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Sensorial, functional, optical and thermal properties of inulin enriched expanded products

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Abstract

In the present work, the functional, optical, thermal and sensorial properties of rice extrudates were investigated. The effect of extrusion parameters, namely extrusion temperature (10-180°C), screw speed (150-250 rpm), feed moisture concentration (14-20%) and inulin replacement level (5-15%) on those properties were studied. Functional and optical properties were correlated with process conditions using simple mathematical models. It was found that die temperature and screw speed caused an increase in water absorption, water solubility and oil absorption, while inulin concentration resulted in their decrease. Colour change was more obvious at a die temperature of 180°C and 14% moisture content. Sensory evaluation proved that the most expanded and crispy extrudates were obtained with 14% feed moisture, 10-15% inulin concentration, 180°C extrusion temperature and 200 rpm screw speed. Glass transition temperature decreased with moisture content and increased with concentration, while it also decreased with temperature and screw speed only at low relative humidity levels (0.11). Based on the evaluation of properties and the sensorial characteristics the optimum conditions for the extrudates are $X = 17\%$, $C = 10\%$, $T = 180°C$, $R = 200$ rpm.

Introduction

Extrusion is a high temperature-short time technology, characterised by continuous cooking, mixing and forming, and aims to produce direct expanded products (Ding *et al*., 2006). The extrudates quality depends on the process conditions, such as extruder type, feed moisture, extrusion temperature and screw speed (Thymi *et al*., 2005). Extrusion is widely used for the production of breakfast cereals, food snacks, bakery and pasta (Rodriguez-Miranda *et al*., 2011).

In the last decade, there has been an increasing trend for the consumption of highly nutritional food products, as well as a preference for ready-to-eat snacks. In order to combine these two needs, healthy ingredients such as legumes, beans, peas, tomato lycopene, apple pomace, herbs, prebiotics, dried fruits, cactus pear, grape seed, grape and olive pomace have been added to the extruded mixtures (Grochowicz and Sobczak, 2007; Anton *et al*., 2009; Khanal *et al*., 2009; Dehghan-Shoar *et al*., 2010; Karkle *et al*., 2012; Bisharat *et al*., 2013). Among these, fibres have attracted scientists' interest (Pastor-Cavada *et al*., 2011) due to their numerous health benefits, i.e. prevention of constipation, reduction in bowel transit time, lowering of blood cholesterol, reduction in risk of colorectal cancer, production of short chain fatty acids and promotion of the growth of beneficial microflora that helps the good function of the intestine (Hager *et al*., 2011). Among these, inulin is a well-known prebiotic and a soluble dietary fibre found in many plants such as onion, chicory, banana, garlic and asparagus. As a prebiotic food ingredient, it is mainly used in dairy or bakery products, as well as a sugar substitute (Rodriguez-Miranda *et al*., 2011).

When fibres are added in the extrudates, they influence not only their nutritional value but also the properties. Functional and optical properties of the extrudates are crucial for their characterisation and selection (Drago *et al*., 2007), while thermal properties affect both storage conditions and the products shelf life. In addition, sensory evaluation is one of the most important criteria affecting consumers acceptance, while glass transition temperature (T_g) is linked with the physicochemical behaviours of

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extrudates and is particularly important for the mechanical properties of the extrudates (de Graaf *et al*., 2003). Finally, water sorption isotherms are of extensive use, especially for low moisture foods, and they can be applied in order to determine the stability of the products during storage (Goula *et al*., 2008).

Many studies have already investigated the functional and colour properties of extrudates using different additives in order to enhance the extrudates properties. Raphaelides *et al*. (2010) studied the physicochemical and structural characteristics of pre-gelatinised starch-fatty acid-glycerol extrudates, and found that water solubility index (WSI) was low at rather low extrusion temperatures and low screw speeds, whereas at high temperatures the WSI increased. In a similar study performed by Obradović *et al*. (2014), the water absorption index (WAI) decreased with increasing soy protein concentrate level, mainly because of a reduction in the starch content, while WSI appeared to increase with increasing soy protein content. Anderson *et al*. (1969) reported that the WAI of extruded cereal products was higher for higher moisture extrudates. On the other hand, according to Jyothi *et al*. (2009), the oil absorption index (OAI) of the extruded arrowroot starch increased with increasing extrusion temperature from 140 to 160°C, while sensory evaluation provided valuable results for the extrudates with the extrudate colour being one major factor that determines extrudates acceptability (Anuonye *et al*., 2012).

The present work was therefore aimed to depict the correlation between sensorial, functional, thermal and optical properties of inulin enriched rice extrudates and their production conditions and materials characteristics. The innovative aspect of the present work is the investigation of the addition of inulin to extruded products, which has not been thoroughly studied, as well as the application of simple mathematical models, that include process parameters and predict the final properties of the extrudates.

Materials and methods

Sample preparation

The rice flour used in the present work was provided by Agrino- Ev. Ge. Pistiolas S.A. (Agrinio, Greece). Inulin was purchased from Cosucra (Fibruline Instant, Warcoing, Belgium), deriving from chicory with DP: 9, dry matter: 95.9%, ash on dry matter: 0,03%, free sugars 8% and fibres 92%. Inulin and rice flour were mixed to the desired ratios. 0%, 5%, 10% and 15% of inulin replacement was selected based on preliminary experiments that revealed that extrudates with more than 15% inulin concentration scored the lowest in sensory evaluation. The moisture content was adjusted to 14%, 17% and 20% w/w by spraying distilled water in the feed mixtures. To maintain the moisture equilibration, the samples were packed in polyethylene bags and refrigerated overnight. In order to determine the moisture content, samples were placed in an oven at 105°C until constant weight was achieved. Prior to extrusion, all samples were brought to room temperature.

Extrusion cooking

Samples were extruded in a co-rotating, twin screw extruder (Prism Eurolab, model KX-16HC, Staffordshire, UK). The screw dimensions were: length 40 cm, external diameter 16 mm, and internal diameter 11 mm. The die had 3 mm diameter and 17.5 mm length. The extruder had five temperature control zones and the temperature of each zone was increased evenly from room to die temperature. Extrudates were produced under three extrusion die temperatures (140°C, 160°C and 180°C) and three screw speed levels (150 rpm, 200 rpm and 250 rpm). The average value of feed rate was 0.99 g/sec. Following the extrusion the samples were cooled to room temperature, dried in air at ambient conditions for 8 h, and then stored in laminated bags until required for analysis. Raw materials characteristics and extrusion conditions are depicted in Table 1.

Experimental design

Central composite design (CCD) was selected as the most suitable experimental design (Table 1). The material characteristics and the extrusion conditions were independent variables for the production of extrudates and varied over three levels as shown in Table 1. The CCD required one control sample (I2022) and 26 independent experiments, which were repeated in triplicates.

Functional properties

The water absorption index (WAI) was determined following the method of Anderson *et al*. (1970): distilled water (5 mL) was added to ground sample (0.2 g) in a weighed 15 mL glass centrifuge tube. The tube was agitated on a Vortex mixer for 2 min, and then centrifuged for 20 min at 3,000 rpm. The supernatant liquid was poured into a tared evaporating dish. The remaining gel was weighed, and the WAI was calculated using Equation 1:

Table 1. Experimental design for the production of extrudates (CCD), coding of extruded samples and reference conditions.

Raw material	Coding	Moisture content X (% w/w)	Inulin concentration C (%)	Extrusion temperature T (°C)	Screw speed R (rpm)
Rice flour / Inulin	I3311	20	15	140	150
	I3313	20	15	140	250
	I3111	20	5	140	150
	I3113	20	5	140	250
	I2212	17	10	140	200
	I1311	14	15	140	150
	I1313	14	15	140	250
	I1113	14	5	140	250
	I1111	14	5	140	150
	I3222	20	10	160	200
	I2322	17	15	160	200
	I2222	17	10	160	200
	I2222	17	10	160	200
	I2223	17	10	160	250
	I2221	17	10	160	150
	I2122	17	5	160	200
	I1222	14	10	160	200
	I3333	20	15	180	250
	I3331	20	15	180	150
	I3131	20	5	180	150
	I3133	20	5	180	250
	I2232	17	10	180	200
	I1333	14	15	180	250
	I1331	14	15	180	150
	I1131	14	5	180	150
	I1133	14	5	180	250
Control	I2022	17	0	160	200
Independent variable		Level		Reference conditions	
Moisture content (% w/w), X	14	17	20	Xo	17
Inulin (%), C	5	10	15	Co	10
Die temperature (ºC), T	140	160	180	To	160
Screw speed (rpm), R	150	200	250	Ro	200
Coding	1	2	3		

$$WAI = m_g/m_s \quad \text{(Equation 1)}$$

where m_g = weight of the hydrated gel (g), and m^s = weight of the sample (g).

The water solubility index (WSI) was determined following the method of Toyokawa *et al*. (1989) from the amount of dry solids recovered by evaporating the supernatant from the water absorption test using Equation 2:

$$WSI = (m_{ds}/m_s)\ 100 \quad \text{(Equation 2)}$$

where m_{ds} = weight of dry solids from the supernatant (g), and m_s = weight of the sample (g).

According to the method of Liadakis *et al*. (1993), the oil absorption index (OAI) was estimated: refined corn oil (3 mL) was added to the ground sample (0.5 g) in a graduated 15 mL glass centrifuge tube. The tube was agitated on a Vortex mixer for 1 min, left for 30 min and centrifuged for 20 min at 3,000 rpm. The experiments were performed in four replicates. OAI was calculated using Equation 3:

$$OAI = V_{oil}/m_s \quad \text{(Equation 3)}$$

where V_{oil} = volume of absorbed oil (mL), and m_s = weight of the sample (g).

Colour change

The variations of colour were determined using a colorimeter, MiniScan XE (Hunter Associates Laboratory Inc, Reston, Virginia), that had a diaphragm measurement head of 4 mm. Four replicates of each extrudate were measured, in order to calculate the L^*, a^*, and b^* values, which are the colour coordinates of the CIELab system. The colour difference (ΔE) was calculated using Equation 4:

$$\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2} \qquad \text{(Equation 4)}$$

where ΔE = colour deference, ΔL, Δa and Δb = changes of L^*, a^* and b^* values, respectively, between each sample and the control (Siddiq *et al*., 2013).

Sensory evaluation

Ten trained panellists participated in the descriptive analysis of the extruded snacks, while overall acceptability was performed by forty untrained panellists. Panellists were asked to evaluate the extruded snacks regarding their appearance, porosity, diameter, crispness, hardness, crunchiness and overall preference (Dijksterhuis *et al*., 2007). A 9-point score scale was used (1: extremely dislike to 9: extremely like), with the exception of colour characteristics, in which 1 referred to dark and 9 referred to light colour. The samples were presented monadically and in a random sequence as pieces, 4 cm in length, in three-digit coded dishes. Panellists rinsed their palates with water in between samples (Waje *et al*., 2009).

Sorption characteristics

In order to evaluate the sorption isotherms, the extrudates were ground to powder. The extruded powdered samples were dehydrated in a desiccator containing phosphorous pentoxide for 3 w and then equilibrated over five saturated salt solutions (LiCl, MgCl2, Mg(NO3)2, NaCl, and KNO3) until constant weight (approximately 3 w). The water activity (aw) levels of the above salt solutions were 0.11, 0.33, 0.53, 075 and 0.94, respectively. At high aw, phenol was added in order to ensure that no mould growth occurred. The equilibrium moisture content was determined at 70°C under vacuum (AOAC, 1990). The equilibration was conducted in three replicates.

Differential scanning calorimetry (DSC)

Calorimetric measurements were performed on the powdered samples using a Perkin-Elmer differential scanning calorimeter (DSC 6, Perkin Elmer Inc., Waltham, Massachusetts, USA), and a Pyris software for Windows. The equipment utilised nitrogen as purge gas with a flow rate of 20 mL/min. The powdered extruded samples were equilibrated over constant aw (0.11, 0.53 and 0.94), as described above. Approximately, 10 mg of each sample were hermetically sealed in aluminium pans (50 µL, Perkin–Elmer) with the use of a proper wringer, and placed into the DSC chamber. Samples were cooled from room temperature to −15°C, heated from −15°C to 150°C, with a rate of 5°C/min, and then cooled to room temperature at a rate of 5°C/min (Oikonomopoulou *et al*., 2011). In the thermographs, the onset, midpoint and endpoint of the shift in heat capacity were determined. All experiments were performed in triplicate.

Mathematical modelling

Equation 5 was the selected mathematical model that contained parameters with physical meaning:

$$M_i = M_0 * \left(\frac{X}{X_0}\right)^{a_X} * \left(\frac{100-C}{100-C_0}\right)^{a_C} * \left(\frac{T}{T_0}\right)^{a_T} * \left(\frac{R}{R_0}\right)^{a_R} \qquad \text{(Equation 5)}$$

where M_i = value of each property (WAI, WSI, OAI, colour), M_o = average value of each property, X = moisture content (%w/w), C = inulin concentration (%), T = extrusion temperature (°C), R = screw speed (rpm), X_o, C_o, T_o, R_o = reference conditions of X, C, T, R (Table 1).

For the estimation of the model parameters, regression analysis was performed, using Statistica Software (Statistica Release 7, Statsoft Inc, Tulsa, OK, USA). The GAB model used is presented in Equation 6:

$$X = \frac{X_m * C * K * a_w}{(1 - K * a_w) * (1 - K * a_w + C * K * a_w)} \qquad \text{(Equation 6)}$$

where X = moisture content (d.b.), a_w = water activity, X_m, K, C = sorption parameters characterising the sorption properties of the material.

Statistical analysis

The sensorial characteristics were first evaluated for homogeneity of variances by Levene's test and Kolmogorov-Smirnov for normality. Univariate Analysis of Variances (ANOVA) was used to detect the significant differences among process conditions and material characteristics, namely moisture content, inulin concentration, extrusion temperature and screw speed. All analyses were computed with the SPSS for Windows software (SPSS 16.0, SPSS Inc, Chicago, Ill.) at a significance level of α = 0.05.

Results and discussion

Water Absorption Index

According to the results obtained through the regression analysis, the selected power model fitted the experimental data, and the model parameters are presented in Table 2. Figure 1 shows that the water absorption index (WAI) of the extruded products increased with increasing extrusion temperature, as heat treatment occurring during extrusion breaks down amylopectin and allows starch gelatinisation (Sacchetti *et al*., 2004; Siddiq *et al*., 2013). At 20% moisture content, WAI increased to 6.33 g/g sample (Figure 1). The increase of WAI with moisture content could also be verified by the results of Lin *et al*. (2002), where products from soy flour appeared to have increased WAI when produced at high moisture content. Ning and Vilota (2012) also found that WAI was directly affected by the porosity of the extrudates, which was a result of increased moisture content in the initial mixture. On the other hand, WAI decreased with inulin content resulting in 5.99 g/g sample for 15% inulin content. The increase of inulin content in the extrudates corresponded to a decrease in WAI, which could probably be due to a reduced starch content, which meant less starch was available for gelatinisation during extrusion and subsequently absorbed water (Obradović *et al*., 2014; Vargas-Solórzano *et al*., 2014). The screw speed caused an increase in WAI which could be attributed to the reduction of dough viscosity and the increment of its elasticity. This could lead to the gelatinisation of starch which in turn would increase the porosity of the extrudates (Bisharat *et al*., 2013), leading to increased WAI.

Water Solubility Index

The water solubility index (WSI) results are also presented in Figure 1. When the extrusion temperature was increased from 140 to 180°C, the WSI of the extrudates increased to 32.55 g/100 g sample, which was also observed for starch based extrudates in a previous study (Chauhan and Bains, 1988; Ding *et al*., 2006). This could be due to starch degradation at higher temperature inside the extruder and greater shearing action of the blend. Anderson *et al*. (1970) reported that this change could be attributed to the amount of free polysaccharides released from the starch granules after addition of water. The increase of moisture content increases the plasticisation of the starch and therefore causes a decrease in water solubility (Chang and Ng, 2011), leading to a WSI of 26.59 g/100 g sample at 20% moisture content. When the percentage of water increases, the flour percentage in the mixture decreases leading to the reduction in amylose content and therefore lower water solubility (Chinnaswamy and Hanna, 1990).

Table 2: Mathematical model parameters of the examined properties, as well as GAB model parameters.

Properties (M_i)	Mathematical model parameters					R_2
	M_0	α_X	α_C	α_T	α_R	
WAI	5.849±0.06	0.383±0.07	1.480±0.22	0.957±0.10	0.257±0.05	0.828
WSI	27.169±0.35	-0.799±0.08	1.293±0.25	1.727±0.12	0.243±0.05	0.897
OAI	0.760±0.01	-0.658±0.09	1.371±0.29	0.774±0.12	0.074±0.01	0.803
ΔE	7.085±0.24	-2.322±0.20	5.105±0.65	1.000±0.27	0.182±0.06	0.846

Feed and extrusion conditions				GAB model parameters			
*X (% g*g⁻¹)*	*C (%)*	*T (°C)*	*R (rpm)*	X_m ($g*g^{-1}$)	*C*	*K*	R^2
14	10	160	200	0.0546	99.675	0.8069	0.997
17	10	160	200	0.0683	39.981	0.7878	0.999
20	10	160	200	0.0700	45.377	0.7807	0.996
17	5	160	200	0.0792	20.404	0.7402	1.000
17	10	160	200	0.0683	39.798	0.7876	1.000
17	15	160	200	0.0644	64.600	0.7867	1.000
17	10	140	200	0.0694	68.984	07958	0.997
17	10	160	200	0.0683	39.798	0.7876	1.000
17	10	180	200	0.0651	39.935	0.8044	1.000
17	10	160	150	0.0667	47.050	0.7898	1.000
17	10	160	200	0.0683	39.801	0.7876	1.000
17	10	160	250	0.0636	54.938	0.8034	1.000

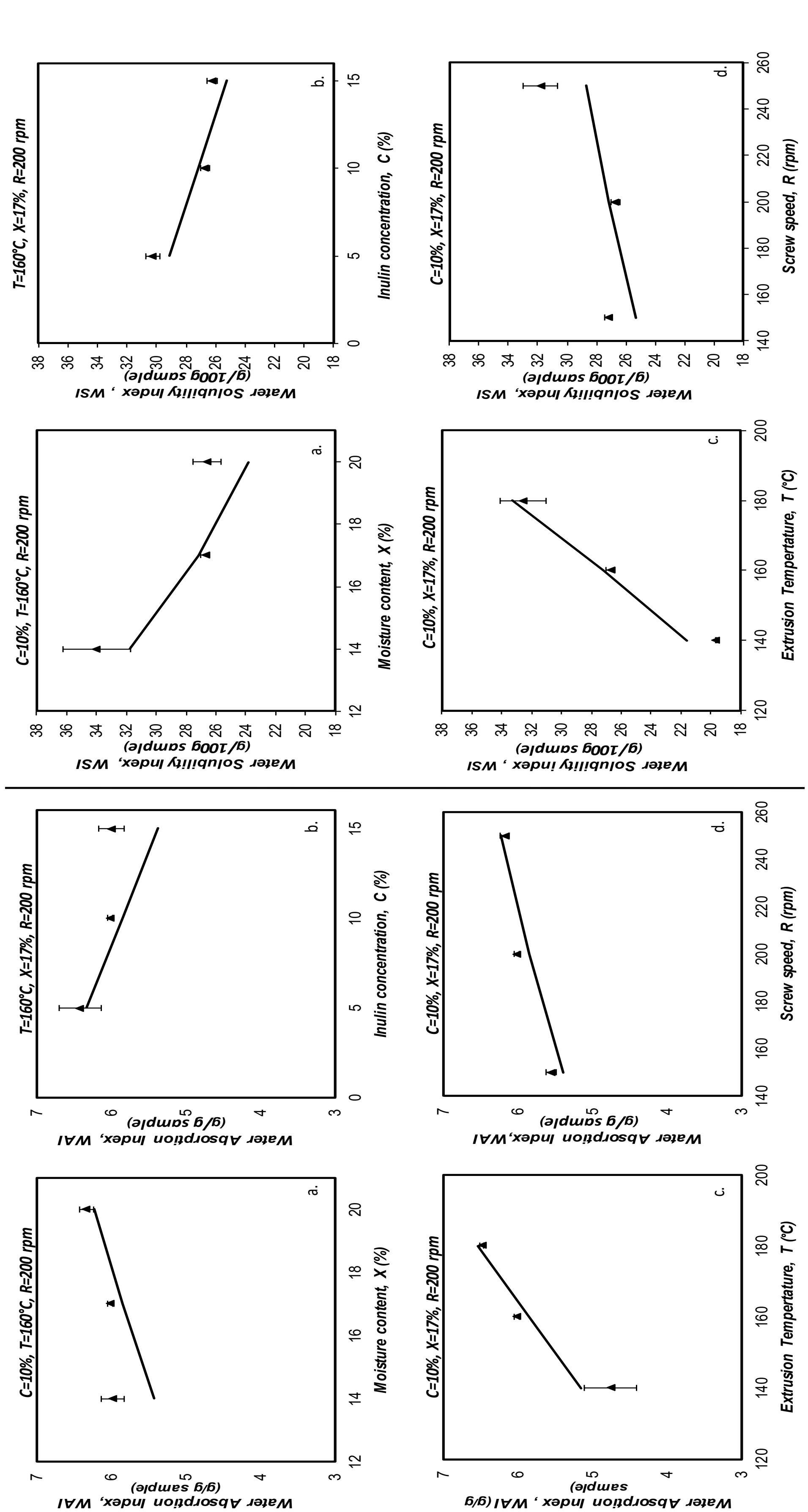

Figure 1. Effect of production conditions on the A) WAI and B) WSI of the extruded products.

Moreover, WSI decreased with the concentration of inulin in the feed mixture. Inulin is 95-100% soluble, while rice is primarily composed of insoluble fibres. White rice consists of 0.6% fibres (FAO, 2004). When the concentration of inulin is increased, the fibre content of the product also increases and their solubility decreases during extrusion because of heat treatment. This results in structural changes which allow the hydrophilic groups such as -OH,-NH2,-COOH and -SH to form connections (bridges) with starch (Fernandez-Gutierrez *et al*., 2004). Therefore, the addition of soluble fibres in extruded products in this case caused a reduction of WSI. The increase of screw speed to 250 rpm caused a decrease in the residence time in the extruder resulting in an increase in WSI at 31.81 g/100 g sample. The extruded melt under high screw speed is subjected to greater shear forces which cause higher molecular degradation.

Oil Absorption Index

Figure 2A shows that the oil absorption index (OAI) of the extruded products decreased with moisture and inulin content, while it increased with extrusion temperature and screw speed. The increase in extrusion temperature raised the level of cooking of the extruded food products (Drago *et al*., 2007) leading to the formation of smaller molecules due to the dextrinisation of the starch, which might be responsible for the increase in OAI. When the moisture content was decreased, oil molecules appeared to be more accessible to the extrudate structure, as there was a higher protein and starch content in the mixture (Lee *et al*., 2006), and the extrudates appeared to have less hard cell walls attracting more oil molecules. It is also noticed in the present work that an increased OAI was connected with high porosity extrudates, which in turn was connected with low protein and fibre content. The rupture of cell walls and the absence of the expansion of air bubbles during extrusion were the main causes of the low porosity of the final products (Bisharat *et al*., 2013), leading to low OAI. Therefore, the increase in the inulin content in the mixture of the extrudate caused the reduction in the OAI. The increase in screw speed seems to have small effect on the OAI. The slight decrease observed could be attributed to the reduction of the degree of starch dextrinisation, as the average residence time of the material in the extruder decreased when the screw speed was decreased.

Colour change

Figure 2B illustrates the colour changes (ΔE) of food extrudates, which could be related to Maillard reactions and caramelisation which occur when foods containing amino-compounds and reduced sugars are heat-treated (Wang and Ryu, 2013), as temperature is the major parameter affecting non-enzymatic browning. As shown in Figure 2B, the colour change increased with temperature, as also found by other researchers (Milán-Carrillo *et al*., 2002; Wang and Ryu, 2013), and darker extrudates appeared when die temperature was set to 180°C. When moisture content increased, the ΔE decreased. The caramelisation that takes place is believed to be affected by the water content and the degradation of the starch because of the shear stress that is exerted (Ma *et al*., 2012). In particular, the highest ΔE was observed for 14% moisture content which was 12.59. Furthermore, when moisture content was increased, the protein content was lowered, as it was replaced by water, leading to a decrease in ΔE, as also reported elsewhere (Amaya-Llano *et al*., 2007). Regarding inulin concentration, the increase in inulin concentration led to a reduction of ΔE, which could be attributed to the increase in the fibre content (Wang and Ryu, 2013). On the other hand, screw speed did not seem to significantly affect the ΔE, as also found by Yuliani *et al*. (2006).

Sensory evaluation

The statistical analysis results for sensory characteristics through ANOVA indicated that overall panel performance was consistent when evaluating all parameters of the extruded inulin enriched snacks. Processing parameters seemed to have a significant effect on sensorial characteristics, apart from screw speed and extrusion temperature that did not significantly influence the porosity and crispness, respectively.

As seen in Figure 3A, porosity seemed to decrease when both inulin concentration and moisture content were increased, while it increased with extrusion temperature. These results are in accordance with the results published by the authors concerning apparent density (Tsokolar-Tsikopoulos *et al*., 2015). When increasing moisture content of rice extrudates, the molecular structure of amylopectin is expected to change and, therefore, the viscosity of the mixture is reduced. Increased moisture also causes a reduction to friction between the dough and the screws while it negatively affects starch gelatinisation (Liu *et al*., 2000). On the other hand, higher temperature lowers dough's viscosity in the extruder die (Yagci and Gogus, 2008) resulting in lower bulk density and higher porosity of the extrudates (Altan *et al*., 2008). The presence of fibres also reduces the elasticity and plasticity of the dough (Yagci and Gogus, 2008) leading to a decrease of porosity since fibre particles tend to rupture the cell walls, before the gas bubbles

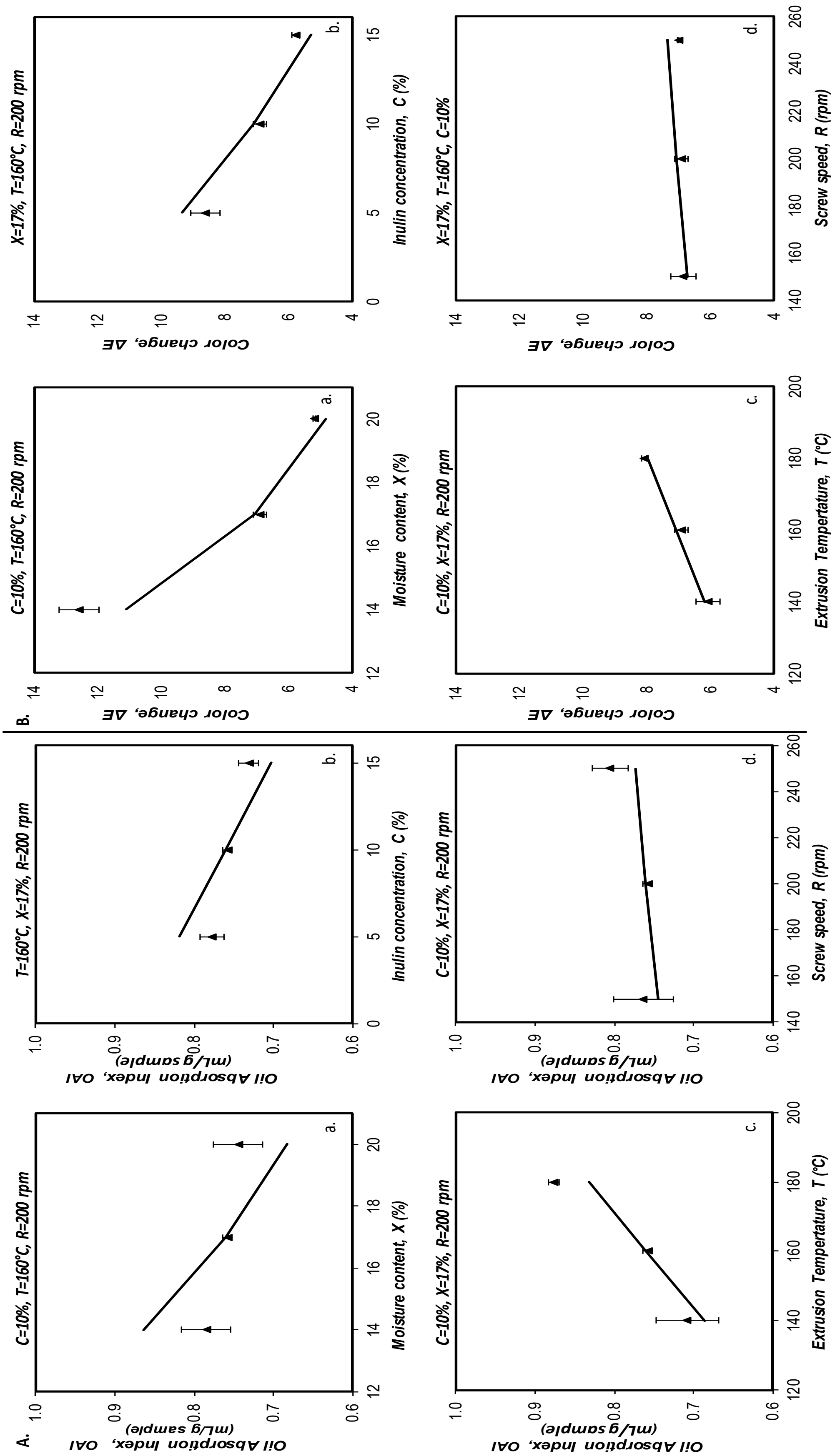

Figure 2. Effect of production conditions on the A) OAI and B) on the colour change of the extruded products.

expand to their full potential (Altan *et al*., 2008). The screw speed seemed not to have a significant effect on the porosity, which is also reported by Jain *et al*. (2013) who investigated rice/maize based extrudates with the addition of tomato or banana.

Higher inulin concentration leads to high fibre content in the mixture, leading to the formation of a complex wall that restricts the extrudates' expansion (Chang *et al*., 1998). This effect was also found by Brennan *et al*. (2008) reporting that the addition of inulin to breakfast cereal products, at concentrations of 5, 10 and 15%, led to a decrease in expansion. At higher screw speeds, a rise in expansion was noticed in accordance with the study of Jain *et al*. (2013), concerning extrudates enriched with banana, as well as corn meal extrudates enriched with soy fibre (Jin *et al*., 1994). Die temperature reduces the expansion ratio, since the sudden drop from high die to ambient temperature increase the plasticisation of the melt (Brümmer *et al*., 2002), causing a reduction in dough elasticity (Jain *et al*., 2013). Moisture content could be considered as a limiting factor for expansion affecting the texture of extruded food products, as reported by Brennan *et al*. (2008).

The hardness of extruded product is associated with expansion and cell structure of the product (Wani and Kumar, 2016). Feed moisture content significantly increased the hardness of the extrudates (Ding *et al*., 2006), which could be attributed to the reduced expansion caused by the high moisture content. On the other hand, screw speed and temperature had a negative effect on extrudate hardness, as also reported by Brnčić *et al*. (2006). Specifically, an increase in temperature is linked with increment of porosity as indicated above, which results in soft texture, leading to low hardness of the

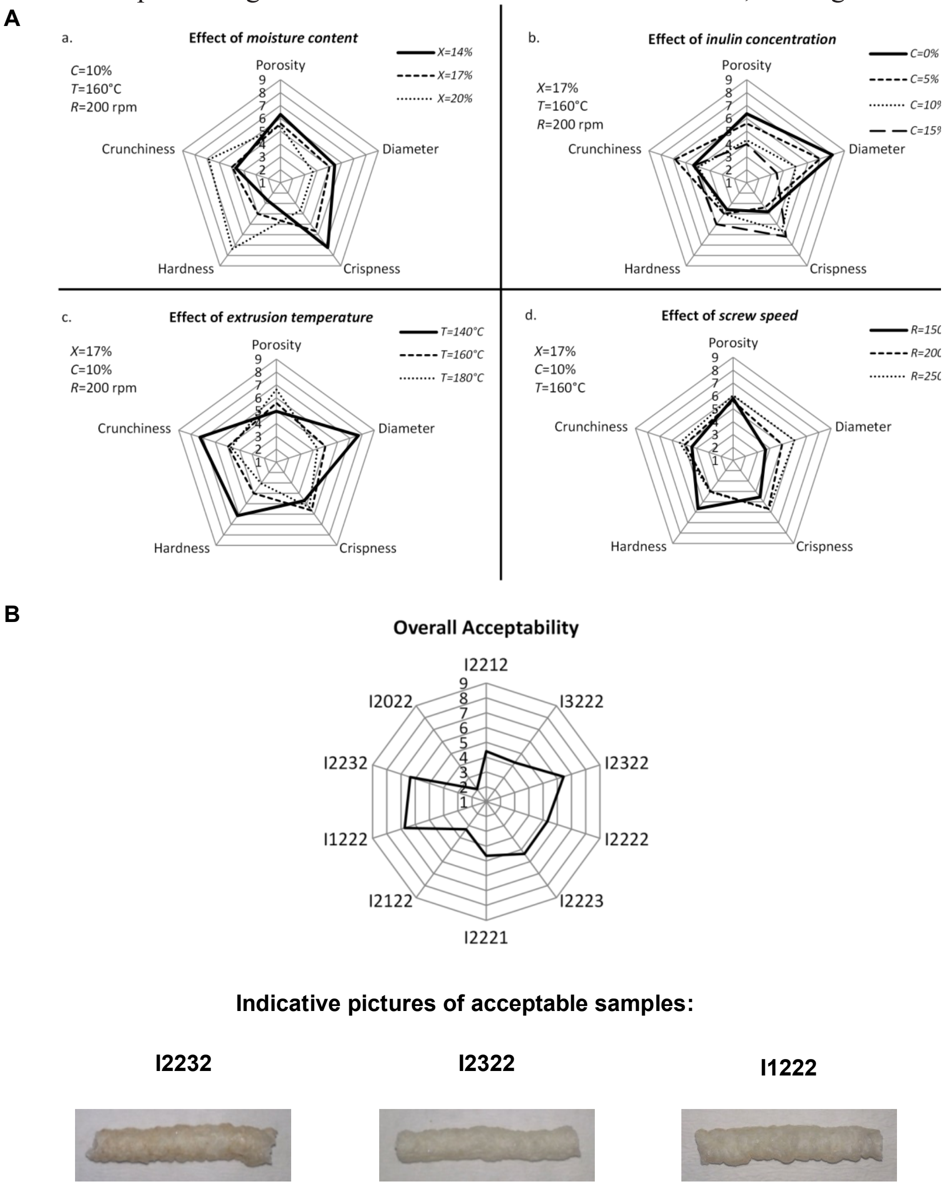

Figure 3. A) Effect of production conditions on sensory estimated porosity, diameter, hardness, crispness and crunchiness and B) Overall preference of extruded products.

extrudates (Singh *et al*., 2012; Gui *et al*., 2013). The addition of inulin caused a decrease in hardness of the extrudates, as fibre concentration increased, as also found elsewhere (Brennan *et al*., 2008).

The feed moisture content significantly decreased the crispness of the products, since the increase in moisture led to the production of dense extrudates with reduced expansion (Ding *et al*., 2006). In addition, extrusion temperature did not significantly influence crispness ($p > 0.05$). When temperature is increased, the viscosity of the mixture decreases, favouring bubble growth and leading to low density products with small and thin cells, thus resulting in higher crispness (Ding *et al*., 2006). Inulin addition also increased the crispiness of the products with 15% inulin enriched extrudates yielded the highest value (Brennan *et al*., 2008), similarly with screw speed which also caused an increase in crispness.

Based on the results of overall acceptability (Figure 3B), the acceptable rice-based extruded products were I2232, I2322 and I1222, with a score over 6 (Waje *et al*., 2009). The highest scores were given to products produced under 14% feed moisture content. A 10-15% addition of inulin might be selected to obtain extruded snacks rich in dietary fibres with good quality and sensorial characteristics (Makowska *et al*., 2013). Extrusion temperature highly affected the sensory characteristics and, in particular, higher acceptability was noticed when extrusion took place at 180°C (Milani *et al*., 2014).

Water Sorption Isotherms

Water sorption isotherms are presented in Figure 4A as a function of process conditions and materials characteristics which present a typical sigmoidal curve. The GAB model (Equation 6) was selected to fit the experimental data, as it is considered the most versatile isotherm (Bisharat *et al*., 2014). The equilibrium moisture content of the extrudates is very important as it is indicative for the determination of storage conditions and products stability. The parameters of the GAB model, X_m, C and K are presented in Table 2, as obtained by the regression analysis.

The parameters of the GAB model have physical significance. The larger the Guggenheim constant (C) is, the stronger the water is bound to the monolayer, and the larger the difference in enthalpy is between the monolayer and multilayer molecules (Quirijns *et al*., 2005). This explains the increase of C with inulin concentration, as inulin is hydrophilic, as well as the decrease with extrusion temperature. K increases with inulin concentration and decreases with moisture content. When K is close to 1, there is almost no distinction between the multilayer molecules and water molecules. The more structured molecules are adsorbed in the multilayer, the lower is the value of K (Quirijns *et al*., 2005). K values in the present work averaged at about 0.78 while C values varied from 20.4 to 99.7. Therefore, the monolayer has different properties than the multilayered with the multilayer behaving similarly to the bulk water ($C >> 1$ and $K \approx 1$) (Timmermann *et al*., 2001).

When moisture content and extrusion temperature were increased, the monolayer moisture increased. This is driven by the fact that at increased moisture content a higher value of X_m is obtained. The increment of X_m at low temperatures presents more sorption available sites for water molecules, which could be attributed to physical or chemical changes induced during cooking (Quirijns *et al*., 2005). It is known that below X_m, the food does not deteriorate since water is strongly bound to it and is not involved in any deteriorative reaction (Shankar *et al*., 2009).

Glass transition temperature

Figure 4B presents the change of the glass transition temperature (T_g) of extrudates enriched with inulin, as a function of processing conditions for three levels of water activity (aw: 0.11, 0.53 and 0.94). T_g is indicative of the temperature range in which the food has desirable properties for consumption and storage, since above T_g the mobility of the molecules is greater and causes accelerated deterioration reactions (Oikonomopoulou *et al*., 2011; Ma *et al*., 2012). In Figure 4Ba, a reduction of T_g when moisture content was increased is shown. This is expected as water acts as a plasticiser (Perdomo *et al*., 2009). The addition of inulin increased the fibre content, which reinforced the matrix of the extrudates and forms harder and more constant structures and textures (Anton *et al*., 2009). The changes in microstructure due to the changes in composition influence the molecular motions and, thus, T_g of the extrudates increased with inulin concentration. T_g decreased when extrusion temperature was decreased, since high temperature leads to increased molecular degradation of the food (Raphaelides *et al*., 2012). Finally, by increasing the screw speed the mechanical stress also increased, resulting in a molecular degradation and a decrease of T_g. In addition, it has been reported that lower T_g was recorded at higher expansion ratio (Yadav *et al*., 2014) which was achieved by increased screw speed.

Conclusion

Rice-based extrudates enriched with inulin were evaluated for their colour and their functional,

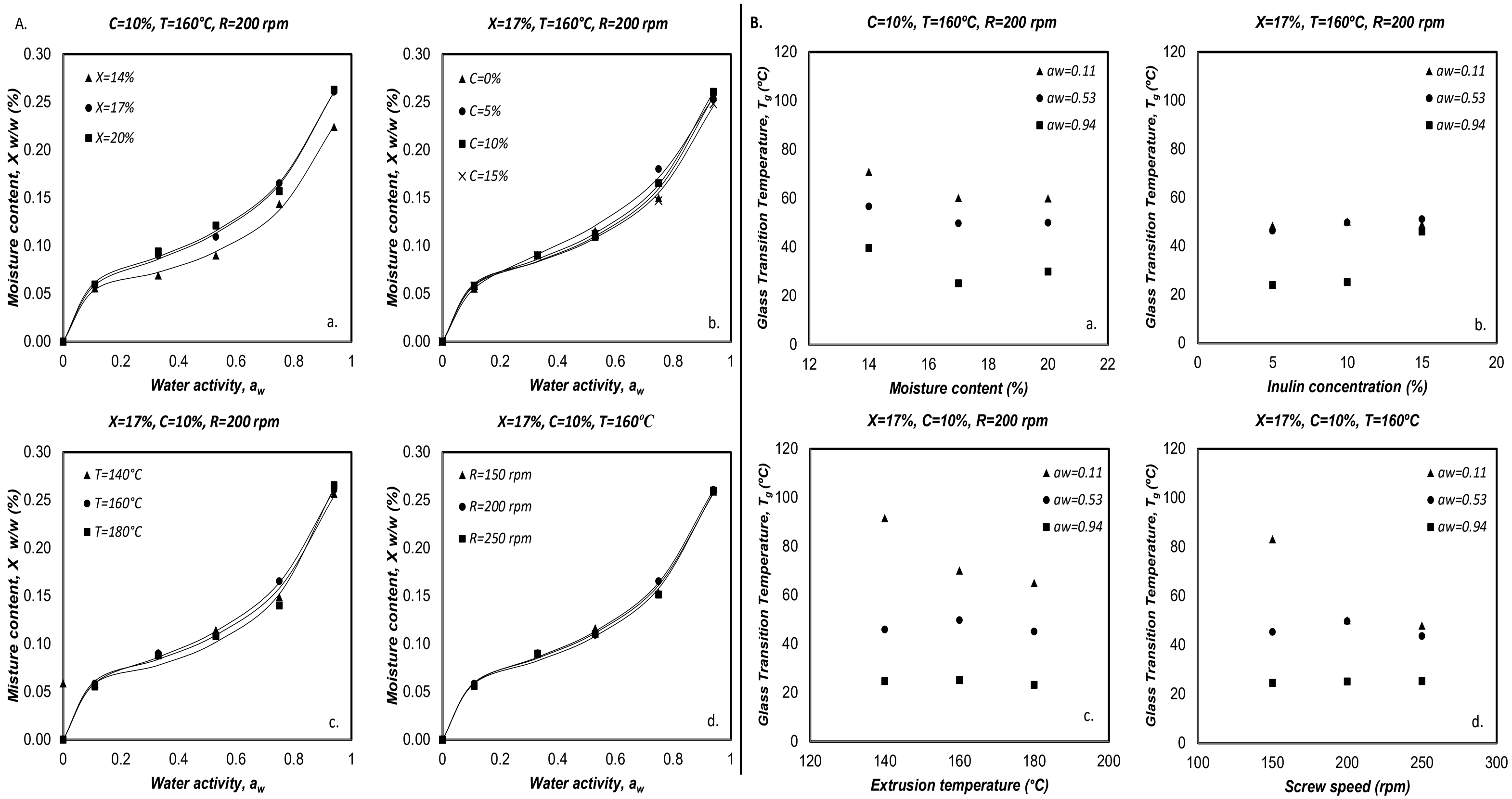

Figure 4. A) Effect of production conditions on the water sorption isotherms (25°C), B) Effect of production conditions in correlation with aw on the Tg of the extruded products.

thermal and sensory properties. It was found that WAI decreased with inulin concentration and increased with moisture content, die temperature and screw speed. WSI reached its highest value of 33.99 g/100 g sample when extrudates were produced under 14% moisture content, 10% inulin concentration, 160°C die temperature and 200 rpm screw speed. Similar to WSI, OAI increased when extrusion temperature and screw speed were increased. The increment of moisture content and inulin concentration led to the decrement in colour change. Colour change was primarily affected by water content, leading to a 12.59 colour change for 14% moisture in the initial mixture. Sensory evaluation also confirmed that the optimal production conditions were feed moisture 14%, inulin concentration 10-15%, 180°C extrusion temperature and 200 rpm screw speed. The GAB model was applied to sorption results of the extrudates, and the GAB parameters were found to be dependent on the process conditions and materials characteristics. Finally, T_g seemed to increase with inulin concentration while decreased with the other process conditions.

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