Hyperspectral image control of the heat-treatment process of oat flour to model composite bread properties

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Abstract

A hyperspectral image analysis was used to characterize heat treatment in oat flour, performed by treating oat flour at 80, 100 and 130ºC for 30 min. Images from both original oat and treated flours were captured, and hyperspectral information was collected. Oat flours were used to obtain composite flours based on two different substitution levels (10 and 20%) of wheat flour. Composite breads were produced from the obtained flours. A battery of analyses was run to characterize them in terms of physical properties. The hyperspectral information of oat flours was analyzed by multivariate statistics and a pattern evolution-depending temperature was observed. Similarly, a set of the physical properties of breads was analyzed based on multivariate statistics, and a pattern of temperature-dependent evolution, in addition to the substitution level, was also recognized. Multivariate non linear regressions were done between both data sets to study their relationship and high values in the calibration and cross-validation results obtained. The changes undergone by oat flour during treatment were characterized with hyperspectral information, which could represent a non destructive monitoring tool to then regulate it until oat flours are obtained that confer composite bread adequate properties.

Keywords: oats flour, heat treatment, hyperspectral image, composite breads, process monitoring

1. Introduction

The cereal processing and transformation industry is one of the most important sectors in the food industry. Type of grains, and derived flours and products, require vast numbers of operations and specific processes, which finally offer a wide variety of transformed products: bread, cakes, snacks, transformed flours, gluten-free products, enriched products, etc. This is the result of the impact that grain components, such as proteins, soluble and insoluble fibers, minerals, oils, etc., have on maintaining and improving human health, which has been an important scientific work area in recent decades (Cleary et al., 2007). Mixing and enriching grain-derived products have led to improved nutritional quality and safety, and to organoleptic features like texture, taste and palatability. In the same way, properties about their behavior during the food-making process have been modified to facilitate easy handling during processing (Angioloni and Collar, 2011). Many grain combinations of bread that originates from composite flours production have been developed and tested (Eriksson et al., 2014; Rehman et al., 2007; Ronda et al., 2015; Verdú et al., 2015b).

In this work, composite flour based on wheat and oats has been examined. Oat flour is becoming an important element as raw material in the cereal-derived industry because of the health benefits obtained from its derived products (Butt et al., 2008). This grain is an interesting resource for preparing composite derivates because we can find β-glucan in its composition. This component is a hydrocolloid, which represents a hydrosoluble fiber with beneficial effects on human health, according to recent works (Whitehead et al., 2014). There are also reports that a high concentration of oat flour in composite flour induces changes that could alter dough properties, and could thus modify the properties of both intermediate operations (e.g. dough rheology and transport, dough fermentation process rates, etc.) and quality features compared to pure wheat breads

(Gill et al., 2002). Therefore, it is usual to find solutions based on chemical modifications, limited concentrations of added oat flours, modification of process parameters during the bread-making process, etc.

In line with this, one of the most widely used procedures is heat treatment of flours at different temperatures and from distinct moisture contents. This is a physical treatment method utilized to modify the functional properties of native starch, including pasting characteristics, granule morphology, amylose leaching, textural properties, etc., which are particularly favorable for food applications (Jiranuntakul et al., 2011; Lee et al., 2012; Sun et al., 2014). However, the heterogeneity of grain flours produced by cultivar type, mixes of varieties, climate conditions during growth, etc., imply difficulties in obtaining a standard optimal combination of time and temperature which reports the stable behavior of product features during the process. To this end, the automatic and non destructive control of each flour batch during heat treatments can improve knowledge about flour state for it to be optimized until the product presents optimal properties. In this work, the hyperspectral image technique is proposed as a non destructive control method in order to test its capability to characterize oat flour evolution during heat treatment, and to study its relationship to flour's behavior in composite bread properties.

2. Material and Methods

2.1 Experiment procedure

Figure 1 shows the scheme of the experiment procedure. Step 1 was based on treating oat flour at three different temperatures, 80, 100 and 130ºC, for 30 min to finally obtain four oat flour types. In Step 2 the hyperspectral image analysis of the flours obtained in Step 1 was done and the obtained data were processed. Step 3 involved the production of composite flours. For this purpose, pure wheat flour was substituted at two levels, 10 and 20% (w/w), using the four oat flour types. Then eight different composite flour types, plus one of pure wheat flour, used as a control, were obtained. Step 4 involved bread production for which the composite and pure wheat flours obtained in Step 3 were employed. In Step 5 the composite bread properties were analyzed by different physico-chemical procedures. Step 6 was based on the joint study of the hyperspectral information of flours and bread properties in order to test the capacity of the former to characterize the heat treatment process of oat flour, and to determinate relationships with bread behaviors.

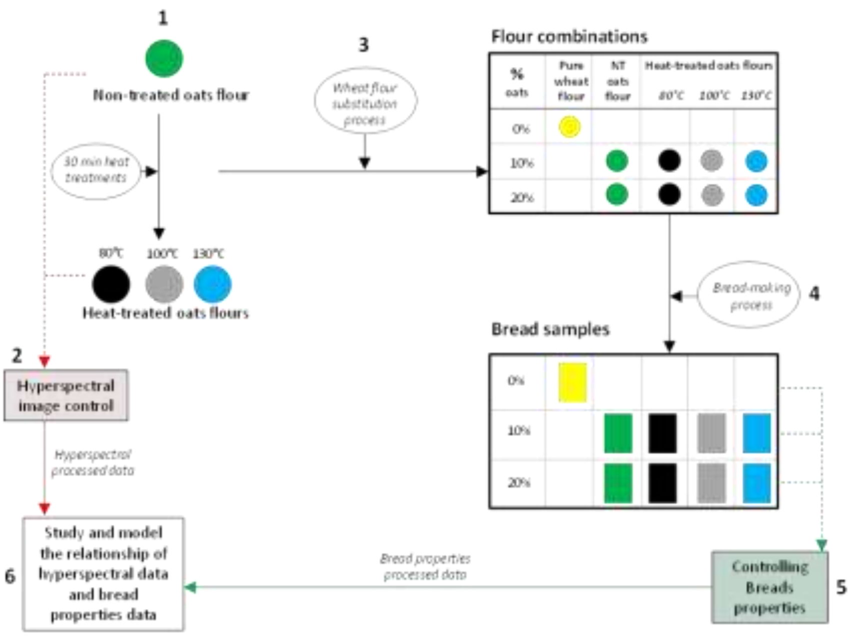

Figure 1. Scheme about the complete experiment procedure. Numbers 1- 6 indicate the steps followed, where 1: heat treatment of oat flour for 30 min at 80, 100 and 130 ºC; 2: collecting the hyperspectral image data of oat flours; 3: obtaining combined flours based on the substitution of pure wheat flour at 0, 10 and 20% (w/w) for oat flour and its heat-treated versions; 4:bread-making process from the combined flours; 5: collecting bread properties data; 6: studying the relationship between the hyperspectral data of flours vs. produced bread properties data. NT oat flour: non treated oat flour.

2.2 Raw materials

The commercial oat flour was obtained from a local producer (La Carabasseta, Valencia, Spain). Its composition was 11.3±0.1% of proteins, 8.0±0.1% of fat, 12.6±0.6% of moisture and 0.92±0.1% of ash (w.b). The commercial wheat flour (WF) was supplied from a different local producer (Molí de Picó-Harinas Segura S.L. Valencia, Spain). Its composition was as follows: 12.7±0.6% of proteins, 1.0±0.03% of fat, 13.09±0.5% of moisture, and 0.32±0.1% of ash (w.b). The alveographic parameters were also facilitated by the seller, which were P = 94±2 (maximum pressure (mm)), L = 128±5 (extensibility (mm)), W = 392±11 (strength (J-4)) and P/L= 0. 73. In order to maintain particle size homogeneity, oat flours were analyzed and remilled in a stainless steel grinder, whenever necessary (Retsch GmbH, ZM 200, Haan, Germany), until particle size distribution was achieved with no significant differences with the used wheat flour. The particle size of flours was measured 6 times by laser scattering in a Mastersizer 2000 (Malvern, Instruments, UK), equipped with a Scirocco dry powder unit. The results were expressed as maximum size in µm at 10%, 50% and 90% (d (0.1), d (0.5) and d (0.9), respectively) of the total volume of the analyzed particles as their averages (D [4, 3]). The average results were d (0.1) = 25.5±1.1, d (0.5) = 92.0±0.6, d (0.9) = 180.6±0.8 and D [4, 3] = 99.4±1.2. Having ensured homogeneous particle size, composed flours were obtained by substituting two distinct percentages of wheat flour with the different oats flour. Those percentages were 10 and 20% (w/w).

The other ingredients used to make bread were sunflower oil (maximum acidity 0.2º Koipesol Semillas, S.L., Spain), pressed yeast (Saccharomyces cerevisiae, Lesafre Ibérica, S.A., Spain), white sugar (≥ 99.8% of saccharose, Azucarera Ebro, S.L., Spain) and salt (refined marine salt ≥ 97% NaCl Salinera Española S.A., Spain), which were purchased in local stores.

2.3 Heat treatment of oat flour

For the purpose of obtaining a register from different treatment intensities, three distinct heat treatments were carried out at 80, 100 and 130ºC for 30 minutes with forced convection hot air. Here the work of (Neill, Al-Muhtaseb, & Magee (2012) was taken as a reference. The time for stabilizing the oven temperature was 1.5 minutes as a maximum for the lower heat treatment (80ºC). Temperature was monitored with a digital thermometer (range 0-300 ºC, resolution 0.1ºC, precision ± 0.2 ºC). Each treatment was carried out by extending 300 g of untreated flour on a layer of a maximum 0.5 cm thickness, which was placed onto a metal plate covered with baking paper. During this process, moisture reduced from 15% to 10.5% (wet basis) as a maximum for 130ºC. Loss of moisture was calculated gravimetrically based on the mass difference between weights after and before heat treatment. In order to recover the original moisture values, flours were placed into a chamber (KBF720 Binder Tuttlingen Germany) with controlled humidity and temperature (15% R.H. and 25 ºC). Flours remained inside the chamber for 48 h as this time was required to recover moisture in a case of maximum loss, which was 130ºC. Finally, in order to homogenize any oversized particles produced during the process, oat flours were analyzed and remilled in the stainless steel grinder until particle size distribution was accomplished with no significant differences with the non treated flours.

2.4 Hyperspectral image data acquisition and processing

Heat-treated oat flours captures were carried out with a Photonfocus CMOS camera, model MV1-D1312 40gb 12 (Photonfocus AG, Lachen, Switzerland), using a

SpecimImSpector V10 1/2″ filter (Specim Spectral Imaging, LTD., Oulu, Finland), which worked as a linear hyperspectral camera. The illuminant was an ASD illuminator reflectance lamp (ASD Inc, Boulder, USA), which produces constant illumination over the full working spectral range. The sample preparation protocol was based on Verdú, Ivorra, et al., (2015). Fifteen grams of each flour (control oats flour and all three heat-treated oats flours) were placed into a glass Petri dish (10-cm diameter) and a homogeneous surface and height were maintained (approx. 0.75 cm). Six samples of each oat flour were prepared. Four images of each sample were acquired by rotating 1.04 radians each time around its normal axis. Twenty-four image acquisitions of each flour were obtained. Spectra were collected directly at room temperature. The position of the illuminant and camera in relation to the sample was always constant in order to control lighting conditions and to obtain constant image size. In order to avoid any heat transfer to samples, the distance between the illuminant and samples was 0.5 m. The distance between the camera and sample was 0.15 m. The obtained image (scanned line) comprised 256 gray levels (8 bits). The diffuse reflectance spectrum was collected with 53 different wavelengths (each wavelength was digitalized with 8 bits). These wavelengths were distributed at intervals of 11.2 nm within the 400-1000 nm range. The scanned line comprised 1312 points, so an image was recorded with a resolution of 1312 x 1082 pixels. The camera was operated by developed software based on SDK Photonfocus-GigE_Tools, and programming language C++ was used. Image reflectance calibration and preprocessing were performed as described in (Verdú et al., 2015a) with the aim of normalising non-linear light source reflectance. This was done by applying Equation (1):

$$R(\Lambda) = \frac{(rS - rD)}{(rW - rD)} \quad (1)$$

where rW is the reflectance value of a white pattern reflectance acquired under the same conditions, rD is the dark measure covering the camera objective and rS is the sample reflectance.

The other operations carried out on the spectra for further statistical processing were Standard Normal Variety (SNV). Image reflectance calibration and preprocessing were performed using a code developed with Matlab R2012a (The Mathworks, Natick, Massachusetts,USA).

2.5 Bread-making process

The formulation used to prepare bread dough was that according to previous works (Verdú et al., 2015b) and was as follows: 56% flour (pure wheat flour or combined flours), 2% refined sunflower oil, 2% commercial pressed yeast, 4% white sugar 1.5% salt and 34.5% water. The process was carried out by mixing all the ingredients in a food mixer (Thermomix® TM31, Vorwerk, Germany) according to the following method: in the first phase, liquid components (water and oil), sugar and salt were mixed for 4 minutes at 37 ºC. Yeast was added in the next phase to be mixed at the same temperature for 30 seconds. In the last step flour was added and mixed with the other ingredients according to a default bread dough mixing program to make homogeneous dough. The program system centers on mixing ingredients with random turns of the mixer helix in both directions (550 revolutions/minute) to obtain homogeneous dough. This process was applied for 4.5 minutes at 37 ºC. Then 450 g of dough were placed in the metal mold (8x8x30cm) for fermentation. Height was approximately 1 cm.

Dough fermentation was carried out in a chamber with controlled humidity and temperature (KBF720, Binder, Tuttlingen, Germany). The fermentation process conditions were 37 °C and 90% relative humidity (RH). Samples were fermented for 1 h. The baking process was carried out at the end of fermentation. Metal molds were placed in the middle of the oven (530x450x340, grill power 1200W, internal volume 32L, Rotisserie, DeLonghi, Italy) plate, which was preheated to 180 ºC. Baking time was 35 minutes.

2.6 Characterization of bread properties

In order to evaluate the effect of wheat substitution and heat treatments of oat flour on bread properties, some of most relevant ones were studied. In this phase, bread volume was measured by the millet seed displacement method (Griswold, 1962), and then the specific volume (*Sv*) was calculated as the ratio between volume (mL) and bread weight (g). The baking process was also studied based on the produced mass loss (ΔM_b). It was concluded by the difference between the pre-baking dough weight (g) and the finished bread weight (g) (cooled previously at room temperature for 1 h). The water activity of raw crumbs (a_w) was determined in an Aqualab® dew point hygrometer (DECAGÓN Aqualab CX-2, Pullman, WA, USA). The texture profile analysis (*TPA)* was performed following the method used by Miñarro et al. (2012), where two 12.5-mm-thick cross-sectional slices were obtained from the center of each bread. The texture profile analysis was carried out in a TA-TX2 texture analyzer (Stable Micro Systems, Surrey, UK). A 25-kg load cell (35-mm diameter) was used. The assay speed was set at 1.7 mm/s to compress the bread crumb center at 50% of its previous height. The time between compressions was 5 s. The studied parameters were hardness (*H*), springiness (*S*), cohesiveness (*C*), gumminess (*G*), chewiness (*Ch*) and resilience (*R*). Ten bread replies of each formula were performed and analyzed.

2.7 Statistical methods

Information from flours based on the hyperspectral variables and the physicochemical properties of breads were processed applying multivariable statistical procedures with the aim of reducing the dimensionality of dataset. To this end, a multivariate unsupervised statistical PCA (Principal Component Analysis) was used for the two different blocks: hyperspectral data results and bread properties results. This method was used to describe and reduce the dimensionality of a large set of quantitative variables to a small number of new variables, called principal components (PCs), which are the result of linear combinations of the original variables. The number of PCs was selected after considering the change in tendency on the screen plot, and also the accumulated percentage of explained variability above 75%.

Bread properties (ΔM_b, a_w and TPA (*H, S, C, G, Ch*)) were also studied by a one-way variance study (ANOVA). In those cases in which the effect was significant (P-value < 0.05), means were compared by Fisher's least significant difference (LSD) procedure.

Support Vector Machines (SVM) were used to evaluate the relationship between the hyperspectral data of the oat flours and the set of bread properties. They were used to carry out non linear regressions between both data sets, which were evaluated based on validation and crossvalidation coefficients. SVM are a powerful supervised learning methodology based on the statistical learning theory, which are commonly used for spectral analyses (Boser, Guyon, & Vapnik, 1992). Several SVM were done, first by employing the score values generated in the bread properties data PCA, which were taken as the descriptor of bread global characteristics since this parameter collects information about the differences among breads influenced by all the properties simultaneously. The remaining SVM were done between the hyperspectral data and each analyzed physical variable. Procedures were performed with PLS Toolbox, 6.3 (Eigenvector Research Inc., Wenatchee, Washington, USA), a toolbox extension in the Matlab 7.6 computational environment (The Mathworks, Natick, Massachusetts, USA).

3. Results

3.1 Hyperspectral image data acquisition

The data obtained from the hyperspectral image control (Step 2) of flours were processed and analyzed. For this purpose, information collected by the camera was studied according to the heat treatment temperature. A PCA was then used to reduce data dimensionality and to observe the spontaneous unsupervised clustering of samples within maximum variance dispersion. Figure 2 shows the PCA space where the scores of samples are represented. It was the result of two PCs, which explain 94.8% of total data set variance. PC1 collected 83.1% and PC2 collected 13.7% of total variance.

A clustering tendency of samples was observed following the pre-established class division (types of flours). Each oat flour class was sited separately from the rest. Thus an evolution following increase in temperature from the NT oat flour (positive PC1 zone) to the maximum treatment temperature (negative PC1 zone) was observed along the PC1 axis. Thus we can initially conclude that the information obtained from the hyperspectral image control allowed us to characterize the processing of oat flours according to temperature.

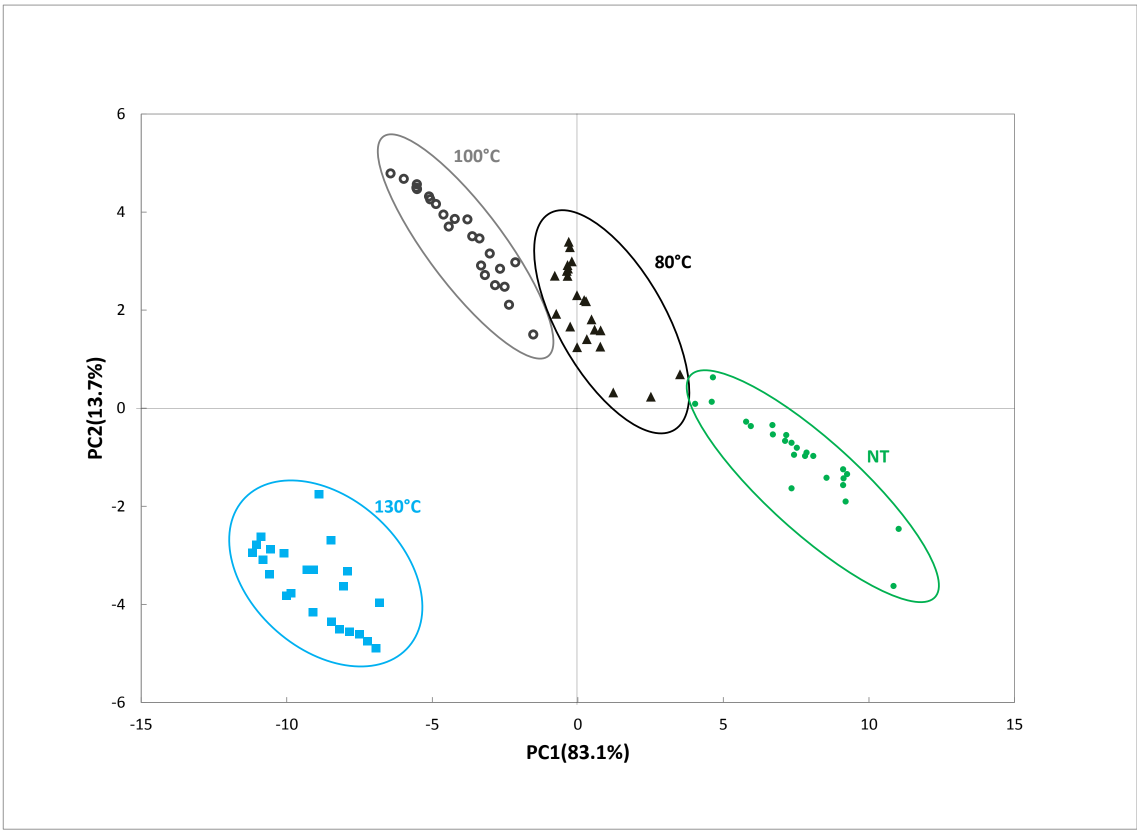

Figure 2. Study of the hyperspectral image data of oat flours. The PCA space with samples scores representation. ●: NT (non treated oat flour); ▲: oat flours treated at 80 ºC; ○: oat flours treated at 100 ºC; ■: oat flours treated at 130 ºC. Circumferences mark classes.

3.2 Characterization of bread properties

The bread properties acquired from using combined flours, based on the different oat flours and the pure wheat flour, were analyzed. Table 1 shows the bread properties results for the studied physicochemical parameters. In spite of oat proteins not possessing characteristic wheat gluten properties (Hüttner et al., 2010) to maintain gas, the specific volume was not significantly modified with the addition of NT oat flour at any tested substitution level. However, the oat flour treated at 100ºC produced a maximum value at both the 10% and 20% substitutions. Water activity presented an increment in all the 10% substitution cases, while reduction was observed for the 20% substitution cases with no clear temperature effect. Mass loss during the baking process for the breads obtained using NT oat flour presented increments up to 3% compared to the pure wheat at each substitution level. For this parameter, mass reduction loss was clear following the increase in the treatment temperature of oat flour, and values were obtained with no significant differences at 130ºC for both substitution levels. Hardness presented a decrease when adding the NT oat flour at both substitution levels. Temperature produced a sharper decrease for the 10% level, while the inverse behavior was observed for the 20% substitution. Springiness presented no clear evolution compared to the pure wheat bread, and values were similar. Gumminess displayed a parallel behavior to hardness. A decrease was noted when adding the NT oat flour at both substitution levels, and a decrease was also observed for the 10% level, but the inverse behavior was observed for the 20% substitution due to temperature. Chewiness lowered for the 10% substitution, while values near to the pure wheat ones were obtained for the flour treated at 130ºC at 20% substitution. Resilience presented a reduction at both substitution levels when the NT oat flour was added. However, an increase occurred almost up to the pure wheat values with increased treatment temperature. Cohesiveness increased with the addition of oat flour and did not appear to be affected by treatment temperature.

The modifications observed on textural properties were in line with known effects of partial lack of gluten and presence of β-glucan in composite breads (Flander et al., 2011). Otherwise, these results are according to other studies about heat treatments on oat and sorghum flours destined to produce composite and free gluten breads. Marston et al., (2016) also reported significant increase in volume and a decrease effect in firmness of breads when heat treated sorghum flour (30-40 min/ 95-125°C) was included in formula. These effects have been also related to the modification of free sulfhydryl groups of proteins because oxidation in this case, producing an increase of disulphide cross-linkages of amino acids and as a consequence, a stronger dough with greater resistance to mechanical shock and a larger dough volume (Gujral and Rosell, 2004). In addition, changes on starch granules conformation, principally in physical reorganization in their structure rather than molecular degradation, resulted in higher viscosities in doughs (Ovando-Martínez et al., 2013). This viscosity is due to the increased ability of the modified starch granules to absorb water, fact that can also explain the decrease of water loss during baking process with the increase in the treatment temperature of oat flour.

Table 1. Bread properties results

	% sustitution	*Sv*	a_w	ΔM_b	*H*	*S*	*Ch*	*G*	*R*	*C*
Pure wheat	0	2.22 ± 0.08 a	0.9579 ± 0.0008 bc	12.5 ± 0.53 a	6.25 ± 0.54 d	0.94 ± 0.05 a	5.1 ± 0.4 c	5.5 ± 0.57 c	0.46 ± 0.01 d	0.78 ± 0.0(a
NT Oats	10	2.16 ± 0.08 a	0.9701 ± 0.0031 d	15.68 ± 0.3 c	4.82 ± 0.66 cd	0.99 ± 0.04 b	4.0 ± 0.54 b	2.5 ± 0.38 a	0.35 ± 0.04 a	0.78 ± 0.01 a
Oats 80°C		2.44 ± 0.08 b	0.9575 ± 0.0003 bc	13.68 ± 0.31 b	4.02 ± 0.97 cd	0.98 ± 0.02 a	3.34 ± 0.78 ab	3.31 ± 0.78 ab	0.42 ± 0.01 c	0.83 ± 0.01 bc
Oats 100°C		2.64 ± 0.09 cd	0.9589 ± 0.0041 cd	13.44 ± 0.37 b	3.22 ± 0.45 b	0.93 ± 0.09 a	2.7 ± 0.38 a	2.58 ± 0.48 a	0.44 ± 0.01 c	0.83 ± 0.01 bc
Oats 130°C		2.34 ± 0.2 b	0.9622 ± 0.0040 d	12.64 ± 0.33 a	3.21 ± 0.57 bc	0.99 ± 0.02 b	2.74 ± 0.4(a	2.71 ± 0.48 a	0.46 ± 0.01 d	0.85 ± 0.01 c
NT Oats	20	2.10 ± 0.1 a	0.9525 ± 0.0021 a	15.0 ± 0.2(c	1.30 ± 0.61 a	0.98 ± 0.04 b	2.5 ± 0.48 a	1.2 ± 0.47 a	0.40 ± 0.04 b	0.84 ± 0.01 c
Oats 80°C		2.56 ± 0.07 bc	0.9525 ± 0.0019 a	14.24 ± 0.25 bc	2.57 ± 0.47 b	0.96 ± 0.1 a	2.16 ± 0.3(a	2.14 ± 0.37 a	0.41 ± 0.01 b	0.84 ± 0.01 c
Oats 100°C		2.74 ± 0.06 d	0.9521 ± 0.0028 a	13.78 ± 0.27 b	3.45 ± 0.8 b	0.98 ± 0.01 a	2.85 ± 0.63 a	2.79 ± 0.61 a	0.41 ± 0.01 b	0.82 ± 0.01 b
Oats 130°C		2.49 ± 0.13 bc	0.9548 ± 0.0017 ab	12.42 ± 0.61 a	3.47 ± 0.57 cd	0.97 ± 0.01 a	4.59 ± 0.47 bc	4.53 ± 0.45 bc	0.44 ± 0.01 c	0.84 ± 0.01 c

NT: non treated oat flour. Sv: specific volume (mL/g); aw: water activity; ΔM_b: mass loss (%), H: hardness (N); S: springiness; Ch: chewiness; G: gumminess; R: resilience; C: cohesiveness. Values followed by different letters are significantly different at P < 0.05 in columns.

In order to observe whether the set of bread properties presented a recognizable pattern according to treatment temperature, all the parameters were studied together. For this purpose, the PCA was done according to the parameters in Table 1. Figure 3 shows the biplot space based on the PCA done using the bread properties data set. Two PCs were selected, where PC1 collected 42.7% and PC2 34.5% of total data variance (77.2%).

The situation of bread samples (cases) and properties (variables) in the biplot space revealed a relationship among them, hence the weight of each property in the explanation of global bread characteristics. Two different tendencies pertained to the

10% and 20% substitution levels. Samples were ordered following an increase in treatment temperature from the NT oat flour to the 130ºC-treated flours. Pure wheat bread appeared on the edge of the positive PC1 zone. Samples presented an equal tendency across PC2, which was inversed across PC1.

To interpret those distributions, the loadings of variables for both PCs were studied. PC1 had high loading values for hardness (*H*), chewiness (*Ch*) and gumminess (*G*) in the positive zone, while cohesiveness (*C*) was found in the negative one. Those breads that contained 10% of NT oat flour and 20% of the 130ºC-treated oat flours came the closest to pure wheat flour as regards these properties. For PC2, mass loss (ΔM_b) in the positive zone and resilience (*R*) in the negative one were the variables with high loadings. Regarding these properties, both substitution levels with the 130ºC-treated oats came the closest to pure wheat flour, while those that contained the NT oats flour differed the most. Water activity (a_w) and springiness (*S*) presented intermediate loadings for both PCs, while specific volume (*Sv*) presented the lowest one.

Overall, increased temperature principally reduces mass loss and water activity in bread, but increases resilience at both substitution levels until it comes close to pure wheat flour. Chewiness, gumminess, hardness and cohesiveness were influenced inversely by temperature as regards the substitution level. The effect of heat treatment on oat flours led to amended bread properties compared to the breads substituted for the NT oat flour, which were almost pure wheat breads for some properties.

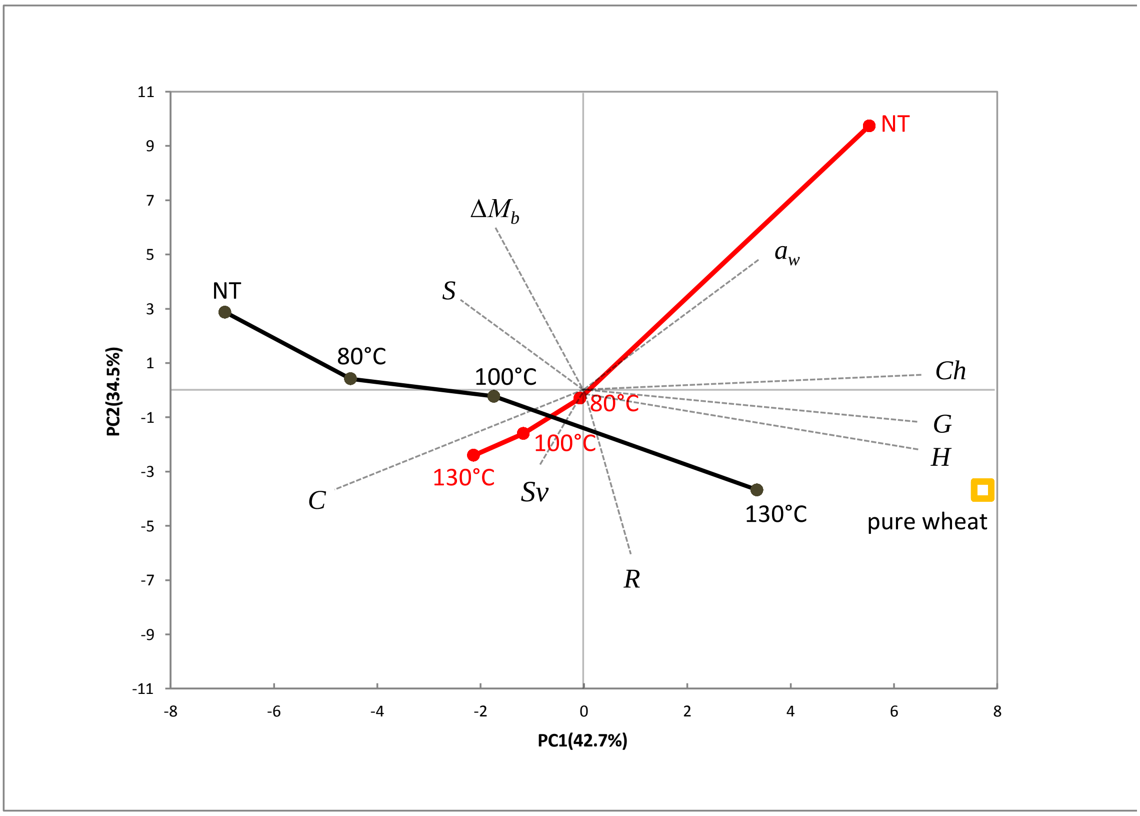

Figure 3. Study of the bread properties data set. Biplot PCA space based on sample' mean scores and variable loadings representation. NT: non treated oat flour; *H*: hardness; *S*: springiness; *C*: cohesiveness; *G:* gumminess; *Ch:* chewiness; *R:* resilience; *Sv*: specific volume; a_w: water activity; ΔM_b: mass loss. Circumferences mark variables. Red: 10% substituted samples; Black: 20% substituted samples. Yellow square: pure wheat bread.

3.3 Studying the relationship of hyperspectral data and bread properties data

The relationship between the hyperspectral data and bread properties was studied by testing the dependence between both datasets. The dependency of the global bread properties was studied by taking the score value generated in the bread properties data PCA as their descriptor (Figure 3). This was done because this value collects any differences among those breads influenced by all properties simultaneously, and it is a feasible parameter to compare them globally. Therefore, the mean of the PC1 scores of the hyperspectral image information of the PCA (Figure 2) was plotted as the Z axis in the bread properties data PCA (Figure 3). Figure 4 shows the resultant plot. Dispersion of points into a generated tridimensional space presented an organized sequence for the hyperspectral image data, with two different recognizable tendencies described according to each substitution level. Having observed these results, a decision was made to test the relationship of the hyperspectral image information with the bread properties data. The objective here was to know whether it was possible to obtain acceptable regression levels between both data set blocks or not.

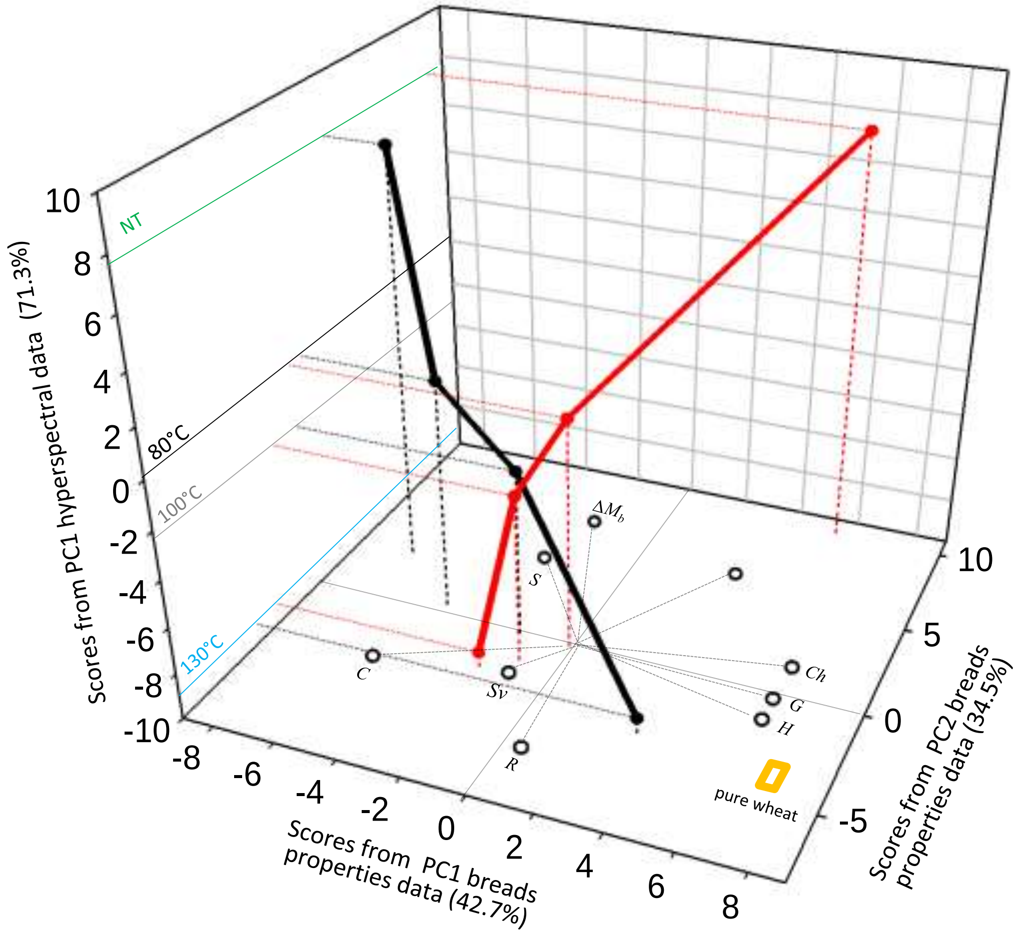

Figure 4. Plot of the relationship between the bread data and the hyperspectral image data. Y axis: mean scores from the PC2 bread properties data; X axis: mean scores from the PC1 bread properties data; Z axis: mean scores from the PC1 hyperspectral data. Black circumferences mark the bread properties variables on the XY plane. Red: 10% substituted samples; Black: 20% substituted samples. Yellow square: pure wheat bread. Lines across the Z axis: Green: NT (non treated oat flour); Black: oat flours treated at 80 ºC; Gray: oat flours treated at 100 ºC; Blue: oat flours treated at 130 ºC.

Since a non linear relationship is observed in Figure 4, Support Vector Machines (SVM) were used to obtain the regression calibration and cross-validation coefficients. The hyperspectral image data were used as independent variables (X) and the scores of the bread properties PCA as the dependent variable.

Calculations were made by taking into account the scores of both PCs from the bread properties PCA, as well as substitution levels, which resulted in four regressions to be studied (the PC1/PC2 scores from the 10% substitution and the PC1/PC2 scores from the 20% substitution). The results for all four regressions were successful, although PC1 presented slightly better values (Table 2) at both substitution levels. The 10% substitution presented cross-validation coefficients 0.95 and 0.91 for PC1 and PC2, respectively. Likewise, 20% presented 0.98 and 0.97 for PC1 and PC2, respectively.

Having observed the results about the relationships globally with bread properties, the dependency of each variable was also singly tested. Those single dependencies between the hyperspectral image and bread properties are included in Table 2. The obtained fit was also successful, although the cross-validation values were lower than those obtained for PC1 and PC2 for the majority. With 10% substitution, maximums R^2 *CV* were obtained for mass loss, chewiness and resilience with 0.97, followed by gumminess. The lowest one was specific volume and cohesiveness, with 0.81 and 0.82, respectively. For the 20% substitution level, the maximum was resilience with 0.98, followed by chewiness and gumminess with 0.95. The lowest ones were springiness and cohesiveness with 0.63 and 0.64, respectively.

The results proved the relationship between the hyperspectral image data obtained at different heat treatment temperatures applied to the oat flours, and also to the properties of the breads made with these flours. This relationship could be understood based on the modifications undergone by main flour components such as starch and proteins, which produce an impact both physicochemical and hyperspectral blocks of data results. These modifications produced variations both processing and end product, as has been reported by authors, and at the same time, these changes modified the interaction of flour samples with radiation collected by hyperspectral camera (Marston et al., 2016). Then, the evolution of both data blocks could be analyzed together as their dependence showed.

These dependencies are interesting because of the possibility of building a general model to obtain knowledge about bread properties by studying the heat treatment process of oat flour, in which more heat treatment temperatures and substitution levels can be included within a higher set of samples that are tested for the validation process.

Therefore, the capability to monitor the heat treatment process of oat flour that corresponded to the hyperspectral image technique was proved. It could be used as a control tool for the multigrain bread-making process to, for example, manipulate the properties of several oat flours to guarantee end product homogeneity.

Table 2. Results of the regressions calculated between the hyperspectral image data of the oat flours and bread properties data.

% substitution	SVM regression parameters	Scores PC1	Scores PC2	Sv	a_w	ΔM_b	H	S	C	G	Ch	R
10	*Number of SVs*	35	36	36	38	35	21	33	41	36	36	35
	RMSEC	0.04	0.1	0.09	0.0	0.01	0.13	0.00	0.00	0.07	0.01	0.00
	RMSECV	0.09	0.7	4.03	0.0	0.1	0.19	0.00	0.01	0.13	0.16	0.00
	R^2 *Cal*	0.97	0.95	0.99	0.99	0.99	0.96	0.93	0.99	0.97	0.99	0.99
	R^2 *CV*	0.95	0.91	0.81	0.86	0.97	0.92	0.86	0.82	0.94	0.97	0.97
20	*Number of SVs*	36	39	92	89	92	89	71	95	95	59	83
	RMSEC	0.03	0.003	2.60	0.00	0.10	0.18	0.00	0.00	0.14	0.16	0.00
	RMSECV	0.05	0.04	6,00	0.00	0.20	0.36	0.03	0.005	0.24	0.25	0.00
	R^2 *Cal*	0.99	0.98	0.96	0.99	0.98	0.98	0.9	0.91	0.98	0.98	0.99
	R^2 *CV*	0.98	0.97	0.83	0.86	0.94	0.94	0.63	0.64	0.95	0.95	0.98

PC1 and PC2: scores from the bread properties PCA; *Sv*: specific volume (mL/g); a_w: water activity; *H*: hardness (N); *S*: springiness; *C*: cohesiveness; *G:* gumminess; *Ch:* chewiness; *R:* resilience; ΔM_b: mass loss (%); *Number of SVs*: number of support vectors used in the regression to calculate; *RMSEC*: root mean square error of calibration; *RMSECV*: root mean square error of cross-validation; R^2 *Cal*: calibration coefficient; R^2 *CV*: cross-validation coefficient.

5. Conclusions

A heat treatment process on oat flour was effectively characterized by the hyperspectral image technique. This characterization reported information that allowed changes in oat flours to be monitored during the process, from non treated oat flour to the 130ºC-treated flour. The pattern between the hyperspectral information analysis and the response of composite breads in physical properties terms was observed. This relationship presented both high correlation and cross-validation values when non linear regression testing was carried out between them. The information obtained from the hyperspectral image system during heat treatment gave a direct relationship with oat flour behavior during the bread-making process. This could represent a non destructive control tool to monitor this process, and to regulate treatment until oat flours that provide bread with the desired properties are obtained.

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