Journal of Food Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Physical and mechanical properties of maize extrudates as affected by the addition of chia and quinoa seeds and antioxidants

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ARTICLE INFO

Article history:
Received 19 November 2014
Received in revised form 13 February 2015
Accepted 19 July 2015
Available online xxxx

Keywords:
Extrudate
Chia
Quinoa
Bioactives
AFM
Sound emission

ABSTRACT

The physical and mechanical properties of maize extrudates have been analyzed in relation to the addition of quinoa flour and two novel ingredients, chia and powder extract of purple corn with antioxidant properties. Maize flour and mixtures with 20% quinoa or 5% chia or 2% antioxidant powder were extruded with a double screw extruder. Physical properties like expansion rate, density, humidity, and mechanical and acoustic properties using a cutting test were measured. Mixtures with chia showed a lower expansion rate, probably related to the higher lipid content of the final mixture. On the other side, quinoa favored the expansion rate compared to maize flour. This was in correlation with the density results, being the quinoa extrudates the ones with the smallest density values. Extrudates with quinoa resulted in a smoother structure while chia addition tended to generate a rougher surface. Also, the addition of antioxidant powder decreased the surface roughness.

1. Introduction

Extrusion cooking is an ideal method for manufacturing a great number of food products as ready to eat cereals, salty and sweet snacks, texture–meat like materials and precooked food mixtures for infants. Beneficial nutritional effects range from increased protein and starch digestibility to the preparation of low cost, protein enriched or nutritionally balanced foods and feeds (Singh et al., 2007).

Nutritional concern about extrusion cooking is reached at its highest level when extrusion is used specifically to produce nutritionally balanced or enriched foods, like weaning foods, dietetic foods, and meat replacers (Cheftel, 1986; Plahar et al., 2003; Singh et al., 2007). However, one of the advantages of extrusion cooking is the destruction of antinutritional factors, especially trypsin inhibitors, haemagglutinins, tannins and phytates, all of which inhibit protein digestibility (Alonso et al., 2000; Armour et al., 1998; Bookwalter et al., 1971; Lorenz and Jansen, 1980).

The most widely used cereals for producing extrudates are maize and wheat. However, blends of these cereals with other seeds have been assayed. There are several studies on the use of quinoa–maize blends in the development of extrudates (Coulter and Lorenz, 1991; De Graaf et al., 2003; Ramos Diaz et al., 2013; Repo-Carrasco et al., 2003). Quinoa (*Chenopodium quinoa*) is a pseudocereal that has been cultivated in South America for more than 5000 years. The studies concerning quinoa proteins revealed that it contains a balanced amino acid composition, with a high content of essential amino acids, and is thus superior to that of common cereals (Drzewiecki et al., 2003). Lipid content of quinoa is also higher (2 or 3-fold) than in common cereals and rich in unsaturated fatty acids, which are desirable from a nutritional point of view (Alvarez-Jubete et al., 2010). Carbohydrates are the major component and their content varies from 67% to 74% of the dry matter (Jancurová et al., 2009). Starch is the only carbohydrate reported and its content varies from 51% to 61%. Cordeiro et al. (2012) showed a potential gastroprotective activity of quinoa polysaccharides.

Chia seeds (*Salvia hispanica L.*), which contain between 25% and 40% fats and up to 68% omega-3 alpha-linolenic acid, are among the plant sources with the highest contents of alpha-linolenic acid (Antruejo et al., 2011). Their protein content is high (19–23%), with

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http://dx.doi.org/10.1016/j.jfoodeng.2015.07.027
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the whole profile of essential amino acids, in particular leucine, lysine, valine, and iso-leucine (Sandoval-Oliveros and Paredes-López, 2012). However, there is a lack of studies on the use of chia–maize blends to prepare extrudates. Thus, specific studies on its effects on physical performance of extrudates are necessary before it can be incorporated as a novel ingredient to enhance the nutritional value of cereal foods.

Purple corn is known as a good source of natural antioxidants (Pascual-Teresa et al., 2002) and its benefic effects on health are under active study (Finkel et al., 2013; Hosoda et al., 2012; Huang et al., 2015). It can also be considered as an interesting natural alternative for mitigating the oxidation of essential fatty acids during extrusion (Camire et al., 2007).

Many processing variables as well as the blend composition affect the characteristics of the final obtained product. The addition of ingredients such as quinoa, chia or purple corn affect the physical characteristics of the extruded products (density and expansion index), as well as their mechanical properties (that correlate with sensory acceptance). Most textural attributes of foods are perceived through chewing, a process by which a solid food is torn, ripped, crushed, ground and mixed with saliva. Among the most important organoleptic attributes of cereal foods, crispness is characterized by brittle fracture at a low fracture force and distinguishable fracture events, and the emission of sound is an important aspect for the perception of crispness and crunchiness (Drake, 1963; Luyten et al., 2004; Van Vliet et al., 2007; Vickers and Bourne, 1976).

According to Bourne (2002) the texture of foods is derived from their structure. Microscopy techniques are successfully employed to obtain information about the microstructure and morphology (Aguilera, 2005). Atomic force microscopy may allow to obtain quantitative information such as (Arzate-Vázquez et al., 2012; Osés et al., 2009; Villalobos et al., 2005). Therefore, the aim of this work was to characterize physical and mechanical properties of extrudate blends of maize with quinoa, chia, with or without purple corn, and to evaluate their microstructure by means of microscopy techniques (SEM, AFM).

2. Materials and methods

2.1. Antioxidant powder

Purple corn was obtained from a local market. The corn cobs were cut and mixed with water in a proportion 1:1. An ultrasonic aqueous extraction of purple corn was performed in a Hielscher UP100H equipment, using a Probe 7S, an amplitude of 100%, and a pulse 0.5 s. Extraction was performed for 5 min. The aqueous extract was filtered through a filter paper (0.45 μm). Maltodextrin (MD) DE15 was added to the aqueous purple solution to obtain final MD concentration of 20%. Spray Drying was performed in a laboratory-scale, Mini Spray Dryer Büchi B290 (Flawil, Switzerland). The operational conditions of the drying process were inlet air temperature 175 ± 3 °C, outlet air temperature 83 ± 3 °C, flow rate 8 ml min^{-1}, air pressure 3.2 bar and nozzle diameter 1.5 mm.

2.2. Samples

Five blends were prepared, containing maize flour either alone or its mixtures with Quinoa, Chia, or antioxidant powder, in the proportions indicated in Table 1. The blending was done at room temperature in a mechanical mixer for one hour. Water content of the raw mixtures was 14% and 8% for the extrudates.

As fat content of the flour mix is an important factor in extrusion process the amount of fat contributed by the components and the percent of fat in the blend was calculated, and is described in Table 2.

Table 1
Composition of the blends used in the extrusion process.

Sample	Maize (%)	Quinoa	Chia	Anti-oxidant (MD)
C1	100			
C2	98			2%
B1	80	20%		
A1	95		5%	
A2	93		5%	2%

The extruder used was a conical, counter-rotating, twin-screw extruder model CM45-F (Cincinnati Milacron, Austria). The general screw geometry was length 1000 mm, diameter from 90 to 45 mm, channel depth 8.5 mm, calender gap 0.5 mm, and flight gap 0.2 mm. A screw configuration with five conveying sections and three drossel zones was employed. A 4.5 mm circular die was fitted in the die plate. The barrel had four heating sections (50, 80, 100, 150 °C). Operating torque was set to 80%. Samples were then collected, cooled to room temperature under natural convection conditions and stored for further analyses in sealed polyethylene bags.

2.3. Water content

Humidity was measured gravimetrically by drying the milled samples (passing 0.420 μm mesh) for 4 h at 130 °C under forced air current until constant weight (±0.0002 g), all samples were run in triplicate.

2.4. Physical properties

Extrudates diameter was measured with a digital caliper in five samples. The relationship between this average value and the die diameter (4.5 mm) was used to calculate an expansion rate (ER) (Alvarez-Martinez et al., 1988). Bulk density (ρ_{ap}) was calculated using a 5 L graduated cylinder filled to the top and weighted. Five replicates were measured for each formulation and results averaged. Real density (ρ_t) was measured after grinding the samples using the volume displacement method (Yan et al., 2008) using toluene as solvent. All values were made in triplicates.

Porosity (ε) was estimated using the relation between both densities (Bisharat et al., 2013) according to Eq. (1).

$$\varepsilon = 1 - (\rho_{ap}/\rho_t) \quad (1)$$

Table 2
Calculated fat content of the blends.

		Total batch (kg)	% fat in each component[a]	Total fat (kg)	% fat over total blend
C1	Maize	10	2	0.2	2
C2	Maize	9.8	2	0.196	1.96
	Antioxidant	0.2			
B1	Maize	8	2	0.16	
	Quinoa	2	6	0.12	
	Blend			0.28	2.8
A1	Maize	9.5	2	0.19	
	Chia	0.5	30	0.15	
	Blend			0.34	3.4
A2	Maize	9.3	2	0.186	
	Chia	0.5	30	0.15	
	Antioxidant	0.2			
	Blend			0.336	3.36

[a] This data was extracted from United States Department of Agriculture, National Nutrient Database for Standard Reference and was used as an estimated quantity for preparing the blends.

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2.5. Mechanical properties

A cutting test was performed with a texure analyser TAXTplus (Stable Microsystems, UK) using a Craft knife blade (0.9 mm thickness) and the acoustic envelop detector for sound measurement. The tests were carried out at a blade speed of 2 mm s^{-1} until the blade cut through the sample. Trigger force was set to 0.1 N. The microphone was positioned at a 3 cm distance with an angle of 45° to the sample. The amplifier was set to level 4 and the data acquisition rate was 500 points per second. 20 replicates of each product were analyzed. Hardness of the extrudates was measured as the maximum force (N). The recorded sound was expressed in dB representing the sound pressure level (SPL). From the force signal the maximum force (N), distance of maximum force (mm), number of force peaks and linear force distance (N s) were measured. From the acoustic signal the mean sound peak (dB), and linear sound distance (dB s) were evaluated. The signals were registered during 8.5 s after trigger force was reached.

2.6. AFM

Surface topography of extrudates at μm scale was analyzed with an AFM (atomic force microscope) (diMultimode V connected to a micro controller di Nanoscope V, Vecco, USA). Sections of samples were scanned in Tapping mode with siliciumnitride (Si_3N_4) edges (Model RTESP, Bruker) having a resonance frequency of 325,363 kHz. Scanned areas were of 100 μm^2 (10 μm × 10 μm), 25 μm^2 (5 μm × 5 μm), 0.25 μm^2 (0.5 μm × 0.5 μm), at a speed of 1 Hz. The NanoScope V8 software was used to asses surface highness (topography) in 3D images. Roughness parameters were obtained as *Ra* (average arithmetic roughness) and *Rq* (average quadratic roughness) according to Eqs. (2) and (3) respectively.

$$Ra = \frac{1}{n_x n_y}\sum_{i=1}^{n_x}\sum_{j=1}^{n_y}[z(i-j) - z_{ave}] \tag{2}$$

$$Rq = \sqrt{\frac{\sum_{i=1}^{n_x}\sum_{j=1}^{n_y}[z(i-j) - z_{ave}]^2}{n_x n_y}} \tag{3}$$

where $Z(i, j)$ are the surface highness values, Z_{ave} is the average surface highness, i and j corresponding to the pixels in directions x, y respectively. The number of maximum pixels in both directions is represented by n_x, $n_{y.}$

2.7. SEM

Raw samples and extrusion cooked samples were fixed on a SEM stub with conductive glue and coated with a 3 nm Au layer (Sputter coater: Leica Sputter SCD 005). SEM measurements were performed in a FEI INSPECT S50 (EDAX GEMINI II, SDD 10 mm^2) in high vacuum atmosphere. Images were recorded at magnifications starting from 100× until 10.000×. Samples were measured with 15 kV and a spot size of 2.5.

2.8. Statistical analysis

Differences were evaluated by ANOVA with Tukeypost test using Infostat 2012 (GrupoInfoStat, FCA, Universidad Nacional de Córdoba, Argentina). Graphs and correlation analysis were performed using GraphPad Prism version 5.00 for Windows (GraphPad Software, San Diego California USA).

3. Results and discussion

3.1. Physical properties

Table 3 shows the physical properties measured for the different formulations. Bulk density and expansion index for plain maize extrudates (C1) were of 0.054 ± 0.001 g/cm^3 and 5.4 ± 0.3 respectively. Coulter and Lorenz (1991) obtained extrudates of similar composition with higher density (0.080 g/cm^3) and lower expansion index (3.36 and 3.99 for 100 and 200 RPM respectively) for the same initial humidity and a similar temperature ramp (100–150 °C). The addition of quinoa to the formulations yielded the extrudates with the lower bulk density (0.046 ± 0.001 g/cm^3). These samples also showed higher expansion index and porosity as compared to plain maize. Coulter and Lorenz (1991) reported density values between 0.090 and 0.150 g/cm^3 on similar maize–quinoa blends with expansion index of 2.73 and 3.36 for 100 and 200 RPM respectively.

Chia blends (A1 and A2) showed lower expansion index as compared to the formulations with maize (C1, C2) and quinoa (B1). It has to be taken into account that chia has a high lipid content. Although the amount of chia added was very low (5% of total weight) it resulted in almost doubling the total lipid content. Singh et al. (2007) pointed out that the torque of the extruder decreases by the effect of lipids that reduce the slip within the barrel and thus less pressure is developed resulting in a less expanded product.

Bulk density did not follow the same behavior showing similar values between samples with and without chia. Regarding the effect of the antioxidant ingredient, only the bulk density of corn flour samples showed significant differences, as for the rest of

Table 3
Physical properties of corn based extudates obtained from different formulations.

	Bulk density (g/cm^3)	True density (g/cm^3)	Expansion index	Porosity (%)
C1	$0.054 \pm 1{\cdot}10^{-3c}$	1.46 ± 0.04^{ab}	5.4 ± 0.3^{b}	96.3 ± 0.2^{ab}
C2	$0.052 \pm 8{\cdot}10^{-4b}$	1.48 ± 0.04^{ab}	5.9 ± 0.2^{c}	96.5 ± 0.2^{ab}
B1	$0.046 \pm 3{\cdot}10^{-4a}$	1.44 ± 0.01^{a}	5.8 ± 0.2^{c}	$96.8 \pm 1{\cdot}10^{-4c}$
A1	$0.052 \pm 2{\cdot}10^{-4b}$	1.53 ± 0.01^{b}	5.0 ± 0.4^{a}	$96.6 \pm 1{\cdot}10^{-4bc}$
A2	$0.052 \pm 2{\cdot}10^{-4b}$	1.49 ± 0.04^{ab}	4.8 ± 0.4^{a}	96.5 ± 0.06^{abc}

Mean ± standard deviation. Different letters indicate significant differences were found among the formulations ($p < 0.05$).

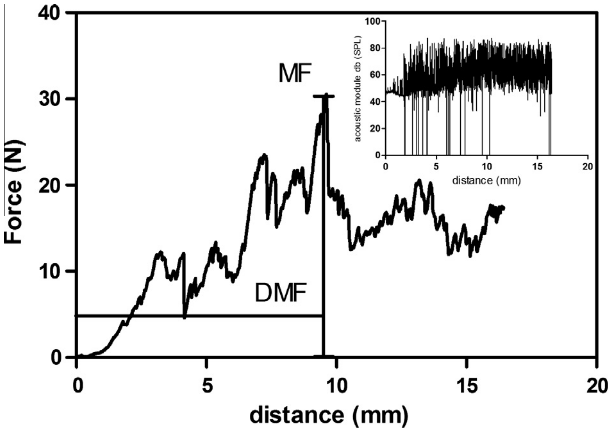

Fig. 1. Force recorded during a cutting test. Trigger force was set to 0.1N to assure that the recording started as soon as the blade touched the sample. From this point, the displacement distance of the blade was set to 17 mm. The upper insert shows the sound wave recorded simultaneously. MF: maximum force; DMF: distance to maximum force.

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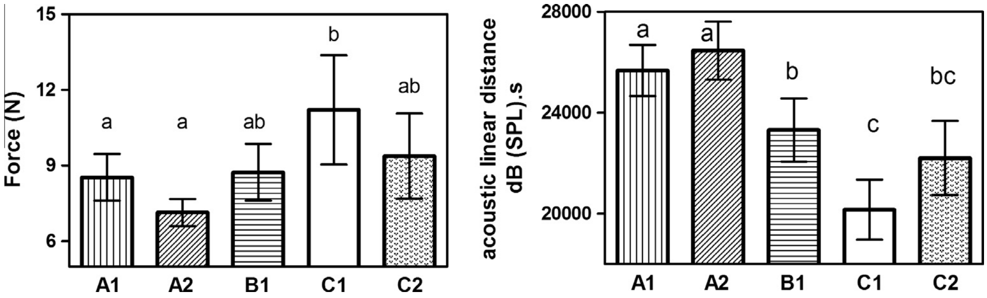

Fig. 2. Maximum Force (Force) and acoustic linear distance obtained from the analysis of cutting test data. Bars represent the mean of 20 replicates with the 95% confidence interval. Different letters represent significant differences ($p < 0.05$).

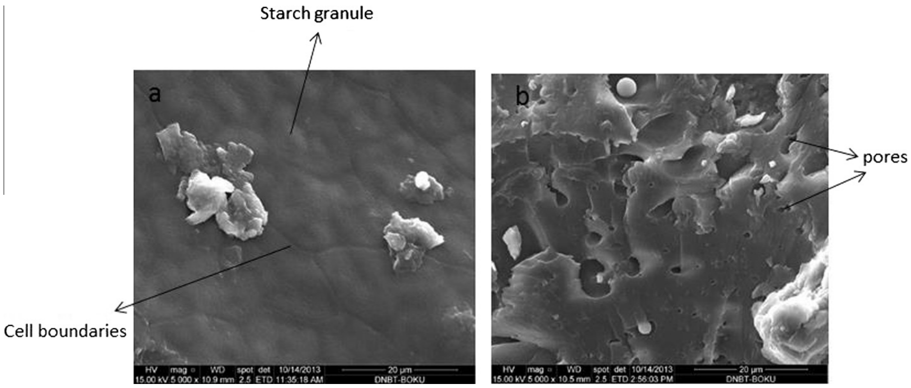

Fig. 3. SEM micrographies (5000×) for Maize and Quinoa blend before (a) and after extrusion (b). As can be seen, the extrusion process promotes the generation of a more porous and compact surface.

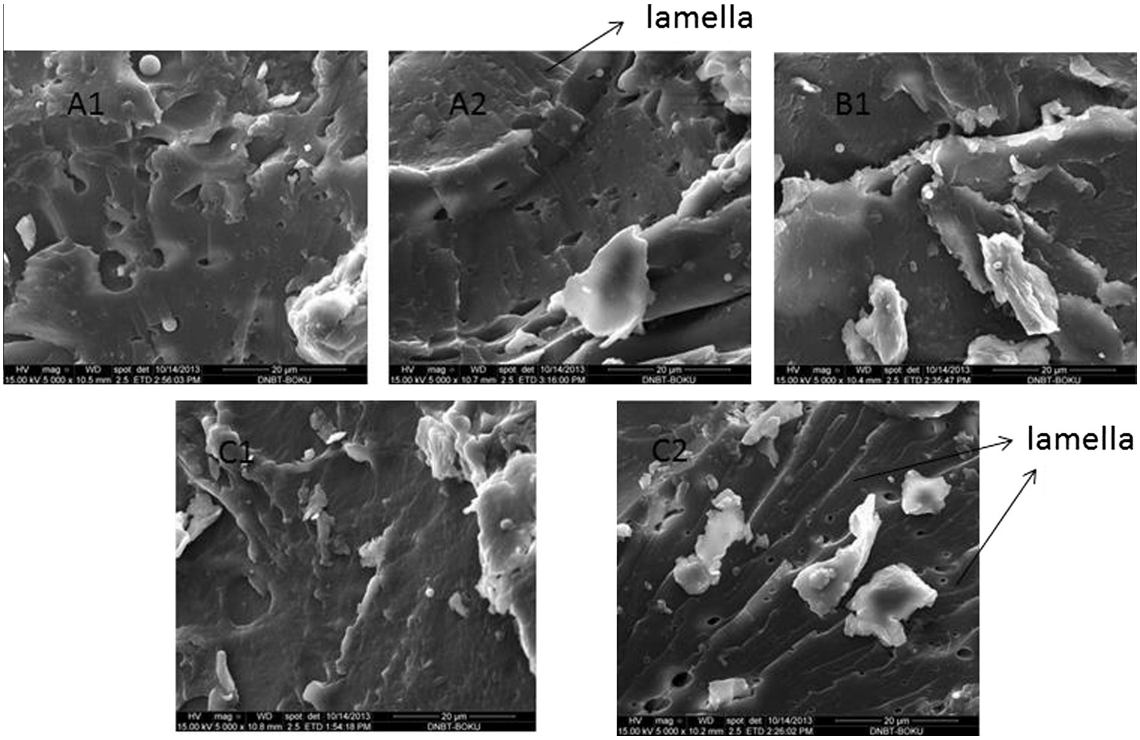

Fig. 4. SEM images (5000×) showing the starting blends (formulations A1, B1, C1) and the ones with addition of antioxidant powder (formulations C2, A2) having a more stacked laminar structure.

formulations it is effect was not reflected in the variables measured, probably due to the low concentration employed.

The porosity of all samples was generally high indicating a well expanded product and only slight differences could be established

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among the formulations being quinoa samples (B1) more porous than corn flour ones (C1, C2). It was expected that the Chia samples would have presented a lower porosity than the others because of their higher lipid content, as was reported by Bisharat et al. (2013), where extrudates with corn flower and olive paste showed a lower expansion value than the other samples. This behavior was attributed to an increment in the lipid content that reduced mechanical energy, therefore lowering the amount of dispersed starch leading to decreased extensibility of bubble cell walls and reduced porosity.

The lowest true density was showed by quinoa (B1) containing formulations and the higher was found for chia (A1) containing samples. As the structure generated by the expansion process was destroyed during milling the true density reflected the differences in sample matrix that are mainly produced by original composition and transformation during cooking. The samples that were more different in original composition and did not share any ingredients, except corn flour, were A1 and B1.

3.2. Mechanical properties

Hardness of the extrudates was measured as the maximum force. When a force is applied to a crisp item, its structure is stressed until a critical point is reached: the action of an external force causes the rupture of the brittle walls of the cellular structure which start to vibrate. The vibration is transmitted through the air as acoustic waves, which generates the sound. Sensory crispness is therefore the perception of deformation and time events. The acoustic envelope promoted by the application of force to the extrudates was measured in parallel to the cutting test. Because of that force cell walls of the product snap and energy is released. It is this energy moving through the air which can be detected and recorded (Duizer, 2004). Fig. 1 shows a picture of raw data from the force profile measured and the corresponding sound wave recorded in an experiment. A program generated trough a macro sequence using the TAXTplus software was used to analyze these raw data and to obtain the different parameters measured: maximum force (maximum peak height), distance (mm) to attain the maximum force, total number of peaks and the linear force distance. The latter was obtained as the force integral in time domain. From the sound wave the mean sound peak was obtained as the arithmetical mean of the sound peaks, the number of peaks was counted and the linear sound distance was calculated as the integral in time domain of the total sound wave recorded.

After analyzing the data recorded on the cutting test (force and acoustic envelope), only two variables were selected to describe the samples. This was done after a principal component analysis (data not shown) which evidenced that 94.7% of the total variance could be explained by the maximum force and the acoustic linear distance (Fig. 2).

The maize blend with the highest expansion index (shown in Table 3) had also the highest force values for the cutting tests. These results agree with the ones found by other authors (Coulter and Lorenz, 1991; Ramos Diaz et al., 2013), who concluded that the highest hardness value was for extrudates obtained with pure maize, in comparison with other blends containing quinoa and amaranth or amaranth/quinoa/kañiwa.

The lowest force appeared for the chia blends, where expansion index was lowest even though bulk density was similar. It has to be taken into account that although the amount of chia added was low (5% of total weight), it resulted in almost doubling the total lipid content (Table 2). Since physical characteristics, such as hardness, are the result of the interaction of biocomponents (e.g., starch and protein) at a physical and/or molecular level, It is probable that, by adding quinoa and chia, plasticizers somehow disrupted polymeric structures thereby reducing hardness compared to pure corn extrudates during the cutting test (Ramos Diaz et al., 2013).

The sound produced during the cutting test, which is related to the sensation of crispness, was evaluated by means of the acoustic linear distance (dB s) of the sound signal produced during cutting of the sample. When a crispy or crunchy cellular material is crushed, it releases a series of noises corresponding to the rupture of cell or cavity walls. Noises may be produced throughout the entire bite for no cells to many cells may be rupturing at any point in time. Crispiness was measured as the sound envelope signal linear distance because this value is affected by the length of the acoustic signal since the highest value corresponds to a longer jagged signal. The results showed that the addition of chia (formulations A1, A2), and quinoa (formulation B1) increased the acoustic linear distance with a significant value of $p < 0.05$. The addition of antioxidant powder (formulations C2, A2) had no significant effect on the acoustic signal. Maize extrudates had a higher mechanical strength measured as the maximum force but they were actually more brittle since the fracture grew faster in all product. Moreover the blade displacement distance value needed to reach this maximum force was lower in plain maize blends compared to chia and quinoa blends (data not shown). This promoted the sample to be torn into pieces faster and also sound faded out in a shorter time. The chia and quinoa samples, on the other side, were more cohesive and presented less maximum resistance to the

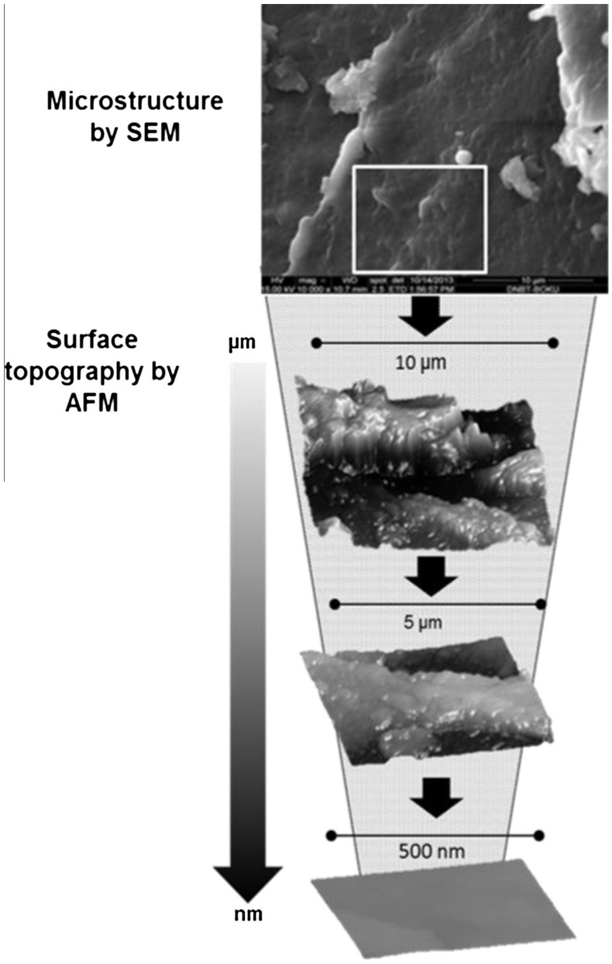

Fig. 5. The information presented by SEM and AFM techniques. Microstructure of SEM images at a resolution of 10000× can be related to the FMA 3D images for better understanding and also to relate them with quantitative information as surface roughness parameters.

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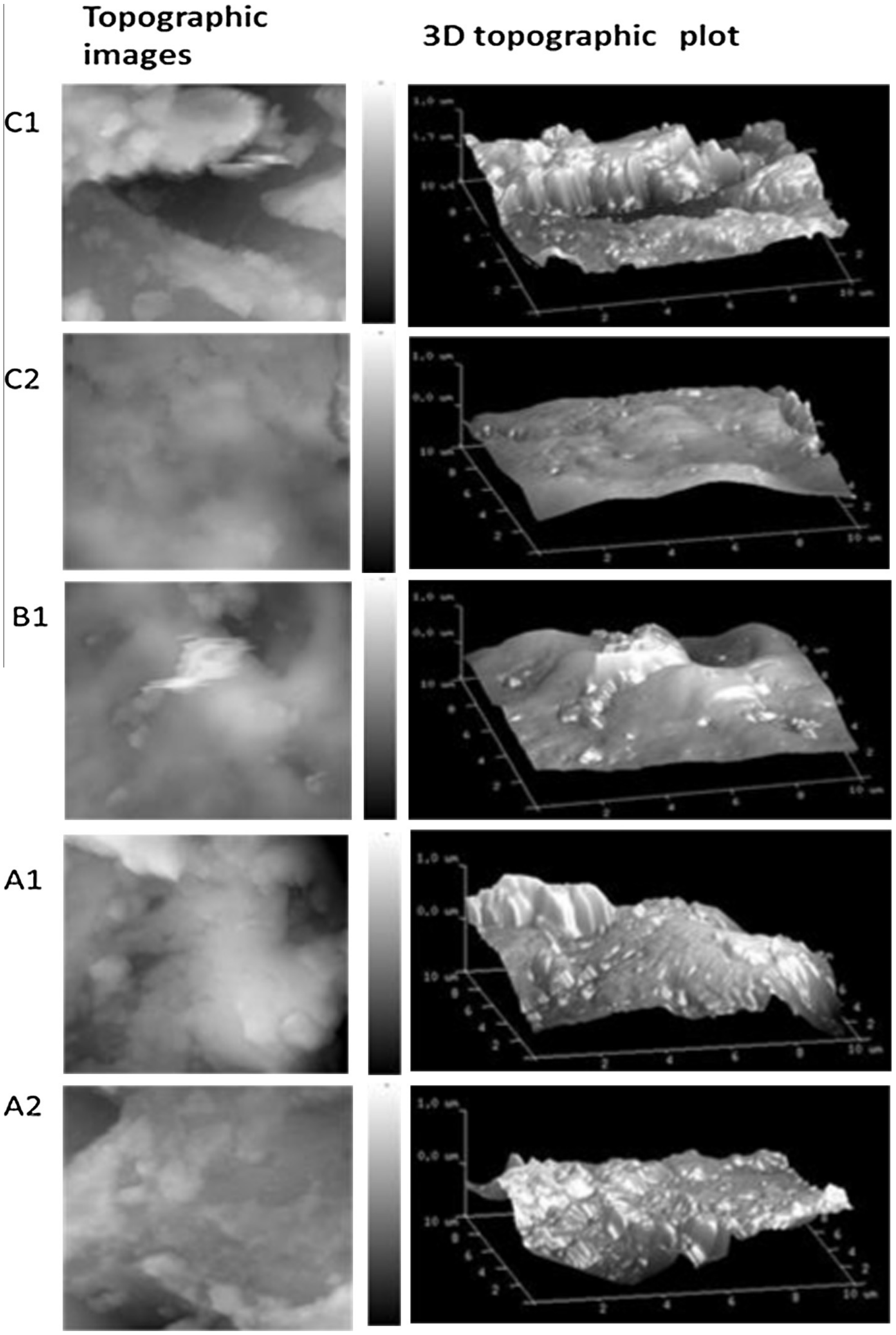

Fig. 6. AFM 2D and 3D topographic images (scanned area of 100 μm^2, scale bar represents 1 μm) obtained for samples A1, B1, and C1 are presented. Gray scale corresponds to the deepness within a 100 nm range, being white the highest points and black the lowest ones.

blade displacement during cutting. The blade displacement necessary to achieve the maximum force was higher in this samples and this effect was more pronounced in the ones with chia probably due to their higher lipid content. These samples were less brittle and, in this way, cell rupture occurred in a more progressive way so samples were torn into pieces more gradually as well, producing a more jagged sound wave resulting in a higher acoustic linear distance.

3.3. SEM and AFM

Fig. 3shows a micrography of formulation B1 before and after extrusion, as an example of the changes promoted by the extrusion process. Before extrusion (Fig. 3a) cell structure and boundaries between cells are clearly visible. The starch granules inside the cell can also be observed as they protrude from the cell surface. After extrusion (Fig. 3b) all the original structures disappeared due to the combination of shear force and temperature inside the barrel. The sample matrix becomes more homogeneous. Small pores lower than 10 μm of diameter are formed due to the resulting expansion and no trace of starch granules can be identified.

A comparison of the microstructure and surface topography of different extruded blends at five magnifications was done in order to analyze the impact of the different ingredients. As shown in Fig. 4, only slight differences were observed by SEM probably because the main component, maize semoline, was present in high

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proportion (>80%) in all samples. However, for the quinoa blend (formulation B1) a more homogeneous surface with fewer pores could be noticed. Sample A1 presented a larger amount of pores similar to samples A2 and C2. The addition of the purple corn antioxidant powder (A2 and C2) had the effect of enhancing the formation of a more stacked layered structure.

A softness sensation during chewing is mechanically related to the sliding of individual cells one past another (like a wall made of Lego cubes) when a force is applied while hardness is the result of fracture across the cellular material (Aguilera and Stanley, 1999). This could explain some of the behavior of the maize extrudates with antioxidant powder. After a free choice profile analysis (data not shown) the samples containing chia were able to be spotted in a different group from the others and they were also described as less brittle, and softer to bite. This group of samples presented as well the lowest average Force value in the cutting test.

AFM allows for the analysis of the surface topography at nanometric levels and makes possible the creation of 3D models, showing in minor detail the microstructure of the samples. In Fig. 5 a comparison between SEM analysis and AFM is shown using images of the samples studied. In SEM images it is possible to visualize sample microstructure and topography. On the other hand, in AFM images, as the probe used can interact with sample surface, the topography is not only visible but can be quantified. It is important to note that for heterogeneous systems AFM analysis results are strongly dependent on the surface area being scanned. An area too small can result in a loss of detail because not enough surface properties are measured or led to a wrong conclusion due to a small area of analysis in this type of samples.

Fig. 6 shows the topographic images, as measured by the AFM, indicating the magnitude of the interaction of the probe with the sample surface in a gray scale. From these data a 3D topographic plot is constructed in which the color corresponds to the deepness within a 100 nm range, being of white color the points with the highest heights values and of black color the ones with the lowest values.

The surface can be characterized by amplitude parameters which are based on the vertical deviations of the roughness profile from the mean line. After testing different surface areas, a value of 100 μm^2 (the biggest possible area) was selected for the analysis of roughness parameters (Rq and Ra) because it better represented the sample characteristics. Ra is the most widely used roughness parameter, which represents the arithmetic average of the absolute deviation values and Rq is the root mean square average of the roughness profile ordinates.

The values for Ra and Rq are shown in Table 4. Both values presented a similar behavior for the five samples. The analysis of variance did not show significant differences among the formulations neither for Ra nor for Rq. The addition of quinoa resulted in a tendency to lower both parameters about 30 units as compared to plain maize blends (formulation C1). In the SEM images presented (Fig. 4) a more regular surface for these formulations can be noticed. An opposite tendency was seen for the addition of Chia (formulation A1) in which the roughness parameters obtained were actually higher. Although the mean values obtained for average roughness indicated a smoother surface for samples containing purple corn, the statistical analysis performed indicated that there were no significant differences on the calculated values from the AFM measurements. Thus, the differences at a macroscopic level cannot be associated to differences which can be perceived at a nanometric scale. Therefore, the interactions that are responsible for this behavior appear to be at the supramolecular level, and not at the molecular scale.

Table 4
Roughness values calculated from FMA images of samples after extrusion.

	Rq (nm)	Ra (nm)
C1	302 ± 76	249 ± 71
C2	189 ± 87	151 ± 73
B1	274 ± 146	217 ± 124
A1	317 ± 58	253 ± 48
A2	251 ± 18	194 ± 19

Values are calculated for a surface of 100 μm^2, and correspond to the mean ± standard deviation, $n = 3$. No significant differences were found among the formulations ($p < 0.05$).

4. Conclusions

The addition of quinoa or chia flours to corn flour, besides incorporating bioactive compounds, allowed the production of extrudates with special microstructural and mechanical characteristics.

Expansion rate and density can be managed by modifying the extrudates formulation. The addition of Chia (A1, A2) yielded products with higher density. Also chia increased the crunchiness shown by higher values for the acoustic linear distance and number of sound peaks.

Extrudates with quinoa resulted in a smoother structure while chia addition tended to generate a rougher surface. Also, the addition of antioxidant powder decreased the surface roughness.

These results indicated that the addition of quinoa or chia flours to corn flour allowed the production of extrudates with good characteristics (i.e. expansion rate, density).

Microstructural studies (SEM and AFM) were successful tools for evaluating the complexity, homogeneity and roughness of surfaces as to evaluate the microstructural changes due to composition.

While in the mean values of the mechanical properties the addition of the purple corn-based antioxidant ingredient showed an effect, it was not statistically significant.

Acknowledgments

This work has been possible through the Bilateral Cooperation Project MINCYT-BMWFAU1205.WTZ Project Nr. AR 16/2013. The authors also acknowledge financial support from Agencia Nacional de Promoción Científica y Tecnológica (PICT 2013-1331), Universidad de Buenos Aires (UBACYT 20020130100443BA) and Instituto Nacional de Tecnología Agropecuaria (PNAyVA 1130043).

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Please cite this article in press as: Cueto, M., et al. Physical and mechanical properties of maize extrudates as affected by the addition of chia and quinoa seeds and antioxidants. Journal of Food Engineering (2015), http://dx.doi.org/10.1016/j.jfoodeng.2015.07.027

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