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The impact of extrusion parameters on physicochemical, nutritional and sensorial properties of expanded snacks from pea and oat fractions

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ABSTRACT

The objective of this study was to explore the production of an expanded snack entirely based on pea- and oat-rich fractions using the extrusion technology. The effect of the die temperature, HZ6 (146–175 °C) and blend moisture content, MC (11.2 and 16.8% dry basis) were investigated aiming at maximizing expansion, while obtaining a good texture and pleasant sensory perception. The best response was obtained with a HZ6 of 160 °C and MC of 11.2%. MC was the parameter that most influenced final extrudate properties/responses. The gross composition of the raw-material was not modified by extrusion processing apart from a decrease in glucose and fructose content attributed to Maillard reactions. The snacks contained 3.5 g of β-glucan per portion. This is high enough for both approved EFSA health claims: lowers cholesterol and reduces post-prandial glucose response.

1. Introduction

A healthy vegetarian diet needs appropriate food choices to provide a balanced amino acid composition and sufficient micronutrients such as iodine, zinc, selenium and vitamin B12 (Sobiecki, Appleby, Bradbury, & Key, 2016). Connected to this, the combination of cereals and pulses play an important role (Pathak & Kochhar, 2018).

Pulses have a high content in fiber and protein and a low fat content (Patil, Brennan, Mason, & Brennan, 2016). Furthermore, pulses are abundant in minerals and vitamins and a very good sources of carbohydrates for slow digestion and assimilation (Arribas et al., 2017). Pea (*Pisum sativum*), like other pulses is highly nutritious and rather inexpensive. It is rich in soluble (10–15% db) and insoluble fiber (2–9% db), protein (19–25% db) and the amino acids tryptophan (≈0.28% db) and lysine (≈1.8% db) (Tiwari & Singh, 2012). Moreover, peas are an exceptional source of complex carbohydrates (60–64% db), low in sodium and fat (0.80–1.5% db), and contain higher amounts of B vitamins, folate and minerals such as calcium, iron and potassium (Tiwari & Singh, 2012). Food habits containing peas have been shown to mitigate colon cancer, type-2 diabetes, LDL-cholesterol and cardiovascular diseases (Sánchez-Chino, Jiménez-Martínez, Dávila-Ortiz, Álvarez-González, & Madrigal-Bujaidar, 2015).

Oat (*Avena sativa*) is special among cereals due to its higher content of protein, unsaturated fatty acids, soluble fiber (β-glucan) and antioxidants (Lásztity, 1998). Moreover, health claims of oat β-glucan both in the US and Europe have been gaining a great interest owed to its cholesterol-lowering effects (EFSA, 2009; Pomeroy, Tupper, Cehun-Aders, & Nestel, 2001) and glycemic control (EFSA, 2011; Mäkinen, Sozer, Ercili-Cura, & Poutanen, 2017; Sayanjali et al., 2017). Even though pulses and cereals lack some essential amino acids, foods produced with mixtures of both can provide a high value and balanced diet (Arribas et al., 2017). Nevertheless, the consumers don't normally recognize the nutritional value of legumes somewhat due to long cooking and soaking procedures required. Therefore, the introduction of new products, such as, ready-to-eat snacks seems to be good candidates to overcome this issue.

Snacks normally existing on the market are mostly based on corn or rice starch with low nutritional quality due to their high energy density and poorness in nutrients. Therefore, pea and oat ingredients seems to be perfect candidates to produce healthier snacks, high in fiber and with an interesting nutrient profile (Alam, Kaur, Khaira, & Gupta, 2016; Kristiawan et al., 2018; Meng, Threinen, Hansen, & Driedger, 2010; Susan Arntfield, 2015).

A well-known technique capable to produce a wide variety of food products is extrusion cooking. During this process, covalent bonds are broken and physical structures of macromolecules are disrupted due to the high temperature, pressure and mechanical forces, changing their functional properties (Philipp, Oey, Silcock, Beck, & Buckow, 2017;

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Abbreviations

a*	Redness
b*	Yellowness
BD	Bulk density
CCRD	Central Composite Rotatable Design
C	Crispiness
CF	Crushing force
DL	Drive load
DSC	Differential Scanning Calorimetry
H	Hardness
HZ6	Die temperature
L*	Lightness
LEI	Longitudinal expansion index
LMW CHO	Low-molecular weight carbohydrates
MC	Blend moisture content
NSP	Non-starch polysaccharides
OF	Oat fiber
P	Pressure
PP	Pea protein
PS	Pea starch
RSM	Response Surface Methodology
SEI	Sectional expansion index
SM	Supplementary Materials
SME	Specific Mechanical Energy
T	Toughness
TP	Throughput
V	Velocity
VEI	Volumetric expansion index

Sayanjali et al., 2017). The raw ingredients are forced to flow along the barrel transported by the screw(s) with increasing pressure and shear, causing the formation of vapor when it passes through a die at atmospheric pressure. This phenomenon leads to the expansion of the melt. After cooling, extrudates are characterized by their crispness and roasted taste (Alam et al., 2016).

With respect to snack foods, the consumer acceptance depend on the nutritional value, convenience, appearance and texture (Anton, Gary Fulcher, & Arntfield, 2009). Some attempts to improve the nutritional profile of corn- and rice-based snacks have been made (Anton et al., 2009; Arribas et al., 2017; Brennan, Derbyshire, Tiwari, & Brennan, 2013; Byars & Singh, 2015; Koksel & Masatcioglu, 2018; Korkerd, Wanlapa, Puttanlek, Uttapap, & Rungsardthong, 2016; Meng et al., 2010; Patil et al., 2016; Philipp, Emin, Buckow, Silcock, & Oey, 2018; Rathod & Annapure, 2016; Susan Arntfield, 2015). On the other hand, the replacement of starch by fiber and/or protein has been shown to significantly affect expansion, texture and the general acceptability of snacks (Korkerd et al., 2016; Philipp et al., 2018). Normally the incorporation of dietary fiber and protein into extruded snacks limits expansion and reduces crispiness (Beck et al., 2018; Day & Swanson, 2013; Lobato, Anibal, Lazaretti, & Grossmann, 2011). However, there is no information available concerning the impact of extrusion parameters on pea and oat-rich fractions to produce expanded healthy snacks. Liu, Hsieh, Heymann, & Huff, 2000 stated that decreasing moisture content and increased product temperature was highly correlated with attributes of an expanded product during extrusion of corn and oat starch based extrudates (Liu et al., 2000). Moreover, Wani & Kumar, 2016a reported that product responses were significantly affected by blend moisture content, die temperature and screw rotation speed, while extrusion of pea and oat flours (Wani & Kumar, 2016a). However, the existing studies containing blend of pea and oat ingredients are based on milled flours and not enriched-fractions (Jacques-Fajardo et al., 2017; Sajad Ahmad Wani & Kumar, 2016a). Therefore, the goal of this study was to explore the impact of extruder process parameters such as die temperature and blend moisture content on snack quality using pea- and oat-rich fractions enriched in starch, protein and fiber. The physicochemical, textural and sensorial properties of produced snacks were assessed.

2. Materials and methods

2.1. Materials

Commercial pea starch and pea protein was kindly provided by AMNutrition (Stavanger, Norway). Commercial oat fiber *Sweoat bran BG28* (OF) was purchased from Naturex (Bua, Sweden). Proximate compositions of ingredients can be found on the Supplementary Materials (SM). Chemicals and materials were bought from regular suppliers and are of analytical grade.

2.2. Preparation of raw-material blend formulation prior to extrusion processing

The raw-material prior to the extrusion process was prepared by adding pea starch (PS), oat fiber (OF) and pea protein (PP) in a closed container. The closed container was mixed and shake to ensure a homogeneous distribution of the ingredients. The final formulation (50% w/w PS, 40% w/w OF and 10% OF w/w) were established based on preliminary trials (data not shown). The blended raw-materials were let to equilibrate at least 12 h (room temperature) before the extruder operation.

2.3. Extrusion processing – experimental design

The production of expanded extrudates (healthy snacks) based on the pea and oat ingredients were investigated using Response Surface Methodology (RSM). The extrusion technology was conducted using a Central Composite Rotatable Design (CCRD), varying two factors: die temperature (HZ6) and blend moisture content (MC). Eleven experiments were performed: four factorial points, four-star points and three centre points. The HZ6 varied from 146 to 175 °C and the moisture content from 11.2 to 16.8% db, following the experimental design presented in Table 1. The ranges were chosen based on preliminary trials (data not shown) and studies conducted with similar raw-

Table 1
Operating conditions, their levels and measured dependent process variables.

Samples	Process conditions		Measured variables			
	HZ6 (°C)	MC (%)	SME (Wh/Kg)	P (bar)	DL (%)	TP (Kg/s) $*10^{-3}$
HSNA-1	160(0)	16.8(+α)	88.1	98.6	22.4	1.63 ± 0.19
HSNA-2	160(0)	14.0(0)	110.7	147	26.9	1.60 ± 0.00
HSNA-3	160(0)	11.2(-α)	145.4	213	34.1	1.58 ± 0.02
HSNA-4	170(+1)	16.0(+1)	83.5	109	22.7	1.75 ± 0.02
HSNA-5	170(+1)	12.0(-1)	129.2	164	28.2	1.62 ± 0.08
HSNA 6	174.5(+α)	14.0(0)	93.1	128	24.4	1.70 ± 0.05
HSNA 7	145.9(-α)	14.0(0)	106.6	137	25.9	1.59 ± 0.07
HSNA 8	150(-1)	16.0(+1)	92.7	111	23.9	1.67 ± 0.00
HSNA 9	150(-1)	12.0(-1)	141.2	206	33.1	1.58 ± 0.02
HSNA-10	160(0)	14.0(0)	100.0	137	25.7	1.68 ± 0.04
HSNA-11	160(0)	14.0(0)	99.76	137	25.6	1.68 ± 0.05

HSNA-1 to HSNA-11 = samples corresponding to different extrusion processing conditions concerning die temperature and blend moisture content. HZ6 = die temperature. MC = blend moisture content. SME = specific mechanical energy. P = pressure. DL = drive load. TP = throughput.
Values of SME, P, DL, V, TP are mean of triplicates.

materials (Jacques-Fajardo et al., 2017; Philipp et al., 2018; Sajad Ahmad Wani & Kumar, 2016b). The raw-material blends were processed in a twin screw extruder (co-rotating KETSE 20/40 Brabender GmbH and Co. KG, Duisburg, Germany) containing a screw diameter of 2 cm and a length of 40 cm (L/D ratio of 20:1). The diameter of the die was kept constant (3 mm), as well as, the blend feed rate (0.68 kg/h). The four-barrel heating zones (HZ) were set at 30/70/90/135 °C, respectively by using electric heaters. The heating ring (HZ5) at the die adaptor was set at 135 °C and the die temperature (HZ6) was set according to the experimental design (Table 1). A liquid pump (model 530d) from Watson Marlow (Cornwall, UK) was used to set the moisture content of the raw-materials. The screw configuration (Fig. 1) and the temperature profile across the first five heating zones were kept constant. The extrudates were allowed to cool down and packed in plastic containers til further analysis.

2.4. Specific mechanical energy

The specific mechanical energy (SME) were determined for each extrusion condition using the following (Equation (1)):

$$SME = \frac{\left(\frac{N_{act}}{N_{max}} * \frac{Md_{act}}{100}\right) - \left(\frac{N_{act}}{N_{max}} * \frac{Md_{empty}}{100}\right)}{M} * P_{max} \quad (1)$$

The unit for SME is Wh/kg. With $N_{act,}$ the actual screw speed in rpm, N_{max}, the maximum screw speed in rpm, Md_{act}, the actual torque in %, Md_{empty}, the base torque in %, M, the mass flow rate in kg/h and P_{max}, the maximum power of gear motor in W. These variables were recorded during the extrusion. The mass flow rate was determined in triplicates, by weighing the amount of material collected per minute.

2.5. Characterization of extrudates

2.5.1. Bulk density and expansion indexes

The extrudates diameter was measured at ten different locations per extrudate and repeated on five samples. The expansion indexes (Sectional Expansion Index, Longitudinal Expansion Index and Volumetric Expansion Index) were calculated following Alvarez-Martinez, Kondury, & Harper (1988) and Horvat and Schuchmann (2013). Bulk density (g/cm^3) was determined at the same time as expansion indexes. Extrudates were cut to have a length of 3 cm and weighed, this experiment was repeated 5 times. The method used was adapted from Arntfield (2015). The bulk density was expressed as the average of 5 measurements.

2.5.2. Image analysis of extrudates - porosity

The digital images were processed to determine the microstructure characteristics of the extrudates. The gas pores were evaluated by an image analysis procedure (Bertrand, Le Guerneve, Marion, Devaux, & Robert, 1992; Rouillé, Valle, Della Devaux, Marion, & Dubreil, 2005) to characterize the visual texture in relation to particle size. Images were obtained with a digital camera Canon EOS 7D with 50 mm focal length. The image resolution was 5184x3456p with 150 ppi of pixel depth. The extrudates were cut longitudinally with a razor blade. During the procedure, the damage of the material was avoided. The measured objects for each sample was in the range of 700–1500 objects in total. All images were processed and analyzed as described by Vasileva et al., 2018.

2.5.3. Differential scanning calorimetry

DSC measurements were conducted using a Mettler Toledo DSC 823e (Parkway, Colombus, USA). Indium was used as reference. Briefly, 30 mg dry weight of sample (ground to 0.5 mm) were weighed into a 120 µL stainless steel pan followed by the addition of 60 µL of water. The pans containing the samples were hermetically sealed and heated at 10 °C/min from 20 to 120 °C. The temperature relative to the onset, the peak maximum, the endset of the endothermic peaks, were given by the STAR SW 9.01 software. The heat flow returned to baseline level at the end point of gelatinization (Tend). If no endothermic peaks are detected, the starch is in an amorphous state and completely gelatinized.

2.5.4. Color properties

The color of extrudates was measured with a Colorimeter (CR-400, Minolta, Japan) calibrated using a standard white tile. The lightness (L), redness (a*) and yellowness (b*) were obtained (illuminant D65). Prior to color analysis, the extrudates were ground using a RETSCH ZM 100 mill (Retsch GmbH, Haan, Germany) containing a 0.5 mm sieve. Three measurements were taken for each sample. Total color change (ΔE) and the browning index (BI) were calculated according to Wani and Kumar (2016). The BI was calculated according to equation (2).

$$BI = \left(100 \times \frac{X - 0.31}{0.17}\right), \quad (2)$$

Where $X = (a^* + 1.75 \times L^* + a^* - 3.012 \times b^*)$.

2.5.5. Textural properties

The texture properties of the snacks were determined based on the hardness, the toughness, the crushing-force and the crispness. The texture analyzer used was a TA-XTPlus (Stable Micro systems,

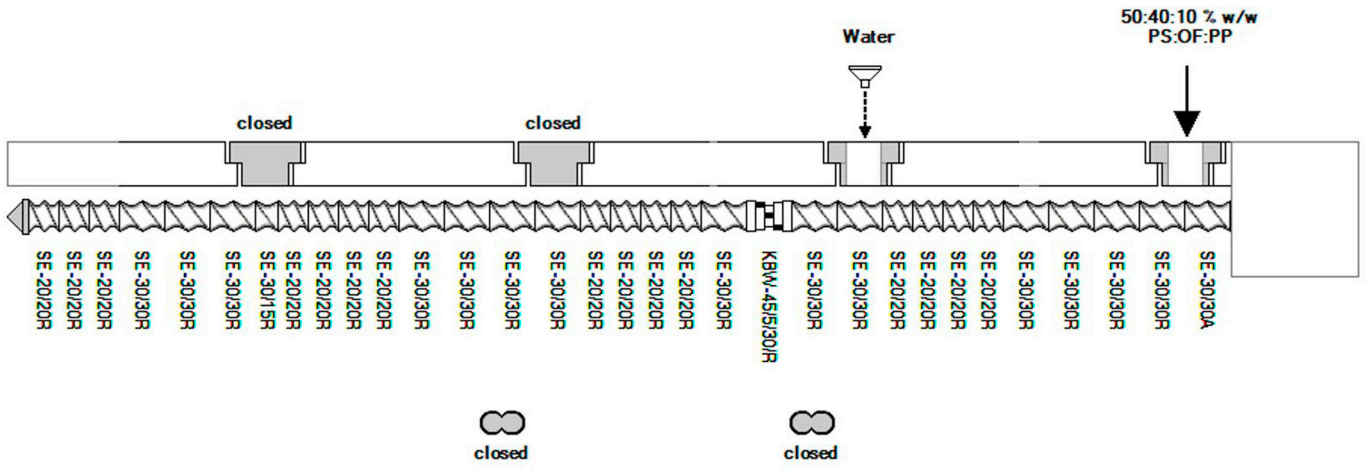

Fig. 1. Screw configuration. Extruder length/diameter ratio is 20:1. Screw diameter = 20 mm. SE-30/30A – Forward conveying element; SE-20/20R – Forward conveying element. lower pitch; KBW-45/5/30R – Kneading block; SE-30/15R – lower pitch than SE-20/20R

Godalming, UK) with a Warner-Bratzler 3 mm thick blade and the software was Exponent (v8.10). The parameters were chosen following Paula & Conti-Silva, 2014, the speed of the probe was 0.17 mm/s or 10 mm/min and the load cell was 5 kg (Paula & Conti-Silva, 2014). The highest value of force achieved was taken as a measurement of hardness, according to Stojceska, Ainsworth, Plunkett, & Ibanoğlu, 2010 (Stojceska, Ainsworth, Plunkett, & Ibanoğ;lu, 2010). The toughness was translated by the total area under the curve (N/mm) (Ritchie et al., 2008). The crushing force was defined as the area under the force-deformation curve divided by the distance of compression (de Mesa et al., 2009). The crispiness was described by the number of force peaks according to Salvador, Varela, Sanz, & Fiszman, 2009.

2.5.6. Sensory evaluation

Six representative samples (HSNA-2, HSNA-3, HSNA-5, HSNA-6, HSNA-7, HSNA-9) were selected for the sensory descriptive analysis based on the process conditions (extremes) and the quality of extrudates to be tested (compact, less expanded products were not selected). The sensory analyses were performed in a sensory laboratory following ISO8589 (ISO, 2007). A descriptive test based on ISO 13299: 2016 was performed by a sensory panel. This panel consisted of ten trained assessors selected and trained following ISO 8586:2012. Before profiling, one session was used to develop twenty-four odor, flavor, taste and texture attributes (Odour: Total odour intensity, Corn, Peas, Grain/flour, Old stuffy. Taste: Sour, Sweet, Salty, Bitter, Umami. Flavour: Corn, Hay/grass, Pea, Grain/flour, Roasted, Nutty, Old stuffy, Cloying. Texture: Hardness, Chewiness, Crispness, Juiciness, Granularity, Pungent) and to agree on the consensus list and on the definition of each attribute. The samples were served in white plastic cups covered with metallic lids and tagged with a random three-digit code. Six snacks samples were evaluated in duplicate by the panel over 3 sessions in a sequential monadic presentation, following a Williams' Latin Square design. The samples were served around 18 °C ± 2 °C. All samples were expectorated, warm and cold water was available for rinsing and unsalted crackers were supplied. Assessors used a 15 cm non-structured continuous scale to evaluate the intensity of each attribute, labelled on the left with "no intensity", and on the right- to the highest intensity. The sensorial analysis was correlated with the instrumental analysis of texture to determine the real perception of texture by the consumers.

2.5.7. Proximate composition of raw materials and extrudates

The moisture content of the blend formulation and the extrudates was obtained using the American Association of Cereal Chemistry (AACC, 1995) moisture air oven method 44-15.01. Starch was determined by standard method AOAC 996.11 (2014) using a Megazyme kit (Megazyme, Wicklow, Ireland). The protein content of pea ingredients and final product (extrudates) was assessed and estimated (N × 6.25) from the analysis of N by the method of Kjeldahl (FOSS Kjeltec 2520 Auto Digester and Kjeltec Auto TM 8400, Denmark). Non-starch polysaccharides (NSP) was determined by the method of Englyst, Quigley, & Hudson, 1994 via GC-FID analysis of alditol acetates using Haricot beans as a positive control (Englyst et al., 1994). β-glucan content was determined following the streamlined method AOAC 995.16 (2000) using a Megazyme kit (Megazyme, Wicklow, Ireland). The low-molecular weight carbohydrates (LMW CHO) were analyzed with HPAEC-PAD following a method adapted from Helgerud et al. (2016). Melibiose, D-Glucose, sucrose, fructose, raffinose, stachyose and verbascose were obtained from Sigma-Aldrich (St. Louis, USA).

2.5.8. Molecular weight (MW) determination of β-glucan

β-glucans were extracted from duplicate samples of ground healthy snacks as previously described (Rieder, Knutsen, & Ballance, 2017). The samples were filtered and beta-glucan molecular weight was analyzed by High Pressure Size Exclusion Chromatography (HPSEC) with post-column calcofluor detection according to Rieder, Ballance, and Knutsen (2015). A β-glucan Molecular Weight (Mw) calibration curve was built with in house β-glucan MW standards and standards acquired from Megazyme (Wicklow, Ireland), with peak MW from 31600 to 2418000 by fitting a proprietory third order polynomial regression (PSS poly 3) to the retention time plotted against the peak MW using PSS WinGPC Unichrome software (PSS Polymer Standard Service, Mainz, Germany). β-glucan weight average molecular weights (Mw) and molecular weight at peak (Mp) were calculated for each sample.

2.6. Experimental design analysis/statistical analysis

The response data from the Central Composite Rotatable Design (CCRD), were conducted using the software Minitab® 18.1, from Minitab Ltd. (UK). Analysis of variance (ANOVA) and Fischer's least significant difference multi-comparison test to determine significant differences between treatments using Minitab Ltd. Sensory descriptive data was collected using EyeQuestion for direct recording of data (v4.10.4, Logic8, Holland), ANOVA and Tukey tests were used for the statistics analyses. Multiple Factor Analysis (MFA) and linear correlations were run to investigate sensory-instrumental correlations. These analyses were run in XLStat 2015, Addingsoft (USA).

3. Results and discussion

3.1. Modelling of extrudates production through extrusion processing

The extrusion experiments were performed following a Central

Table 2
Impact of extrusion parameters on the physical properties (expansion and colour parameters) of pea and oat-based extrudates.

	HZ6	MC (%)	Expansion indexes					Colour properties				
			$MC_{extrudates}$ (%)	SEI	LEI	VEI	BD	L*	a*	b*	ΔE	BI
RM	–	–	–	–	–	–	–	**90.07 ± 0.10**	**0.33 ± 0.01**	**13.96 ± 0.10**	–	–
HSNA-1	160	16.8	15.5 ± 0.07^{a}	2.3 ± 0.14^{a}	0.27	0.62	0.83 ± 0.02^{a}	86.1 ± 0.31^{a}	0.9 ± 0.09^{a}	20.0 ± 0.21^{a}	7.29	3.04
HSNA-2	160	14.0	12.0 ± 0.41^{b}	3.8 ± 0.25^{b}	0.27	1.0	0.52 ± 0.03^{b}	82.6 ± 0.48^{b}	1.8 ± 0.15^{bc}	23.2 ± 0.62^{b}	11.94	4.32
HSNA-3	160	11.2	6.40 ± 0.08^{c}	5.8 ± 0.13^{c}	0.30	1.8	0.27 ± 0.01^{c}	83.5 ± 0.15^{c}	2.0 ± 0.08^{d}	22.5 ± 0.03^{c}	10.90	4.39
HSNA-4	170	16.0	14.3 ± 0.02^{d}	2.4 ± 0.21^{a}	0.27	0.66	0.78 ± 0.03^{d}	84.9 ± 0.10^{d}	1.1 ± 0.07^{e}	21.0 ± 0.21^{d}	8.82	3.42
HSNA-5	170	12.0	10.4 ± 0.10^{e}	3.7 ± 1.1^{b}	0.27	0.99	0.47 ± 0.01^{e}	82.8 ± 0.09^{be}	1.9 ± 0.07^{bd}	22.9 ± 0.09^{bc}	11.62	4.37
HSNA-6	174.5	14.0	12.0 ± 0.04^{b}	3.4 ± 0.13^{b}	0.27	0.91	0.57 ± 0.02^{f}	83.0 ± 0.02^{be}	1.7 ± 0.03^{c}	22.5 ± 0.33^{c}	11.18	4.13
HSNA-7	145.9	14.0	13.0 ± 0.10^{f}	3.6 ± 0.22^{b}	0.25	0.90	0.57 ± 0.01^{f}	83.3 ± 0.33^{ce}	1.5 ± 0.08^{f}	22.6 ± 0.79^{bc}	11.08	4.01
HSNA-8	150	16.0	15.5 ± 0.10^{a}	2.5 ± 0.13^{a}	0.25	0.63	0.82 ± 0.02^{a}	86.4 ± 0.07^{a}	0.8 ± 0.05^{a}	19.3 ± 0.19^{a}	6.52	2.86
HSNA-9	150	12.0	9.3 ± 0.00^{g}	5.7 ± 0.19^{c}	0.28	1.6	0.31 ± 0.01^{g}	82.9 ± 0.27^{be}	1.9 ± 0.06^{d}	22.6 ± 0.20^{bc}	11.32	4.38

RM = Raw-material blend (non-extruded product). HSNA-1 to HSNA-9 = samples corresponding to different extrusion processing conditions concerning die temperature and blend moisture content. HZ6 = die temperature. MC = blend moisture content. $MC_{extrudates}$ = moisture content of the extrudates. SEI = sectional expansion index. LEI = lateral expansion index. VEI = velocity expansion index. L* = lightness (+), darkness (−), a* = redness (+), greenness (−), b* = yellowness (+), blueness (−). ΔE = Colour difference. BI = Browning index. BD = Bulk density. Means with different letters are significantly different ($p < 0.05$).

Composite Rotatable Design (CCRD). The acquire results, i.e. Dependent process variables: Specific Mechanical Energy (SME), Pressure (P), Drive Load (DL), Velocity (V) and Throughput (T); Expansion indexes (SEI, LEI and VEI), Color properties (L*, a* and b* values, color differences and browning index) and textural properties (toughness, hardness, crushing force and crispiness) are presented in Tables 1 and 2.

HSNA-2, 10 and 11 are central points of the design of experiments (triplicates), enabling to check the repeatability (coefficient of variation) of the extrusion process. SME values were used to calculate the repeatability of the extrusion process, that was found to be 7%. The average and standard deviation of the central points were calculated, and these three samples were grouped in one sample (HSNA-2) for further statistical analysis, presentation and discussion of the results. Moreover, the fitted response surfaces have taken into consideration the three independent central points. The linear and quadratic effects of variables and their interactions were estimated (SM). As observed in Fig. 2, the impact of the MC was always higher than the effect of HZ6. Higher values of blend moisture content (MC) within the tested range correspond to a decrease in the P, DL, SME, SEI, VEI, crispiness (C), a* and b* response variables. On the other hand, at higher values of moisture content (MC), the $MC_{extrudates}$, BD, hardness (H), toughness (T), crushing force (CF) and L* values also increase (see SM - Supplementary Materials).

A good agreement between the experimental data and the theoretical values predicted by the model was found (SM). For the longitudinal expansion index (LEI), throughput (TP) and velocity (V), a lack of fit was revealed by low values of R^2 and $R_{adj}{}^2$. About 90–98% of the obtained results concerning all responses evaluated are explicated by the respective models. Nevertheless, no optimal conditions were found in the response surfaces. Consequently, only the identification of the best response could be achieved (region of the experimental domain). Fig. 2 presents the response surfaces fitted to the Sectional Expansion Index (SEI), Bulk Density (BD), Hardness, Crispiness and SME as a function of die Temperature (HZ6) and moisture content (MC). For more details on the response surfaces fitted to other measured responses, the reader can refer to the SM. Higher expansion, higher crispiness, lower hardness and lower bulk density of extrudates were achieved at an HZ6 of 160 °C, a MC of 11.2% db and an SRS of 200 rpm, corresponding to a higher SME (Fig. 2).

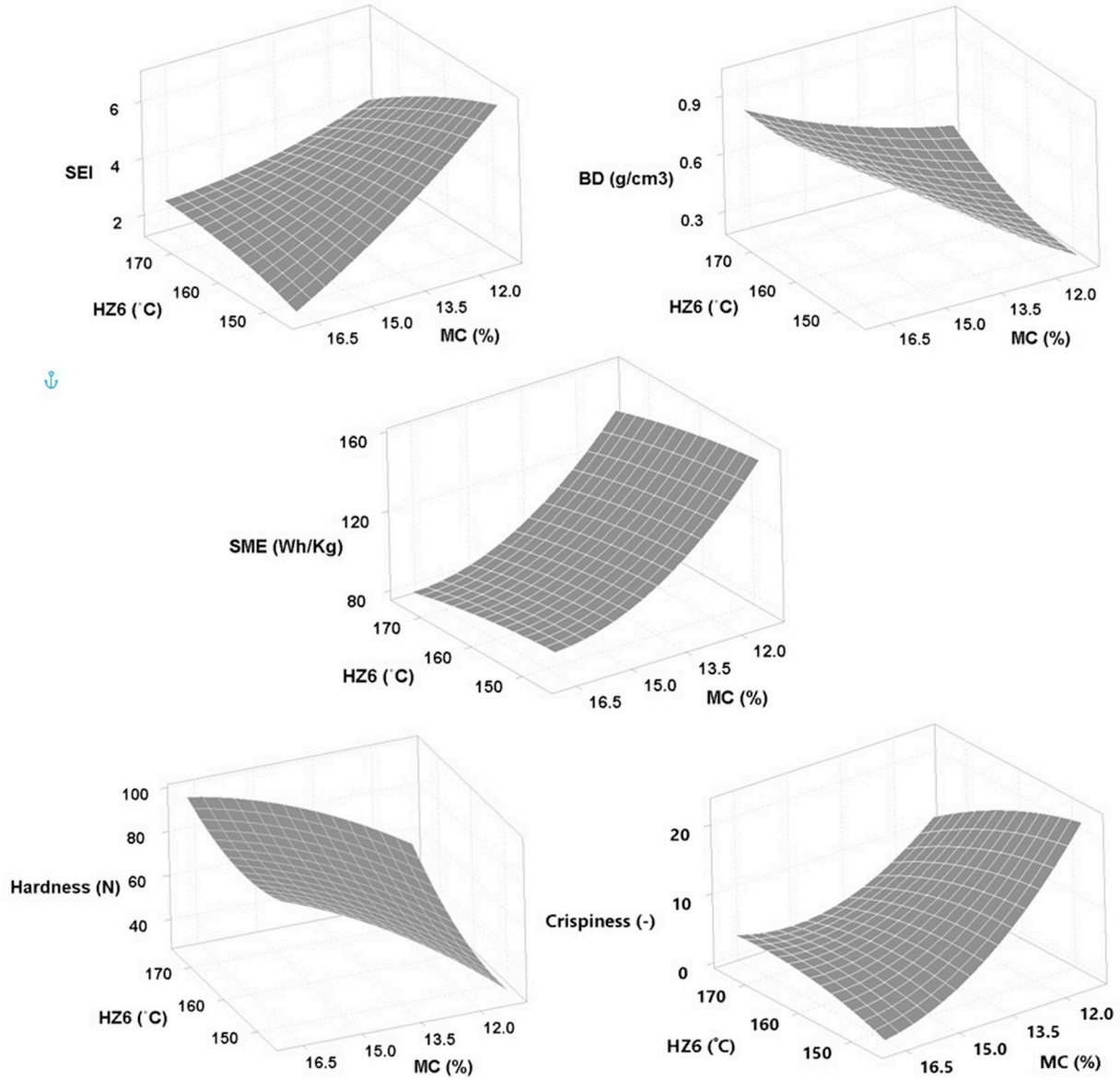

Fig. 2. Fitted response surfaces to the Sectional Expansion Index (SEI), Bulk Density (BD), Hardness (H), Crispiness (C) and Specific Mechanical Energy (SME) as a function of die Temperature (HZ6) and blend moisture content (MC).

SME describes the amount of mechanical energy imparted by the process to the product, also translating the shear history present in the extruder. It was verified that a strong correlation exists between SME and P, SME and DL, and between DL and P. The lowest value of SME was obtained when operating at high temperature and high blend moisture content (83.5 Wh/Kg) and the highest SME was obtained when operating at lower blend moisture content (145.4 Wh/Kg). Meng et al., 2010 studied the extrusion of chickpea flour with similar composition and process condition of this study (Meng et al., 2010). The range of SME achieved was between 87.9 and 115.8 Wh/Kg, being in agreement with results obtained in this study. Chinnaswamy at al., 1988 and Jacques-Fajardo et al., 2017 also found similar SME values (61.1 and 149.8 Wh/Kg) with a comparable blend composition (pea, oat, corn) and similar process conditions (Chinnaswamy & Hanna, 1988; Jacques-Fajardo et al., 2017). Higher SME values can be linked to the composition of the raw material mix, with for instance, higher content in proteins and lower in starch that is responsible for a decrease in the blend viscosity (Alam et al., 2016).

Diameter, expansion indexes (SEI, VEI and LEI), bulk density (BD) and porosity are all linked and enable to estimate the expansion of the extrudates. SEI is dependent on the diameter and was the most relevant expansion index (significant differences between the samples). LEI depends on extrudates velocity and did not show any significant differences between the different samples.

VEI is the result of the combination of both LEI and SEI. SEI had the main impact on the VEI and thus, it followed the same pattern as SEI. SME was well linearly correlated to SEI (SM). Higher SME corresponded to higher SEI. Onwulata, Konstance, Smith, & Holsinger, 2001 has obtained similar results when producing snack products based on milk proteins and wheat fiber (Onwulata et al., 2001). In fact, SEI is expected to increase with increasing shear and SME. SEI, VEI and BD were shown to be strongly correlated to the MC. Higher MC gave low SEI and VEI and high BD. The highest SEI was obtained for samples HSNA-3 and 9 with 5.8 and 5.7, respectively. The BD enabled to significantly differentiate these samples and sample HSNA-3 had the lowest BD with 0.27 against 0.31 for the sample HSNA-9. From the results present in Fig. 2 it is possible to observe the link between SEI and BD with MC. As MC increased, SEI decreased and BD increased. Similar results were obtained by Jacques-Fajardo et al., 2017, in which this effect was attributed to a decrease in the blend viscosity (Jacques-Fajardo et al., 2017). Viscosity of the melt should be low enough to enable bubble growth and at the same time, high enough to get strength to the network (Kristiawan, Chaunier, Della Valle, Ndiaye, & Vergnes, 2016). Horvat & Schuchmann, 2013 reported that the higher the MC, the less resistance against bubble growth and thus an improvement of expansion occurs (Horvat & Schuchmann, 2013). Inversely, Ding, Ainsworth, Plunkett, Tucker, & Marson, 2006 reported that the increasing MC can decrease the expansion and increase bulk density because of the plasticization of the melt, thus decreasing the elasticity of the melt, SME and gelatinization (Ding et al., 2006). The last explanation can justify the loss of expansion when the moisture content of the raw material was increased from 12 to 16%.

Fig. 3a showed that highly expanded snacks gave higher porosity with small air bubbles well spread in the snacks, compared to the less expanded snacks where fewer and bigger bubbles are present.

The size distribution of all samples (Fig. 3b) is hardly differentiating but all of them follow normal left skewed unimodal distribution with a peak within the area class a < 0,05 mm^2. More than 50% of the pores among all samples have area < 0,2 mm^2 with dominating samples HSNA-2 and HSNA-4 having respectively 76.4% and 74.5% of their gas pores within area class < 0,2 mm^2. More differentiating results are demonstrated in Fig. 4a and b that represents the effect of the accumulated specific mechanical energy (SME) during extrusion on number of gas pores per unit area of extrudates and their apparent porosity,

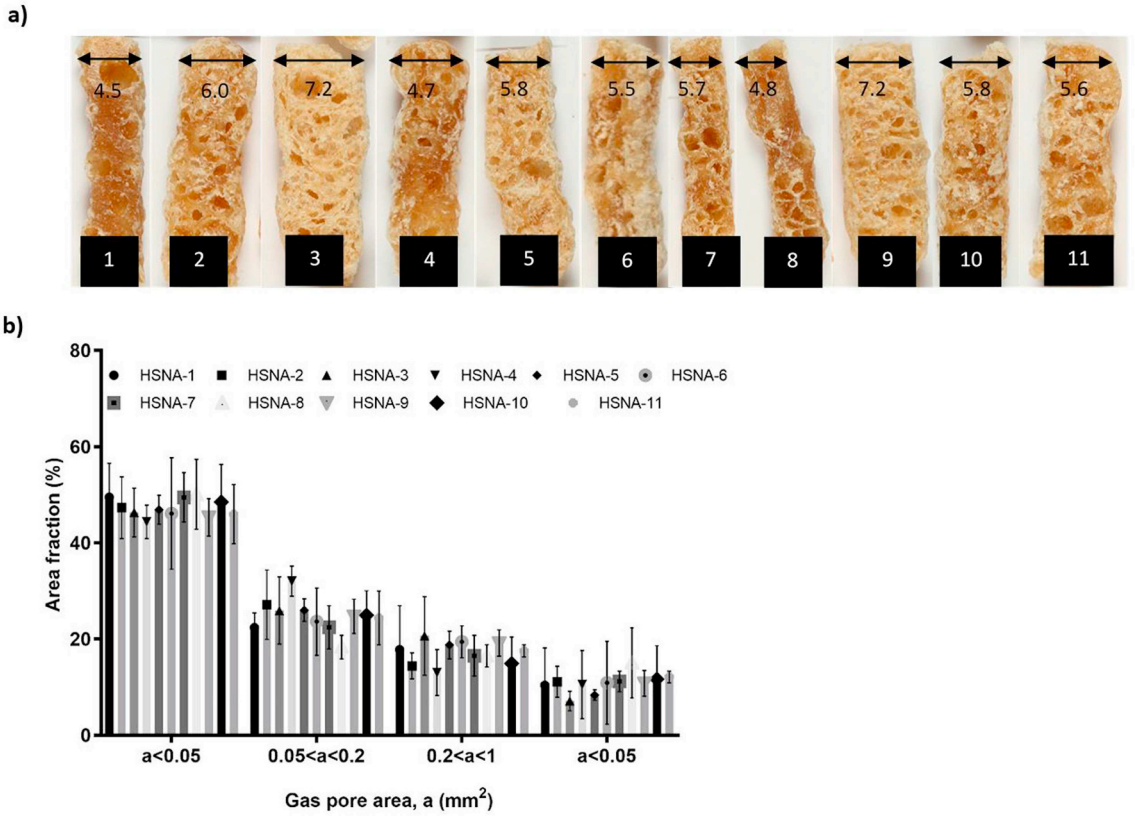

Fig. 3. a) Pictures of the snacks cut transversally. The scale is represented by the diameters (mm) determined with a calliper (± 0.1 mm); b) Gas pore area distribution of the extrudates. HSNA-1 to HSNA-11 = samples corresponding to different extrusion processing conditions concerning die temperature and blend moisture content.

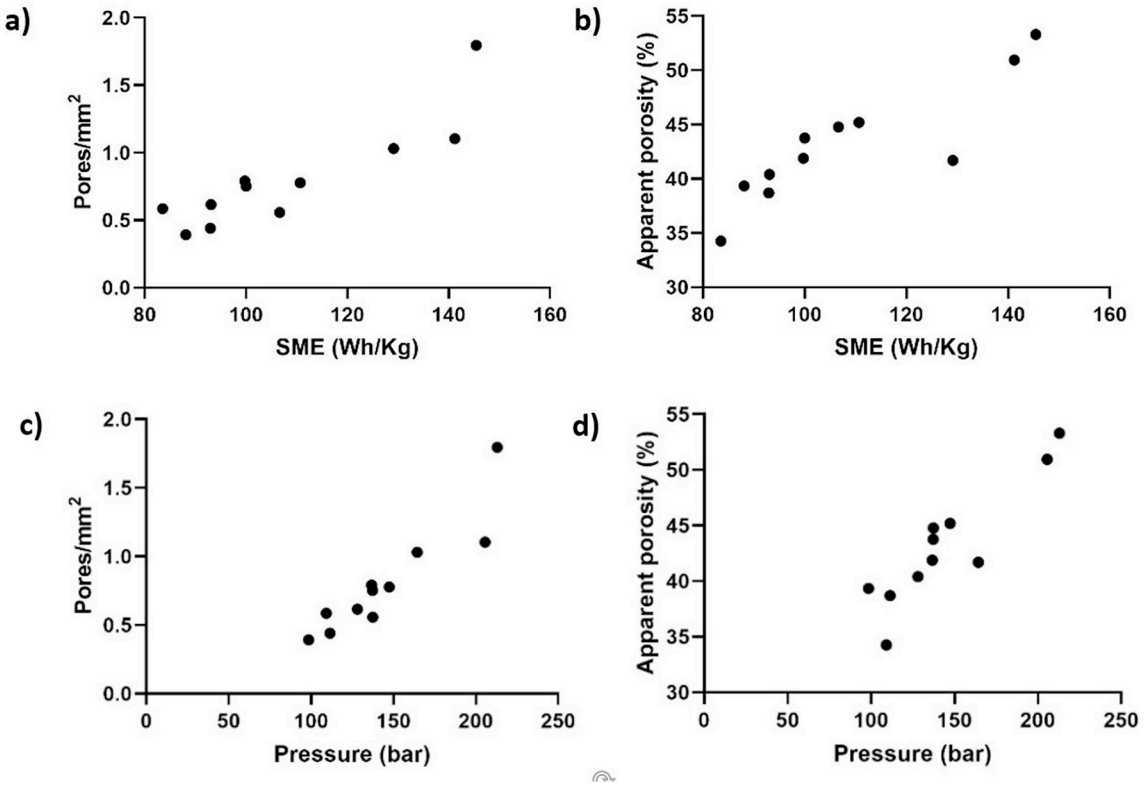

Fig. 4. Effect of Specific Mechanical Energy (SME) on the microstructure of the extrudates - number of pores per unit area (a) and apparent porosity (b); Effect of die pressure on the microstructure of the extrudates - number of pores per unit area (c) and apparent porosity (d).

respectively. The increased level of the accumulated SME typically causes an increased level of protein depolymerization i.e. increased proportion of low Mw protein fractions as suggested by Fang, Zhang, Wei, & Li, 2013 (Fang et al., 2013). This generally leads to decrease of the apparent viscosity of the processed slurry due to the shear thinning effect of SME. This decrease in the apparent viscosity of the processed slurry from the other hand favors the flow ability of the material through the different processing zones of the extruder and die as well as strongly improves the distributive mixing in the extruder (Fang, Zhang, & Wei, 2014; Wang, Bhirud, & Tyler, 1999). Lower blend moisture content represents an important driving force for higher level of expansion of the extrudates. Lower moisture content increases the slurry apparent viscosity which in turn affects the imparted SME and generates higher pressure at the extruder barrel that favors expansion. This is demonstrated in Fig. 4a and b where a strong positive correlation between SME and porosity of the extrudates exists. Pressure in the relevant processing zones of the extruder is also increased. Higher pressure means a greater driving force for expansion of extrudates when they leave extruder die and set. This is evident by Fig. 4c and d that represents the impact of die pressure on the porosity of the extrudates. Similar to Fig. 4a and b, a strong positive correlation between die pressure and extrudate porosity can be identified.

3.2. Impact of process conditions on color and texture properties of extrudates

Color is a product characteristic which has an important impact on the consumer and will be decisive in the buying act. The impact of the process conditions and measured variables on the color of the extrudates was also determined. The lightness (L*), the redness (a*) and the yellowness (b*) were assessed and the results are reported in Table 2. The samples processed at the lowest MC showed the lowest lightness and highest a* values (darker and more brownish) and b* values. Kristiawan et al., 2018 correlated the increasing red color with the protein aggregation and formation of disulphides bonds at the same time (Kristiawan et al., 2018). A decrease in lightness can be explained by the Maillard reaction which is the result of the reaction between amines from proteins and a carbonyl from reducing sugars at high temperatures (Damodaran, 1996). In the present study, the results for LMW carbohydrates (Table 3) showed an important decrease in glucose that had been probably used during the Maillard reaction (non-enzymatic browning), leading to the development of a typical brown color and distinguishing flavor. The browning color is one of the important characteristics that consumers preferentially consider (Sajad Ahmad Wani & Kumar, 2016b). The browning index (BI) was calculated based on the colorimeter results. The results of the BI were in the range of 2.86 (150 °C, 16%) and 4.39 (160 °C, 11.2%). From the regression analysis (SM), both temperature and moisture content and the interaction of both had an impact on the browning index. At lower moisture content (11.2–12%) the browning index didn't change among the different die temperatures tested (150–175 °C). On the other hand, at higher moisture contents (16.0–16.8%) the impact of the die temperature was more pronounced. Parker, Hassell, Mottram, & Guy, 2000 showed an important increase of Maillard reaction during the extrusion of oat at a HZ6 of 180 °C and with a low blend moisture content (14%) (Parker et al., 2000). Moreover, Andersson at al., 1973 showed that addition of water in the blend decreased the Maillard reaction and HZ6 increased the brown color (Andersson et al., 1973), which was also verified in this work. The samples that showed the best expansion (HSNA-3 and 9) and the highest SME values showed darker and more brownish color.

Concerning color differences, the moisture content was also the parameter that had a very significant impact on this response. Color differences (ΔE) of extrudates varied between 6.52 (HSNA-8) and 11.94 (HSNA-2). A strong linear correlation exists between ΔE and BI (R^2 = 0.95), meaning that the color changes are mainly driven by Maillard reaction (SM).

The texture attributes, namely toughness (T), hardness (H),

Table 3
Starch, non-starch polysaccharides (NSP), β-glucan and low molecular weight (LMW) carbohydrates contents of extrudates and raw materials.

Sample (conditions)	Starch (% db)	NSP (% db)	β-glucan (% db)	Beta-glucan Mp (*10^4)	LMW carbohydrates (mg/100g dry basis)					
					Glucose (mg/100 g db)	Fructose (mg/100 g db)	Sucrose (mg/100 g db)	Raffinose (mg/100 g db)	Stachyose (mg/100 g db)	Verbascose (mg/100 g db)
HSNA-1 (160 °C, 16.8%)	41.7 ± 0.7	24.6 ± 0.1	13.7 ± 0.2	200 ± 27	11.2 ± 2.4^{a}	18.6 ± 4.4^{ab}	2809 ± 325^{a}	545 ± 36^{a}	1401 ± 59^{a}	1088 ± 34^{a}
HSNA-2 (160 °C, 14.0%)	39.7 ± 0.8	23.9 ± 0.2	13.2 ± 1.0	211 ± 11	14.2 ± 5.7^{a}	18.7 ± 4.6^{ab}	3198 ± 309^{a}	613 ± 34^{a}	1471 ± 53^{a}	1075 ± 63^{a}
HSNA-3 (160 °C, 11.2%)	39.1 ± 0.3	24.0 ± 0.1	13.2 ± 0.3	180 ± 4	12.3 ± 4.8^{a}	25.7 ± 8.9^{a}	2962 ± 368^{a}	575 ± 21^{a}	1466 ± 95^{a}	1159 ± 66^{a}
HSNA-4 (170 °C, 16,0%)	41.6 ± 1.7	nd	nd	212 ± 8	11.9 ± 4.2^{a}	20.1 ± 3.8^{ab}	3062 ± 391^{a}	593 ± 47^{a}	1473 ± 115^{a}	1187 ± 84^{a}
HSNA-5 (170 °C, 12.0%)	40.5 ± 0.8	nd	12.9 ± 0.5	209 ± 0.4	12.8 ± 5.4^{a}	15.8 ± 1.4^{ab}	3205 ± 313^{ab}	618 ± 22^{a}	1414 ± 74^{a}	1024 ± 35^{a}
HSNA-6 (175 °C, 14.0%)	40.5 ± 0.5	nd	nd	221 ± 12	13.3 ± 5.0^{a}	17.1 ± 1.8^{ab}	3241 ± 318^{a}	616 ± 25^{a}	1426 ± 64^{a}	1019 ± 33^{a}
HSNA-7 (146 °C, 14.0%)	39.8 ± 0.3	nd	nd	214 ± 3	14.8 ± 5.6^{a}	15.9 ± 1.8^{ab}	3168 ± 264^{a}	603 ± 28^{a}	1420 ± 50^{a}	1020 ± 36^{a}
HSNA-8 (150 °C, 16.0%)	39.0 ± 0.8	nd	nd	229 ± 2	14.2 ± 5.2^{a}	17.6 ± 2.4^{ab}	3308 ± 306^{a}	620 ± 23^{a}	1480 ± 59^{a}	1057 ± 48^{a}
HSNA-9 (150 °C, 12.0%)	39.0 ± 0.8	nd	13.2 ± 0.1	191 ± 13	14.5 ± 6.0^{a}	14.4 ± 2.3^{b}	3299 ± 236^{a}	627 ± 26^{a}	1454 ± 71^{a}	1050 ± 43^{a}
RM	nd	nd	12.6 ± 1.0	212 ± 10	150 ± 5.0^{b}	19.1 ± 1.7^{ab}	3529 ± 149^{ab}	555 ± 25^{a}	1429 ± 12^{a}	974 ± 60^{a}
PPC	nd	nd	nd	nd	375 ± 18	26.8 ± 3.3	4616 ± 162	1029 ± 42	4664 ± 256	3758 ± 296
PS	nd	nd	0	nd	163 ± 17	35.7 ± 4.6	4481 ± 259	672 ± 102	1674 ± 174	1199 ± 100
OF	39.0 ± 0.3	nd	28*	nd	7.9 ± 1.4	8.5 ± 6.8	2092 ± 32	243 ± 9.0	505 ± 6.1	79.9 ± 4.0

RM = Raw-material blend (non-extruded product). HSNA-1 to HSNA-9 = samples corresponding to different extrusion processing conditions concerning die temperature and blend moisture content.
PPC = pea protein concentrate. PS = pea starch. OF = oat fibre. nd = non-determined; Mp = Peak molecular weight. db = dry basis.
The standard error deviations were done on duplicates for starch and β-glucan contents to have an indication about the quality of the measurement but will not be used for statistical analysis. Means with different letters are significantly different ($p < 0.05$).

crispiness (C) and crushing force (CF) were assessed (SM) and results showed that in general, HSNA-3 and HSNA-9 were significantly different from other samples concerning all texture properties measured. They were found to be less tough, less hard, easier to crunch and crispier. On the other hand, samples HSNA-4 and HSNA-8 were found to be the toughest, hardest, more difficult to crush and less crispy

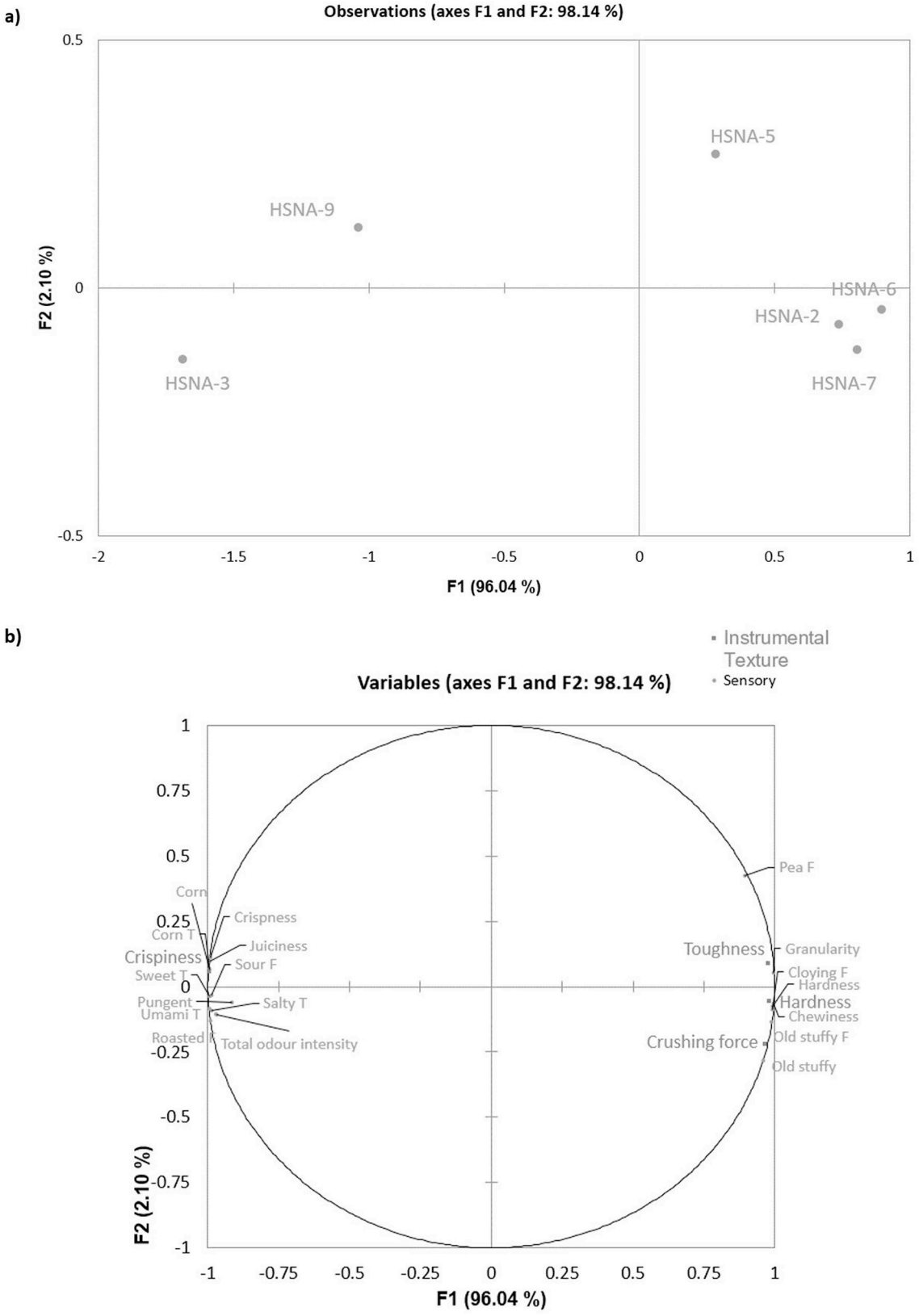

Fig. 5. Correlation of sensory variables (smaller font) and instrumental texture (larger font) data via Multiple factor analysis (MFA): (a) sample plot, (b) variable plot. Instrumental data are overimposed as supplementary variables on the map.

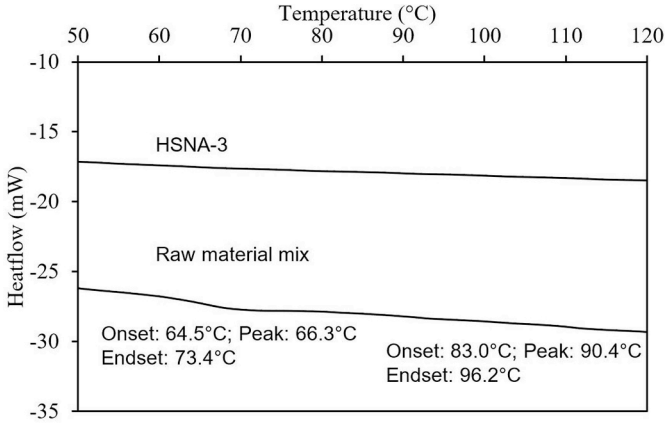

Fig. 6. DSC heating scan of raw-material (non-extruded blend) and extruded blend (HSNA-3) processed at a temperature of 160 °C, a blend moisture of 11.2% and a screw speed of 200 rpm.

among all samples evaluated. As already mentioned previously, the blend moisture content (MC) had a very significant impact on all the measured properties. Higher MC led to increased hardness, toughness, crunching force and decreased crunchiness (Fig. 2). Stojceska et al., 2008 analyzed the effect of different blend MC during extrusion of ready-to-eat snacks and also found a negative effect of MC on hardness and SEI (Stojceska, Ainsworth, Plunkett, Ibanoğlu, & Ibanoğ;lu, 2008).

3.3. Sensory perception and its correlation to instrumental variables

Expanded snacks were characterized by their structure, in which air bubbles are prisoned in a crispy network made of starch, fiber and protein. The impact of the process conditions on some textural properties was assessed, namely: toughness, hardness, crushing force and crispness and their correlation with sensory perception as assessed by the sensory panel.

Eighteen of the 24 attributes evaluated by the trained panel were significantly different among the samples (Non-significantly different: pea odor, grain odor, bitter taste, hay/grass flavor and nutty flavor). Sensory panelists were able to discriminate well the snack samples based on their sensory characteristics. Fig. 5 displays the sensory space defined by the 6 samples based on the assessed attributes. In this plot, instrumental attributes were overimposed as supplementary variables. Samples were well separated in the perceptual space, mainly by the textural and flavor characteristics. Samples processed at lower MC (HSNA-3 and HSNA-9: left side of the map) were associated to positive sensory attributes for this category of products, as crispy and juicy, with roasted and corn flavor, and typical cereal taste attributes as sweet, umami and sour. Crispness measured instrumentally was highly correlated to sensory crispness and characterized these two samples. On the other hand, samples processed at higher MC (HSNA-6, HSNA-2, and HSNA-7: on the other side of the plot), were sensorially described as hard, chewy and granular in texture, and with pea flavor, cloying and old/stuffy, attributes negatively associated to these kinds of products. Instrumental parameters toughness, hardness and the crushing force were associated to this area of the map (right side). On the other hand, the sample processed at higher T and lower MC (HSNA-5) was middle way into the map. For more details on the sensory-instrumental correlations, the interested reader can refer to the Pearson's correlation matrix in the supplementary materials (SM). All sensory and instrumental parameters studied were highly correlated. Concerning the correlation of the sensory and instrumental parameters with other chemical evaluations (browning index, color differences and sugars), no statistically significant correlations were found. Overall, sample processed at higher MC over a wide range of temperatures were not considered sensorially and texturally good for consumption. On the other hand, samples processed at lower MC and lower T (150–160 °C) were considered good, both sensorially and texturally.

In line with the sensory analysis, it was interesting to see that the samples with the highest SME (HSNA-3 and HSNA-9), highest redness and darkness were also the samples which had a roasted, corn taste and a high intensity odor (Fig. 5). In fact, Maillard reaction give also specific aromas compounds. An increase of the toasted taste and Maillard volatile in oat flour during extrusion (130–180 °C HZ6, 14.5–18% MC) was observed by Parker et al., 2000 (Parker et al., 2000). Overall, the best response was achieved with a die temperature of 160 °C, a blend moisture of 11.2% and a screw speed of 200 rpm, enabling the production of a snack with higher expansion (HSNA-3), best sensory and texture attributes, obtained at the highest values of SME, pressure and drive load.

3.4. Effect of the process conditions on the extrudates composition

The impact of extrusion on the composition of the snacks were analyzed and particularly the impact of extrusion on total starch content, total fiber content, total β-glucan and LMW carbohydrates contents were evaluated (Table 3). The starch content in the extrudates varied between 39.0 and 41.7 g/100g. Fig. 6 presents the DSC thermogram of the raw material mixture and the extrudates produced at optimum conditions (HSNA-3). For the raw-material, a first peak was obtained at 66.8 ± 0.7 °C and a second peak at 90.6 ± 0.3 °C could be observed. The first peak corresponds to the disordering of amylopectin crystallites (Fredriksson, Silverio, Andersson, Eliasson, & Åman, 1998). The second peak is associated to the complex of amylose and lipid or to the denaturation of pea proteins. Moreover, results showed that no endothermic peaks were observed for HSNA-3 (Fig. 6), showing that the starch is in an amorphous state and was entirely gelatinized under processing at optimum conditions.

From the results in Table 3 it is possible to conclude that NSP was not changed during extrusion. Camire and Flint, 1991 reported an increase in NSP in oatmeal (with a die temperature fixed at 135 °C and 20% MC but didn't find differences after extrusion of cornmeal (Camire & Flint, 1991). However, Alonso, Rubio, Muzquiz, & Marzo, 2001 showed a decrease in NSP (14.89–14.38% dm) in peas with die temperatures between 150 and 155 °C and MC at 25% (Alonso et al., 2001). It was explained by several authors that high temperature and pressure can result in degradation of polysaccharides, with a release in oligosaccharides and an increase in soluble dietary fiber (Berrios, Morales, Cámara, & Sánchez-Mata, 2010; Esposito et al., 2005; Gajula, Alavi, Adhikari, & Herald, 2008).

Pea protein was shown to contain 1029, 4664 and 3758 mg/100 g raffinose, stachyose and verbascose, respectively compared to oat fiber 243, 505 and 79.9 mg/100 g, respectively. All the raw materials contained high amounts of sucrose (Table 3). Content of sucrose, raffinose, stachyose and verbascose did not change significantly during extrusion. This agrees with the results obtained for pea protein and pea starch fractions used in the raw-material blend. The non-variation of these LMW carbohydrates could be correlated to the non-variation of NSP during extrusion. Glucose was significantly decreased from 151 to less than 20 mg/100 g. Fructose did not change significantly by extrusion, but minor variations were observed for the samples HSNA-3 and 9 that can be related to the Maillard reaction (Kristiawan et al., 2018). Similar amounts in LMW carbohydrates were observed by Alonso et al., 2001 for yellow pea flour (Alonso et al., 2001). Alonso et al., 2001 reported no impact of extrusion on the amount of sucrose, raffinose and verbascose but a decrease was shown for stachyose. During extrusion of dry pea, Berrios et al., 2010, found lower contents in LMW carbohydrates for the raw material (dry pea flour) and found that after extrusion, fructose was decreased but glucose, galactose and sucrose were increased (Berrios et al., 2010). However, no significant effect was observed on stachyose, raffinose and maltose.

Mixed linked β-glucans are linear polysaccharides composed of β-

(1,3) and β-(1,4) linked glucose monomers. They are mainly found in the aleurone and endosperm cell walls of cereals with highest levels in barley and oat and have been proven to reduce serum cholesterol levels and post-prandial glycemic responses (Izydorczyk & McMillan, 2011; Rieder et al., 2017) in humans. This effect is attributed to the capacity of this polymer to form viscous solutions and a gelatinous barrier in the intestine, which requires a high MW (Rieder, Knutsen and Balance 2017). The only significant β-glucan contribution is from oat (Table 3). The β-glucan content of the snacks was not influenced by extrusion. All snack samples contained β-glucan of very high MW (Mp > 1600000). There was a tendency towards a lower β-glucan MW in HSNA-3, which differed significantly from HSNA-8 (ANOVA, Tukey test) and also HSNA-9 (not significant). HSNA-3 and HSNA-9 were the samples with the highest SME input. SME has previously been found to correlate with β-glucan degradation during extrusion of oat fiber breakfast cereals (Tosh et al., 2010). However, Tosh et al. (2010), found a much more pronounced β-glucan depolymerization from Mp 2484000 to 251000 during extrusion with the highest SME input (148 Wh/kg) (Tosh et al., 2010). These differences might be attributed to the much lower moisture content (only 7%) and higher die temperature (237 °C) used by Tosh et al. (2010) compared to the moderate variations of extrusion parameters in the present study.

4. Conclusion

An expanded healthy snack from a blend containing pea starch, pea protein- and oat fiber-rich fractions were successfully produced and investigated for the first time. Higher expansion and higher crispiness of snacks was obtained at a die temperature of 160 °C, a blend moisture content of 11.2% db and a screw rotation speed of 200 rpm, corresponding to the highest SME achieved. The impact of blend moisture was always higher than the impact of the die temperature among all responses studied. Moreover, highly expanded snacks had higher porosity and a more brownish color driven by Maillard reactions. The snacks processed at optimum conditions also presented positive sensory attributes, highly correlated to the parallel parameters determined by texture analysis. The process conditions used enabled to entirely gelatinize the starch during extrusion. Moreover, it was concluded that extrusion led to a decrease in the amount of glucose and fructose which was correlated to the color development in snacks due to increased Maillard reaction. The protein content in these products qualifies for a nutrition claim: “rich in protein”. The β-glucan content of the expanded snacks is high enough to qualify for both approved EFSA health claims for oat β-glucan on lowering of cholesterol and reduction of post-prandial glucose response. The molecular weight of the β-glucans was marginally reduced during the highest energy input, indicating that these extrusion conditions are approaching those that induce a reduction of β-glucan quality.

Conflicts of interest

The authors declare that they have no conflict of interests.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2019.108252.

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