Relationship between instrumental parameters and sensory characteristics in gluten-free breads

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Abstract

Numerous bread-like gluten free products have been lately developed due to the rising demand on wheat free foods. A range of parameters has been used to describe these products, but there is no general agreement about the most suitable assessment to characterize them. The objective of this research was to characterize diverse gluten free like breads (GFB) in order to discriminate them and to establish possible correlations among descriptive parameters of GFB features determined by instrumental methods and sensory analysis. Statistical analysis showed that all physical, physicochemical characteristics (specific volume, moisture content, water activity, *L**, *a**, *b**, hue and chroma), hydration properties (swelling, water holding capacity and water binding capacity), texture profile analysis (TPA) parameters (hardness, springiness, chewiness, cohesiveness and resilience) and structural analysis of the crumbs (number of cells and total area) significantly (p<0.05) discriminated between the GFB types tested. Sensory analysis revealed great divergences in crumb appearance, odour, springiness, crumbliness and colour of samples, but not significant differences (p<0.05) in flavour, aftertaste and hardness of them. Certain significant correlations were established within the parameters determined by instrumental methods. Hydration properties of the crumb showed to be positively correlated with cohesiveness and resilience. Significant correlations, but scientifically meaningless, were observed among the instrumental and sensory parameters, because correlation coefficients were rather low, which represent very weak or low linear correlations ($r\leq0.35$). The principal component analysis showed that sensory parameters described in this study and also hydration properties besides texture parameters would be suitable for characterizing bread like gluten free products.

Highlights:

- Gluten-free breads are evaluated by instrumental and sensory parameters

- Physicochemical characteristics discriminate gluten-free breads
- Correlations among sensory and instrumental characteristics are established

Key words: gluten-free, bread, quality, crumb, sensory characteristics.

Introduction

Celiac disease (CD), also known as gluten-sensitive enteropathy, is a chronic disorder of the small intestine caused by exposure to gluten in the genetically predisposed individuals [1,2]. It is characterized by a strong immune response to certain amino acid sequences found in the prolamin fractions of wheat, barley, rye, and certain varieties of oats, resulting in inflammation and damage of the small-intestine mucosa and leading to malabsorption of nutrients [1,3]. Nowadays, the general prevalence of CD was estimated to be 1 in 300, although population-based screening studies carried out in 2008 suggest that the prevalence may be 1 in 100 [4]. Persons with CD are unable to consume some of the most common products in the market, including breads, baked goods, and other food products made with wheat flour. Until now, the only effective treatment for CD is strict adherence to gluten-free (GF) diet throughout the patient's lifetime [4].

The apparent or real increase in celiac disease or other allergic reactions and intolerances to gluten consumption has prompted the rising demand for gluten-free products. A range of bread-like gluten-free products has been designed trying to resemble wheat bread. The gluten-free bread recipes contain mainly rice or maize flours combined with potato, maize or wheat starches [5-7]. In recent years there has been extensive research for the development of gluten-free bread, involving diverse approaches, like the use of different starches (maize, potato, cassava or rice), dairy products, gums and hydrocolloids, emulsifiers, other non-gluten proteins, prebiotics or combinations thereof, as alternatives to gluten, to improve the structure, mouthfeel, acceptability and shelf-life of gluten-free bakery products [5-6, 8-16]. The development of such bread is frequently difficult having in mind that gluten is the main structureforming protein in wheat flour, responsible for the elastic and extensible properties to produce good quality bread [17].

In those researches, different features of the gluten free breads have been evaluated to assess their quality. Despite the different characteristics of the gluten free bread compared to its wheat counterparts, the same evaluation methods have been usually applied. Instrumentals analysis, including loaf weight and volume, specific volume, colour parameters, and textural parameters have been frequently used to characterize gluten-free breads [12, 14, 16, 18-22]. Sensory analysis has been also considered in some of the studies when developing gluten-free breads [7, 10, 13-15, 20, 23, 24]. Other researches have also characterized the crumb microstructure by using image analysis [19, 23] or scanning electron microscopy [12].

Therefore, instrumental measurements and sensory analysis have been applied to characterize gluten free breads. However, no correlation between instrumental parameters and sensory analysis has been previously established in this type of products, which would be very helpful for defining the best quality attributes of gluten-free breads. Additionally, principal components analysis (PCA) could be used to identify the best parameters or descriptors of the quality of gluten-free breads that allow the discrimination among bread features.

The aim of this research was to characterize a range of gluten free breads in order to establish possible correlations among descriptive parameters of gluten free bread like features determined by instrumental methods and sensory analysis. For that purpose, eleven gluten-free breads like products, which represent a large range of commercial gluten-free breads, were evaluated regarding physicochemical analysis, hydration properties, crumb microstructure, crumb texture and sensory analysis.

Materials and methods

Materials

Eleven specialties of gluten-free breads (GFB) with either loaf or sliced presentations were selected and purchased in general and specialized supermarkets. Gluten-free breads are marketed in polyethylene pouches and packaged under modified atmosphere for keeping their characteristics during at least four months. All breads were purchased within the first month after its production. Breads were kept at 20ºC till analysis. Information on the ingredients of each bread type, according to the labeling is given in Table 1. Due to commercial sensitivity the branded bread (n=11) varieties were labeled as GFB. Abbreviations of the samples are listed in Table 1. Samples from two different batches were used for the characterization.

Physicochemical analysis

Bread moisture content was determined following the ICC Standard Methods (110/1) [25]. Volume was determined by rapeseed displacement method and specific volume (cm^3 /g) of the individual loaf was calculated by dividing volume by weight. Water activity (a_w) of bread samples was measured using an Aqua Lab Series 3 (Decagon devices Pullman, USA) at 22ºC. The colour of the bread crumbs was measured at three different locations by using a Minolta colorimeter (Chromameter CR-400/410. Konica Minolta. Japan) after standardization with a white calibration plate (L*= 96.9, a*= -0.04, b*=1.84). The colour was recorded using CIE-L*a*b* uniform colour space (CIE-Lab) where L* indicates lightness, a* indicates hue on a green (-) to red (+) axis, and b*

indicates hue on a blue (-) to yellow (+) axis. Data from three slices per bread were averaged. Additionally the cylindrical coordinates: hue or hue angle (h_{ab}) and Chroma (C^*_{ab}) were defined by the following equations:

$$C^*_{ab} = \sqrt{((a^*)^2 + (b^*)^2)}$$

$$h_{ab} = \arctan(b^*/a^*)$$

Hue angle is the angle for a point calculated from a^* and b^* coordinates in the colour space. Chroma is the quantitative component of the colour [26], which reflected the purity of colour in the CIELAB space.

Hydration properties

Swelling or the volume occupied by a known weight of sample was evaluated by mixing 5g (±0.1 mg) of dried gluten-free bread with 100 mL distilled water and allowing it to hydrate during 16h. Water holding capacity (WHC) defined as the amount of water retained by the sample without being subjected to any stress was determined by suspending 5g (±0.1 mg) of commercial gluten-free bread sample with 100mL distilled water and allowing them to hydrate overnight. After removing the excess of water, the hydrated solid was weighed and expressed per one gram of solid. Water binding capacity (WBC) or the amount of water retained by the bread after being subjected to centrifugation was measured as described the AACC International method (56-30.01) [27].

Crumb cell analysis

Images of the gluten-free bread slice (10-mm thick) were captured using a flatbed scanner equipped with the software HP PrecisoScan Pro version 3.1 (HP scanjet 4400C, Hewlett–Packard, USA). The default settings for brightness (midtones 2.2) and contrast (highlights 240, midtones 2.2, and shadows 5) of the scanner software were used for acquiring the images. The images were scanned full scale at 1200 pixels per inch and analysed in levels of grey (8 bits, readout 0–255) and captured in jpeg format for each measurement. A 30x30-mm square field of view (FOV) was evaluated for each image. This FOV captured the majority of the crumb area of each slice. Images were analysed by Image J software (National Institutes of Health, Bethesda, MD, USA) using the Otsu's algorithm for assessing the threshold according to Gonzales-Barron and Butler [28]. Data derived from the crumb structure analysis included: number of cells or alveoli, average cells area and cell circularity, and were used for comparing purposes among different samples. Circularity was calculated using the following equation:

$$\text{Circularity} = 4 \times \pi \times \text{area} / (\text{perimeter})^2$$

A value of 1.0 indicates a perfect circle.

Crumb texture analysis

Crumb texture analysis was measured on uniform slices of 10mm thickness. Three slices from the center of each loaf were taken for evaluation [29]. Texture profile analysis (TPA) was performed using a universal testing machine TA-XT2i (Stable Micro Systems, Surrey, UK) equipped with a 30 Kg load cell and 25 mm aluminium cylindrical probe. The settings used were test speed of 2.0 mm/s with a trigger force of 5 g to compress the middle of the bread crumb to 50% of its original height at a crosshead speed of 1mm/s. Values were the mean of three replicates.

Sensory evaluation

A descriptive sensory analysis was performed for evaluating the sensory characteristics of commercial gluten-free breads. Bread slices, including crust and crumb, were presented (1cm thick) on plastic dishes coded and served in randomised order. A quantitative descriptive sensory analysis was carried out with twelve trained panellists under normal lightening conditions and at room temperature. The range of time that test panellist had participated in descriptive analysis and scale rating of a wide range of bread products varied from 3 to 20 years. Preliminary training test was performed, in which they were sat in a round table and after evaluating the sample, an open discussion was initiated for defining and describe the best descriptors for characterizing the product. Evaluation included perception at first glance of the bread slice (crust and crumb included) and mastication with the molar teeth up to swallowing. The attributes assessors finally agree were appearance (by observing the product slice), flavour, colour, taste, aftertaste (taste remaining in the mouth after swallowing), texture attributes during chewing and springiness (ability to regain original shape after pressing down the crumb with the middle finger). The descriptors for each attributes were appearance (visually liking or disliking), flavour (scale goes from high when typical of bread or bakery products to low, uncharacteristic of bakery products), colour (scales goes from high yellow/beige to low when brown or grey), taste (scale goes from high when typical taste of bread or bakery products to low, uncharacteristic of bakery products), aftertaste (scale goes from high when agreeable taste to low when distaste after swallowing), texture attributes during chewing (scales goes from hard-soft, crumbly-cohesive). Attribute intensity was scored on a scale varying from 1 (disliked extremely) to 5 (like extremely). Two samples were evaluated during one session. Breads were considered acceptable if their means score for overall acceptance were above 2.5.

Statistical analysis

The results were expressed as mean values. For each quality parameter, a one way analysis of variance (ANOVA) was applied using Statgraphics Plus V 7.1 (Statistical Graphics Corporation, UK). Fisher's least (LSD) test was used to assess significant differences (p<0.05) among samples that might allow discrimination among them. Simple correlations were performed using Statgraphics V.7.1 software. Principal component analysis (PCA) was also performed to determine the number of principal components that significantly (p< 0.05) discriminated samples.

Results and discussion

Technological and sensory characteristics of gluten free bread

The characterization of diverse gluten-free breads was carried out to identify the most discriminating parameters. With that purpose, an in-depth analysis of the gluten free breads was carried out (Table 2, 3). The analysis included physical, physicochemical properties, crumb structure analysis, also hydration properties of the crumb and sensory analysis. Mean values from two different batches for each sample are showed in table 2. Analysis of data collated using ANOVA showed that all physicochemical characteristics significantly (p<0.05) discriminated between the breads tested. GFB samples presented specific volume values that ranged from 1.54 to 4.79 mL/g. Those agree with the ones reported by Sabanis, Lebesi and Tzia [13] when they evaluated enrichment of gluten-free baked products with different cereal fibres (2.7 to 3.9 mL/g), or with Marco and Rosell [12] findings (1.57 to 2.71 mL/g). Moisture content values ranged from 21.10 g/100g (GFB8) to 42.03 g/100g (GFB11). The present study included a range of marketed GFB specialties, thus probably differences might be attributed to the different bread formulations. In general, the moisture content values reported for gluten-free breads obtained from different formulations are rather high, for instance rice based bread enriched with proteins showed values of 41.66- 46.13 g/100g [12] and the enrichment of gluten-free breads with fibres even enhances those values (49-53 g/100g) [13]. Water activity values of crumb were also high (Table 2). Those values agree with the findings of Lazaridou, Duta, Papageorgiou, Belc and Biliaderis [10], that reported water activity values of GFB crumb in the range of 0.97-0.99. Likely, the high water activity as well as the moisture retention might be ascribed to the high water holding capacity of the incorporated hydrocolloids [30] that are usually added to GFB formulations as thickeners for improving volume (see Table 1). It has been reported 0.95 as typical aw value for breads [31]. Therefore, GFB samples tested, according to the above results, covered a good range of characteristics previously reported for this type of breads.

The colour of the crumb has been also an important parameter for characterising GFB. Lower $L*$ value indicates darker crumb, $a*$ positive value is associated with crumb redness, whereas $b*$ positive value indicates yellow colour. To obtain a good characterisation of the colour, it is necessary to bear in mind the psychophysical parameters, which correspond with the cylindrical coordinates: hue (h_{ab}) and chroma ($C*_{ab}$). Great variability was observed in lightness. GFB8 and GFB9 showed the highest values (83.83 and 80.20, respectively), indicating more reflectance of light when compared with the rest of the breads. Additionally, darker crumb was observed for GFB1, GFB4, GFB5 and GFB7. The darkening of the crumb colour is desirable as gluten-free breads usually tend to have lighter colour than wheat breads [23], and darker bread are usually associated with whole grains and wholesomeness [15]. Regarding a^*, only GFB2 and GFB3 showed low positive value indicating hue on red axis, whereas the other breads presented negative a^* value (hue on green axis). In addition, all samples presented positive b^* value (indicating hue on yellow axis), showing significant differences among them ($p<0.05$). In relation to hue (h_{ab}) and chroma (C^*_{ab}) colour attributes, great variation was observed (Table 3). The majority of the GFB samples presented negative hue values that reflected yellow-greenish hue, with the exception of GFB2 and GFB3 samples that presented hue positive values, which reflected yellow-orange hue. Chroma is the quantitative component of the colour associated to the colour purity in the CIELAB space. Both GFB2 and GFB3 showed chroma values higher than the other samples, which revealed its higher purity of colour related to major intensity of the yellow component (Figure 1).

Gluten-free breads have low ability to retain moisture during storage [11], thus hydration properties of the bread crumbs might be interesting properties to characterize this type of products. Hydration parameters are generally used for assessing the water uptake ability of different ingredients like hydrocolloids or fibers. GFB9 exhibited the highest values for swelling, WHC and WBC indicating that it can retain significantly more water than the other breads (Table 2). In addition, GFB4 showed the lowest value for swelling while GFB3 presented lowest values to WHC and WBC. In GFB, dietary fibre (mainly hydrocolloids incorporated as ingredient into gluten-free bread formulations) might be a major determinant of the water retention capacity of these products. Significant differences were found among the samples, which could be useful for discriminating GFB and maybe those properties could be related to sensory attributes. Presumably, water retention capacity of the crumb could affect the perception of textural properties when these samples are eaten.

Parameters from the image analysis of the gluten-free bread crumbs (Figure 1) showed a large variability among crumb bread structures (Table 3). GFB6 exhibited significantly high cells or alveoli number value and total area value, whereas lower values were seen for GFB5 and GFB7. The unique reported values of this parameter in gluten-free breads ranged from 15 to 20 cells/cm^2 [32]. No significant differences were observed for average cell area (mm^2). Nevertheless, significant differences were found for circularity values ($p<0.05$). It has been described that up to certain limit, the number of cells/cm^2 increases as HPMC and water increase [24]. Nonetheless, the combination of high levels of both decreases the cell/cm^2, likely due to the coalescence of many gas cells into one large cell. Carboxymethyl cellulose and xanthan gum has been associated with higher cell average size, while breads with carrageenan and alginate had smaller cell sizes [22]. Gluten free crumbs had circularity values ranging from 0.60 to 0.81, indicating less uniform shape (Figure 1). Beside, cell (air) total area of bread crumbs showed significant differences among gluten-free breads.

In addition, significant differences were observed in the crumb texture properties of the different gluten free breads (Table 3). Gluten free bread like products due to their complex formulation, mainly based in carbohydrates [33], present high crumb hardness, which agree with the results of crumb image analysis. The majority of GFBs presented hardness values ranging from 10.33N to 14.60N; however GFB2 and GFB11 had the highest and lowest values, respectively. With respect to springiness, GFB8 showed the highest value, while GFB5 presented the lowest. Springiness is associated to a fresh and elastic product; therefore high quality bread will be related to high springiness values. Marco and Rosell [12] found springiness values that ranged from 0.77 to 0.94 when study the protein enrichment of rice based gluten-free breads. Low springiness value is indicative of brittleness and this reflects the tendency of the bread to crumble when is sliced [24]. Cohesiveness characterises the extent to which a material can be deformed before it ruptures, reflecting the internal cohesion of the material. Bread with high cohesiveness is desirable because it forms a bolus rather than disintegrates during mastication, whereas low cohesiveness indicates increased susceptibility of the bread to fracture or crumble [16]. With the exception of the GFB8 and GFB9, low cohesiveness values (0.20-0.44) were observed, which implies that lower compression energy was required and consequently those breads more easily crumbled. Chewiness varied from 1.69 to 32.90 N, but the majority of breads presented values comprised between 2.33 to 5.77N and only GFB2 showed higher value. Therefore, the time required masticating a bread piece prior to swallow showed great variation. Low chewing value means easy break of the bread in the mouth like a biscuit. It was also observed that hardness and chewiness showed similar traits for all breads. Resilience values showed that GFB7 had the lowest elasticity, whereas GFB8 and GFB9 presented the highest values. It has been reported that the reduction in resilience or springiness characterizes loss of elasticity [16].

A quantitative descriptive analysis was performed for the sensory evaluation of the breads. Although 50 panellist are recommended for this analysis, in this study 12 long trained judges participate in the sensory evaluation, which agree with method of Heenan et al [34]. According to ANOVA results, the gluten-free breads differed significantly (p<0.05) in crumb appearance, odour, springiness and crumbliness, also significant differences (p<0.1) were found in colour (Table 4). Conversely, no significant differences were observed in taste, aftertaste and hardness. GFB6 showed the highest appearance score. The less intense odour was perceived in GFB9. GFB4 received the highest score for springiness. In general, GFB6 was scored higher for majority of the sensorial attributes evaluated. Conversely, GFB9 and GFB10 were scored lower for most of the sensory attributes. These results clearly revealed great variability on sensory quality.

Relationship among technological and sensory parameters of gluten free bread like products

The assessment of technological or instrumental quality is the most preferred analysis for characterizing gluten-free breads because they are not subjected to consumer perceptions, which are greatly dependent on individual backgrounds, locations and so on. Therefore, the establishment of possible relationship between sensory and quality parameters or within the technological parameters would be very useful. With that purpose multivariate data handling was applied by using Pearson correlation analysis.

Significant correlations were observed within the parameters used for characterizing gluten free bread like products, but they were mainly obtained within the instrumental parameters (Table 5). Strong linear relationships were observed within the colour parameters, but also a strong positive linear relationship was obtained between $L*$ and cohesiveness (p<0.001) and resilience (p<0.001). Presumably, crumb structure has great influence on the texture properties and the luminosity of the crumb. The initial observation about the hardness and chewiness trend was confirmed with the high relationship (r<0.9043) detected between those parameters. Additionally, cohesiveness was strongly linear related to resilience (r<0.9895), showing the importance of the internal cohesion of the crumb on the ability to recover after compressing. In this type of products, water activity showed a significant positive relationship with the moisture content. It must be highlighted the relationships observed among the crumb hydration properties and some other parameters, since those properties have not been previously determined in bread crumbs. Water hydration properties (swelling, WHC and WBC) were significant positively related within them. Moreover, strong positive relationships were observed between the WHC with resilience (r<0.7020) and between WBC with cohesiveness (r<0.7633) and resilience (r<0.7901).

Some relationships between sensorial parameters and instrumental parameters were statistically significant, although the correlation coefficients were rather low, which represent very weak or low linear correlations ($r \leq 0.35$). With these type of products no linear relationships were detected between the instrumental and sensory parameters likely due to their complex formulations.

In order to propose a small number of parameters that allow gluten free bread characterization, a principal component analysis (PCA) with the significant quality parameters was carried out. Significant quality parameters analysed by PCA indicated that six principal components significantly ($p < 0.05$) discriminated between breads, which accounted for 91% of the variability in the original data (data not showed). This analysis described 35% and 18% of variation on principal components 1 (PC1) and 2 (PC2), respectively (Figures 2 and 3). Component 1 was defined by hydration properties, instrumental cohesiveness, resilience and springiness, and luminosity (L^*) along the positive axis, which were present in GFB8 and GFB10. Along the negative axis, PC1 was described by sensory parameters, moisture content and area and number of alveoli that were present in the majority of the gluten free breads tested. Conversely, the component 2 was mainly defined by specific volume, colour parameters (a^*, b^*, chroma and hue) and hardness, along the positive and negative axis, respectively. GFB8 and GF10 were positively located along PC1 and PC2 (Figure 3). On the other hand, the breads located along the negative axis of PC1 and PC2 were GFB2 and GFB3. Therefore, PCA allowed discriminating among gluten free breads and it showed that crumb hydration properties, besides texture parameters like cohesiveness, resilience and springiness could be of great importance for characterizing gluten free breads. In addition, most of the gluten free breads tested (GFB1, GFB4, GFB5, GFB6, GFB7, GFB11) were mainly grouped by the sensory parameters. Descriptive sensory attributes have been reported for discriminating among different wheat bread types [34]. In that study, porous appearance and odour attributes were the most important descriptors. Simultaneously, quality parameters obtained from instrumental analysis have been selected for defining the consumers' acceptability of wheat breads, which have been useful for identifying the main discrepancies of wheat breads produced by different breadmaking processes [35].

Conclusions

The assessment of the physicochemical, hydration properties, crumb texture and microstructure of a range of gluten free breads showed great divergence among their properties and the same observation was perceived in the sensory analysis. Sensory analysis revealed also great divergences in crumb appearance, odour, springiness, crumbliness and colour. Among all the assessed parameters, from the correlation matrix it was observed that colour, texture and hydration parameters were highly correlated within them. In addition, hydration properties were significantly positive correlated with cohesiveness and resilience. Significant but scientifically meaningless correlations were found between sensory and instrumental parameters. According to the principal component analysis, gluten free breads could be classified along the first component on the basis of sensory properties (negative side) and hydration properties, instrumental cohesiveness, resilience and springiness (positive side). Therefore, sensory parameters described in this study and also hydration properties besides texture parameters would be suitable for characterizing bread-like gluten free products.

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FIGURE CAPTIONS

Figure 1. Digital images of commercial gluten-free bread crumb samples (30x30 mm field of view of GFB).

Figure 2. Correlation loadings plot from principal component analysis showing the quality parameters of the eleven gluten free breads evaluated.

Figure 3. Scores plot from principal component analysis of the eleven gluten free breads evaluated.

Table 1. Ingredients in gluten-free breads (GFBs) according to supplier information

Product code	Ingredients
GFB1	Corn starch, water, sugar, egg, vegetal margarine, acidifier, preservative, aromas and colorant, yeast, thickener, emulsifier, salt, preservative, raising agents, antioxidants. May contain traces of soy.
GFB2	Corn starch, water, vegetal margarine, emulsifiers, salt, acidifier, preservative, antioxidants, aromas and colouring (betacarotene), egg, sugar, yeast, dextrose, humidifier, stabilizers, salt.
GFB3	Corn starch, water, vegetal margarine, emulsifiers, salt, acidifier, preservative, antioxidants, aromas and colorant, egg, sugar, yeast, dextrose, humidifier, stabilizers, salt.
GFB4	Potato starch, water, corn starch, caseinate (milk protein), sugar, vegetal oil, corn flour, yeast, soy protein, stabilizers, salt, preservative.
GFB5	Corn starch, water, sugar, egg, vegetal margarine, acidifier, preservative, aromas and colorant, stabilizers, yeast, emulsifiers, salt, raising agents, anise, cinnamon, and antioxidant.
GFB6	Corn starch, water, rice flour, vegetal oil, sugar, stabilizer, lupine protein, yeast, salt, vegetal fibre, aroma, emulsifiers.
GFB7	Corn starch, water, sugar, egg, vegetal margarine, acidifier, preservative, aromas and colorant, yeast, thickener, emulsifier, salt, raising agents, antioxidants. May contain traces of soy.
GFB8	Corn starch, water, sugar, yeast, thickeners, salt, raising agent, preservative.
GFB9	Corn starch, water, sugar, thickeners, emulsifier, salt, yeast, preservative, raising agents, antioxidants. May contain traces of egg.
GFB10	Corn starch, vegetal margarine, salt, sugar, emulsifier, raising agents, antioxidant, thickener, preservative, and yeast.
GFB11	Corn starch, vegetal margarine, salt, sugar, emulsifier, raising agents, antioxidant, thickener, preservative, and yeast.

Table 2. Different quality characteristics of different gluten-free breads.

Sample codes	Specific volume ml/g	Moisture g/100 g	a_w	Swelling ml/g	WHC g water/g solid	WBC g water/g solid	*L**	*a**	*b**	Chroma	Hue angle °
GFB1	3.37 cde	29.63 d	0.91 b	1.49 a	2.55 ab	2.31 a	64.71 a	-2.01 cd	11.85 a	12.02 a	-80.36 def
GFB2	3.47 de	31.63 f	0.95 e	1.58 bc	2.63 ab	2.47 ab	72.93 f	0.50 d	21.78 g	21.78 f	88.67 h
GFB3	1.54 a	29.50 d	0.94 d	1.49 a	2.41 a	2.39 a	71.86 ef	0.97 d	19.86 f	19.88 e	87.20 g
GFB4	4.79 f	27.17 c	0.94 d	1.38 a	2.50 ab	2.60 bc	65.77 a	-1.63 abc	10.72 a	10.84 a	-81.37 cd
GFB5	3.88 e	26.27 b	0.89 a	1.99 de	3.23 c	2.90 d	67.95 b	-0.25 bcd	15.97 de	15.97 c	-89.10 a
GFB6	2.89 c	41.66 i	0.97 g	1.59 ab	2.84 b	2.70 c	72.77 f	-2.74 a	17.17 e	17.39 d	-80.93 cde
GFB7	3.14 cd	33.60 g	0.94 d	1.79 bc	2.72 ab	2.41 ab	69.21 bc	-2.44 a	13.97 b	14.18 b	-80.09 ef
GFB8	4.77 f	21.10 a	0.92 c	2.58 e	3.49 c	3.19 e	83.83 h	-2.21 a	11.92 a	12.13 a	-79.44 f
GFB9	2.31 b	31.33 e	0.96 f	3.48 f	3.86 d	3.35 e	80.20 g	-2.28 a	15.86 de	16.02 cd	-81.82 c
GFB10	3.70 e	36.13 h	0.97 g	2.09 d	3.25 c	2.78 cd	71.13 de	-1.99 a	14.09 bc	14.23 b	-81.99 bc
GFB11	3.47 de	42.03 j	0.97 g	1.90 cd	3.24 c	2.72 cd	70.37 cd	-1.90 ab	15.44 cd	15.55 bc	-83.00 b
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

For each parameter values followed by the same letter are not significantly different at $p \leq 0.05$.
WHC: water holding capacity (ml/g); WBC: water binding capacity (g water/g solid).

Table 3. Analysis of crumb microstructure and texture.

Sample codes	Number of alveoli/cm^2	Total area alveoli mm2/cm2	Hardness N	Springiness	Chewiness N	Cohesiveness	Resilience
GFB1	4 ab	9.07 a	20.50 e	0.95 de	5.77 d	0.29 b	0.11 abc
GFB2	6 ab	7.53 a	80.20 g	0.95 de	32.90 g	0.43 c	0.17 d
GFB3	6 ab	36.70 b	14.53 c	0.85 bc	3.53 abc	0.29 b	0.09 ab
GFB4	6 ab	24.26 ab	14.60 cd	0.90 cd	4.83 cd	0.37 c	0.13 bcd
GFB5	2 a	2.50 a	11.27 abc	0.76 a	2.33 ab	0.24 ab	0.84 ab
GFB6	16 c	130.03 c	11.47 abc	0.88 c	4.04 bcd	0.37 c	0.15 cd
GFB7	2 a	8.80 a	10.83 ab	0.79 ab	1.69 a	0.20 a	0.06 a
GFB8	5 ab	18.70 ab	18.23 de	1.00 f	14.94 e	0.82 d	0.39 e
GFB9	4 ab	23.50 ab	32.77 f	0.96 de	24.07 f	0.77 d	0.40 e
GFB10	7 b	21.33 ab	12.57 bc	0.95 de	3.74 abcd	0.38 c	0.15 cd
GFB11	6 ab	3.17 a	8.47 a	0.87 c	3.60 abc	0.44 c	0.18 d
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

For each parameter values followed by the same are not significantly different at $p \leq 0.05$.

Table 4. Sensory analysis of different gluten-free bread like products.

Sample codes	Crumb appearance		Taste	Odour		Color	Aftertaste	Springiness		Hardness	Crumblines	
GFB1	2.57	bc	2.71	2.28	bc	3.43	3.14	1.86	a	3.14	2.29	ab
GFB2	2.83	abc	2.33	2.67	c	3.00	2.67	3.33	bc	2.67	3.00	bc
GFB3	2.33	ab	2.66	3.00	c	3.00	3.33	2.50	ab	3.33	2.50	ab
GFB4	2.83	bcd	1.33	2.00	abc	3.50	2.50	4.83	d	4.17	1.33	a
GFB5	3.33	bcd	3.00	2.16	abc	3.83	2.67	2.67	ab	3.67	3.83	c
GFB6	4.00	d	2.66	2.83	c	3.83	3.83	4.17	cd	3.67	2.50	ab
GFB7	3.50	bcd	2.83	3.00	c	3.50	3.33	3.33	bc	3.16	2.33	ab
GFB8	3.16	bcd	2.66	2.66	c	3.17	3.50	4.33	cd	3.33	2.00	ab
GFB9	1.16	a	2.16	1.16	a	1.83	2.67	2.17	ab	2.16	2.83	bc
GFB10	3.50	bcd	1.83	1.50	ab	2.83	1.83	1.33	a	2.17	2.33	ab
GFB11	3.67	cd	2.50	2.66	c	3.67	3.83	4.17	cd	3.83	2.33	ab
p-value	0.01		0.24	0.030		0.078	0.101	0.000		0.130	0.033	

For each parameter values followed by the same are not significantly different at $p \leq 0.05$.

Table 5. Correlation matrix (correlation coefficients and *p*-value) between characterizing parameters of gluten-free bread like products.

	Specific volume	*L**	*a**	*b**	Chroma	Tono º	Hardness	Springiness	Cohesiveness	Chewiness	Resilience	Moisture content	Swelling	WHC	WBC
Instrumental parameters															
*b**	-0.6049***		0.6375***												
Chroma	-0.6049***		0.6232***	0.9998***											
Tono º	-0.6049***		0.8082***	0.7737***	0.7688***										
Hardness			0.4333***	0.5434***	0.5413***	0.6235***									
Springiness		0.4659***	-0.2515*				0.3569**								
Cohesiveness		0.8650***	-0.2829*					0.6643***							
Chewiness				0.4103***	0.4111***	0.4364***	0.9043***	0.5273***	0.6002***						
Resilience		0.858***	-0.3076*					0.6197***	0.9895***	0.6034***					
Moisture content	-0.3628**		-0.296*	0.2846*	0.2934*				-0.2707*		-0.2579*				
Aw	-0.2781*		-0.2823*	0.2417*	0.2511*			0.2859*				0.7431***			
Total area			-0.3173**									0.4118***			
Swelling		0.5210***	-0.4993***	-0.3849**	-0.3801**	-0.5864***	-0.4517***		0.5613***		0.6195***				
WHC		0.6186***	-03422**			-04446***			0.6604***	0.2442*	0.7020***		0.8146***		
WBC		0.7083***	-0.2905*			-03943***			0.7633***	0.3017*	0.7901***		0.8014***	0.9323***	
Sensory parameters:															
Appearance										-0.3184**					
Odour													-0.3086*	-0.3321**	-0.3098*
Colour		-0.2662*							-0.2860*	-0.2909*				-0.2493*	
Springiness	0.2829*	0.4659***													
Crumbliness				0.3047*	0.3034*										

p≤0.05 *; p≤0.01**. p≤0.001***