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Apple pomace in gluten-free formulations: effect on rheology and product quality

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Summary The objective of the present work was to formulate a gluten-free (GF) baked product based on a cassava starch, rice flour and egg white mixture and enriched with apple pomace with minimum processing as source of fibre. Effects of apple pomace and water amount on batters and product quality were analysed by response surface methodology (RSM). Dynamic moduli of batters, specific volume and crumb texture were highly dependent on both apple pomace and water. Higher levels of fibre rendered less cohesive and less resilient crumbs and diminished specific volumes. A suitable balance between amounts of apple pomace and water led to products with enough specific volume and sponginess. Up to 12.5 g apple pomace and water ranging from 115 to 150 g (each 100 g mixture), specific volumes were maintained higher than 2 $cm^3\ g^{-1}$; if apple pomace was increased up to 20 g, water amounts higher than 140 g were necessary to obtain similar results.

Keywords Apple pomace, cassava starch, gluten-free, response surface methodology, rheology, rice flour.

Introduction

Coeliac disease is a permanent intolerance to certain peptide sequences found in the proteins of wheat, barley and rye and derivatives of these cereals. The effect of oat proteins on patients with coeliac is still under discussion. This disease occurs in adults and children at rates approaching 1% of the population (Green & Cellier, 2007). So far, the only effective method for the treatment of coeliac disease has been to adopt a strict diet free of allergenic proteins. Baked products in this type of diet are mainly based on flours and starches from different botanical origins: corn, cassava, rice, soya bean and buckwheat among others.

Replacement of wheat flour in breadmaking presents a major technological challenge as gluten is an essential structure-building protein contributing to the appearance and crumb structure of many baked products. Besides, gluten matrix is a major determinant of important rheological characteristics of dough (Wieser, 2007). In contrast, gluten-free (GF) doughs are unable to develop a protein network with characteristics like gluten. Consequently, in GF products, the choice of a suitable protein source is a critical subject as it should provide the features of gluten network to support the solid matrix of the baked product. Different studies have highlighted the power of egg as a foaming agent in various baked products (Crockett *et al*., 2011; Licciardello *et al*., 2012). In addition, egg white has advantages with respect to whey proteins because in diets for patients with coeliac, lactose intake should be avoided for preventing lactose intolerance.

Previous research has led to progress in developing GF leavened breads with good acceptability characteristics (Alvarez-Jubete *et al*., 2010; Hüttner & Arendt, 2010; Sciarini *et al*., 2012; Hager & Arendt, 2013).

In spite of technological improvements, there is concern about the adequate nutritional level of GF diets because they are often characterised by an excessive intake of carbohydrates (sugars) and a reduced intake of protein, vitamins and minerals. Particularly, they have a low content of dietary fibre, which is necessary for proper functioning of digestive tract (Wild *et al*., 2010). Consequently, the enrichment of GF products with fibre appears to be necessary, as would contribute to cover the recommended daily intake of 25 g day^{-1} (Hager *et al*., 2011). Apple pomace, the by-product of apple juice and cider production, is a good source of fibre, particularly insoluble one. The remaining apple pulp contains 12% dry residue, which is half dietary fibre. Its calorie contribution is only 45 cal/100 g

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(Sotelo *et al.*, 2007). Another remarkable aspect is its richness in polyphenols, components with antioxidant activity (Bai *et al.*, 2013).

According to latest trends in GF baked products with increased nutritional value, apple pomace could be an interesting alternative source for fibre and polyphenols.

The objectives of the present work were (i) to optimise the use of apple pomace with minimum processing in the formulation of a GF baked product as a function of apple pomace content and water amount, (ii) to characterise the rheological behaviour of batters and (iii) to describe quality attributes of GF bread.

Materials and methods

Materials

Crude apple pomace, the source of fibre, was provided by the food company Jugos SA (Villa Regina, Rio Negro, Argentina). Rice flour and cassava starch were gluten-free grade (Kapac, Argentina). Dried egg white (Ovobrand, Argentina) was used as protein source. Other ingredients and additives used were sucrose (Ledesma, Argentina), margarine (Danica, Argentina), yeast (Calsa, Argentina), chemical leavening (Royal, Argentina), hydroxypropyl methylcellulose-HPMC F 4M (Methocel; Dow Chemical Company, Midland, MI, USA) and sodium stearoyl lactylate-SSL (Danisco, Denmark). A minimum addition of sucrose was performed because the dried apple pomace confers a slight sweet taste to GF bread which could be enhanced by sucrose in order to obtain a definite sweet flavour.

Methods

Apple pomace pretreatment

For the present work, crude apple pomace was dried at 50 °C in a forced convection oven (GMX 9203A PEET LAB, USA) during 24 h, then ground and sieved through a sixty mesh (250 μm) to uniform particle size (Masoodi *et al.*, 2002 with slight modifications). After this procedure, the fine powder obtained was sterilised at 121 °C during 20 min to eliminate natural flora (mainly yeasts and moulds) for preventing noncontrolled fermentations during breadmaking process.

Physical and chemical analysis

Moisture determinations were performed according to AOAC method 964.22 (AOAC, 1990). Total dietary fibre was determined by enzymatic method, total protein content by Kjeldahl (AACC 46-12, 2000; with slight modifications: $CuSO_4$ as catalyst and Methyl red-bromocresol green as indicator) and ash by calcination at 550 °C (AACC 8-1, 2000). Carbohydrates different from fibre were calculated by difference. Water activity of dry powder was determined according to AOAC method (AOAC 978.18, 1995) with an Acqualab equipment (DECAGON DEVICES, Inc., Pullman, WA, USA). Reported values correspond to the average of three determinations. Particle size of ground apple pomace was determined by light scattering using a MASTERSIZER 2000E equipment with a HYDRO 2000 MU dispersion unit (MALVERN Instruments, Malvern, UK). Powder was dispersed in an ethanol–water solution (70:30) in a ratio 0.5 g apple pomace to 4.5 g solution. Refractive index of the dispersion was 1.367. Pump speed was 1800 r.p.m. Particle size is reported as the Sauter diameter, defined as the diameter of a sphere that has the same volume/surface area ratio as the measured particle. Means were obtained from ten readings made on two independently prepared dispersions.

Experimental design for GF formulations

Response surface methodology (RSM) was applied and a central composite design was used. Preliminary tests were carried out to establish the levels of the different design factors. Three replicates at the central point of the design were used to allow estimation of pure error. A total of eleven points (corresponding to nine formulations) were evaluated. Two independent variables were used: apple pomace percentage (X_1) and water percentage (X_2). Percentages are expressed on 100 g cassava–rice–egg white mixture (cassava starch 45 g, rice flour 45 g, egg white 10 g). After preliminary baking tests, the upper and lower limits for the independent variables could be established. Apple pomace levels were 5–20 g, and water levels were 115–150 g. Other ingredients were sucrose 10 g, fresh yeast 3 g, margarine 2 g, HPMC 1 g, SSL 0.5 g and chemical leavening 0.1 g. Apple pomace and water amounts for each point of the design are shown in Table 1.

Table 1 Experimental design: apple pomace and water amounts

	Apple pomace amount		Water amount	
Run	Coded	Uncoded (%*)	Coded	Uncoded (%*)
1	0	12.5	−1.41	115
2	0	12.5	0	133
3	1	17.8	−1	120
4	−1	7.2	−1	120
5	1.41	20	0	133
6	0	12.5	1.41	150
7	−1	7.2	1	145
8	0	12.5	0	133
9	0	12.5	0	133
10	−1.41	5	0	133
11	1	17.8	1	145

*Based on 100 g cassava–rice–egg white mixture.

Different dependent variables were selected as responses for representing the main batter characteristics and GF bread quality.

To establish predictive models for batter and bread properties, experimental data for each response variable were fitted to polynomial equations like eqn (1).

$$Y = b_0 + b_1X_1 + b_2X_2 + b_{11}X_1X_1 + b_{22}X_2X_2 + b_{12}X_1X_2 \quad (1)$$

where Y = response, X_i = independent variables (apple pomace and water levels %) and b_i = factors obtained from each fitting.

The statistical software Design-Expert 7 (Stat-Ease Inc., Minneapolis, MN, USA) was used to determine significant differences among factors, fit linear or second-order models and generate response surface plots. Significant differences among factors were assessed by F-tests ($P < 0.05$).

Breadmaking

Breadmaking was performed according to Sciarini *et al.* (2012) with minor technical modifications. Dry ingredients were mixed with the melted margarine into the bowl of a mixer (KENWOOD MAJOR 1200W; KENWOOD, Treviso, Italy). Water containing the dispersed yeast was slowly added while mixing at 52 r.p.m. for 4 min and then at 124 r.p.m. for 5 min. The bowl with the batter was put into a proofer (ROTATE, Brito Hnos, Argentina) at 30 °C for 30 min. After this first bulk fermentation step, the leavened batter was mixed at the lowest speed for 1 min to uniform bubbles size and distribution. The mixture was then fractionated into conical individual moulds (base diameter 4.0 cm, top diameter 6.5 cm, height 5.5 cm, 50 g capacity) and proofed for 25 min at 30 °C. After this second fermentation step, moulds were carried into the oven (ARISTON, Fabriano, Italy) and baked at 210 °C for 45 min. Hot pieces were removed from moulds and allowed to cool at room temperature before measurements.

Batter characterisation

For batter characterisation by dynamic rheometric measurements, formulations were prepared as described above except for the addition of yeast to avoid changes during measurements.

Rheological measurements were taken using a controlled stress rheometer (Haake RS600; Thermo Fisher Scientific, Waltham, MA, USA) with a serrated parallel plate fixture (diameter of 35 mm with a gap of 1.5 mm) at a constant temperature (25 ± 0.1 °C). The linear viscoelasticity region was determined through stress sweep tests at 1 Hz. Frequency sweeps (from 0.005 to 100 Hz) were performed at constant deformation within the linear viscoelastic range. Mechanical spectra were obtained (dynamic moduli G', G'' as frequency functions). G' (elastic modulus) is related to the material response as a solid, while G'' (viscous modulus) is related to the material response as a fluid.

Product quality attributes

The following measurements were taken on the final products:

Moisture: according to AACC method 44-19 (AACC. 2000)

Bread volume: It was determined by rapeseed displacement. For each piece, weight, volume and specific volume were calculated.

Texture profile analysis (TPA): Compression assays with a texture analyser (TA-TXT2i; Stable Micro Systems, Surrey, UK) were performed. Central slices from each bread, without crust (1.5 cm height), were compressed twice up to a percentage of 40% of the total height, with a SMPSP/75 probe. Results were reported as the average from six slices from different breads. The parameters determined were hardness (N), cohesiveness (dimensionless), resilience (dimensionless) and chewiness (N). These determinations were made on fresh bread (day 0) and after 24 h storage (day 1). Storage was performed in plastic bags in a chamber at 20 °C.

Crust and crumb colour: Colour was measured using a colorimeter (Chroma Meter CR-400C; Minolta, Osaka, Japan). The Hunter scale parameters were determined: L, a and b. L (lightness) ranges from 0 to 100, from black to white, a ranges from positive values indicating redness to negative values indicating greenness and b, from positive values indicating yellowness to negative values indicating blueness.

Crumb image analysis: Images from the centre of each slice were acquired with a resolution of 350 dots per inch with a HP scanner 4070 model. Images were binarized using (Image J 1.43u software; National Institutes of Health, Bethesda, MD, USA). In order to avoid distortions on image parameters due to differences in brightness, this parameter was uniformed previous to binarization. The crumb grain characteristics studied were cell density (number of air cells cm^{-2}) and void fraction.

Statistical analysis

Parameters of stored bread were subjected to one-way ANOVA. Significant differences among means were determined according to Tukey HSD test with a confidence level of 95%.

Results and discussion

Apple pomace characterisation

Dried apple pomace was a slightly brown and aromatic powder. Its composition, determined through official methods, was (on 100 g basis) as follows: moisture 14.02 ± 0.06 g; protein 4.28 ± 0.02 g; ash 1.77 ± 0.02 g, dietary fibre 41.04 ± 1.02 g and carbohydrates different from fibre (calculated by difference): 38.89 g. Water activity of the dried product was 0.321 ± 0.001.

Particle size determined by light scattering indicated a bimodal distribution. Sauter diameter values were 0.84 μm for the principal population and 241.03 μm for the minor population of particles.

Batters rheology

Mechanical spectra of batters obtained at two constant levels of water and different levels of apple pomace (selected from de experimental design) are shown in Fig. 1a,b. The type of viscoelastic behaviour of batters was greatly affected by the amount of apple pomace and level of water. At a constant water level, higher amounts of fibre led to higher values for both moduli. At higher levels of apple pomace (17.8, 20%), both moduli (G′ and G″) showed a dependency with frequency and a crossover point was observed. This behaviour has been reported as characteristic of concentrated polymeric systems (Ross-Murphy, 1988). At frequencies below the crossover point, loss moduli (G″) were higher than storage moduli (G′), thus indicating a more viscous response. In this zone, corresponding to the lowest frequencies, the system can recover an equilibrium configuration within the time scale of the experiment, thus the behaviour results predominantly viscous (Lapasin & Pricl, 1995). After the crossover point, the opposite behaviour was found and the elastic modulus G’ predominated, resulting into a more elastic behaviour, with a tendency to a ‘plateau’. The existence of a ‘plateau’ is a consequence of entanglements; within this frequency region, the structure is locked into a temporary network where moduli are more independent from frequency (Lai *et al.*, 2008).

Comparing the spectra obtained for 133% water and 20% apple pomace (Fig. 1a) with the one obtained for 120% water and 17.8% apple pomace (Fig. 1b), it can be observed that the crossover point appears at lower frequencies for the more concentrated system. This shifting is indicating a more elastic response when increasing concentration.

At intermediate levels of apple pomace (7.2; 12.5%), G′ was always higher than G″ within all the assayed range, although showing a slight dependency on frequency for both moduli; this behaviour was closer to that of a gel. At lower levels of apple pomace (5%) without water restriction (133%), an increase of both moduli with frequency was observed, and there was a similar contribution of G′ and G″ to the global viscoelastic response. G″ was slightly higher than G′ during almost all the assayed range, and a crossover seems to appear at higher frequencies.

These results indicate an important influence of apple pomace concentration on the type of rheological behaviour of the batter.

Apple pomace fibre is mainly composed by cellulose, pectin and hemicelluloses (i.e. cell wall polysaccharides). Lazaridou *et al.* (2007) studied the effect of the addition of different hydrocolloids on GF dough rheology. They found that gums addition implicates the use of higher amounts of added water to obtain a dough of adequate consistency. However, in the cases of β-glucan and pectin, the GF doughs became stronger (higher G′ values) with increasing hydrocolloid concentration indicating that the rise of polymer level

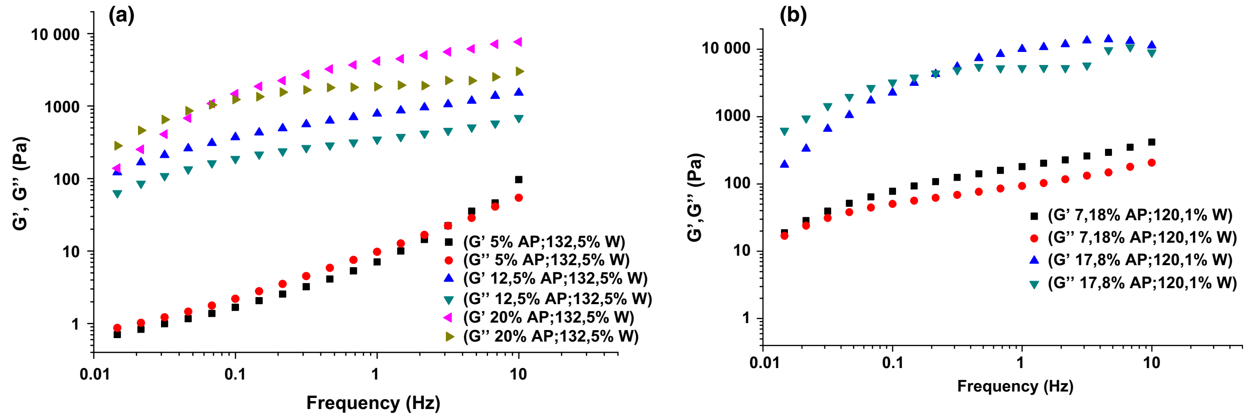

Figure 1 Typical mechanical spectra for batters with different levels of apple pomace (AP) and water (W).

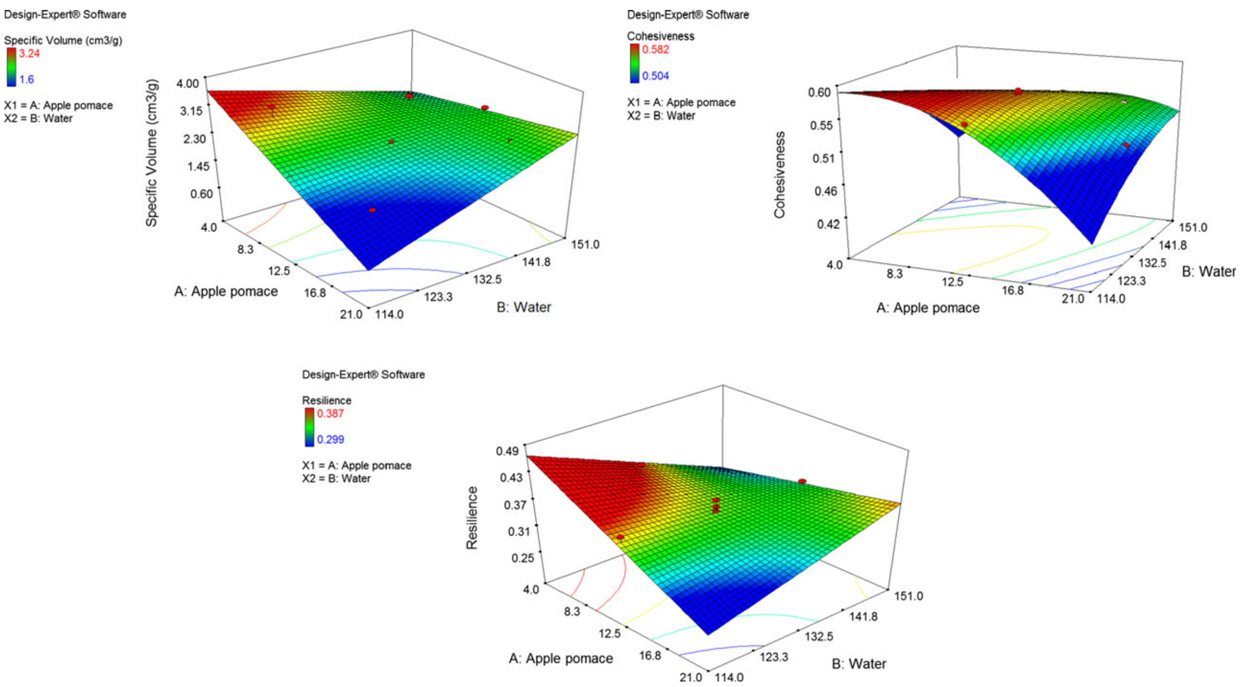

Figure 2 Response surfaces for quality attributes (specific volume, cohesiveness and resilience) of bread and crumb as a function of apple pomace and water amounts.

affected the rheological properties of the dough more than the increasing content of water.

Bread volume

In Fig. 2, response surface for specific volume of breads is shown. The corresponding polynomial model exhibited a R^2 (adjusted) higher than 70% (Table 2). Increasing the level of apple pomace and reducing the level of water decreases the specific volume. Reported specific volumes obtained for GF breads highly vary according to the ingredients and the preparation procedure; different authors have reported values between $1.3\ \mathrm{cm}^3\ \mathrm{g}^{-1}$ (Alvarez-Jubete *et al.*, 2010) and $4.5\ \mathrm{cm}^3\ \mathrm{g}^{-1}$ (Andersson *et al.*, 2011). Specific volume values obtained in the present work ranged between 1.6 and $3.2\ \mathrm{cm}^3\ \mathrm{g}^{-1}$ in agreement with those reported for GF breads based on corn and rice starches (Sabanis & Tzia, 2011a,b) or different flours (Hager *et al.*, 2012). The same tendency was obtained for bread height, which ranged from 3.8 to 6.2 cm being formulations with the highest levels of apple pomace those with the lowest heights. Formulations with high levels of apple pomace and low levels of water showed a typical compact structure and irregular crust on the top. As apple pomace absorbs large amounts of water, a

Table 2 Coefficients for polynomial expressions of response surfaces of volume and crumb texture characteristics

	Y (dependent variable)					
Factor	Specific volume ($\mathrm{cm}^3\ \mathrm{g}^{-1}$)	*P*-value	Cohesiveness	*P*-value	Resilience	*P*-value
b_0	11.70		0.05		1.25	
b_1	−0.84	0.0052	−0.04	0.0007	−0.06	0.0218
b_2	−0.06	0.2994	0.01	0.0440	−6.45E-03	0.2516
b_{11}	–		−6.63E-04	0.0005	–	
b_{12}	5.81E-03	0.0165	3.77E-04	0.0003	4.60E-04	0.0165
b_{22}	–		−6.46E-05	0.0085	–	
R^2 adj.	0.71		0.95		0.63	
Lack of fit (*P*)	0.05		0.61		0.29	

lack of enough hydration could render dry crumbs and crusts.

Bread volume depends on many factors such as viscosity of batter, the amylose/amylopectin ratio and the presence of active surface components or protein aggregation by heating (Schober, 2009). Due to the absence of a protein network, retention of the CO_2 produced during fermentation is difficult in GF breads, thus leading to a product with low specific volume and a compact crumb (Brites *et al.*, 2010). Fibre-rich ingredients like apple pomace could make more critical this problem.

Textural quality and air cell structure of crumb

Response surfaces obtained for some textural attributes of crumbs like cohesiveness and resilience are shown in Fig. 2. Lack of fit was significant for hardness; so a response surface could not be obtained. For most formulations, hardness ranged from 1.98 to 3.90 N without significant differences among them, but at higher levels of apple pomace (17.8–20%) and with water limitations (120, 133%), hardness resulted ten times higher reaching up to 25.42–27.71 N. These higher values would indicate a hardening effect of fibre depending on water amount. These values are comparable to those reported by others authors (Alvarez-Jubete *et al.*, 2010; Crockett *et al.*, 2011). A similar tendency was obtained for chewiness (data not shown). Sabanis *et al.* (2009) found a similar hardening effect of wheat fibre on GF breads that could be attributed to its water binding properties.

Cohesiveness is related to the strength of the internal bonds among components. Cohesiveness varied between 0.504 and 0.582. The response surface for this attribute indicates that the increase in the level of apple pomace decreases cohesiveness and, on the other hand, the raise of the level of water increases this attribute. This trend is evident in the polynomial equation from the negative and positive coefficients for apple pomace and water, respectively. Coefficient for interaction between apple pomace and water is also significant (Table 2).

Resilience (which expresses the ability or speed of material to return to its original shape after a stress) showed the same tendency as cohesiveness: when the amount of apple pomace increases and the amount of water decreases, resilience exhibits the lowest values. Experimental values varied between 0.299 and 0.385 for this parameter.

In Fig. 3, examples of crumb obtained with two different levels of apple pomace and the same level of water are shown. A more compact and darker crumb is obtained with 20% apple pomace.

Air cell structure characteristics could not be fitted with polynomial expressions, but ANOVA was performed with the results of the different runs (Table 3). The minor average size and the highest density were found for those formulations rich in apple pomace but restricted water (20;133, 17.8;120). These formulations exhibited a compact crumb, with the lowest void fraction, in agreement with the highest hardness observed.

Highest air cell average size with highest void area corresponded to formulations with intermediate-high apple pomace content but a more adequate ratio between apple pomace and water (12.5;133, 12.5;150, 12.5;115). A minor air cell density was also observed for these samples. These results can be related to the rheological characteristics of batters: highest dynamic moduli observed for those formulations with high levels of apple pomace restrain leavening, thus leading to a more compact crumb.

Bread colour

Colour is an important characteristic of baked products and contributes to consumer preference. It depends on factors such as formulation or baking conditions. The response surfaces for colour parameters fitted linear models. Coefficients of the respective polynomial expressions are shown in Table 4. In both cases (crumb and crust), similar trends were obtained: when the level of apple pomace increased, the *L* values decreased. Little influence was found for the variation of the amount of water. Experimental values varied in

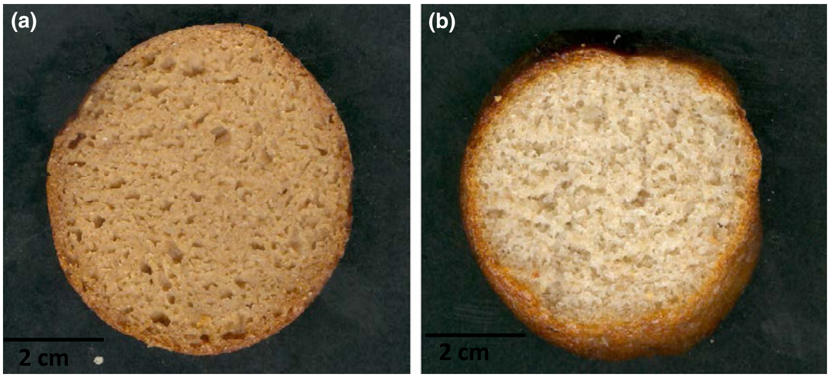

Figure 3 Photographs of typical bread slices corresponding to different levels of fibre and water (a) Run 5 (20%, 133%) (b) Run 10 (5%, 133%).

Table 3 Air cell structure for the formulations of the experimental design

Apple pomace (%)*; water (%)	Average size (mm^2)	Air cell density (number cells cm^{-2})	Void fraction (%)
20:133	1.39^{a}	24.63^{c}	31.96^{a}
17.8:120	1.80^{ab}	23.61^{c}	37.61^{ab}
12.5:133	5.31^{cde}	10.59^{ab}	52.46^{e}
12.5:133	5.68^{de}	9.34^{a}	52.73^{e}
12.5:133	6.60^{e}	10.10^{a}	52.31^{de}
17.8:145	5.85^{de}	9.20^{a}	50.27^{cde}
7.2:120	2.85^{abc}	15.00^{b}	41.28^{abc}
7.2:145	3.00^{abcd}	11.79^{ab}	34.43^{a}
12.5:150	4.35^{cde}	13.21^{ab}	50.03^{cde}
12.5:115	4.27^{bcde}	11.57^{ab}	47.20^{bcde}
5:133	2.88^{abc}	15.10^{b}	42.17^{abcd}

Different letters indicate significant differences ($P < 0.05$).

*Based on 100 g cassava–rice–egg white mixture.

crumb and crust between 47.2–62.6 and 28.4–38.7, respectively. These values were similar to those reported by Demirkesen *et al.* (2010) in GF breads elaborated with chestnut and rice flours at different ratios.

In formulations with high levels of apple pomace, positive and high values of parameters *a* and *b* were found indicating also a darkening effect.

This result is related to the typical colour characteristics of the apple pomace but also to browning reactions (Maillard and caramelisation) occurring during heating. These reactions are influenced by the distribution of water and the levels of reducing sugars and amino acids (Gallagher *et al.*, 2003).

Bread storage

In many cases, GF breads production continues to be a small-scale process and consumption is accomplished within few hours after preparation. As a first approach, a 24 h assay was performed to analyse the tendency to crumb hardening and loss of cohesiveness.

In Fig. 4, variation of hardness and cohesiveness as a function of the storage time (24 h) is shown. When the amount of apple pomace increased from 17.8% up to 20% (based on 100 g cassava–rice–egg white mixture), a significant increment of hardness was observed ($P < 0.05$). Hardness increase during storage was significantly higher when apple pomace was present at the maximum levels (17.8–20%).

Table 4 Coefficients for polynomial expressions of response surfaces of colour attributes of crumb and crust

Factor	Y (dependent variable)							
	L crumb	*P*-value	*a* crumb	*P*-value	*b* crumb	*P*-value	*L* crust	*P*-value
b_0	64.26		2.28		25.98		36.73	
b_1	−0.88	0.006	0.36	0.0001	0.51	0.0001	−0.54	0.0002
b_2	–		–		−0.06	0.0234	–	
R^2 adj.	0.72		0.89		0.92		0.78	
P-value	0.16		0.42		0.32		0.05	

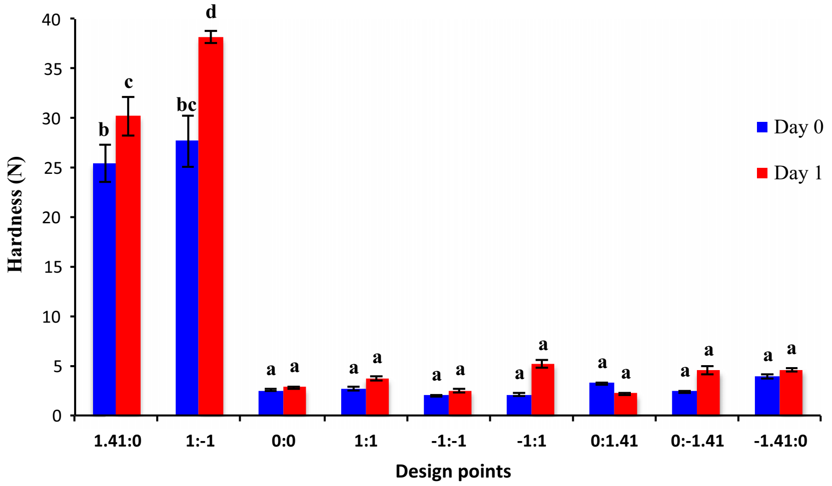

Figure 4 Textural parameters of stored breads. Day 0 = day of breadmaking. Day 1 = 24 h. Different letters above bars indicate significant differences ($P < 0.05$).

For all experimental points, a decrease in the cohesiveness was observed after 24 h storage but there were no significant differences ($P > 0.05$) in each experimental point.

In wheat breads, staling is caused by a combination of phenomena as starch retrogradation, and water migration towards bread crust and it also depends on time and temperature treatment (Zobel & Kulp, 1996; Majzoobi *et al.*, 2011). In GF breads, the absence of gluten proteins and the addition of other hydrophilic components (hydrocolloids and/or added fibre) could induce a different water distribution and retention that could facilitate staling. It has been suggested that the absence of gluten network could increase the movement of water from the bread crumb to crust, leading to a harder crumb and a softer crust (Gallagher *et al.*, 2003). The ageing of bread also reduces cohesiveness (Ronda & Roos, 2011) usually due to the loss of intermolecular attractions between ingredients that cause the crumbling of crumb and that is usually associated with the loss of water.

Conclusions

Apple pomace, a by-product derived from the juice industry, was dried, ground and applied in GF breads formulations in order to obtain a fibre enriched product. Increasing addition of apple pomace led to an increase in crumb hardness and a decrease in cohesiveness and resilience, but the quantity of added water was critical to moderate these effects. Up to 12.5 g apple pomace each 100 g cassava–rice–egg white mixture, products with specific volumes higher than 2 $cm^3\ g^{-1}$ were obtained, even with variable amounts of water (115–150 g each 100 g mixture). Particularly, when apple pomace level was lower than 9 g, it was possible to obtain specific volumes higher than 2.6 $cm^3\ g^{-1}$ varying water between 115 and 137 g. However, if apple pomace level was fixed at 20 g, water had to be increased to values superior to 140 g to maintain specific volumes at 2 $cm^3\ g^{-1}$ or more. Within these ranges, resilience and cohesiveness are maintained in values higher than 0.3 and 0.5, respectively.

In accord with a diminished specific volume, crumbs of breads with apple pomace also exhibited more compactness, with a reduced void area. Crumb hardness significantly increased during the first 24 h storage when apple pomace was added at the maximum levels.

Although fibre incorporation is an additional load to the GF matrix, leading to more compact crumbs, it is possible to obtain formulations with a suitable balance between the amount of apple pomace and water, leading to products that had enough specific volume and sponginess.

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