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Cauliflower by-products as a new source of dietary fibre, antioxidants and proteins in cereal based ready-to-eat expanded snacks

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Abstract

Cauliflower is a vegetable rich in nutrients but has a highest waste index. The incorporation of cauliflower trimmings into ready-to-eat expanded products and their effect on the textural and functional properties of extrudates have been studied. Dried and milled cauliflower at levels of 5–20% was added to the formulation mix. The results obtained from the analysis of the extrudates are discussed in terms of the effect of cauliflower co-products on nutritional and textural characteristics, and the effects of processing conditions. The samples were processed in a twin-screw extruder with a combination of parameters including: solid feed rate of 20–25 kg/h, water feed adjusted to 9–11%, screw speed of 250–350 rpm and process temperatures 80–120 °C. Pressure, torque and material temperature during extrusion were recorded. It was found that addition of cauliflower significantly increased the dietary fibre ($r^2 = 0.9^{***}$) and levels of proteins. Extrusion cooking significantly ($P < 0.0001$) increased the level of phenolic compounds and antioxidants but significantly ($P < 0.001$) decreased protein in vitro digestibility and fibre content in the extruded products. The expansion indices, total cell area of the products, wall thickness showed negative correlation to the level of cauliflower. Sensory test panel indicated that cauliflower could be incorporated into ready-to-eat expanded products up to the level of 10%.

Keywords: Cauliflower by-products; Extrusion technology; Ready-to eat snacks

1. Introduction

The food processing industry produces large quantities of waste co-products. Over 1 million tonnes of vegetable trimmings from the vegetable processing industry and around 3.4 million tonnes of spent grain from the brewing industry are produced in the EU every year (Eurostat data). They are inexpensive, available in large quantities, characterised by a high dietary fibre content resulting with high water binding capacity and relatively low enzyme digestible organic matter (Serena and Bach-Knudsen, 2007). Due to the high dietary fibre content and contrasting dietary fibre properties, the co-products could be used to change physicochemical properties of diets.

A number of researchers have used fruits and vegetable by-products such as apple, pear, orange, peach, blackcurrant, cherry, artichoke, asparagus, onion, carrot pomace (Grigelmo-Miguel and Martin-Belloso, 1999; Ng et al., 1999; Nawirska and Kwasnievska, 2005) as sources of dietary fibre supplements in refined food. Dietary fibre concentrates from vegetables showed a high total dietary fibre content and better insoluble/soluble dietary fibre ratios than cereal brans (Grigelmo-Miguel and Martin-Belloso, 1999).

Cauliflower has a very high waste index (Kulkarni et al., 2001) and is an excellent source of protein (16.1%), cellulose (16%) and hemicellulose (8%) (Wadhwa et al., 2006). It is considered as a rich source of dietary fibre and it

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possess both antioxidant and anticarcinogenic properties. Phenolic compounds and vitamin C are the major antioxidants of brassica vegetables, due to their high content and high antioxidant activity (Podsedek, 2007). Lipid-soluble antioxidants (carotenoids and vitamin E) are responsible for up to 20% of the brassica total antioxidant activity. The level of non-starch polysaccharide (NPS) in the upper cauliflower stem is similar to that of the floret and both are rich in pectic polysaccharides, while the cauliflower lower stem is rich in NPS due mainly to cellulose and xylan deposition (Femenia et al., 1998).

Limited information is available on extrusion processing of vegetable by-products. Some authors have used extrusion technology to solubilise pectic substances from sugarbeet pulp by-products (Ralet et al., 1991). Ng et al. (1999) investigated the effects of extrusion cooking on the physicochemical characteristics and microstructure of cell walls on onion waste. They found that extrusion cooking increase the solubility of pectic polymers and hemicelluloses accompanied by an increase in swelling of the cell-wall material. Later, Larrea et al. (2005) modified the properties of fibre components in orange pulps using extrusion technology. They reported that extrusion conditions decreased insoluble dietary fibre and increased soluble fibre.

The objective of this study was to incorporate cauliflower by-products as a source of dietary fibre into ready-to-eat snacks. The results obtained from the nutritional and textural analyses together with sensory evaluation of the extrudates are discussed in the terms of interaction between the ingredients and effects of process conditions. Reference searches indicate that no research on the incorporation of cauliflower by-products into extruded products has been published.

2. Materials and methods

The ingredients used for the cauliflower ready-to-eat snack preparation were: wheat flour with composition (w/w) of 12.6% protein, 1.3% fat, 0.9% sugar, 77.3% starch and 0.9% fibre (Smiths Flours Mills, Workshop, UK); cauliflower (purchased from a local supermarket in Manchester); corn starch (w/w) with moisture content of 12% and composition of 80% amylopectin, 20% amylose and 88% carbohydrates (Cerestar, A Cargill Company, Manchester, UK); oat flour (Avenaflo, Crewe, UK); egg whites (Renshaw Scott Ltd., Liverpool, UK); milk powder (w/w) 12.2% protein, 61.9% carbohydrate, 20.4% fat and 0.4% sodium (Foodsavile, Welwyn Garden City, UK); onion powder (db) with 6% moisture content, 1.2% protein, 0.2% fat and 92.6% carbohydrates (Fisue Food Ingredients, Milton Keynes, UK); tomato powder (w/w) with the composition of 14.1% protein, 55.7% carbohydrates, 3% fat and 12.3% fibre (Fisue Food Ingredients, Milton Keynes, UK); carrot powder (J.L. Priestley & Co Ltd., Lincolnshire, UK); dill and mint (Chat Moss Herbs, Manchester, UK); paprika and salt (purchased from a local supermarket in Manchester).

2.1. Preparation of dry cauliflower

Cauliflower with some florets, curd, stem and leaves were washed thoroughly and then ground in a Kilia Bowl Chopper (Kilia, Kiel, Germany). The sample was kept at the 5 °C for 16 h and then dried at 80 °C for 10 h in a Teknotronic reel oven (Teknigas Ltd., Sussex, England) to a moisture content of 6.9–8.1%. The dried sample was then milled using a 0.5 mm mesh screen, packed and then sealed in polyethylene bags and kept at room temperature until use.

2.2. Preparation of sample

Ingredient formulations for extrusion products are given in Table 1. Wheat flour was replaced with dry cauliflower at levels of 5%, 10%, 15% and 20%. All the ingredients were weighed and then mixed in a Hobart NCM mixer (Process Plant and Machinery Ltd., UK) for 20 min. Five samples in total were prepared. After mixing samples were stored in polyethylene bags at room temperature for 24 h.

The moisture content of all the samples was estimated using the oven method (AOAC method, 1984) and later adjusted by pumping water into the extruder during extrusion runs.

2.3. Extrusion experiments

Extrusion trials were performed using a Werner and Pfleiderer Continua 37 co-rotating twin-screw extruder (Stuttgart, Germany). The barrel diameter and L/D ratio were 37 mm and 27:1, respectively. A screw configuration that was a standard design for processing cereals and flour-based products was used. This screw profile was made up of conveying self-wiping elements except for a section consisting of short reverse and forwarding elements to improve mixing and apply shear to the material being extruded while restricting flow and building up pressure. The exit diameter of the circular die was 4 mm. A twin-screw volumetric feeder (Rospen, Gloucestershire, UK) was used for feeding the dry mixture to the extruder and a Watson–Marlow 505 DI pump (Cornwall, UK) which was used to control the solid feed and water inputs respectively.

Table 1
Formulations for extrudate development

Ingredients	(% w/w)
Wheat flour	16.4–36.4
Cauliflower	0–20
Corn starch	20
Oat flour	10
Egg whites	10
Milk powder	10
Onion powder	3
Tomato powder	5
Carrot powder	5
Dill	0.1
Mint	0.1
Salt	0.4

The process conditions were set as follows: solid feed rate of 20–25 kg/h, water feed adjusted between 9% and 11%, screw speeds of 250, 300 and 350 rpm and two barrel temperatures in two zones 80 °C at the feed entry and 120 °C at the die exit. Pressure, material temperature and torque were monitored during extrusion runs.

Once the extrusion response parameters, screw speed, die temperature and die pressure were constant, extrudates were cut (approximately 40 cm long) with a sharp knife as they emerged from the die and left to cool at room temperature for about 30 min, packaged in plastic bags and stored at room temperature until analyzed.

Specific mechanical energy (SME) was calculated as the total power supplied (Hu et al., 1993):

$$\mathrm{SME(kW\ H/kg)} = \frac{\text{Screw speed} \times \text{Power (KW)} \times \text{Torque (\%)}}{\text{Max. screw speed} \times \text{Throughput (kg/h)} \times 100}$$

2.4. Analyses of extrudates

2.4.1. Protein content (PC)

PC was estimated from the crude nitrogen content of the sample determined by the Kjedahl method (Nx 6.25), (AOAC, 1984).

2.4.2. Fat content (FC)

Total fat content was determined based on a gas chromatographic technique (Gertz and Fiebig, 2000).

2.4.3. Phytic acid (PA)

PA was measured by a colorimetric method according to Haugh and Lantzsch (1983). Phytic acid in the sample was extracted with a solution of HCl (0.2 N) and precipitated with a solution of Fe III (ammonium iron (III) sulphate · 12 H_2O).

2.4.4. Total antioxidant capacity (TAC)

TAC of samples was determined according to the method given by Erel (2004). This method is based on the decolourization of ABTS (2-2 azinobis (3-methybenzothiazoline-6-sulfonate)) radical action. The samples were extracted using 50% methanol.

2.4.5. Total phenolic compounds (TPC)

TPC was determined according a modified method of Skerget et al. (2005). This was used to calculate the concentration of total phenolics in the samples as mM gallic acid/g dry sample using a UV spectrometer, based on a colorimetric oxidation/reduction reaction. The oxidizing agent used was Folin–Ciocalteu reagent. The samples were extracted with pure methanol at 40 °C.

2.4.6. Protein in vitro digestibility (PIVD)

The samples were investigated for their in vitro protein digestibility by the modified method of Hsu et al. (1977). Fifty milliliters of aqueous protein suspension having 6.25 mg protein/ml was mixed for 60 min at 5 °C. The samples were then placed in a water bath at 37 °C and the pH was adjusted to 8 using 0.1 N NaOH and/or 0.1 N HCl, while stirring. Lyophilized, crystallized trypsin (Sigma Chemical Co., St Louis, Mo) at a concentration of 1.6 mg/ml was maintained in an ice bath and the pH was adjusted to 8.00 with 0.1 N NaOH and/or 0.1 N HCl. Five millilitres of enzyme solution were then added to the protein suspension, which was being stirred at 37 °C. The trypsin had an activity of 13,766 BAEE units/mg protein. A rapid decline in pH was observed. The pH drop was recorded 15 s after enzyme addition and at 1 min intervals for 10 min. Triplicate analyses were performed for each sample. The enzyme solution was freshly prepared before each series of the test. The percentage of protein digestibility (Y) was calculated by the equation:

$$Y = 210.4 - 18.1x$$

where x is the change in pH after 10 min.

2.4.7. Fibre content

The total dietary fibre content of extrudates was determined using a combination of enzymatic and gravimetric methods (Sigma–Aldrich, Inc., Saint Louis, Missouri, US) (AOAC, 1997). Milled and dried samples were gelatinized with heat stable α-amylase and then enzymatically digested with protease and amyloglucosidase to remove protein and starch present in the sample. Ethanol was added to precipitate the soluble dietary fibre. The residue was then filtered and washed with ethanol and acetone. After drying, the residue was weighed. Half of the samples were analyzed for protein and the others ashed. Total dietary fibre is the weight of the residue less the weight of the protein and ash.

2.4.8. Colour

The colour of the extrudate was assessed using a Hunter-Lab colorimeter (Optical Sensor, Hunter Associates Laboratory Inc., Reston Virginia, USA). In the Hunter-Lab colorimeter, the colour of a sample is denoted by the three dimensions, L^*, a^* and b^*. The L^*, a^* and b^* readings were then taken from a digital display unit (Model D 25-2). The L^* value gives a measure of the lightness of the product colour from 100 for perfect white to 0 for black, as the eye would evaluate it. The redness/greenness and yellowness/blueness are denoted by the a^* and b^* values, respectively. The colour of the samples was measured after grinding the samples to fine flour (particle size <200 μm) using a type ZM100 ultra centrifugal mill (Retsch GmbH& Co., Haan, Germany).

2.4.9. Water absorption index (WAI) and water solubility index (WSI)

WAI and WSI were determined according to the method developed for cereals (Anderson et al., 1969). The ground extrudate was suspended in water at room temperature for 30 min, gently stirred during this period, and then

centrifuged at 3000*g* for 15 min. The supernatant was decanted into an evaporating dish of known weight. The WSI was the weight of dry solids in the supernatant expressed as a percentage of the original weight of sample. The WAI was the weight of gel obtained after removal of the supernatant per unit weight of original dry solids.

2.4.10. Bulk density (BD)

BD (g/cm^3) was calculated according to the method of Alvarez-Martinez et al. (1988):

$$\mathrm{BD} = \frac{4m}{\pi d^2 L}$$

where m is mass (g) of a length L (cm) of extrudate with diameter d (cm).

2.4.11. Expansion indices

The determination of volumetric, radial (or sectional) and longitudinal (or axial) expansion indices (denoted volumetric expansion index (VEI), sectional expansion index (SEI), and longitudinal expansion index (LEI)) were determined according to the definition given by Alvarez-Martinez et al. (1988):

$$\mathrm{LEI} = [(1 - M_\mathrm{d}) * \rho_\mathrm{d} * S_\mathrm{d}]/(1 - M_\mathrm{e}) * \rho S_\mathrm{e}$$

$$\mathrm{SEI} = (D_\mathrm{e}/D_\mathrm{d})^2$$

$$\mathrm{VEI} = \mathrm{SEI} * \ \mathrm{LEI}$$

where ρ_d is the melt density at the die ($\rho_\mathrm{d} = 1400$ kg/m^3), ρ is the apparent density of the extrudate (kg/m^3), S_d and S_e were respectively the cross section of the die and cross section of the extrudate (m^2). D_e and D_d were respectively the diameter of extrudates and die diameter.

2.4.12. Texture analysis

Mechanical properties of the extrudates were determined by a three-point bend method using a TA – XT2 texture analyzer (Stable Micro Systems Ltd., Godalming, UK)

Table 2
Process conditions recorded during each experimental run obtained using design expert program

Run	Wheat flour (%)	Cauliflower	Solid feed (kg/h)	Water feed (%)	Screw speed (rpm)	Material temperature (°C)	Pressure	Torque	SME
1	80	20	25	11	250	150	0	42	0.08
2	90	10	20	11	350	133	0	38	0.13
3	90	10	25	9	250	140	10	42	0.08
4	80	20	25	11	350	150	0	34.5	0.09
5	80	20	22.5	10	250	150	0	40	0.08
6	80	20	20	10	300	145	0	34	0.10
7	90	10	20	9	350	138	0	36	0.12
8	85	15	20	11	350	140	0	34	0.11
9	100	0	25	9	350	130	0	34	0.09
10	80	20	22.5	11	300	150	0	38	0.10
11	90	10	20	9	250	145	0	40	0.10
12	90	10	22.5	10	250	145	5	42	0.09
13	80	20	20	9	250	145	0	34	0.08
14	100	0	25	9	250	132	0	34.5	0.07
15	80	20	25	9	250	150	5	44	0.08
16	80	20	22.5	10	350	150	0	40	0.12
17	95	5	22.5	10	250	140	0	34	0.07
18	90	10	25	9	350	145	5	40	0.11
19	80	20	20	11	350	145	0	34	0.11
20	90	10	20	9	350	140	0	40	0.13
21	95	5	22.5	11	300	140	0	32	0.08
22	95	5	25	11	250	140	0	38	0.07
23	100	0	22.5	10	350	135	0	34	0.10
24	100	0	20	11	250	135	0	25	0.06
25	95	5	22.5	9	300	135	0	32	0.08
26	85	15	25	9	250	140	0	41	0.08
27	100	0	20	11	350	135	0	30	0.10
28	80	20	25	9	350	150	0	36	0.10
29	100	0	20	10	300	135	0	33	0.09
30	80	20	20	11	250	145	0	38	0.09
31	100	0	22.5	11	300	130	0	28	0.07
32	100	0	25	10	300	135	0	32	0.07
33	100	0	25	11	250	125	0	34.5	0.07
34	95	5	20	11	250	135	0	31	0.07
35	80	20	20	9	350	140	0	34	0.11
36	100	0	20	9	250	133	0	32	0.08
37	100	0	25	11	350	130	0	32	0.09
38	80	20	22.5	9.5	300	150	0	38	0.10
39	85	15	25	11	350	150	0	36	0.10
40	85	15	25	10	300	145	0	38	0.09

equipped with a 25 kg load cell. An extrudate 100 mm long was compressed with a probe 90 mm long at a crosshead speed 3 mm/sec to 4 mm of original diameter of the extrudate. The compression generated a curve with the force over distance. The highest value of force was taken as a measurement for hardness.

2.4.13. Image analysis

Image analysis was conducted on samples number 1, 13, 17 and 40 (Table 2). All the samples contained different levels of cauliflower and were obtained using similar screw speeds. Cylindrical shape extrudates were cut using a blade to obtain a product 10 mm in length. Images of sectional and longitudinal cross sections of extrudates were captured with a 5x magnification using a digital camera, Sony, MVC-CD500 (Sony Electronics, Inc., NJ, US). Image analyses were performed using the UTHSCSA Image tool program (Version 2.0, University of Texas Health Science Centre, and San Antonio, Texas, available by anonymous FTP from maxrad6.uthscsa.edu). Analyses were carried out on sub images of 500×500 pixels representing 422 mm^2 of the slice area and processed into gray level (8 bits). Extrudates were analyzed in the longitudinal and transversal directions. The cells density, total cell area and wall thickness were studied. Cell density was calculated by dividing cell numbers by cross-sectional area.

2.4.14. Sensory analysis

Sensory analysis was conducted on five samples with cauliflower levels of 0%, 5%, 10%, 15% and 20%. Twenty panelist were asked to assess the expanded snacks for flavour acceptability, and to mark a 10 cm line (0 – unacceptable, 5 – acceptable and 10 – excellent) in accordance with their opinion.

2.4.15. Reproducibility

All the experiments were replicated, so that the data in the paper are all mean values of three tests. The coefficient of variation (CV) of all the tests was lower than 10%.

2.4.16. Statistical analysis

Statistical analyses were conducted using a commercial statistical package, Design Expert version 6.01 (Statease Inc., Minneapolis, USA). Statistical significant difference between values was evaluated at $P < 0.05$ level with a multiple comparison test using SPSS 12.0.1 (SPSS Inc., Chicago, Illinois, US) and correlation between parameters using Microsoft Excel 2002 (Microsoft Corporation, Sacramento, USA).

3. Results and discussion

3.1. Process conditions analysis

All the data obtained during extrusion runs and Specific Mechanical Energy (SME) are presented in Table 2. Process parameters were set as follows: solid feed rate of 20–25 kg/h, water feed adjusted to 9–11% and screw speeds of 250–350 rpm and barrel temperature between 80 and 120 °C. SME was correlated to screw speed ($r = 0.7$) due to the increase of shear rate when screw speed was raised (Baik et al., 2004), no significant difference was found between runs in terms of material temperature, pressure and torque.

3.2. Nutritional analyses of extrudates

The results obtained from PIVD, TAC, TPC and PA for raw material and extrudates are presented in Table 3. The different levels of cauliflower did not affect raw material of those parameters (Table 3A). There was a significant difference ($P < 0.05$) between samples in terms of TAC and PIVD for the finished products containing different levels of cauliflower, between 0–10% and 15–20%. Extrusion processing significantly ($P < 0.0001$) increased TPC (all levels of cauliflower) and TAC (0% and 10% cauliflower levels) while significantly ($P < 0.001$) decreased the level PIVD. The lowering was more evident in samples containing higher level of wheat flour or cauliflower level between

Table 3
Some nutritional characterization of raw materials (A) and extruded products (B)

Level of cauliflower (%)	Total phenolics (mM Gallic acid/g)	Total antioxidant capacity (MM trolox equiv./g)	Protein in vitro digestibility (%)	Phytic acid (mg/100 g)	Fibre (%)	Protein (%)
A						
0	3.4[a]	20.3[a]	82.9[a]	1278[a]	6.0[a]	14.0[a]
5	3.6[a]	20.8[a]	82.5[a]	1287[a]	6.6[a,b]	17.8[b]
10	3.6[a]	20.6[a]	82.9[a]	1265[a]	9.1[c]	18.0[b]
15	3.8[a]	21.0[a]	83.1[a]	1264[a]	12.2[d]	19.0[c]
20	3.8[a]	21.0[a]	83.1[a]	1264[a]	13.2[e]	20.0[d]
B						
0	7.3[b]	25.6[b]	79.6[b]	1234[a]	5.6[a]	16.3[f]
5	7.1[b]	25.3[b]	79.3[b]	1224[a]	7.6[b]	19.0[c]
10	7.2[b]	25.1[b]	79.2[b]	1243[a]	8.3[f]	19.0[c]
15	7.0[b]	20.5[a]	83.5[a]	1257[a]	10.5[h]	19.5[c]
20	6.9[b]	21.0[a]	83.8[a]	1258[a]	11.6[i]	20.4[d]

Different letters in the same column shows statistically significant values (0.05).

0% and 10%. The phenolic compounds are the main contributors to the changes of antioxidant activity (Karadenuz et al., 2005; Reyes et al., 2007; Dykes and Rooney, 2007). There are opposing reports of TPC and TAC stability during food processing. In the review carried out by Podsedek (2007), the antioxidant concentrations and activities in processed vegetables (blanching, canning, sterilisation and freezing) were lower than those of corresponding raw materials. This was caused by their degradation and water absorption during boiling, which diluted the compounds and decreased their content. In our study, extrusion cooking increased TPC (all cauliflower levels) and TAC (0–10% cauliflower level), which seems likely a normal consequence of the high temperature, water-stress and wounding (Reyes et al., 2007) that could induces the synthesis of enzymes in the metabolic pathway that are responsible for increased production of phenolic compounds (Saltveit, 1998). It has been shown that wounding increase antioxidant capacity and total phenolic compounds in lettuce, celery, carrot, parnships and sweetpotato (Heredia and Cisneros-Zevallos, 2002; Saltveit, 1998; Reyes et al., 2007) depending on the type of vegetable tissue.

The lowering of PIVD (0–10% cauliflower level) seems to be as a result of a combination of shearing, heat and pressure during extrusion. It has been suggested that low protein digestibility must result from changes in the proteins themselves during cooking (Duodu et al., 2002). The formation of enzyme-resistant, disulphide-bonded oligomers may be the cause of the low digestibility.

There was no significant difference in PA of extruded cauliflower products compared with raw materials which supports the findings of Sandberg et al. (1986) that extrusion cooking did not change the content of PA.

Analyses of the finished products obtained from different levels of cauliflower indicated a wide range of fibre content between 5.6% and 11.6% and protein content between 16.3% and 20.4%, resulting with the significant correlation of fibre ($r^2 = 0.9^{***}$) and protein ($r^2 = 0.8^{**}$) as cauliflower levels increase. It has been reported that fibre content in vegetables are generally lower than in cereals (Englyst et al., 1989). The content of fibre in extrudates at 10% and 20% supplementation in this study were compared with previous studies (Ainsworth et al., 2007; Stojceska et al., in press) where brewer's by-product was used as a source of fibre and resulted in extrudates with fibre content between 9.8–14.7% and 6.1–11.3%. In the study of Ainsworth et al. (2007) extrudates contained higher levels of fibre compared with this study, where as in the study of Stojceska et al. (in press) slightly lower fibre contents were obtained. However, different ingredients used in these studies and their interaction and effect of process conditions have to be taken into consideration. It has been reported that dietary fibre concentrates from vegetables and cereal by-product brans contain a greater percentage of proteins and ash than those from fruits (Grigelmo-Miguel and Martin-Belloso, 1999). Dietary fibre concentrates from fruits and vegetable by-products contain a lower percentage of fat than cereals, which could be used directly as alimentary ingredients. Extrusion cooking in this study, increased the level of proteins in samples containing lower levels of cauliflower and significantly ($P < 0.001$) reduced the level of dietary fibre, which is probably as a result of the change from insoluble to soluble dietary fibre. Decreasing the level was more evident with samples containing higher levels of cauliflower (10–20%). It has been reported that extrusion cooking increased the dietary fibre level of cereals due to the formation of resistant starch (Englyst et al., 1989), while in vegetables heat and moisture solubilises and degrades pectic substances (Anderson and Clydesdale, 1986) leading to the decrease in the fibre content. The results observed in this study are in agreement with a number of studies. Ralet et al. (1991) reported that extrusion cooking resulted in decreased swelling of sugar-beet samples, probably because the cohesiveness of the cell walls had been partially destroyed by the severe extrusion conditions. Later, Larrea et al. (2005) showed that the total dietary fibre content in orange pulps decreased with higher barrel temperatures and lower moisture contents with the screw speed fixed at 160 rpm.

3.3. The effect of dietary fibre on textural, colour, WAI and WSI characteristics of extrudates

The hardness, bulk density and expansion of the product obtained from 40 runs are given in Table 4. The maximum force obtained has been taken as a measure of hardness of the products. It is well known that fibre increases the hardness of extruded products (Mendonca et al., 2000; Yanniotis et al., 2007; Ainsworth et al., 2007) as a result of its effect on cell thickness. In the study of Stojceska et al. (in press) it has been shown that hardness of extrudates was reduced as the level of corn starch increased. All these authors were using dietary fibre from cereals. Our results clearly demonstrated that the hardness of the extruded product was not related to the level of cauliflower which was the only source that increased the level of dietary fibre.

With regards to expansion of the product and bulk density, all the indices showed a significant high correlation to the level of cauliflower as follows: SEI ($r = -0.95^{***}$), LEI ($r = -0.8^{***}$), VEI ($r = -0.9^{***}$) and bulk density ($r = 0.7^{***}$). All the indices were positively correlated with each other, which means that decreased diametric enlargement results in decreased elongation. Our results appear to disagree with some observations of Alvarez-Martinez et al. (1988). They found inversely related LEI and SEI as a result of increasing energy stored in the melt from radial compression of the elastic gelatinized starch network passing through the die. It is postulated that the mechanisms responsible for radial and longitudinal expansion are related to the melt's capability for the elastic storage of energy inputs occurring with high shear strains in the screw and die. However, these differences could be explained by using different ingredients and their contribution to expansion, for example

Table 4
Textural characteristics of finished products obtained from 40 extrusion runs

Run	Bulk density (g/cm^3)	Hardness (N)	SEI (%)	LEI (%)	VEI (%)	Colour			WAI (ggel/g)	WSI (%)
						L^*	a^*	b^*		
1	0.32	8.57	2.25	0.36	0.81	49.27	0.03	24.10	3.79	20.30
2	0.25	9.34	5.06	0.79	3.99	51.97	0.90	26.00	4.19	19.56
3	0.27	11.74	5.52	0.78	4.32	53.97	0.67	26.57	4.16	19.09
4	0.26	7.04	2.40	0.44	1.05	47.70	0.70	23.40	3.81	22.80
5	0.27	8.32	2.72	0.39	1.07	49.30	0.47	24.00	3.88	20.64
6	0.24	6.38	2.48	0.47	1.16	45.53	1.07	22.03	3.94	21.76
7	0.24	9.95	4.73	0.87	4.11	51.83	0.77	25.50	4.23	22.15
8	0.23	7.20	3.90	0.74	2.89	49.03	1.20	24.30	4.30	22.88
9	0.21	9.95	7.43	1.07	7.97	56.90	1.30	28.33	4.91	22.01
10	0.26	6.89	2.18	0.44	0.95	45.53	0.80	22.17	4.10	21.06
11	0.29	9.38	4.00	0.60	2.39	52.80	0.17	25.80	4.27	19.09
12	0.26	10.00	4.10	0.68	2.78	50.00	1.00	24.70	4.26	19.34
13	0.33	8.80	2.10	0.35	0.74	46.30	0.63	22.70	3.45	23.04
14	0.25	12.16	8.41	0.87	7.29	57.47	1.17	28.90	4.80	17.62
15	0.35	9.11	2.18	0.39	0.84	49.90	0.03	24.17	3.83	22.76
16	0.29	6.03	1.89	0.35	0.66	46.53	0.40	22.60	4.02	23.34
17	0.26	9.83	5.64	0.72	4.06	55.33	0.47	27.47	4.56	21.66
18	0.23	9.57	4.41	0.86	3.81	50.23	0.50	24.63	4.25	21.63
19	0.22	6.75	3.52	0.51	1.79	43.57	1.23	21.33	3.99	19.08
20	0.25	9.04	3.24	0.84	2.72	52.53	−0.33	25.37	3.83	24.43
21	0.22	7.09	5.52	0.84	4.66	52.07	1.53	26.10	4.44	24.04
22	0.24	10.35	6.25	0.89	5.54	51.10	1.70	25.60	4.45	19.66
23	0.16	6.06	7.29	1.93	14.06	49.43	2.30	24.30	4.50	28.65
24	0.22	9.18	7.56	0.92	6.95	51.20	3.33	26.60	4.76	16.37
25	0.20	7.67	5.88	1.12	6.57	51.73	1.57	25.67	4.38	24.46
26	0.29	10.60	4.62	0.52	2.41	51.20	0.63	25.37	3.99	20.75
27	0.17	7.51	6.25	1.52	9.50	51.30	1.57	24.60	4.49	27.96
28	0.28	7.02	2.18	0.37	0.81	45.17	0.60	21.90	3.72	23.64
29	0.20	8.84	7.16	1.13	8.11	52.03	2.03	25.90	4.58	22.06
30	0.30	7.19	2.25	0.34	0.77	47.43	0.63	23.57	3.84	23.07
31	0.19	6.92	7.56	0.96	7.24	52.73	2.60	26.83	4.86	18.49
32	0.21	9.90	8.70	1.05	9.13	56.13	1.73	28.00	4.90	18.70
33	0.29	12.60	7.29	0.54	3.96	60.10	1.20	30.57	5.68	19.33
34	0.23	8.73	6.25	0.83	5.18	52.33	1.07	25.77	4.82	18.82
35	0.30	8.77	2.25	0.58	1.30	46.23	0.67	22.60	3.91	26.33
36	0.18	6.90	7.29	1.18	8.62	51.27	2.03	25.33	4.46	23.83
37	0.22	10.27	6.38	1.01	6.42	53.77	2.00	26.93	4.80	22.06
38	0.29	6.48	1.89	0.31	0.59	45.67	0.77	22.63	3.82	24.02
39	0.23	8.79	4.20	0.73	3.05	46.13	1.67	23.03	4.27	20.45
40	0.26	7.46	3.42	0.48	1.63	46.13	1.77	22.97	4.32	19.29

fibre molecules disrupting the continuous structure of the melt impending its elastic deformation during expansion. It is likely that at lower levels of cauliflower the long and stiffer fibre molecules align themselves in the extruder in the direction of flow, reinforcing the expanding matrix and increasing the mechanical resistance in the longitudinal direction (Moraru and Kokini, 2003).

Results of colour recorded for the extrudates containing different level of cauliflower obtained using different process conditions are presented in Table 4. Increasing the level of cauliflower resulted in lowering the brightness with significant correlation of $r = -0.8^{***}$. Redness of the product was negatively correlated to the level of cauliflower ($r = -0.64^{***}$). Similarly the yellowness of the products was negatively correlated ($r = -0.81^{***}$) with cauliflower levels.

WAI showed high correlation to the level of cauliflower ($r = -0.85^{***}$) as a result of increasing fibre content while WSI was not affected by cauliflower levels. These findings were in agreement with a study where brewer's spent grain by-product was incorporated into extrudates (Stojceska et al., in press) where dietary fibre levels increased WAI while WSI was not affected. It has been reported that increasing the barrel temperature during the extrusion of onion waste increased WSI and decreased WAI (Ng et al., 1999). They reported that SME for samples of different feed moisture showed a close correlation to WSI, which was not consistent with our study. Increased SME by the elevated screw speed probably promotes the molecular disruption, leading to the increase in WAI (Baik et al., 2004).

3.4. Image analysis of extrudates

The quantitative description of the cellular structure was determined using an image analysis technique. Images of

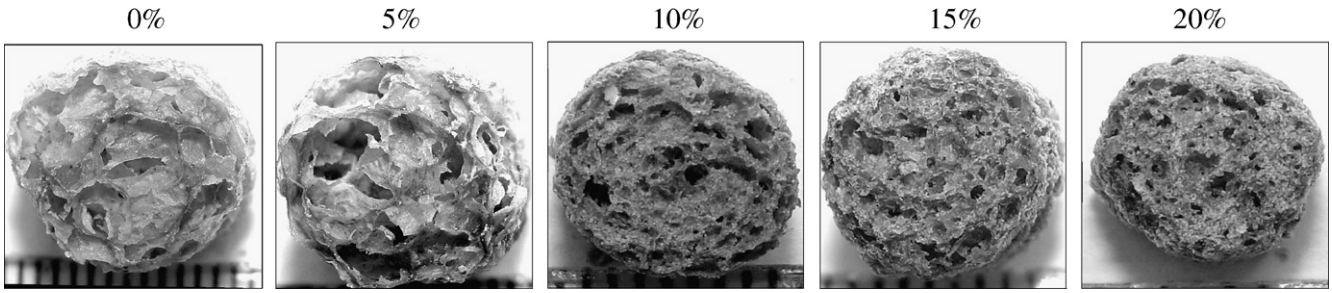

Fig. 1. Images of extrudates containing different levels of cauliflower.

extrudates containing different levels of cauliflower are presented in Fig. 1. Density, total area of cells and wall thickness of the product's sectional and longitudinal cut, respectively are discussed and correlated to different levels of cauliflower, expansion indices and bulk density. Total cell area in the sectional cross section varied between 31% and 54%, density of the cells between 61 and 93 cells/cm^2 and wall thickness between 0.3 and 0.5 mm (Figs. 2–4). The level of cauliflower was significantly ($P < 0.001$) negatively correlated to the total cell area of

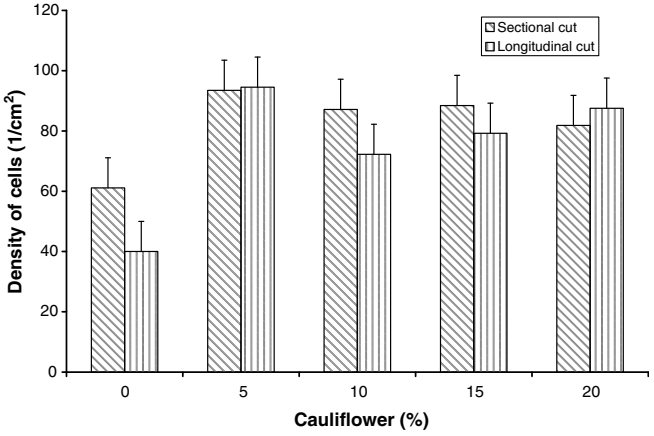

Fig. 2. Density of cells (sectional and longitudinal cut) using image analysis of extrudates containing different levels of cauliflower.

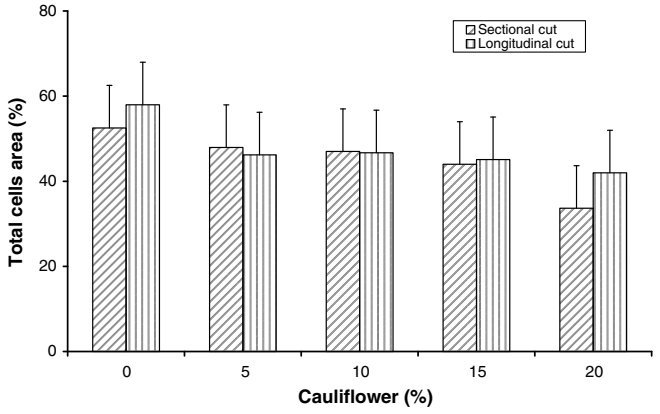

Fig. 3. Total cells area (sectional and longitudinal cut) using image analysis of extrudates containing different levels of cauliflower.

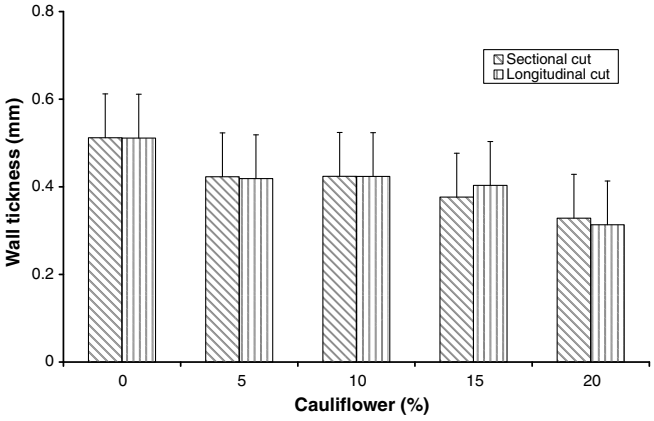

Fig. 4. Wall cell thickness (sectional and longitudinal cut) using image analysis of extrudates containing different levels of cauliflower.

the product ($r^2 = -0.9$) and wall thickness ($r^2 = -0.88$) but not to the density of the cells. These data are consistent with the limited literature data that is available, namely Yanniotis et al. (2007) reported that wheat fibre in starchy extruded products resulted in extrudates with smaller size and a higher number of the cells. Stojceska et al. (in press) found, in high-fibre extrudates, a high correlation between mean cell area to the SEI, indicating that the higher level of fibre lowed the expansion of the products, giving a structure containing more small cells. Total cell area obtained from 2D image analysis was positively correlated to the SEI ($r = 0.7$), LEI ($r = 0.7$), VEI ($r = 0.6$) and negatively to bulk density ($r = -0.6$). When cells expand their walls are stretched and become thinner, which results in increased expansion and decreased bulk density. It has been reported that extrudate expansion is governed by the biaxial extension of individual bubbles, and the driving force for bubble growth is the pressure difference between the inside and the exterior of the matrix (Moraru and Kokini, 2003).

When extrudates were studied longitudinally the total cell area varied between 45% and 57%, density of the cells between 40 and 95 cells/cm^2 and wall thickness between 0.3 and 0.5 mm (Figs. 2–4). Total cell area ($r = -0.8$) and wall thickness ($r = 0.85$) were affected by the different level of cauliflower but they were not related to the SEI, LEI, VEI and bulk density.

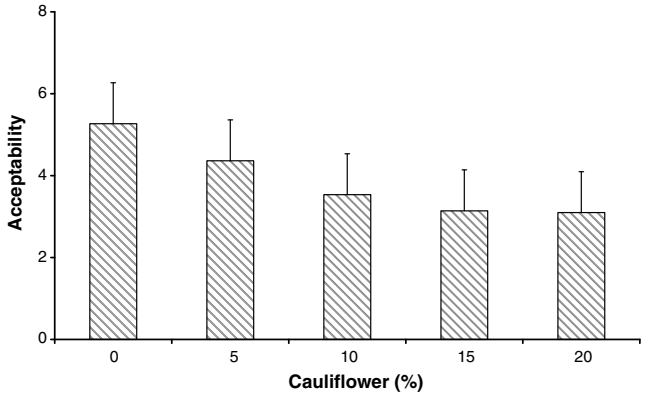

Fig. 5. Influence of cauliflower level on taste panel acceptability score.

3.5. Sensory evaluation

Fig. 5 gives the mean of the values obtained by the sensory panel of extrudates containing different levels of cauliflower. Extrudates containing 0–10% cauliflower were judged to be significantly ($P < 0.05$) more acceptable than samples containing 15–20% cauliflower. However, improving the flavour of extrudates is still in progress. It was noted that above 10% cauliflower addition the flavour of the extrudates was too strong.

4. Conclusion

The data presented in this study show the incorporation of cauliflower by-products into ready-to-eat snacks and their effect on nutritional and textural characteristics. Increasing the cauliflower to levels of 5–20% increased dietary fibre in the finished product by over 100%, increased protein content and WAI. It was found that addition of cauliflower significantly affected expansion indices, bulk density, colour and total cell area. Very little effect was observed with hardness. The extrusion process affected TPC, TAC, PIVD, fibre content and protein content. The taste panel acceptability score showed that cauliflower by-products could be added up to 10%. This issue will be addressed in future trials where the flavour of the extrudates containing 15% and 20% cauliflower will be improved by coating or spraying.

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