‘The effect of inulin addition on structural and textural properties of extruded products under several extrusion conditions’

The effect of inulin addition on structural and textural properties of rice flour extrudates

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Abstract The growing consumer demand for healthy snacks has turned the interest of industry and research in the development of new ready-to-eat products, enriched with dietary fibers. Inulin is a soluble fiber with a neutral taste that promotes the good function of the intestine. Rice flour extrudates were produced under various extrusion temperatures, screw speeds, feed moisture concentrations and inulin replacement levels. The objective of this study was to investigate the effect of the material characteristics and the extrusion conditions on the structural and textural properties of the extrudates. Simple mathematical models were used for properties correlation with process conditions and through regression analysis it was revealed that there is a significant effect of extrusion temperature, screw speed, feed moisture content and inulin concentration on the final properties. Both density and maximum stress increased when moisture content and inulin concentration increased, while they decreased when extrusion temperature and screw speed increased. These results were also strengthened by scanning electron microscopy. The highest expansion ratio was presented when decreasing all process conditions apart from screw speed.

Highlights

- Rice flour extrudates enriched with inulin were investigated
- Various process parameters and raw materials characteristics were modeled
- Moisture, inulin concentration, temperature and screw speed seemed to affect the properties
- Increased moisture content and inulin concentration led to denser and less expanded extrudates
- Strain and modulus of elasticity increased with moisture content and decreased with temperature and screw speed.

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Introduction

The current way of life has turned the interest of the consumers on ready-to-eat products, such as snacks. Snacks are also very popular to the children’s daily habits. Statistics showed that 91 % of children in Europe have reported snacking at least once per day (Savigne et al. 2007). Therefore, food industries have increased the development of ready-to-eat products using several processes, in order for the products to be healthy and preferable. Among these processes, extrusion is a high temperature-short time, low cost, and very efficient technology in food processing, which is characterized by continuous cooking, mixing and forming processing (Ding et al. 2006) and produces direct expanded materials with high quality.

Extrusion process is a very frequently used method for the production of food snacks due to the technological advantages it presents over other traditional food processing techniques. However, some commercial snacks have high glycemic index (Conti-Silva et al. 2012; Foschia et al. 2013) and several researches have been performed in order to improve the nutritional characteristics of the extruded products (Liu et al. 2000; Onwulata et al. 2001; Anton et al. 2009; Bisharat et al. 2013). A current trend focuses on the addition of inulin in food products, which contributes to the improvement of the product, providing also a beneficial effect on humans (Saavedra-Leos et al. 2014).

Inulin is a well-known prebiotic and belong to a class of dietary fibers, known as fructans. The main use of inulin is as prebiotic food ingredient that in dairy and bakery products, in beverages, in cereals, in ice cream and in confectionary products and generally as a sugar substitute (Meyer et al. 2011;

Rößle et al. 2011). Inulin is encountered in chicory (*Cichorium intybus* L.), Jerusalem artichoke (*Helianthus tuberosus* L.), onion, in the root of garlic etc. and it has been proven that it redounds to the absorption of iron, calcium and magnesium in the human body (Meyer et al. 2011).

Structural properties are proven to be of high importance for consumer acceptability, since they indicate the texture and quality of expanded products and they also affect taste and appearance (Krokida et al. 2001, 2009). Low apparent density and consequently high porosity extrudates are desirable as food snacks. Another important parameter is the degree of expansion, which also indicates the degree of cooking. Higher expansion is desirable for increased product acceptability and is also associated with other important properties, such as crispness, water absorption, etc. (Jyothi et al. 2009; Rodriguez-Miranda et al. 2011; Velasco 2011; Bisharat et al. 2013). On the other hand the textural properties indicate the fragility and the stiffness of the product. Processing conditions, such as temperature, moisture content and screw speed appear an effect on the extrudates' properties as studied elsewhere (Raphaelides et al. 2012).

The present study examines the production of rice extrudates enriched with inulin. The main purpose is to produce high nutritional rice-based extruded products, that will be acceptable to public consumers and to study the effect of raw materials characteristics (inulin concentration and moisture) as well as production conditions (extrusion temperature and screw speed) to structural and textural properties. For this reason simple mathematical models have been used to correlate extrusion conditions and materials characteristics with the measured properties. The innovative aspect of the present study is the use of simple mathematical models and the addition of highly nutrient ingredients on the extrudates, such as inulin.

Materials and methods

Sample preparation

For the preparation of the extrudates rice flour (Agrino-EU.Ge., Greece make) and inulin (Cosucra, Belgium make) were used during the experimental study. Feed mixtures were consisted of rice flour, inulin and water in different proportions. Inulin and rice flour were mixed to the desired ratios: 5:95, 10:90, 15:85 inulin/rice flour. Feed moisture was adjusted to desired moisture content by spraying calculated amounts of distilled water and mixing. The samples were packed in polyethylene bags and kept in the refrigerator overnight to equilibrate the moisture. Sample moisture content was determined in an oven at 105 °C to constant weight. The moisture content levels were 14, 17 and 20 % w/w. Corrections in moisture were done in cases of deviation from the set values. The samples were brought to room temperature before extrusion cooking.

Extrusion cooking

A co-rotating twin screw extruder (Prism Eurolab, model KX-16HC, Staffordshire, UK) was used. The screw geometry was: length 40 cm, diameter 16 mm, and die diameter 3 mm. The extruder had five temperature control zones. The temperature during extrusion was adjusted by varying the temperature in the barrel, screw and die using electric heaters. The barrel and screw die temperature, as well as the screw speed were displayed on the control panel. Extrudates were produced in three extrusion temperatures (140, 160 and 180 °C) and three levels of screw speeds (150, 200 and 250 rpm). The extrudates were cooled to room temperature and stored in laminated bags until required for analysis.

From the data above it is concluded that the full control of the selected experimental measurements require 243 experiments ($1 \times \text{material} \times 3 \text{ material concentrations} \times 3 \text{ moisture contents} \times 3 \text{ extrusion temperatures} \times 3 \text{ screw speeds} \times 3 \text{ repetitions}$).

Experimental design

A central composite design (CCD) was used to reveal the effect of process conditions and material characteristics on the final properties of extrudates. Feed moisture, inulin concentration, extrusion temperature and screw speed were used as independent variables for the production of extrudates. Process parameters varied over three levels, as shown in Table 1. The design required 26 independent experiments, as well as a control sample. Extruded products were produced in triplicate.

Structural properties

True density

The samples were ground to powder in order to remove most of the internal pores (Krokida et al. 1998), and their true volume was estimated using a helium stereopycnometer (Quantachrome multipycnometer MVP-1, Florida, USA), with an accuracy of 0.001 cm³. True density was expressed by the equation:

$$\rho_{ts} = \frac{m_s}{V_s} \quad (1)$$

where ρ_{ts} (kg/m³) is the true density, m_s (kg) is the mass and V_s (m³) is the volume of the solids. 3 repetitions were done to these experiments.

Apparent density

The extrudates were cut in cylinders of specific length (approx. 4 cm) and their apparent volume was obtained by measuring their actual geometric characteristics (diameter,

Table 1 Extrusion processing conditions and raw material characteristics, as well as mathematical model parameters for structural and mechanical properties

Independent variable	Level			Reference conditions		
	–1	0	1			
Moisture content (% w/w), X	14	17	20	X_o	17	
Material concentration (%), C	5	10	15	C_o	10	
Extrusion temperature (°C), T	140	160	180	T_o	160	
Screw speed (rpm), R	150	200	250	R_o	200	
Coding	1	2	3			
Properties (M_i)	Mathematical model parameters					
	M_o	α_X	α_C	α_T	α_R	R^2
ρ_{ap}	0.307±0.00	1.491±0.07	–2.558±0.22	–1.378±0.09	–0.477±0.05	0.744
Exp	2.216±0.02	–0.485±0.04	1.819±0.14	–0.509±0.06	0.270±0.03	0.744
σ_{max}	193.557±8.86	3.023±0.23	–4.816±0.55	–2.202±0.23	–1.128±0.12	0.730
ε_{max}	0.235±0.00	0.077±0.01	–1.318±0.40	–0.078±0.01	–0.321±0.08	0.713
E	484.886±26.36	2.901±0.30	1.322±0.63	–3.227±0.34	–0.996±0.14	0.755
N	34.498±0.57	–0.773±0.09	2.995±0.32	–1.359±0.14	0.641±0.07	0.774

length), using an electronic digital Vernier caliper with an accuracy of 0.001 cm. The apparent volume was determined using the equation:

$$V_{ap} = \frac{\pi \cdot d^2 \cdot h}{4} \quad (2)$$

where V_{ap} (kg/m³) is the apparent volume, d (m) is the diameter and h (m) is the length of each extrudate. There have been 7 repetitions for each extrudate-sample. The length and the diameter of a specific extrudate were determined as the average of the 7 repetition samples.

Apparent density was determined as:

$$\rho_{ap} = \frac{m_s}{V_{ap}} \quad (3)$$

where ρ_{ap} (kg/m³) is the apparent density and m_s (kg) is the mass of the extrudates.

Porosity

Porosity, ε , was determined using the equation:

$$\varepsilon = 1 - \frac{\rho_{ap}}{\rho_{ts}} \quad (4)$$

Expansion ratio

The expansion ratio, Exp , was estimated by the quotient of the diameter of the extrudates to the diameter of the die (Ahmed 1999):

$$Exp = \frac{d}{d_o} \quad (5)$$

where d (m) is the diameter of the extrudates and d_o (m) is the diameter of the die. Seven replicates were used for the determination of expansion ratio.

Scanning electron microscopy

Scanning Electron Microscopy (SEM) was used for the visualization of exudate's microstructure. Representative samples were cut with a blade at a thickness of 1–2 mm. In order to make the surface reflect the electron beam, the samples were sputtered with gold particles creating a layer with 11 nm thickness, using a SC7620 Mini Sputter Coater (Quorum Technologies, West Sussex, UK). The specimens were then photographed using an electron microscope (Quanta 200 FEI (2004), OR, USA) operated at 25 kV. The materials were examined at 10–12 mm working distance and spot size equal to 5, using large field detector (LFD).

Textural properties

The compression tests were performed at room temperature (25 °C) using a Zwick Universal Testing Machine (Zwick, Model 1120, Ulm, Germany). The samples were compressed between two parallel plates of diameter 10 cm each, at a crosshead speed of 5 mm/min, with a 100 N load cell. Force and deformation were recorded and the resulting stress-strain compression curves were constructed and used for the evaluation of textural parameters. The results are reported as the average of 5 replicate measurements.

Maximum stress, σ_{max} (kPa), maximum strain, ε_{max} (mm/mm), modulus of elasticity E (kPa) and the number of peaks during compression, N , were measured.

Fig. 1 Effect of **a)** feed moisture content, **b)** inulin concentration, **c)** extrusion temperature and **d)** screw speed on the apparent density and **e)** feed moisture content, **f)** inulin concentration, **g)** extrusion temperature and **h)** screw speed on the porosity of extruded products

Modulus of elasticity was calculated from the slope of the linear part of the compression curve as:

$$E = \frac{\sigma}{\varepsilon} \quad (6)$$

Fracture of cellular brittle materials during compression test occurs in several small stages resulting in a jagged force-deformation signature. The jaggedness of the compressive curves was quantified using the number of positive peaks (local maxima) during compression.

Mathematical modeling

The value of each property of extrudate was determined by using the following model (Katsavou et al. 2011):

$$M_i = M_0 * \left(\frac{X}{X_0}\right)^{\alpha_X} * \left(\frac{100-C}{100-C_0}\right)^{\alpha_C} * \left(\frac{T}{T_0}\right)^{\alpha_T} * \left(\frac{R}{R_0}\right)^{\alpha_R} \quad (7)$$

where: M_i : is the value of each property, M_0 : the average value of each property, X : the moisture content (%w/w), C : inulin concentration (%), T : extrusion temperature (°C) and R : screw speed (rpm). X_0 , C_0 , T_0 and R_0 are the corresponding values of the experimental parameters at reference conditions and α_X , α_C ,

α_T , and α_R are the exponents of moisture content, inulin concentration, extrusion temperature and screw speed, respectively.

For the estimation of the model parameters regression analysis was performed, using Statistica Software 7.1.

Results and discussion

Mathematical modeling

Table 1 summarizes the three levels of the process parameters, as well as the reference conditions used in the model. The reference conditions correspond to the 0 level of parameters. Table 1 also presents the model parameters of the selected power model received after regression analysis, which describe well the experimental data, according to statistical results (R^2) and are analyzed in detail below.

Structural properties

True density

True density of extrudates was not significantly affected by process conditions and material characteristics. And since

Fig. 2 Effect of **a)** feed moisture content, **b)** inulin concentration, **c)** extrusion temperature and **d)** screw speed on the expansion ratio of extruded products

extrudates are characterized by low moisture content, true density was similar to the density of the solids at zero moisture

content (Lazou and Krokida 2010). True density of the inulin extrudates was estimated as 1.417 g/cm^3 .

Fig. 3 Extruded products produced under different: **A.** feed moisture content: **a)** $X=14\%$, **b)** $X=17\%$ and **c)** $X=20\%$ (const. $C=10\%$, $T=160^\circ\text{C}$, $R=200 \text{ rpm}$). **B.** inulin concentration: **a)** $C=5\%$, **b)** $C=10\%$ and **c)** $C=15\%$ (const. $X=17\%$, $T=160^\circ\text{C}$, $R=200 \text{ rpm}$). **C.**

extrusion temperature: **a)** $T=140^\circ\text{C}$, **b)** $T=160^\circ\text{C}$ και **c)** $T=180^\circ\text{C}$ (const. $X=14$, $C=10\%$, $R=200 \text{ rpm}$) and **D.** screw speed: **a)** $R=150 \text{ rpm}$, **b)** $R=200 \text{ rpm}$ and **c)** $R=250 \text{ rpm}$ (const. $X=14$, $C=10\%$, $T=160^\circ\text{C}$)

Apparent density-porosity

The results concerning apparent density and porosity are graphically presented in Fig. 1. The solid lines represent the calculated values of the model fitting to the experimental data.

Apparent density increased with the increase of moisture content and inulin concentration in the mixture. The increased moisture content of extruded products changes the molecular structure of amylopectin that is contained in the corn starch and reduces the viscosity of the mixture. Moisture also reduces friction between the dough and the screw and affects negatively starch gelatinization. As a result, expansion decreases and apparent density increases (Liu et al. 2000).

As expected from the literature, the increase of the inulin concentration has led to an increase on the density of the extrudates. When dietary fiber is added to starchy products causes the rupture of cell walls and prevents air bubbles from expanding. This phenomenon leads to an increase in density (Sacchetti et al. 2004; Obatolu et al. 2006; Anton et al. 2009; Pastor-Cavada et al. 2011).

On the other hand, the increase of extrusion temperature caused the decrease of apparent density. That could be attributed to the decrease of the melt viscosity of the mixture, which leads to bubble growth during extrusion, allowing the dough to expand more rapidly and to create a less dense structure. In

addition, the increase of the vapor pressure at higher temperatures leads to increased puffing and consequently lower apparent densities. This observation is in accordance with other bibliographic references (Suvendu 1997; Ding et al. 2005; Lazou and Krokida 2010).

Moreover, the increase of screw speed caused the decrease of apparent density. This can be attributed to the reduction of the viscosity, the increase of the elasticity of the dough and the gelatinization of starch, that increases the volume of the expanded products and decreases the apparent density (Sacchetti et al. 2004; Hagenimana et al. 2006). Porosity of extrudates presented the opposite trend than apparent density, as expected from Eq. 4.

Expansion ratio

As shown in Fig. 2, the selected mathematical model is well fitted to the obtained data, as it was revealed by statistical analysis. Regression analysis also revealed that the expansion ratio of the extrudates decreased with increasing initial moisture content, inulin concentration and extrusion temperature. Expansion ratio follows an increasing trend when the screw speed increases.

The increased feed moisture of the extrudates causes the change of the molecular structure of amylopectin that is contained in the starch of the rice flour. As a result, the

Fig. 4 Effect of **a)** feed moisture content, **b)** inulin concentration, **c)** extrusion temperature and **d)** screw speed on the maximum stress of the extruded products

viscosity and the expansion ratio decreases and that leads to a more compact-solid structure (Baik et al. 2004).

Moreover, the increase of inulin concentration caused the decrease of the expansion ratio. A characteristic of fibers is that they can bind water more strongly than starch, inhibiting water loss at the die and reducing its ability for expansion. The lower expansion ratio may also be justified by the fact that fibers can cause rupture of cell walls and prevent air bubbles to expand to the maximum level (Lue and Huff 1991; Anton et al. 2009).

The increasing extrusion temperature has led to the decrease of the expansion ratio. Probably that phenomenon is caused by the fragmentation of the starch in high extrusion temperatures (Hagenimana et al. 2006).

The increase of the expansion ratio was a consequence of the increasing screw speed, which could be linked to the fact that the mixture had less residence time and therefore a decrease of the degree of gelatinization of starch occurred, causing more expanded extrudates (Lue and Huff 1991; Bisharat et al. 2013).

Scanning electron microscopy

The images of rice extrudates from scanning electron microscope are provided in Fig. 3. The alternations of the porosity in correlation of the process conditions and materials' characteristics can be observed.

The SEM images (Fig. 3a) show that while increasing feed moisture the porosity is decreasing, as expected from the previous results. It is observed that the pores are getting less in number and bigger by the increasing moisture content. It can also be observed in Fig. 3b that the increase of inulin concentration and the decrease of screw speed led to the development of thicker cell walls and as a result more crispy products. The increase of the extrusion temperature has influenced the extrudates to products with increased viscosity and as a consequence a formation of microporous structure with more air cells.

Textural properties

Maximum stress

As it is presented in Fig. 4 the increase of feed moisture and inulin concentration in the mixture caused the increase of the maximum stress. On the other hand, maximum stress decreases by increasing extrusion temperature and screw speed. Maximum stress represents the hardness of the extrudates.

In addition, texture is linked with density, expansion and thickness of cell walls (Agbisit et al. 2007). Higher wall thickness or higher density results in an increase in maximum stress. As the increase of moisture content and inulin

Fig. 5 Effect of **a)** feed moisture content, **b)** inulin concentration, **c)** extrusion temperature and **d)** screw speed on the maximum strain of the extruded products

composition, as well as the decrease of screw speed, led to extrudates with high density, this leads therefore to the increase of maximum stress.

On the other hand, when increasing temperature the maximum stress seemed to decrease. The increase of temperature leads to the increase of porosity as indicated above. A high porosity extrudate has soft texture leading to lowering of the maximum stress, as maximum stress represents the hardness of the extrudates. The reduction of stiffness of extruded snacks with temperature has been reported for rice based extrudates (Ding et al. 2005; Gui et al. 2013). In order to produce extrudates enriched with inulin with these characteristics, the optimal value of inulin concentration is between 5 and 10 %.

Maximum strain

Maximum strain is also indicative of the breakage point during compression test. According to regression analysis, moisture content and extrusion temperature did not significantly ($p>0.05$) affect maximum strain, which is also observed in Fig. 5. However, it increases when the inulin concentration, while the increase of screw speed caused the decrease of the maximum strain. Extruded products containing fibers, such as inulin, in high concentrations are usually compact, tough, not

crisp, and with undesirable texture due to the low expansion ratio (Bisharat et al. 2014). This justifies the increase of the maximum strain in high concentrations of inulin. On the other hand, higher screw speed resulted in products with higher porosity and decreased rupture point and therefore maximum strain (Hayter and Smith 1988).

Modulus of elasticity

The modulus of elasticity (Fig. 6) has similar behavior with the density of the extrudates (Hutchinson et al. 1987) and it is indicative of the stiffness of the products (Corradini and Peleg 2008). Feed moisture content increased modulus of elasticity of rice extrudates. The presence of water, that behaves like a plasticizer in low temperature, leads to a decrease of the viscosity of the products and also to a decrease of the gelatinization ratio of the starch and the growth of air bubbles, that then leads to more fragile structures leading to low resistant cell walls and more structural fractures and less crunchy extrudates (Ferreira et al. 2011).

As it is shown in Fig. 6, the increase of extrusion temperature led to a decrease in the modulus of elasticity in accordance with the results referring to maximum stress. In more detail, the increase of extrusion temperature can be linked with

Fig. 6 Effect of **a**) feed moisture content, **b**) inulin concentration, **c**) extrusion temperature and **d**) screw speed on the modulus of elasticity of the extruded products

the decrease of the thickness of cell walls (Saeleaw et al. 2012), which therefore leads to the decrease of modulus of elasticity.

Different results are presented by the increase of inulin concentration. By decreasing the rice flour percentage in the initial mixtures and increasing the concentration of fibers through the addition of inulin the elasticity of the products was reduced (Onwulata et al. 2001). Extruded products enriched with high level of dietary fibers are usually compact, hard, not crunchy and appear a textural undesirable because of their low expansion. This phenomenon can be attributed to the dietary fibers, that decrease the expansion of the air bubbles by breaking the cell walls before the final expansion (Liu et al. 2000; Ferreira et al. 2011).

Number of peaks

As it is shown in Fig. 7 the extrusion temperature decreased the number of peaks during compression of the extruded snacks. The number of peaks is also related with the crispness of the extrudate, as it is linked with the rapid drop of force during mastication process (Bisharat et al. 2014). As it has been stated above increased temperature produces softer structure that is formed under higher temperatures, due to increased porosity, resulting in lower number of peaks.

On the other hand, screw speed increased the number of peaks during compression. The increased screw speed is responsible for the production of less dense extrudates with less thick cell walls. The crunchiness of such products is expected to be increased. This fact can explain this variation in number of peaks during compression.

In addition, feed moisture content and inulin concentration decreased the number of peaks during compression. It has been shown that increasing the values of these independent variables has led to the formation of more rigid structures with increased apparent density.

Conclusion

Structural and textural properties of rice based extrudates enriched with inulin were investigated as a function of process conditions and material characteristics. Simple mathematical models were developed in order to determine how the extrusion conditions and feed composition influenced apparent density, porosity, expansion ration, maximum stress and strain, modulus of elasticity and number of peaks under compression.

Structural properties of the extrudates play a key role in the design, since they are directly linked with the organoleptic characteristics during chewing, and their preservation time.

Fig. 7 Effect of **a)** feed moisture content, **b)** inulin concentration, **c)** extrusion temperature and **d)** screw speed on the number of peaks of the extruded products

It is observed that the two main factors that affected the porosity is the moisture content of the product and the concentration of inulin in the extrudate. The best products are those which have the feed moisture of 14–17 % and an inulin concentration of 5–10 %. In addition, expansion ratio increased when increasing screw speed and decreased when increasing moisture content, inulin concentration and extrusion temperature.

Concerning textural properties it was observed that the process parameters and the material characteristics significantly affected the value of the maximum stress, which represents the fragility of products. Medium and especially high concentrations of inulin (10–15 %) in mixtures with rice flour, high feed moisture (20 %), low extrusion temperatures (140–160 °C) and the minimum experimental value of the screw speed (150 rpm) have led to increased maximum stress. The modulus of elasticity is indicative of the hardness of the samples. Usually, the higher the modulus of elasticity of an extrudate is, the more compact, hard and less crispy texture product has. By increasing the moisture content of the mixtures the modulus of elasticity has raised. That can also be justified by the increased density of the products. On the other hand the increase of inulin concentration, the extrusion temperature and the screw speed is observed to reduce the modulus of elasticity.

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References

- Agbisit R, Alavi S, Cheng E, Herald T, Trater A (2007) Relationships between microstructure and mechanical properties of cellular corn-starch extrudates. *J Texture Stud* 38(2):199–219
- Ahmed ZS (1999) Physico-chemical, structural and sensory quality of corn-based flax-snack. *Food Nahrung* 43(4):253–258
- Anton AA, Gary Fulcher R, Arntfield SD (2009) Physical and nutritional impact of fortification of corn starch-based extruded snacks with common bean (*Phaseolus vulgaris* L.) flour: effects of bean addition and extrusion cooking. *Food Chem* 113(4):989–996
- Baik B-K, Powers J, Nguyen LT (2004) Extrusion of regular and waxy barley flours for production of expanded cereals. *Cereal Chem J* 81(1):94–99
- Bisharat GI, Oikonomopoulou VP, Panagiotou NM, Krokida MK, Maroulis ZB (2013) Effect of extrusion conditions on the structural properties of corn extrudates enriched with dehydrated vegetables. *Food Res Int* 53(1):1–14
- Bisharat GI, Eleni PN, Panagiotou NM, Krokida MK, Maroulis ZB (2014) Thermal, textural, and physicochemical analysis of corn extrudates enriched with broccoli or olive paste. *Int J Food Prop* 17(9):2100–2116
- Conti-Silva AC, Bastos DHM, Areas JAG (2012) The effects of extrusion conditions and the addition of volatile compounds and flavour enhancers to corn grits on the retention of the volatile compounds and texture of the extrudates. *Int J Food Sci Technol* 47:1896–1902
- Corradini MG, Peleg M (2008) Solid food foams. *Food materials science: principles and practice*: 169–202
- Ding Q-B, Ainsworth P, Tucker G, Marson H (2005) The effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice-based expanded snacks. *J Food Eng* 66(3):283–289
- Ding Q-B, Ainsworth P, Plunkett A, Tucker G, Marson H (2006) The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. *J Food Eng* 73(2):142–148
- Ferreira RE, Chang YK, Steel CJ (2011) Influence of wheat bran addition and of thermoplastic extrusion process parameters on physical properties of corn-based expanded extruded snacks. *Alim Nutr Araraquara* 22(4):507–520
- Foschia M, Peressini D, Sensidoni A, Brennan CS (2013) The effects of dietary fibre addition on the quality of common cereal products. *J Cereal Sci*. doi:10.1016/j.jcbr.2011.03.031
- Gui Y, Gil SK, Ryu GH (2013) Effects of extrusion conditions on the physicochemical properties of extruded red ginseng. *Prev Nutr Food Sci* 17(3):203–209
- Hagenimana A, Ding X, Fang T (2006) Evaluation of rice flour modified by extrusion cooking. *J Cereal Sci* 43(1):38–46
- Hayter AL, Smith AC (1988) The mechanical properties of extruded food foams. *J Mater Sci* 23(2):736–743
- Hutchinson RJ, Siodlak GDE, Smith AC (1987) Influence of processing variables on the mechanical properties of extruded maize. *J Mater Sci* 22(11):3956–3962
- Jyothi AN, Sheriff JT, Sajeew MS (2009) Physical and functional properties of arrowroot starch extrudates. *J Food Sci* 74(2):E97–E104
- Katsavou ID, Krokida MK, Ziomas IC (2011) Effect of production conditions on structural properties of refractory materials. *Mater Res Innov* 15(1):47–52
- Krokida MK, Karathanos VT, Maroulis ZB (1998) Effect of freeze-drying conditions on shrinkage and porosity of dehydrated agricultural products. *J J Food Eng* 35(4):369–380
- Krokida MK, Oreopoulou V, Maroulis ZB, Marinou-Kouris D (2001) Effect of pre-treatment on viscoelastic behaviour of potato strips. *J Food Eng* 50(1):11–17
- Krokida MK, Michailidis PA, Bisharat GI, Marinou-Kouris D, Rahman MS (2009) Measurement of density, shrinkage, and porosity. CRC Press, New York
- Lazou A, Krokida M (2010) Functional properties of corn and corn - lentil extrudates. *Food Res Int* 43(2):609–616
- Liu Y, Hsieh F, Heymann H, Huff HE (2000) Effect of process conditions on the physical and sensory properties of extruded oat-corn puff. *J Food Sci* 65(7):1253–1259
- Lue S, Huff HE (1991) Extrusion cooking of corn meal and sugar beet fiber: effects on expansion properties, starch gelatinization, and dietary fiber content. *Cereal Chem* 68(3):227–234
- Meyer D, Bayarri S, Tarrega A, Costell E (2011) Inulin as texture modifier in dairy products. *Food Hydrocoll* 25(8):1881–1890
- Obatolu VA, Omuetti Olusola O, Adebawale EA (2006) Qualities of extruded puffed snacks from maize/soybean mixture. *J Food Process Eng* 29(2):149–161
- Onwulata CI, Smith PW, Konstance RP, Holsinger VH (2001) Incorporation of whey products in extruded corn, potato or rice snacks. *Food Res Int* 34(8):679–687
- Pastor-Cavada E, Drago SR, Gonzalez RJ, Juan R, Pastor JE, Alaiz M et al (2011) Effects of the addition of wild legumes (*lathyrus annuus* and *lathyrus clymenum*) on the physical and nutritional properties of extruded products based on whole corn and brown rice. *Food Chem* 128(4):961–967
- Raphaelides SN, Dimitreli G, Exarhopoulos S, Mintzas D, Lykidou A (2012) Effect of processing conditions on the physicochemical and structural characteristics of pregelatinised starch-fatty acid-glycerol extrudates. *Carbohydr Polym* 88(1):282–289
- Rodriguez-Miranda J, Ruiz-Lopez II, Herman-Lara E, Martinez-Sanchez CE, Delgado-Licon E, Vivar-Vera MA (2011) Development of extruded snacks using taro (*Colocasia esculenta*) and nixtamalized maize (*zea mays*) flour blends. *LWT-Food Sci Technol* 44(3):673–680

- Rößle C, Ktenioudaki A, Gallagher E (2011) Inulin and oligofructose as fat and sugar substitutes in quick breads (scones): a mixture design approach. *Eur Food Res Technol* 233(1):167–181
- Saavedra-Leos MZ et al (2014) Physical properties of inulin and inulin-orange juice: physical characterization and technological application. *Carbohydr Polym* 105:10–19
- Sacchetti G, Pinnavaia GG, Guidolin E, Rosa MD (2004) Effects of extrusion temperature and feed composition on the functional, physical and sensory properties of chestnut and rice flour-based snack-like products. *Food Res Int* 37(5):527–534
- Saeleaw M, Durrschmid K, Schleining G (2012) The effect of extrusion conditions on mechanical-sound and sensory evaluation of rye expanded snack. *J Food Eng* 110(4):532–540
- Savage G, MacFarlane A, Ball K, Worsley A, Crawford D (2007) Snacking behaviours of adolescents and their association with skipping meals. *Int J Behav Nutr Phys* 4:Article number 36
- Suwendu B (1997) Twin-screw extrusion of rice-green gram blend: extrusion and extrudate characteristics. *J Food Eng* 32(1):83–99
- Velasco P (2011) Antioxidant potential of broccoli stalk: a preliminary investigation. *Med J Nutr Metab* 4(3):227–230