fibre, and that this increase (darker colour) was higher for shorter chain inulins, as they posses more low molecular weight fructans. Poinot et al. (2010) reported an enhancement of bread crust colouration (higher a^* and b^* values), while Mandala et al. (2009) did not observe significant effect of inulin addition on crust colour.

3.2.4. *Crumb grain features*

Crumb grain has been defined as the exposed cell structure of crumb when a loaf of bread is sliced. Images of the crumb grain of fibre enriched breads are shown in Fig. 3. As an illustration of the images digitalization process, Fig. 3b shows a binarized image of the selected field of view of the Control breadcrumb. Crumb grain features obtained from the analysis of digitalized images are listed in Table 3. ANOVA results showed that bread enrichment with IRC had a significant effect on the crumb grain features studied. Addition of 5.0 g of IRC-C to 100 g of flour gave the crumb (Fig. 3e) with the smallest mean cell area (significant), and the highest cell density (not significant). On the contrary, addition of 5.0 g of IRC-J gave the crumb (Fig. 3f)

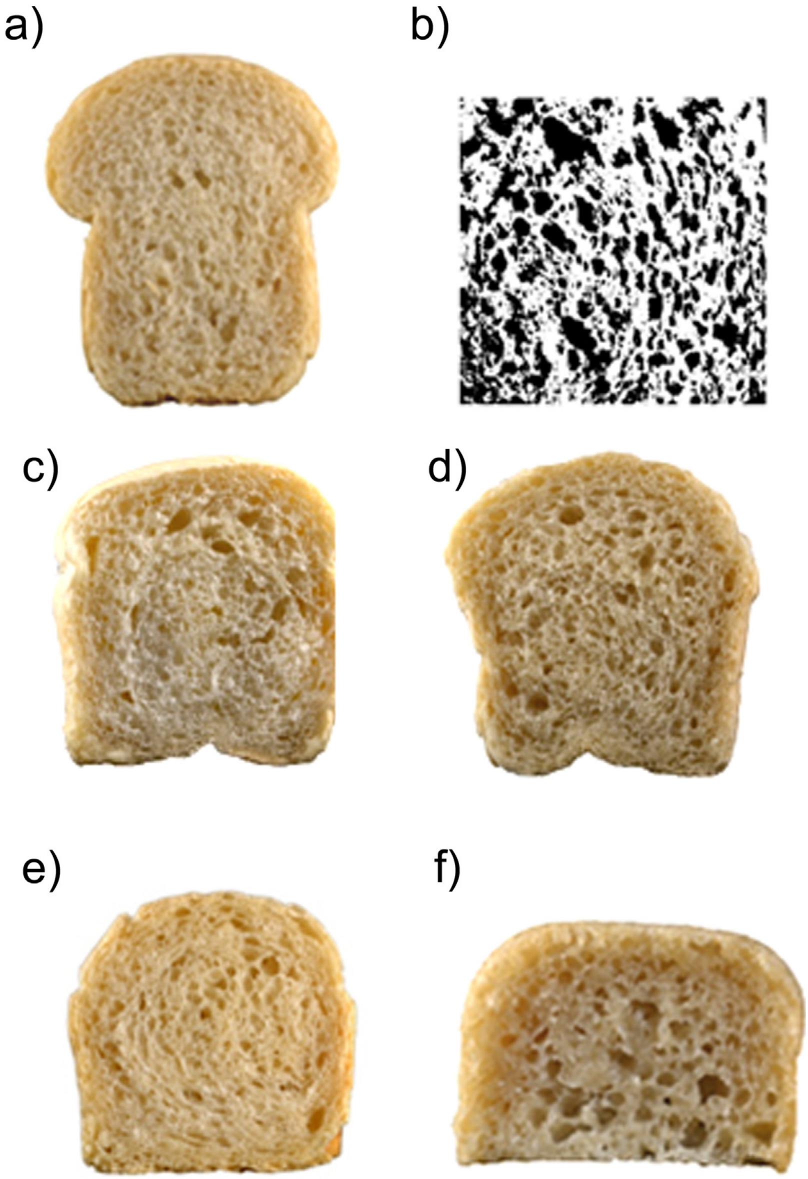

Fig. 3 – Crumbs of bread enriched with different types and concentrations of inulin: Control (a), and its binarized image (b); C-2.5 (c), J-2.5 (d), C-5.0 (e), and J-5.0 (f).

Table 3 – Effect of inulin powder addition (0, 2.5 and 5.0 g/100 g of wheat flour) on breadcrumb grain features.

Sample	Mean cell area (mm^2)	Cell area polidispersity	Cell/total area ratio (%)	Cell density (cells/cm^2)
Control	1.08 ± 0.33 b	9.6 ± 3.3 ab	54.9 ± 4.4 b	53.6 ± 11.8 b
J-2.5	1.05 ± 0.24 ab	17.4 ± 6.7 c	62.9 ± 7.7 bc	56.4 ± 11.5 b
C-2.5	1.26 ± 0.23 b	15.5 ± 3.8 bc	65.3 ± 5.8 c	52.7 ± 6.0 b
J-5.0	1.39 ± 0.17 b	6.1 ± 1.8 a	41.1 ± 5.3 a	30.1 ± 6.4 a
C- 5.0	0.67 ± 0.14 a	9.8 ± 4.3 ab	41.8 ± 4.7 a	64.3 ± 9.1 b

Means with a common letter within a column are not significantly different ($p \leq 0.05$).

with the biggest mean cell area (not significant), and the lowest cell density (significant). In other words, C-5.0 and J-5.0 were the crumbs with the finest and the coarsest structures, respectively. Addition of 2.5 g of either IRC (Fig. 3c and d) did not have a significant effect on these two properties, but gave the highest values of cell area polidispersity (P_A), which means the crumbs with lower grain uniformity. In contrast, addition of 5.0 g of IRC-C did not have a significant effect on P_A compared to the Control sample, while addition of 5.0 g of IRC-J gave the lowest P_A, i.e. the bread with the highest crumb grain uniformity. On the other hand, addition of 5.0 g of either IRC significantly decreased the cell/total area ratio (void fraction) compared to the Control sample. Addition of 2.5 g of either IRC increased the cell/total area ratio, although the difference with the Control sample was only significant in the case of IRC-C.

According to these results, it seems that addition of 5.0 g of IRC-C facilitated the formation of cell nuclei during mixing, but inhibited the growth of these cells during fermentation, and/or did not allow gas retention during baking, while the addition of 5.0 g of IRC-J apparently induced coalescence of cells during fermentation. The decrease in cell/total area ratio (void fraction) of crumb at the highest IRC concentration of both fibres seems to be associated with the decrease in specific volume of bread (Table 1), which was attributed to the reduction in the gas retention capacity due to the interaction of the fibres with the gluten network (the diluting effect, discussed in Section 3.2). Also, the lowest void fraction of sample J-5.0 was believed to slow down moisture migration and bake loss, giving the sample with the highest moisture content (Table 1), as discussed in Section 3.2.1.

It is worth mentioning that the addition of 2.5 g of IRC of either fibre to 100 g of flour did not produce significant changes in dough elastic modulus (Fig. 1), bread moisture and volume (Table 1), crumb cell density and mean cell area (Table 3). However, at this fibre level, IRC-C (but not IRC-J) produced a significant increase in bread hardness and chewiness (Table 1), and a significant increase in crumb void fraction (Table 3). The decrease of crumb grain uniformity upon addition of 2.5 g of IRC of either fibre may have been caused by disproportionate growth of gas cells during fermentation and/or baking. However, addition of 5.0 g of IRC produced the opposite (IRC-J) or no effect (IRC-C). The reason of this remains unclear for us.

3.2.5. *Sensory evaluation*

It was shown in this work that IRC addition of both fibres at the highest concentration (5.0 g in 100 g of flour) had a significant effect on all of the bread physical properties. Furthermore, simple observation showed that the quality of bread made with 5.0 g of IRC-J (sample J-5.0) was unacceptable (too flat, too humid, and too dark). Therefore, breads with 5.0 g of IRC of both fibres (J-5.0 and C-5.0) were discarded for sensory analysis. On the other hand, the lowest IRC concentration (2.5 g in 100 g of flour) had a lower effect on bread properties, but still significant in the case of some of these properties. Therefore, it was of major importance to determine whether these differences had an impact on breads sensory properties and consumers' acceptance. Then, breads enriched with 2.5 g of IRC of both fibres (J-2.5 and C-2.5) were subjected to sensory analysis, together with the Control sample. All the attributes evaluated (smell, taste, sponginess, crumb colour, and crumb texture) of these three samples scored more than six points (Table 4), meaning that these samples were acceptable. No significant differences were found between the three samples, in any of the attributes evaluated. In particular, it is worth to note that even though addition of 2.5 g of IRC of either fibre produced significant changes in some of the crumb mechanical properties, colour parameters, and grain features, consumers did not find differences in related attributes like crumb texture, sponginess and colour (neither in smell and taste). This is a very positive result because it means that addition of inulin to wheat flour was not detrimental to any of the sensory attributes of the bread, and that the regular consumer was unable to distinguish the difference between normal and inulin enriched breads.

Table 4 – Effect of inulin powder addition (0 and 2.5 g/100 g of wheat flour) on sensory properties of bread (in all cases $p > 0.05$).

Sample	Smell	Taste	Sponginess	Crumb colour	Crumb texture
Control	6.64 ± 2.16	6.61 ± 2.25	6.86 ± 2.00	6.78 ± 1.91	6.92 ± 2.03
J-2.5	6.24 ± 2.41	6.12 ± 2.65	6.76 ± 2.12	6.54 ± 2.22	6.93 ± 2.06
C-2.5	6.18 ± 2.35	6.50 ± 2.44	6.75 ± 2.20	6.35 ± 2.34	6.79 ± 2.28

4. Conclusions

Fibre enrichment of white bread with 5.0 g of inulin powder extracted from Jerusalem artichoke tubers (IRC-J) per 100 g of wheat flour produced significant changes in dough viscoelastic properties and bread physical properties, due to the diluting effect, giving a bread of unacceptable quality. However, addition of a lower concentration of IRC-J (2.5 g/100 g flour) did not produce significant changes in dough rheology and bread quality parameters, except colour and crumb grain uniformity. Most importantly, no significant differences were found in any of the sensory attributes evaluated, compared to the Control sample. These findings indicate that wheat bread may be enriched with IRC-J fibre up to 2.5 g/100 g flour, without detrimental consequences on dough machinability and gassing power, keeping the quality attributes of the conventional bread. Similar results were found with the commercial chicory inulin.

Industrial relevance

Enrichment of white bread (a product of massive consumption) with dietary fibre is of great interest for the bakery industry due to the increasing demand of healthier food products. In particular, inulin has been proved to provide many health benefits, including its prebiotic capacity. Determination of its effect on bread quality, texture, and sensory attributes are fundamental to assure consumers' acceptance. No less important is to determine the effect of inulin on dough rheological behaviour, in order to predict how it would affect dough handling and machinability during the bread making process.

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REFERENCES

AACC. (2000). *Method 10-05.01. Guidelines for measurement of volume by rapeseed displacement approved methods of analysis* (10th ed.). St. Paul, MN, USA AACC International.

Bonnand-Ducasse, M., Della Valle, G., Lefebvre, J., & Saulnier, L. (2010). Effect of wheat dietary fibres on bread dough development and rheological properties. *Journal of Cereal Science, 52*(2), 200–206http://dx.doi.org/10.1016/j.jcs.2010.05.006.

Bourne, M. C. (2002). Principles of objective texture measurement. In S. L. Taylor (Ed.), *Food texture and viscosity: Concept and measurement* (pp. 182–186). San Diego: Academic Press.

Collar, C., Santos, E., & Rosell, C. M. (2007). Assessment of the rheological profile of fibre-enriched bread doughs by response surface methodology. *Journal of Food Engineering, 78*(3), 820–826http://dx.doi.org/10.1016/j.jfoodeng.2005.11.026.

Crowley, P., Grau, H., & Arendt, E. K. (2000). Influence of additives and mixing time on crumb grain characteristics of wheat bread. *Cereal Chemistry, 77*(3), 370–375.

Dobraszczyk, B. J., & Morgenstern, M. P. (2003). Rheology and the breadmaking process. *Journal of Cereal Science, 38*(3), 229–245.

Franck, A., & De Leenheer, L. (2005). Inulin. In Steinbuchel, A. (Ed.). *Biopolymers online*. Vol. 6 (pp.439–479). Weinheim, Germany: Wiley-VCH.

Gan, Z., Ellis, P. R., & Schofield, J. D. (1995). Gas cell stabilisation and gas retention in wheat bread dough. *Journal of Cereal Science, 21*(3), 215–230http://dx.doi.org/10.1006/jcrs.1995.0025.

Hager, A. S., Ryan, L. A. M., Schwab, C., Gänzle, M. G., O'Doherty, J. V., & Arendt, E. K. (2011). Influence of the soluble fibres inulin and oat β-glucan on quality of dough and bread. *European Food Research and Technology, 232*(3), 405–413.

Kays, S. J., & Nottingham, S. F. (2007). *Chemical composition and inulin chemistry biology and chemistry of jerusalem artichoke: Helianthus tuberosus L.*. CRC Press (pp. 53–96).

Krupa-Kozak, U., Altamirano-Fortoul, R., Wronkowska, M., & Rosell, C. M. (2012). Breadmaking performance and technological characteristic of gluten-free bread with inulin supplemented with calcium salts. *European Food Research and Technology, 235*(3), 545–554.

Liu, Z., & Scanlon, M. G. (2004). Revisiting crumb texture evaluation methods: Tension, compression, and indentation. *Cereal Foods World, 49*(2), 76–82.

Mandala, I., Polaki, A., & Yanniotis, S. (2009). Influence of frozen storage on bread enriched with different ingredients. *Journal of Food Engineering, 92*(2), 137–145http://dx.doi.org/10.1016/j.jfoodeng.2008.06.020.

Meyer, D., & Peters, B. (2009). Enhancing the nutritional value of bread with inulin. *Agro Food Industry Hi-Tech, 20*(3), 43–47.

Mirsaeedghazi, H., Emam-Djomeh, Z., & Mousavi, S. M. A. (2008). Rheometric measurement of dough rheological characteristics and factors affecting it. *International Journal of Agriculture and Biology, 10*(1), 112–119.

Morris, C., & Morris, G. A. (2012). The effect of inulin and fructo-oligosaccharide supplementation on the textural, rheological and sensory properties of bread and their role in weight management: A review. *Food Chemistry, 133*(2), 237–248.

O'Brien, C. M., Mueller, A., Scannell, A. G. M., & Arendt, E. K. (2003). Evaluation of the effects of fat replacers on the quality of wheat bread. *Journal of Food Engineering, 56*(2/3), 265–267.

Peressini, D., & Sensidoni, A. (2009). Effect of soluble dietary fibre addition on rheological and breadmaking properties of wheat doughs. *Journal of Cereal Science, 49*(2), 190–201.

Poinot, P., Arvisenet, G., Grua-Priol, J., Fillonneau, C., Le-Bail, A., & Prost, C. (2010). Influence of inulin on bread: Kinetics and physico-chemical indicators of the formation of volatile compounds during baking. *Food Chemistry, 119*(4), 1474–1484http://dx.doi.org/10.1016/j.foodchem.2009.09.029.

Praznik, W., Cieślik, E., & Filipiak-Florkiewicz, A. (2002). Soluble dietary fibres in Jerusalem artichoke powders: Composition and application in bread. *Nahrung – Food, 46*(3), 151–157.

Rubel, I. A., Pérez, E. E., Genovese, D. B., & Manrique, G. D. (2014). In vitro prebiotic activity of inulin-rich carbohydrates extracted from Jerusalem artichoke (*Helianthus tuberosus* L.) tubers at different storage times by *Lactobacillus paracasei*. *Food Research International, 62*, 59–65http://dx.doi.org/10.1016/j.foodres.2014.02.024.

Sangnark, A., & Noomhorm, A. (2004). Chemical, physical and baking properties of dietary fiber prepared from rice straw. *Food Research International, 37*(1), 66–74http://dx.doi.org/10.1016/j.foodres.2003.09.007.

Wang, J., Rosell, C. M., & Benedito de Barber, C. (2002). Effect of the addition of different fibres on wheat dough performance and bread quality. *Food Chemistry, 79*(2), 221–226.