Extrusion of a curcuminoid-enriched oat fibre-corn based snack product

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Abstract

Extruded snack products were made from an oat fibre-corn flour matrix fortified with 1.5% (w/w) curcuminoids (750 mg curcuminoids/100g) to improve the solubility and stability of curcuminoids. The effects of extruder feed moisture content (21, 28, and 35%) and screw speed (200 and 300 rpm) on the extrusion parameters and physical properties of final snacks were investigated. Curcuminoids lost during extrusion and curcuminoids loss during subsequent drying of extrudates were analysed, in order to separate the losses occurring in each unit process. Drying post extrusion (at 50°C for 4 h) was essential to obtain a crunchy

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shelf stable product (5% moisture). Curcuminoids loss during extrusion was from 17 to 84%, with high loss for the extrusion with low feed moisture content (21%). A further curcuminoids loss of 4 to 44% occurred during drying, with much higher loss for the extrudate with high moisture content. Total curcuminoids retained after extrusion and drying was 12 to 41% (59 to 88% loss), equivalent to 180-616 mg curcuminoids retained per 100g snack, levels within recommended daily dose. Curcuminoids retained after drying was stable during 80 days of storage at 25 °C. The results highlighted the importance of understanding the impact of each unit process separately (e.g. extrusion and drying) on the stability of curcuminoids for the development of healthier extruded snacks.

Keyword: Curcuminoids, extrusion, oat fibre, functional foods.

Practical Application

Extruded snacks products were developed by fortifying the snacks with oat fibre and curcuminoids in order to address the need for a healthy ready to eat food products. Some extrusion characteristics were selected to produce snack products which have favourable properties in terms of consumer acceptance.

1. Introduction

Ready-to-eat snacks are popular among consumers due to their convenience and attractive appearance and texture (M. Brennan, Derbyshire, Tiwari, & Brennan, 2013). These snacks are regarded as high energy, nutritionally poor food products (M. Brennan et al., 2013) but bioactive components can be added to improve their nutritional value. Curcuminoids are hydrophobic polyphenols, derived from the rhizome of turmeric plants (Anand, Kunnumakkara, Newman, & Aggarwal, 2007) that offer great potential for inclusion in snacks to create fortified functional foods. There are three major curcuminoids including curcumin (curcumin I), demethoxycurcumin (curcumin II) and bisdemethoxycurcumin (curcumin III) (Anand et al., 2007; Schaffer, Schaffer, Zidan, & Sela, 2011). Together, they display a broad range of biological and pharmacological activities (Anand et al., 2007), they can also act as natural food colorants. Encouragingly, a minimum recommended dosage of 500 mg curcuminoids per day has been shown to decrease the levels of serum cholesterol and lipid peroxide (Pari, Tewas, & Eckel, 2008). This provide an opportunity to have at least 180 mg curcuminoids (a third of daily recommended dosage) per serving of a food product. The potential of curcuminoids as a bioactive ingredient in functional snack foods and the effect of its inclusion on the physical properties of snack foods have not yet been explored.

One of the main technologies known for manufacturing of snack products is extrusion cooking. During extrusion cooking, the raw materials are subjected to high temperature and shear. These conditions can result in many chemical and structural changes, including the molecular transformation of biopolymers, such as starch and proteins (Moscicki & Zuilichem, 2012; Wolf, 2010) and the degradation of bioactive components (C. Brennan, Brennan, M., Derbyshire, E., & Tiwari, B. K, 2011; Hirth, Leiter, Beck, & Schuchmann, 2014; Ying et al., 2015). The effect of extrusion cooking on curcuminoids, in the context of a snack material, however, is not known.

As curcuminoid is poorly soluble and unstable in water, a carrier material could prove effective for improving handling, stability and bioactivity. Such a carrier material will also ideally add further nutritional value to the apparent matrix of the snack food. Oat fibre is a good potential candidate for a carrier material. It is rich in soluble fibre, such as β-glucan and is known for its beneficial effects, including the reduction of blood cholesterol and the risk of heart diseases (Wood, 2007). Our previous study has also shown that curcuminoids and oat fibre effectively interact, demonstrating the potential of oat fibre to act as a curcuminoids carrier (Sayanjali, Sanguansri, Buckow, Gras, & Augustin, 2014). The inclusion of oat fibre together with curcuminoids would add both novelty and nutritional value to snack products.

In current study, we produced extruded snack made from an oat fibre-corn flour matrix fortified with 1.5% (w/w) curcuminoids. We aim to demonstrate the potential of extrusion technology to produce functional food products that incorporate the benefits of curcuminoids and oat dietary fibre. The effect of curcuminoids addition, feed moisture content and screw speed on the physical/structural properties of the extrudates and stability of curcuminoids during extrusion, drying and storage were also investigated.

2. Materials and Methods

2.1. Materials

Corn grit (Polenta No 1) was purchased from Scalzo Food Industries (West Melbourne, Victoria, Australia). Calcium carbonate ($CaCO_3$) from IMCD Ltd (Melbourne, Victoria, Australia) was added to improve expansion of the final extruded snacks (Boonyasirikool & Charunuch, 2000). Oat fibre was purchased from CreaNutrition (Sumpfstrasse, Zug, Switzerland). All HPLC solvents were purchased from Merck (Melbourne, Victoria, Australia). Ethanol (EtOH, 100%) was obtained from Sigma-Aldrich (Sydney, New South Wales, Australia). Sodium chloride was purchased from a local supermarket and was added as flavour enhancer.

2.2. Gross compositions

Corn grit containing 79.5% carbohydrate, 7.4% protein, 3.1% dietary fibre, 0.7% fat and 10.2% moisture (according to product specification) was used. The protein, β-glucan, total fat and total solids content in the oat fibre were determined. The protein content was analysed using a LECO FP-2000 Nitrogen Analyser (LECO Australia Pty Ltd., Castle Hill, New South Wales, Australia). The quantification of β-glucan, lipid and total solids was carried out based on the AOAC Official Method 995.16 (AOAC, 2005), Australian Standard Method (Standards Association of Australia, 1988) and AOAC official method 990.20 (AOAC, 1993) respectively. The oat fibre contained 27.11 ± 0.02 (% w/w) protein, 27.54 ± 1.12 (% w/w) β-glucan, 5.20 ± 0.02 (% w/w) total fat, 6.6 ± 0.2 (% w/w) moisture, and 33.5 ± 0.5 (% w/w) other components (including carbohydrates and other dietary fibre), as previously determined (Sayanjali et al., 2014). A powdered turmeric extract (Biocurcumin, BCM- 95CG, total curcuminoids complex, purity: 95.7%) was provided by Arjuna Natural Extracts Ltd (Aluva Kerala, India). Previous analysis in our laboratory indicated that this material consists 88% (w/w) curcuminoids, (of 70 ± 0.5% curcumin, 16.0 ± 0.2% demethoxycurcumin, and 2% ± 0.1 bisdemethoxycurcumin) (Fu et al., 2014).

2.3. Sample formulation

In our preliminary experiments (data not shown) 30% maximum oat fibre content in the formulation provided desirable expansion in extruded snacks. The composition of the pre-mixed dry powder formulation used for extrusion was 30.0% (w/w) oat fibre, 68.7% (w/w) corn grit, 0.3% (w/w) NaCl and 1% (w/w) $CaCO_3$. NaCl and $CaCO_3$ were added to assist with the nucleation and expansion process at the extruder die. Two formulations were prepared for extrusion: one without curcuminoids, described as “(-) curcuminoids” and the other with curcuminoids added as a powder at 1.5 % w/w, described as “(+) curcuminoids”.

2.4. Extrusion

The extrusion process was carried out in a co-rotating twin-screw extruder (MPF 19:25, APV Barker Ltd., Peterborough, East England, United Kingdom). The barrel diameter was 19 mm and the length to diameter ratio (L/D) was 25. The pre-mixed dry powder formulation was fed with a twin screw volumetric feeder (K-MV-KT20; K-Tron LLC, Niederlenz, Lenzburg, Switzerland). The melt pressure was monitored with a pressure transducer (Terwin 2076, Terwin Instrument Ltd., Bottesford, Nottinghamshire, United Kingdom) fitted into the die block. The barrel has 4 temperature zones set to 80 / 90 / 100 / 110 °C. The temperature profile was selected based on our earlier experiments (data not shown).

Deionized water was injected into the extruder barrel to achieve the desired feed moisture content (21%, 28%, and 35% w/w moisture). These levels of moisture content were higher than settings typically used for extrusion because of the strong water absorption capacity of oat fibre (Skendi, Biliaderis, Lazaridou, & Izydorczyk, 2003). A low feed moisture of 21% was selected to give good expansion but still not too low to block the extruder; and a high feed moisture of 35% was selected to give a reasonable expansion but not too high to cause "runny" of the extrudate. The screw speed is a further process variable that was also adjusted to 200 rpm (low speed) or 300 rpm (high speed). These screw speeds are commonly used in small-scale extruders (B. Q. Ding, Ainsworth, Plunkett, Tucker, & Marson, 2006; Zhang, Bai, & Zhang, 2011). Extruded samples were made from duplicate runs for each treatment. The ratio of dry feed and water was adjusted so that a total materials feed rate (dry feed plus water) of ~ 4 kg/h was maintained. After extrusion, samples were dried at 50 °C for 4 h in an oven with air circulation (Thermotec 2000, Contherm, Lower Hutt, Wellington, New Zealand). Samples were sealed in moisture barrier bags and kept at 4 °C prior to analysis.

For each treatment, the specific mechanical energy (SME) input was calculated using the following equation (1) (Ryu & Ng, 2001):

$$\mathrm{SME} = \frac{\text{rpm (test)}}{\text{rpm (rated)}} \times \frac{\text{\% Motor load}}{100} \times \frac{\text{Motor power (rated)}}{\text{Feed rate}} \qquad (1)$$

The unit for SME is Wh/kg. The “rpm (test)” is the set screw speed during extrusion and the “rpm (rated)” is the rated screw speed of the drive motor for the extruder (500 rpm). The rated motor power is 2.0 kW, and the feed rate is total mass input of dry-feed and water injection rate (kg/h). The extrusion condition and corresponding SME and torque are presented in Table 1.

2.5. Curcuminoids stability

Samples of oat fibre-corn based mixture (+) curcuminoids were taken (1) before extrusion, (2) immediately after exiting the extruder and (3) after drying. The dried oat fibre-corn based extrudates (+) curcuminoids were stored at 25 °C for 80 days, and 6 g samples of each treatment were taken every 10 days and kept at -80 °C until ready for curcuminoids analysis.

2.6. Physical analysis

2.6.1 Apparent Density

Apparent density (BD) (g/cm^3) was calculated according to the following equation (2) (Alvarez-Martinez, Kondury, & Harper, 1988):

$$\mathrm{BD} = 4m/\pi d^2 L \qquad (2)$$

Where, m is the mass (g), L is length (cm) and d is diameter (cm) of the extrudates. The dimensions of an extrudate were measured using a Vernier calliper and the apparent volume was calculated assuming the shape of the extrudate was cylindrical consistent with the moulded shape of the die. Four randomly selected extrudates of 10 mm in length were used for the measurement (10 diameter measurements for each 10 mm length) and the values reported were the average ± standard deviation (sd) of forty diameter measurements.

2.6.2 Expansion ratio

The expansion ratio was defined as the ratio between the diameter of the extrudate and the diameter of the die (Alvarez-Martinez et al., 1988). Ten samples for each process condition were measured and the values reported were the average ± sd.

2.6.3 Breaking Force

The breaking force (kN) required to fracture the extrudates were measured using a Lloyd LRX/plus Universal Testing Machine (Lloyd Instruments Ltd., Bognor, West Sussex, United Kingdom) with a 2.5-kN load cell (Pitts, Favaro, Austin , & Day, 2014). Four pieces of extrudates were chosen randomly, cut to approximately 8 cm in length and placed across the bottom of a Kramer Type Shear Cell. Samples were compressed perpendicular to the length of the extrudate at a compression speed of 60 mm/min. The compression force was recorded using the manufacturer's Nexygen V4.6 software. The observed peak force was taken as the breaking force of the samples. A minimum of ten replicate tests were carried out for each sample. The data presented in the average ± sd.

2.6.4. Cross sectional examination

Scanning electron microscopy (Quanta; Hillsboro, Oregon, United State of America) was used to analyse the cross-section of the extrudates (+) curcuminoids. For SEM examination, the extrudates were cut using a sharp blade, mounted on double sided carbon tape and then coated with gold. The SEM examination was carried out with a 10 kV beam power and magnification range of 59-63x.

2.7. Curcuminoid analysis and quantification

2.7.1. Extraction of Curcuminoids

Extrudates containing curcuminoids were ground using a grinder (CG2B, Breville, Sydney, New South Wales, Australia) and passed through a 250 μm sieve to remove large particles. Sieved samples (100 mg) were then mixed with 10 ml of ethanol (EtOH). Samples were sonicated in an ultrasonic bath (Unisonic Australia Pty, Sydney, New South Wales, Australia) at 20 kHz and 30 °C for 60 min followed by shaking at 30 °C for 4 h. Samples were then centrifuged at 1000 g for 5 min to obtain the supernatant. A second extraction of the pellet was carried out and the supernatants from the first and second extractions were combined, weighed and kept at 4 °C before analysis.

The concentration of curcuminoids from the extracts was analysed by high-performance liquid chromatography (HPLC). The supernatants were filtered through a 0.45 μm syringe filter (Merck Millipore, Carrigtwohill, Cork, Ireland). The concentration of curcuminoids was quantified using a calibration curve of curcuminoids in EtOH at concentrations of 3.68-184 μg/mL. The standard solutions were kept at -18 °C before analysis. To evaluate the accuracy of the extraction method, spiking experiments with a known amount of curcuminoids were also conducted. The results showed a recovery of approximately 91% of curcuminoids from the matrix.

2.7.2. High-performance liquid chromatography (HPLC) analysis

The curcuminoids content of extrudates was determined by a 1100 series HPLC (Agilent, Santa Clara, California, United States) consisting of a binary pump, an Agilent 1100 series diode-array detector, a ChemStation software, an 1100 well plate auto sampler and an X Terra MS C18 column (4.6 mm × 250 mm; 5 µm, Waters Corporation, Milford, Massachusetts, United State of America). The mobile phase was composed of 2% (v/v) acetic acid in MilliQ water as mobile phase A and 2% (v/v) acetic acid, and 10% (v/v) methanol in acetonitrile as mobile phase B. The gradient program was as follows: 0–10 min, 45% B increasing to 50% B; 10–25 min, decreasing to 45% B (Fu et al., 2014).

2.8. Statistical Analysis

The experimental data were analysed using an analysis of variance (ANOVA) using VassarStats. A probability of $p < 0.05$ was considered to be statistically significant. Results are presented as the average of duplicate analysis of each formulation produced in duplicated extrusion trials (n=4).

3. Results and Discussion

3.1. Apparent density and expansion ratio

Fig. 1 shows the effect of feed moisture content and screw speed on apparent density and expansion ratio of the dried extrudates. The apparent density of extrudates was significantly decreased ($p<0.05$) from ~ 1.0 to ~ 0.2 g/cm^3 by decreasing the feed moisture content from 35% to 21%, while the expansion ratio was significantly increased ($p<0.05$) from ~ 1.5 to ~ 2.8. The inverse relationship between apparent density and expansion is significant and is as expected. The apparent density and expansion ratio of extruded snacks for corresponding extrusion conditions were not significantly affected ($p>0.05$) by the addition of 1.5% curcuminoids (w/w dry basis) in the formulation.

The dough viscosity and elastic force (i.e. the die swell) affects the expansion and density of extrudates (Moraru & Kokini, 2003). The bubbles inside the viscoelastic melt grow when the melt exits the extruder die due to moisture flash-off (Patil, Berrios, Tang, & Swanson, 2007). The higher moisture content of feed materials reduces the elasticity of the dough due to the plasticization effect of water on the dough (Singh, Rachna, Hussain, & Sharma, 2015). The reduction in the elasticity of the dough causes the bubbles to collapse inside the dough, resulting in a lower expansion and higher density in high moisture treatment (Gulati, Weier, Santra, Subbiah, & Rose, 2016). Reducing the moisture content inside the extruder feed increases the melt viscosity and porosity that leads to enhanced expansion and a reduction of apparent density. There is an optimum moisture content for achieving the maximum expansion (Baik, Powers, & Nguyen, 2004). At a moisture content below a certain level, the shear rate of the feed increases, resulting in molecular disruption that causes a reduction in the expansion ratio (Baik et al., 2004).

The effect of feed moisture content on apparent density and expansion has already been reported in expanded snacks made of waxy and regular barley flour (Baik et al., 2004), which were extruded at a moisture content ranging from 17 – 21 %, screw speed of 50, 75, 100, 125 and 150 rpm. The expansion ratio increased from 1.81 to 2.68, but the apparent density decreased from 0.46 g/mL to 0.18 g/mL as the moisture content decreased from 21% to 17% (Baik et al., 2004). Similar trends have also been reported for changing apparent density (0.2 to 0.7 g/cm^3) and expansion ratio (2 to 4) for corn starch material which were extruded at a screw speed of 150 or 250 rpm, die temperature of 100 °C or 260 °C and feed moisture content of 12 or 25 kg/100 kg wet basis (Thymi, Krokida, Pappa, & Maroulis, 2005).

In another study, the expansion ratio of expanded snacks made from rice flour, wheat bran and corn grits decreased up to 25% due to the presence of tomato paste (containing ~ 2.5 % w/w lycopene, dry basis) (Dehghan-Shoar, Hardacre, & Brennan, 2010). The authors attributed the reduced expansion to the lubricating effect of tomato paste on the dough, leading to a reduction in SME and die pressure. The tomato paste also contained fibres, resulting in higher water absorption, leading to a higher apparent density compared with snacks without tomato paste (Dehghan-Shoar et al., 2010). In the current study, the addition of powder curcuminoids into the feed material did not significantly affect the apparent density and expansion ratio of extruded snacks. This may be in part because curcuminoids itself is hydrophobic and does not absorb water; hence it is unlikely that curcuminoids influence the properties of the dough. Whilst the interaction of curcuminoids with macromolecules in the feed materials may be altered as a result of extrusion, this did not appear to affect the properties of the extrudates. The lack of a marked influence of curcuminoids addition (1.5 % w/w) on the extrudability of the formulation means that this amount of curcuminoids can be readily added into ready-to-eat cereals/snacks without compromising the expansion and density of extrudates when the same processing conditions are used.

3.2 Breaking force

The breaking force (kN) values obtained for dried extrudates are shown in Fig.2. No consistent trend was observed for the effect of the extruder feed moisture content and screw speed (Fig. 2). The change in breaking force is not significant ($p>0.05$) when the feed moisture content was reduced from 35% to 28% in spite of the enhanced expansion ratio (from ~ 1.5 to ~ 2) (Fig. 1b). Increasing the expansion ratio from 1.5 to 2 is not sufficient to significantly reduce the breaking force of the extrudates ($p<0.05$). However, when the feed moisture content was further reduced to 21%, the breaking force of extrudates was reduced significantly ($p<0.05$).

The effect of extruder feed moisture content on the breaking force of extrudates has been widely studied (Liu, Hsieh, Heymann, & Huff, 2000; Seth, Badwaik, & Ganapathy, 2015; Zarzycki et al., 2015). At a higher feed moisture content, the viscosity of the dough and mechanical energy in the extruder decreased, stopping the bubble growth at temperatures below the glass transition temperature (Kristiawan, Chaunier, Della Valle, Ndiaye, & Vergnes, 2016). Under these conditions, vapour condensation occurred and extrudates became more dense and hard (Q.-B. Ding, Ainsworth, Tucker, & Marson, 2005; Kristiawan et al., 2016). In one study, where the hardness of corn-oat extrudate was investigated, the hardness of the dried extrudate increased as the feed moisture content increased from 18% to 21%, whereas an increase in the screw speed from 200 rpm to 400 rpm led to a decrease in hardness (Liu et al., 2000). However, in our study no consistent trend was observed for breaking force of the different dried extrudates produced at different screw speeds between 200 and 300 rpm.

3.3 Cross sectional examination

The expansion, apparent density and the breaking force of the extrudates were not significantly affected by the addition of curcuminoids ($p > 0.05$) (Fig. 1 and 2). Therefore, examination of the cross-sectional structure was only carried out on the extrudates with curcuminoids. The SEM images of extrudates (+) curcuminoids are shown in Fig. 3. The moisture content had a considerable effect on structure of extrudates. In extrudates produced at 35% moisture, bubbles were surrounded by thick walls of extrudates materials, which resulted in harder and denser extrudates. Decreasing the moisture content from 35 to 28% resulted in a structure where the pores appeared more numerous and the walls thinner, although these pores remained discrete. Further reducing the moisture to 21% resulted in larger bubbles and thinner walls due to the greater expansion of the extrudates. Under these conditions, the thinner walls also appear more susceptible to mechanical damages during sample preparation. Similar trends have been found for rye snacks (Saeleaw, Dürrschmid, & Schleining, 2012) that were extruded under two barrel temperature profiles (150 °C and 190 °C) and feed moisture content (12% and 16%). The higher feed moisture content (16%) with low barrel temperature (150 °C) resulted in thicker cell walls (Saeleaw et al., 2012). Furthermore, increasing the feed moisture content from 13% to 19 %, in corn-lentil extrudates, resulted in thicker cell walls and reduction in the number of bubbles (Lazou & Krokida, 2010). The structure of extrudates (+) curcuminoids did not appear to be significantly ($p>0.05$) affected by the screw speed under conditions with the same feed moisture.

3.4 Colour

Colour is an important physical characteristic of foods that affects consumer acceptability. Fig. 4 shows the colour of the dried extrudates. The visual observations of samples showed that extrudates containing curcuminoids have a bright orange colour (lighter colour) when the feed moisture was reduced from 35% to 21% without any noticeable colour difference between the products produced with two screw speeds. Samples without curcuminoids also showed a similar trend displaying a lighter colour as the feed moisture decreased from 35% to 21%. The lighter colour is due to the enhanced expansion of the samples when extruded at lower feed moisture (Fig. 1b).

3.5 Curcuminoids stability

3.5.1 Curcuminoids stability during processing

Curcuminoids loss during the extrusion, during drying of the extrudate and on subsequent storage is shown in Fig. 5. Curcuminoids loss in extrudates produced at 21% feed moisture content was much higher (~ 82 %) than the loss observed during extrusion at 28% or 35% feed moisture content (~ 38 % and ~ 18 %), respectively. However, curcuminoids loss was not affected by screw speed under conditions with the same feed moisture content.

It has been reported that thermally sensitive substances, such as polyphenolic compounds, are stabilized to a greater extent when the moisture content of extruder feed is increased (Hirth, Preiß, Mayer-Miebach, & Schuchmann, 2015; Ozer, Herken, Guzel, Ainsworth, & Ibanoglu, 2006). A higher feed moisture results in a reduction in dough viscosity and SME (i.e. effectively produced at milder extrusion conditions), reducing the destruction of polyphenolic compounds (Leyva-Corral et al., 2016; Ozer et al., 2006). At lower feed moisture content, the thermal energy that is generated by friction is higher (Hirth et al., 2015). Therefore, the combined effects of lower feed moisture content, higher SME and higher melt temperature resulted in greater degradation of phenolic compounds, leading to the reduction in their chemical activity or extractability (Obradovic et al., 2015; Sarawong, Schoenlechner, Sekiguchi, Berghofer, & Ng, 2014). One study reported that the retention of cyanidin glycosides improved from 25% to 65% when the feed moisture content increased from 15 g/100 g to 22 g/100 g using a constant barrel temperature of 100 °C and screw speed of 300 rpm (Hirth et al., 2015). Another study reported that a higher feed moisture content (45%) could prevent anthocyanins from extensive degradation (Khanal, Howard, Brownmiller, & Prior, 2009).

It is possible that the conditions with higher feed moisture content facilitate more interactions between curcuminoids and the oat fibre (including protein, fibre and lipids), or amylose on corn starch resulting in the greater protection of curcuminoids against thermal and oxidative degradation. Such interactions were previously observed between curcuminoids and oat fibre (Sayanjali et al., 2014) and may be enhanced under controlled conditions during extrusion.

After extrusion, the extrudates were dried at 50 °C for 4 hours. The moisture content of the extrudates before drying were 28.4±0.93 (35% feed moisture), 21.4±0.08 (28% feed moisture) and 13.9±1.14 (21% feed moisture). The final moisture content of dried extrudates reached to ~ 5% for all dried snacks after drying. The curcuminoids loss during drying were 42% (35% feed moisture), 34% (28% feed moisture) and 5% (21% feed moisture). These results showed that the samples with higher moisture content lost more curcuminoids (42% loss w/w) during drying compared to the samples with lower moisture content (34% and 5% loss w/w). These suggest that after extrusion the moisture content of the samples need to be reduced as quickly as possible to minimise loss during drying. The curcuminoids loss during drying is strongly correlated ($p < 0.01$) to the starting moisture content of the extrudates. This is in agreement with other researchers that high temperature short time drying favour the retention of bioactives (Adak, Heybeli, & Ertekin, 2017).

3.5.2 Curcuminoids stability during storage

Fig. 6 shows the stability of curcuminoids in dried extrudates stored at 25 °C under natural fluorescent light in open containers for 80 days. The initial amount of curcuminoids was different for each sample at day zero, which corresponds to the amount remaining after extrusion and drying. Previously it has been reported that encapsulation of curcuminoids with β- cyclodextrins could not improve curcuminoids stability stored at 25 °C under natural light for 90 days (Mangolim et al., 2014). However, in our study curcuminoids remained stable in all samples during 80 days of storage at concentration ranging from around 0.15 - 0.4% due to protective effect of oat fibre-corn grit matrix (Fig. 6). The stability of curcuminoids in dried extrudates stored for 80 days can be attributed to the limited molecular mobility and diffusion rates associated with the low moisture content of the dried extrudates (Galmarini et al., 2012).

4. Conclusions

This study showed that the highest amount of curcuminoids lost during extrusion occurred at 21% feed moisture content and increasing the feed moisture reduced degradation. However, the post-extrusion drying process significantly affected curcuminoids degradation, and the highest curcuminoids loss occurred during drying of the extrudates produced with higher feed moisture content. Curcuminoids between 12 and 42% could be retained after extrusion and drying. Curcuminoids did not degrade in dried extrudates during storage at 25 °C for 80 days under natural light in an ambient atmosphere. The addition of curcuminoids in the formulation at 1.5% (w/w) did not influence expansion, apparent density and mechanical properties of the extrudates. A feed moisture content of 21% resulted in higher expansion and lower breaking force and density of extrudates, which are favourable properties in extruded snacks for a better consumer acceptance. Further process optimisation such as die section temperature (melt temperature) and sensory evaluation including the consumer acceptance are recommended to achieve good curcuminoids retention and overall snacks quality. To assist the introduction of curcuminoid-enriched extruded snacks as a new functional food, flavours can be applied to extruded snacks to enhance sensory properties of the final extruded snacks.

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Author Contributions

All authors designed the study and interpreted the results. S. Sayanjali collected test data and drafted the manuscript. L. Sanguansri and D. Ying contributed to the details of the experimental design. M. Augustin, S. Gras and R. Buckow supervised the project, analysed and interpreted the data and critically revised the manuscript.

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Table 1. Extrusion conditions and corresponding SME during extrusion

Extrusion Condition		**SME* (W·h/Kg)**	
Moisture Content (%)	Screw Speed (rpm)	(-) curcuminoids	(+) curcuminoids
35	300	60 ± 1.2	65 ± 1.3
	200	57 ± 1.2	48 ± 1.0
28	300	86 ± 1.7	87 ± 1.7
	200	81 ± 1.6	78 ± 1.6
21	300	146 ± 2.9	129 ± 2.6
	200	127 ± 2.6	109 ± 2.2

*SME - Specific mechanical energy..

(+) Curcuminoids formulation: 67.2 % (w/w) corn grit, 30 % (w/w) oat fibre, 0.3 % (w/w) NaCl, 1 % (w/w) $CaCO_3$, 1.5 % (w/w) Curcuminoids

(-) Curcuminoids formulation: 68.7 % (w/w) corn grit, 30 % (w/w) oat fibre, 0.3 (w/w %) NaCl, 1 % (w/w) $CaCO_3$

Figure 1- Apparent density (a) and expansion ratio (b) of dried extruded snacks with and without curcuminoids (MC – moisture content). The data is the average ± s.d. (n =4), $p < 0.05$.

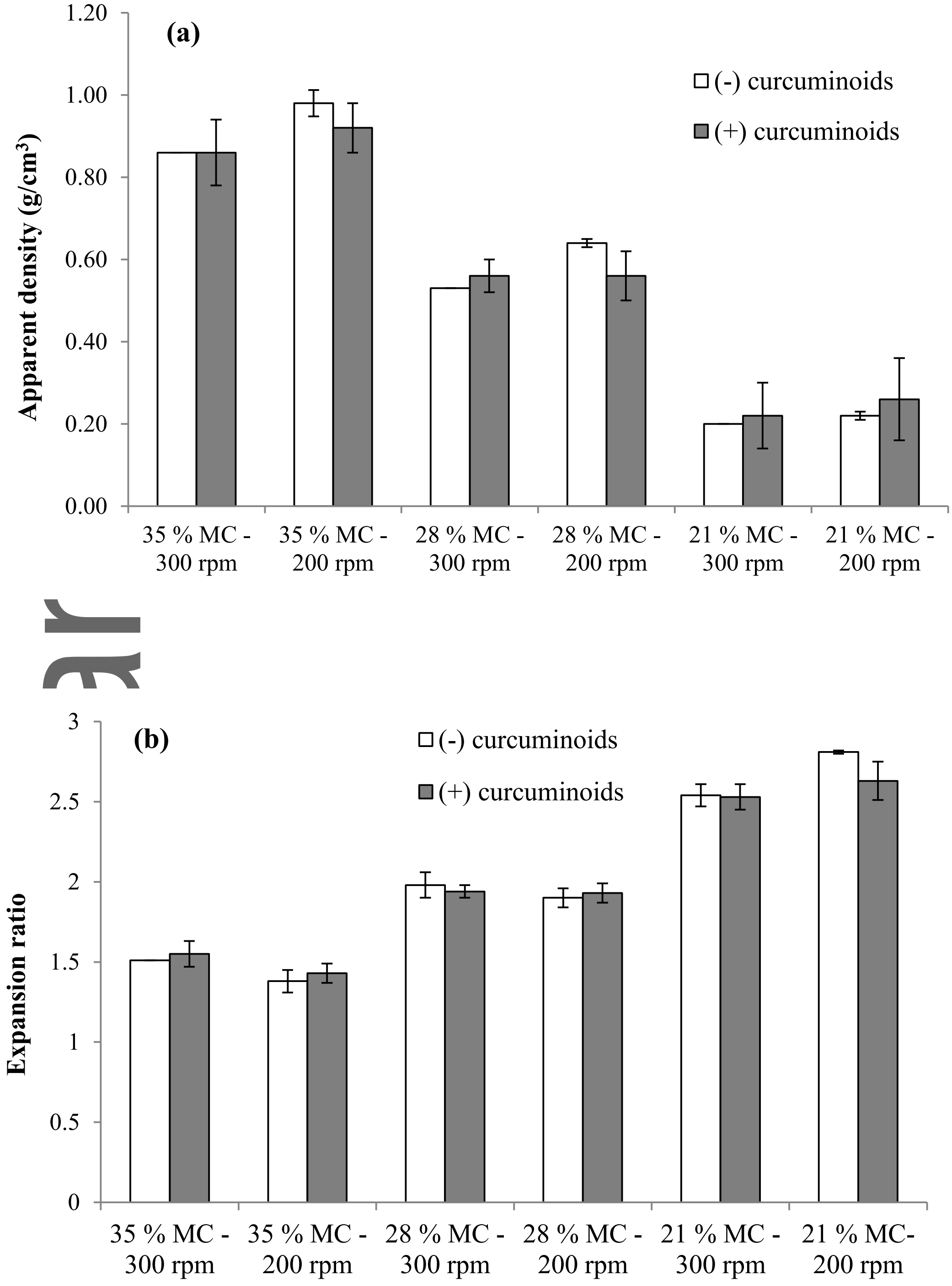

Figure 2- Breaking force of dried extruded snacks (MC – moisture content). The data is the average ± s.d. (n =4), $p < 0.05$.

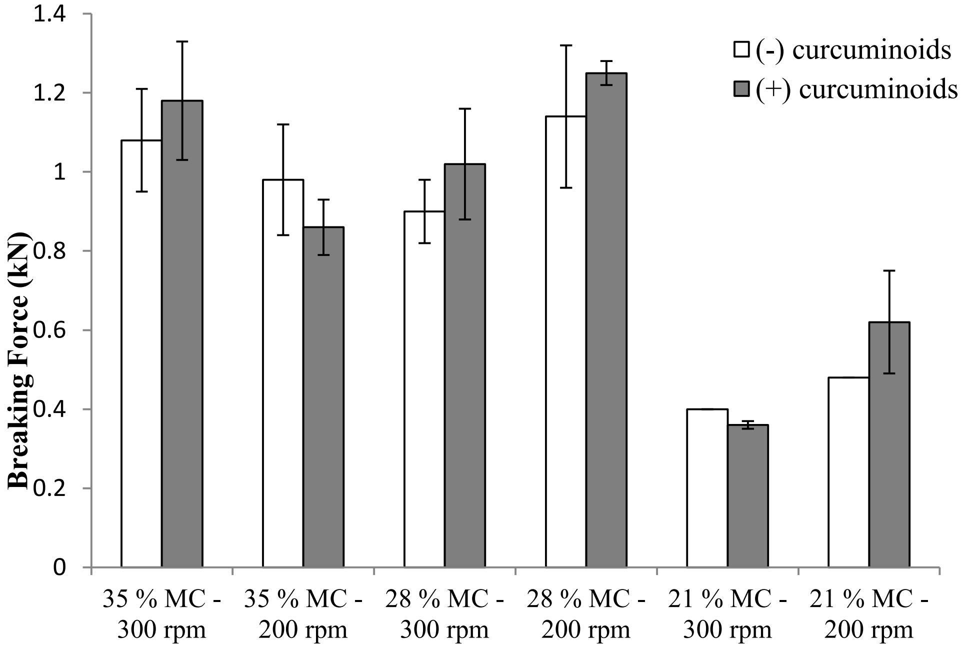

Figure 3- Scanning electron microscopy (SEM) images of the cross section of the extrudates containing curcuminoids extruded at (A) 35% MC-300 rpm, (B) 35% MC-200 rpm, (C) 28% MC-300 rpm, (D) 28% MC-200 rpm, (E) 21% MC-300 rpm and (F) 21% MC-200 rpm (MC – moisture content). The scale bars are 2.0 mm in length in A-F figures.

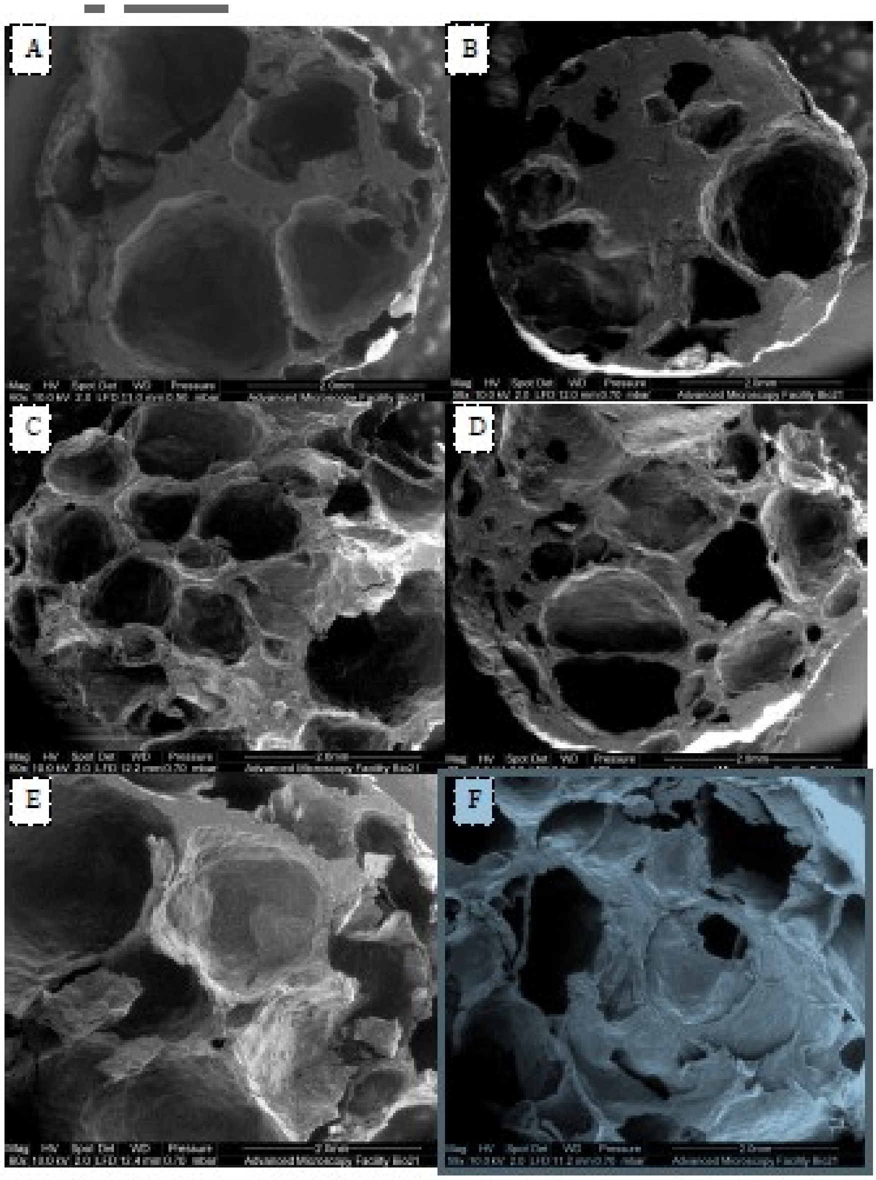

Figure 4- Dried extrudates produced at 21%, 28% or 35% moisture content (MC) and 200 or 300 rpm screw speed.

Figure 5- Percentage of curcuminoids loss during extrusion processing and drying of extruded snacks produced under different extrusion conditions (MC – moisture content). The data is the average ± s.d. (n = 4), $p < 0.05$.

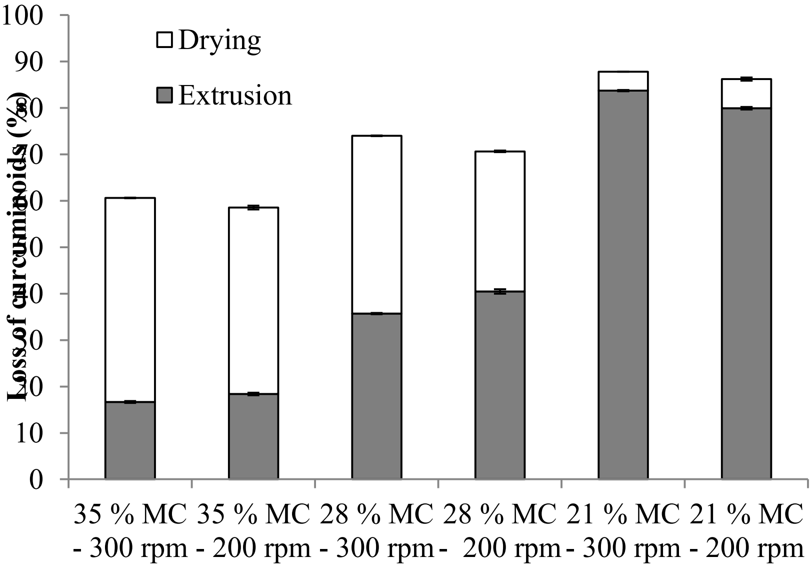

Figure 6- Stability of residual curcuminoids in dried extrudates during storage at 25 °C in open container under light for 80 days (MC – moisture content). The data is the average ± s.d. (n = 4), $p < 0.05$.