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Abstract

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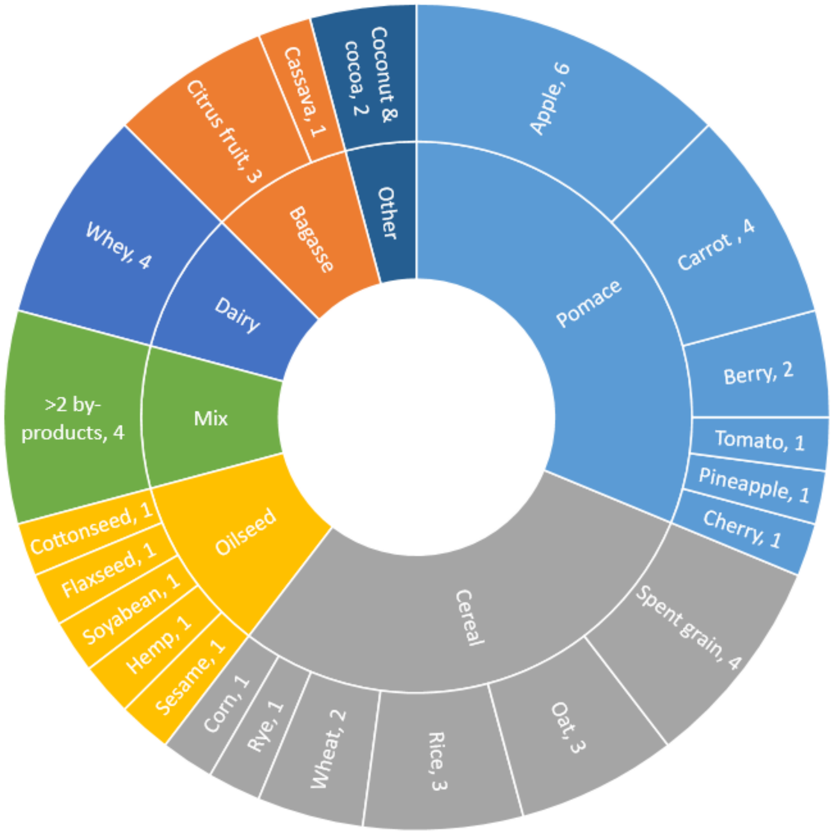
Scope and approach

With the growth of healthy and sustainable diets and with consumers better understanding the links between diet, health and the environment, there is an opportunity to develop novel healthy and eco-friendly extruded snacks. Within this context, food industry by-products, such as fruit and vegetable pomace and bagasse, oilseed cakes, brewers spent grains, cereal brans and whey, could be used as excellent sources of nutritionally enhancing and eco-friendly compounds. This review summarizes the research published within the last five years on cereal-based snacks produced using food by-products.

Key Findings and Conclusions

The production of extruded snacks with food by-products will need novel technologies that limit heat damage, both during drying of the food by-product and the extrusion process. The percentage of by-product inclusion and the particle size of the by-product added require further investigation. The economic sustainability and the environmental impact of snacks produced with food by-products should be explored in a more holistic approach. Current research is focussed mainly on reformulation strategies rather than sensory or consumer aspects. These gaps needs to be addressed and future research on extruded snacks from by-products should be more multidisciplinary, covering technical, sensory, consumer, economic and sustainability aspects.

Categories and number of articles published on extruded snacks with by-products in 2014-18



Extruded snacks from industrial by-products: a review

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1. Introduction

The UK retail value sales of crisps, savoury snacks and nuts was estimated at £3.9 billion in 2017 and it is forecasted to reach £4.8 billion in 2022. Crisps and crisp-style snacks are a UK staple, being eaten frequently and as part of lunch, with 90% of households consuming them (Mintel, 2018b). According to a recent UK survey (Mintel, 2018a), 96% of people snack (based on 2000 internet users aged 16+) and 69% of those who snack do so at least once a day (based on 1923 internet users aged 16+ who eat snacks). The same survey reports that about 39% of people who snack look for healthy products all or most of the time when choosing a snack (based on 1923 internet users aged 16+ who eat snacks). Also 52% of people think that snacks made with pulses are healthier than potato-based snacks (based on 1852 internet users aged 16+)(Mintel, 2018b). This increase in health consciousness is also backed up by public health campaigns and improved nutritional guidelines. In January 2018, Public Health England launched the first Change4Life campaign around children's snacking, encouraging parents to look for 100 calorie snacks, two a day max, in order to cut children's sugar intake, which is three times more than recommended (UK Government, 2018). In 2015, the Scientific Advisory Committee on Nutrition brought the recommended daily intake of fibre to 30 grams, while the average intakes in adults are around 18g of fibre daily (SACN, 2015). The European Food Safety Authority (EFSA) currently allows "source of fibre" and "high fibre" nutritional claims on packaging for foods containing respectively at least 3% or at least 6% fibre (EFSA, 2012).

For all these reasons there is a growing interest in improving the nutritional quality of snacks in the market, with the industry being challenged to develop healthier and calorie-reduced snacks that also deliver in taste. Within this context, improvements in the nutritional quality of extruded snacks could be achieved by using food industry by-products, which have a low value but are rich sources of antioxidants, dietary fibres, minerals and essential fatty acids (Maskan & Altan, 2016).

According to a recent report by WRAP (2017), in 2015 the UK manufacturing sector was the main supply chain producer of food waste (which includes both wasted food and inedible parts), with 1.85 million tonnes of food waste produced, a 9% increase compared to the 1.7 million tonnes estimated in the previous 2016 WRAP report. Of this amount, almost 1 million tonnes were estimated to be edible parts. Economic and environmental motives have brought increasing demand for the conversion of food processing by-products into useful products, thanks also to the recent technological advances in processing techniques (Maskan & Altan, 2016) and methodologies, such as the 5-Stage Universal Recovery Process, where by-product processing progresses from the macroscopic (I) to the macromolecular level (II) and then to the extraction of specific micro-molecules (III), to end with the purification (IV) and encapsulation of the target ones (V)(Galanakis, 2012). The extrusion process is versatile, highly productive, low-cost, energy efficient and lacks of effluents (Maskan & Altan, 2016), therefore it is ideal to incorporate food industry by-products into novel snacks. Extrusion consists in forming and shaping a dough-like material by forcing it through a restriction called the die. This technology is used extensively by the cereal-processing industry, converting cereal flours by kneading, cooking, forming and texturizing, to produce ready-to-eat food products such as noodles and pastas, breakfast cereals, baby foods and snack foods (Bouvier & Campanella, 2014). Extruded snacks can be divided into different categories, however for the purpose of this review we will focus only second and third generation snacks. Directly expanded snacks (also called second generation snacks or collets) include the majority of extruded snacks, such as puffed snacks. These products can then be seasoned, baked or fried (Hui & Sherkat, 2005). Indirectly expanded snacks (also called third generation snacks or half products) are mixed during the extrusion process, dried into a shelf-stable form (pellets) and then expanded using frying, hot air or microwaving at a later stage (Van der Sman & Broeze, 2014). Typical starch sources for both directly and indirectly expanded snacks are corn, potato, rice and wheat (Bouvier & Campanella, 2014). The resulting snack products are usually high in starch and dense in energy, but poor in nutritional value, in terms of micronutrients, proteins and fibre (Brennan, Derbyshire, Tiwari, & Brennan, 2013). Food industry by-products could be used to add value to extruded snacks, as shown in articles summarised by recent reviews (Obradović, Babić, Šubarić, Ačkar, & Jozinović, 2014; Offiah, Kontogiorgos, & Falade, 2018; Quiles, Campbell, Struck, Rohm, & Hernando, 2018).

This review illustrates the most recent efforts (2014-2018) made in research to incorporate food industry by-products in the production of healthier second and third generation extruded snacks, focusing on nutritional improvement and highlighting consumer and sensory gaps.

Recently food industry by-products have been used in extrusion processes. Some examples of non-puffed snack applications include breakfast cereals made with carambola seeds (Borah, Mahanta, & Kalita, 2016), crackers made with by-products from Roselle processing (Ahmed & Abozed, 2015), gluten-free pretzels made with brewer's rice flour (Paykary, et al., 2016) and breadsticks made with substandard bread (Vanshin, Vanshina, & Erkaev, 2017). Food by-products have been used as sources of fibre, protein and antioxidants. New dietary fibre sources derived from fruit and vegetable by-products, can be added to food products as cheap and low-calories bulking agents to partially replace flour, fat or sugar (O'Shea, Arendt, & Gallagher, 2012). We will now discuss extruded snack applications of food by-products such as pomace and bagasse from fruit and vegetables, bran and spent grains from cereals, oilseed cakes and whey from dairy (categorised as per Figure 1).

2. Pomace

2.1. Apple

Apple pomace is the by-product of apple processing, representing 25-35% of the total apple (Đilas, Čanadanović-Brunet, & Ćetković, 2009). Apple pomace can be used for cattle feed supplement, recycled as compost or used for pectin recovery (Singha & Muthukumarappan, 2017), however it often goes to landfill as these applications are not sufficient to use the apple pomace produced and up to 1.3 million metric tons are produced in the US every year (Jung, Cavender, & Zhao, 2015).

Extruded snacks with corn (10%), sorghum flour (70-90%) as an under-utilised cereal, and apple pomace (10-30%) as industrial waste were developed by Lohani and Muthukumarappan (2017). The authors used natural fermentation followed by hydrodynamic cavitation with the aim to improve the total phenolic content and antioxidant activity (to compensate the loss during extrusion) as well as to improve total dietary fibre in the final product. Hydrodynamic cavitation is a novel technology consisting in the formation and collapse of microbubbles over a short time, releasing high energy and resulting in high localised pressures and temperatures, which has been used in food sterilization, microbial cell disruption, water disinfection and wastewater treatment (Gogate, 2011). Similarly, the cavitations and disrupting properties of ultrasound waves (Galanakis, 2013) have been used to enhance extraction of anthocyanins and beta-carotene from grape seeds, citrus and pomegranate peels (Ghafoor, Choi, Jeon, & Jo, 2009; Pan, Qu, Ma, Atungulu, & McHugh, 2012). Pan, et al. (2012) reported that pulsed ultrasound assisted extraction also provided similar antioxidant yield in pomegranate peel, but 50% energy saving compared to conventional ultrasound-assisted extraction. Extrusion cooking with higher apple pomace content (30%), low temperature (80 ˚C) and screw speed (100 rpm), increased the total phenolic content and antioxidant activity of the final product. After extrusion, starch digestibility and dietary fibre content increased. Paraman, Sharif, Supriyadi, and Rizvi (2015) also used apple pomace (22-28%) in the manufacture of extruded snacks, together with another waste stream product, concentrated liquid whey (20% total solids), instead of water. The authors used supercritical fluid extrusion, a novel extrusion technology where supercritical CO_2 is used as an expansion agent instead of steam, which has the advantages of keeping the temperature below 100 ˚C, have low energy input and better control on the expansion compared to steam (Manoi & Rizvi, 2010). The authors claim that the high-temperature (130-200 ˚C) and high shear (150-300 rpm) used on previous extrusion studies with pomace, invariably lead to the loss of both sensory and nutritional quality. Thanks to the more gentle supercritical fluid extrusion process used in this experiment, 84% of the total phenolic compounds and 74% of total antioxidants present in the original apple pomace were retained in the final product. By incorporating 22% pomace (containing 83% fibre on a dry basis), the fibre content in the final product increased from 0.8 g/100 g of control extrudates to 14 g/100 g product, which would allow for a “high fibre” nutritional claim according to EFSA (2012), as it contains more than 6% fibre.

Reis, Rai, and Abu-Ghannam (2014) developed rice-wheat based extruded snacks using apple pomace at different inclusion levels (10-30%). Extruded products with apple pomace incorporation showed a decrease in protein and starch contents and an increase in total dietary fibre compared to control. The addition of apple pomace significantly increased the phenolic compounds in the extrudates compared to control, however the recoveries of phenolic compounds went down as the apple pomace incorporation went up. According to the authors this might be due to polymerisation which affected the extractability of phenolic compounds, therefore the more phenolic compounds were incorporated, the higher the polymerisation. No sensory analyses were carried out as part of these studies.

Freeze-dried apple pomace at 5-10% inclusion in corn snacks was used by O'Shea, Arendt, and Gallagher (2014). Extrudate characteristics, such as expansion ratio, bulk density, porosity and volume, were analysed. Optimal apple pomace inclusion was found to be 7.7%, while high die head temperatures and high screw speeds were found to be detrimental to the quality of the extrudates. No nutritional or sensory analyses were carried out in this study.

Drozdz, et al. (2014) produced extruded con-based snacks with 10-20% apple pomace or rosehip pomace. Corn-rosehip pomace snacks had higher polyphenols content and antioxidant activity than corn-apple pomace snacks. A ten member panel carried out sensory evaluation showed that the addition of pomace to extrudates resulted in progressively lower evaluation of some attributes, however overall the sensory properties of corn-pomace extrudates were acceptable, scoring 3.5–4 in 1-5 scales.

2.2. Carrot

Carrot pomace is the pulpy residue that is left over after juice extraction. This waste, accounting for up to 12% of the fresh carrot and containing valuable compounds such as carotenes and fibres, is generally discarded or used as feed and fertiliser (Anal, 2017).

Kaisangsri, et al. (2016) developed corn starch extrudates with carrot pomace at 5, 10 and 15%. Higher levels of pomace inclusion were associated with a decrease in expansion compared to a pomace-free control, similar to other fibre-enrichment studies (Nascimento, Calado, & Carvalho, 2017; Oliveira, et al., 2015). The β-carotene content reduced significantly after extrusion, however the higher the carrot pomace inclusion, the lower the β-carotene retention in the final product. The authors claim that at the lowest carrot pomace inclusion of 5%, the β-carotene might have been more protected from thermal degradation, compared to higher inclusion levels of 10 and 15%.

Another recent study on carrot pomace was carried out by Dar, Sharma, and Kumar (2014). The authors developed extruded snacks with broken rice flour, where 10-30% or the rice flour was substituted with mixed pigeon pea powder and carrot pomace powder in equal quantities. Vitamin C and β-carotene contents decreased with increasing extrusion temperatures and increasing storage period. In a follow-on study Dar Aamir, Sharma Harish, and Kumar (2014), fried the extrudates at different temperatures and for different times, and sensory analysis after a six-month storage suggested that the product was still acceptable.

Alam, Kumar, and Khaira (2015) developed extruded snacks using rice flour (60-80%), red lentil flour (10-30%) and 10% carrot pomace, using a Box-Behnken design. Optimal extrusion parameters were obtained with an 80:10:10 rice flour/lentil flour/carrot pomace powder formulation, however no nutritional or sensory analyses were carried out. In a similar study by the same group (Alam, Pathania, Kumar, & Sharma, 2015) extruded snacks using broken rice flour, chickpea flour, carrot pomace powder and cheese powder in the proportion of 75:11.25:11.25:2.5 were developed. The authors investigated the effects of different types of packaging during a six-month room temperature shelf life. After manufacture, the extrudates evaluated by ten semi-trained panellist using nine-point hedonic scales, scored high for overall acceptability.

2.3. Cherry

Cherry pomace is the residue left from cherries after juice extraction (Luca, Cilek, Hasirci, Sahin, & Sumnu, 2013). Nawirska and Kwaśniewska (2005) reported that the total dietary fibre content in cherry pomace is 71.44%, consisting of pectin (1.51%), hemicellulose (10.7%), cellulose (18.4%), and lignin (69.4%).

Wang, Kowalski, et al. (2017) used dried cherry pomace at 5-15% inclusion with different particle sizes to produce corn based snacks. Inclusion of the smallest particle size (<125 µm) cherry pomace at 5% level of inclusion yielded extrudates with the highest expansion ratio among all treatments, including the control. Extrusion processing did not significantly affect the total phenolic content of extrudates with the added cherry pomace, probably due to a protective effect of the starch matrix. The authors explain this mechanism, hypothesising that the fibre represented an inert material and acted as a filler dispersed in the walls of the expanded starch matrix. Therefore with low levels of pomace inclusion (such as 5%), there was not enough fibre to fill the cell wall matrix, but with the increase in the pomace level, the amount of the fibre was more than what the starch matrix could sustain. At this point, the starch matrix (or better the walls of the cells) collapsed as the fibre particles pierced through them, resulting in lower expansion ratio.

2.4. Pineapple

Pineapple production was estimated to be 27.8 million tons in 2016 (FAO, 2018). Approximately 40–80% of pineapple fruit is discarded as waste in the form of pineapple peel and pomace after juice extraction (Anal, 2017).

Selani, et al. (2014) developed extruded snacks with 10.5-21% freeze-dried pineapple peel and pomace. The authors choose these levels to aim to deliver 5% or 10% of the recommended daily intake of dietary fibre (25 g/day) in one serving size (28.35 g). Extruded products with added pineapple pomace at both levels expanded less and were darker than the control, however at 10.5% addition there was no effect on hardness or bulk density compared to control. No nutritional or sensory analyses were carried out as part of this experiment on the final product.

2.5. Berries

The industrial transformation of berries into juices and jellies results in high amounts of by-products, which could be used in food applications (Anal, 2017). The press cake or pomace left after juice extraction accounts for about 30% of the total, but these nutritionally-rich compounds are currently discarded or composted (Kryževičiūtė, Kraujalis, & Venskutonis, 2016).

2.5.1.Blackcurrant

Mäkilä, et al. (2014) developed snacks using the residues from blackcurrant juice production at 30% inclusion. Two types of press residues were used: residues from conventional enzymatic pressing (where the fruit is treated with pectinase before pressing) and residues from non-enzymatic juice pressing. The two types of residues were added to a base of either barley, oat or oat bran, for a total of six treatments. Sensory evaluation, consisting of hedonic scales and preference ranking, was carried out by seventy-seven participants on all the samples. Extrudates made with untreated blackcurrant were the most preferred and had higher liking scored compared to pectin-treated extrudates. The authors concluded that the conventional enzymatic press residue may lack the wanted flavour unique to berry material, therefore the fresher berry taste and colour of non-enzymatically processed press residue might be better suited for extrusion application.

2.5.2.Bilberry

Höglund, et al. (2018) developed extruded snacks using bilberry (*Vaccinium myrtillus L.*) press cake, a by-product of the berry juice production made of skins and seeds. The press cakes, produced by cold pressing without enzymatic treatment, were transformed in powders using two different drying techniques at 40 ˚C, either hot air or microwave assisted hot air drying. The snacks were based on organic wholegrain rye flour, with either 10 or 25% bilberry press cake powder inclusion. Although the microwave drying was shorter than hot air alone, the retention of total phenolics and physical characteristics were similar for snacks extruded from bilberry powders produced with different drying techniques. Extrusion processing of bilberry press cake caused a significant reduction in the total phenolics content, however the increase in total phenolics in puffed extrudates was proportional to the addition level. Addition of bilberry press cake powder to wholegrain rye flour significantly increased the insoluble dietary fibre content but it also caused a significant decrease in expansion and increase in density. Sensory analysis carried out with fifteen consumers showed that a 10% inclusion was preferred for texture compared to the 25% inclusion and the decrease in expansion and increase in density, proportional to bilberry press cake powder addition, was perceived by the consumers as decreased porosity and increased hardness. Visual appearance and taste were moderately acceptable for all extrudates with average scores around the hedonic scale's mid-point.

2.6. Tomato

Tomatoes are commonly transformed in soup, ketchup, juice and paste, which generates huge amounts of by-products and wastes, accounting for 40% of the total fresh weight of the tomatoes (Anal, 2017). The dry tomato pomace contains on average 44% seeds and 56% pulp and skins (Singh & Bawa, 1998).

Devi, Kuriakose, Krishnan, Choudhary, and Rawson (2016) developed corn flour (40-60%) and rice flour (30-40%) extruded snacks with dried and milled tomato peel (5-30%) or seed (2.5-5%) powder. Sensory analysis indicated that tomato pomace could be incorporated into extrudates up to 30%. Optimization using D-optimal mixture design suggested that the best extruded product formulation with high desirability was the one consisting of 40% corn flour, 30% rice flour, 25% milled tomato peel and 5% tomato seed powder.

3. Bagasse

3.1. Cassava

Cassava bagasse, the solid residue leftover from the cassava starch industry, is usually disposed of in water course or left in ditches. Similarly to many other food industry by-products, cassava bagasse has a high moisture content (85%), which causes fermentation, therefore drying needs to happen during production (Fiorda, Soares, da Silva, de Moura, & Grossmann, 2015). Fiorda, et al. (2015) studied the effects of moisture and extrusion temperature on the quality of extruded snacks made with cassava starch and dehydrated cassava bagasse in a 70:30 ratio. The authors concluded that higher expansion and intermediate specific volume were obtained in intermediate conditions of extrusion temperature (104.1 ˚C) and moisture (16%).

3.2. Citrus fruits

Following the processing of citrus fruits such as oranges, lemons, grapefruits and limes, peel, pulp and seeds remain, making up 50% of the fresh fruit weight (Chandrasekaran, Nout, & Sarkar, 2012). Orange bagasse, for example, contains 57% of total fibre (dry base), where approximately 48% is insoluble fibre (cellulose) and 9% is soluble fibre (pectin) (Chau & Huang, 2003).

Pitts, McCann, Mayo, Favaro, and Day (2016) used citrus fibre (5-10%) to replace sugar in wheat-corn extrudates. No nutritional analyses or sensory evaluations were carried out, but inclusion of citrus fibre up to 10% increased the expansion ratio and decreased the bulk density of the extrudates.

Cortez, et al. (2016) developed snacks using orange bagasse at 10-25% inclusion. The authors concluded that as the orange bagasse content increased, so did the fibre content, however the bagasse inclusion at any level negatively affected the expansion and increased hardness.

Ruiz-Armenta, et al. (2018) developed corn snacks using the industry by-product (bagasse) of naranjita fruit (*Citrus mitis B.*) at 1.12–11.88% inclusion. This by-product of the juice industry is generally discarded, although it contains excellent amounts of dietary fibre, carotenoids and flavonoids (Delgado-Nieblas, et al., 2017). Sensory evaluation of the snacks was performed by thirty non-trained panellists. The optimal processing conditions were found to be at 125°C extrusion temperature and 8.03% bagasse content, at which levels the product was low in fat (lipids = 1.58%) and a source of fibre (crude fibre = 5.38). It is worth pointing out that the authors only measured the crude fibre and not the total dietary fibre. It has been recognized for many years (Cummings, 1973) that the crude fibre method underestimates the total amount of fibre in the product, therefore it is likely the total dietary fibre in the snacks would have been higher than the amount reported by the authors.

4. Cereals

4.1. Brewer’s spent grain

Brewer’s spent grain is the main by-product of the brewing industry representing around 85% of the total by-products generated (Reinold, 1997). Malted barley or other cereal grains are milled and mixed with water to produce the wort, the liquid fermentation medium to produce beer, while the leftover insoluble fraction of the malted barley is referred to as brewer’s spent grain (Anal, 2017). Rich in dietary fibre (about 70%), protein (about 20%) and minerals such as silicon, phosphorus and calcium, it is commonly used as animal feed (Mussatto, Dragone, & Roberto, 2006; Mussatto, 2014). The dietary fibre of brewer’s spent grain consists of mainly water insoluble fibre (lignin and cellulose constitute about 37-45% brewer’s spent grain dry weight) with a smaller contribution of non-cellulosic polysaccharides, (mostly arabinoxylans, about 22-28% of brewer’s spent grain dry weight) while β-glucans represent less than 1% as they are hydrolysed during wort production (Mussatto, et al., 2006). Before it can be used in foods, brewer’s spent grain needs to be dried as the high moisture and fermentable sugars content make is susceptible to bacterial proliferation (Mussatto, et al., 2006). After drying, the brewer’s spent grain can be turned into flour, although its use has some limitations due to its flavour and brownish colour (Mussatto, et al., 2006). Spent grain accounts, on average, for 31% of the original malted barley weight (Townsley, 1979). Annually, around 3.4 million tonnes of brewer’s spent grain are produced within the European Union, with Germany contributing with approximately 2 million tonnes (Steiner, Procopio, & Becker, 2015).

Brewer’s spent cassava, a by-product of beer produced with cassava flour, has not received much attention. Ha, Nga, Phu, Anh, and Tosch (2014) developed corn-rice snacks using brewer’s spent cassava flour (4-8%). A 4% brewer’s spent cassava inclusion caused no significant changes on the extrudate’s expansion and density, however no nutritional or sensory analyses were carried out on the final product. Reis and Abu-Ghannam (2014) developed extruded products using blends of rice flour and wheat semolina in a ratio of (2:1) with different proportions of brewer's spent grain (10-40%). Straight after extrusion and drying, the extrudates were ground, therefore expansion and density of the final products are unknown. Although no sensory analyses were carried out, adding brewer's spent grain increased the phenolic content and the antioxidant properties compared to control and 20-40% inclusions produced "high fibre" extrudates (>6% fibre). Adding brewer's spent grain did not lower the glycaemic index of the extruded snacks, probably due to other factors preventing a steeper decrease, such as the increase in starch digestibility. Kirjoranta, Tenkanen, and Jouppila (2016) used 10% of brewer's spent grains to produce barley-based snacks with various combinations of barley flour, barley starch, corn starch and whey protein isolate (20% of solids). All recipes containing brewer's spent grains were "high fibre" (10-17%) and recipes containing whey protein isolates and starches expanded well. However, the authors did not carry out any sensory evaluations and did not produce a control to refer the results to. Finally, Nascimento, et al. (2017) developed extruded broken rice snacks with brewer's spent grain at 15% or 30% inclusion. Adding brewer's spent grains produced denser and less expanded extrudates compared to control. No nutritional or sensory analyses were carried out on the final products, with the study focussing on the physical properties of the puffed snacks.

4.2. Rice

4.2.1.Broken rice

When rice is milled from whole rice grains into polished rice, about 30% of white rice breaks (Kadan, Bryant, & Miller, 2008). Broken kernels that are less than three quarters of the original grain's length are considered broken rice (Courtois, Faessel, & Bonazzi, 2010). Broken rice is currently used as animal feed, in pet foods and to make beer (Paranthaman, Alagusundaram, & Indhumathi, 2009). Broken kernels have a nutritive value similar to polished rice and are available at relatively lower cost (Dar, et al., 2014), therefore its transformation into higher value products would be desirable.

Oliveira, et al. (2015) developed extruded snacks using 80-90% broken rice and 10-20% lupin flour. As the rice concentration in the mixture increased, the expansion index increased, while the inclusion of lupin flour resulted in a structural changes and reduced expansion rate. No nutritional or sensory analyses were carried out.

4.2.2.Rice bran

Rice bran is a by-product of the rice paddy milling industry, which is used as fertilizer or animal feed (Anal, 2017). It contains 13-17% proteins, 20-23% fat, about 38% fibre and it is high in phosphorus (above 1.7%), although over half of the phosphorus is in phytate form which may render minerals poorly available (Warren & Farrell, 1990). Rice bran is also used for the extraction of rice bran oil, which results in de-oiled or de-fatted rice bran, a by-product is rich in dietary fibre, antioxidants and micronutrients (Anal, 2017). The rice paddy production in 2016 was 952 million tonnes (FAO, 2018), so since rice bran represents about 8-10% of the total rice grain (Tuncel, Yılmaz, Kocabıyık, & Uygur, 2014), about 76-95 million tonnes were represented by bran. Lipases in rice bran cause rancidity during storage, therefore enzymes in rice bran can be inactivated through extrusion producing “stabilised” rice bran (P. Wang et al., 2017).

De-oiled rice bran was used by Sharma, Srivastava, and Saxena (2016, 2017). The authors developed recipes containing 10% corn flour, 55-75% rice flour and 15-35% de-oiled rice bran. Using a numerical multi-response optimization technique, optimum conditions were obtained with 72% rice flour and 18% de-oiled rice bran inclusion, however no nutritional or sensory analyses were carried out on the extrudates. Wang, Fu, et al. (2017) developed snacks using rice starch with 10% of stabilized rice bran and investigated the changes in gelatinization and retrogradation properties after extrusion. The authors did not measure expansion or density of the pellets, nor did they conduct nutritional or sensory analyses. No recent articles on the sensory quality of snacks with rice bran were found, however Sekhon, Dhillon, Singh, and Singh (1997) used rice bran (both full fat and defatted) to manufacture extruded snacks and carried out sensory analysis with a 6-person panel using 9-point hedonic scales. The authors concluded that full-fat rice bran could not be used in the production of extruded snack foods due to the dark color, oily appearance and unacceptable taste, while snacks prepared from blends containing up to 10% defatted rice bran were nearly comparable to control snacks in sensory terms. Rafe, Sadeghian, and Hoseini-Yazdi (2017) investigated the effects of stabilisation through extrusion on rice bran, concluding that extrusion lowered the protein and vitamin E content, but improved the colour, enhanced the dietary fibre and lowered the phytic acid content. This suggests that extruded rice bran could be successfully exploited as an ingredient in a variety of food formulations.

4.3. Corn bran

Corn bran is a by-product of dry and wet milling of corn, with a high dietary fibre content (up to 90%), therefore it can be used at low levels of inclusion to increase the total dietary fibre content in foods (Duxbury, 1988).

Ogunmuyiwa, et al. (2017) used corn bran at 10% to 80% inclusion in extruded snacks made with starch (10-80%) and bambara nut flour (10-80%), an underutilized indigenous legume of African origin. Corn bran contained 10% protein, 14% fat, 59% carbohydrate and 35% fibre, while bambara nut contained carbohydrates (60%), proteins (21%), fat (5%), and 20% protein. The total dietary fibre in all treatments was above 7%, therefore the extrudates can be considered to be “high fibre”. No sensory analyses were carried out as part of this study.

4.4. Wheat bran

The bran portion of wheat accounts for most of the micronutrient, phytochemical and fibre content of the grain (Anal, 2017). Some wheat milling by-products are used for breads, breakfast cereals and ‘all-bran’ breakfast extruded products, however bran is also currently used as livestock feed or disposed of in landfills (Anal, 2017; Hossain, et al., 2013). Wheat bran represents 14-19% of the wheat grain (Maes & Delcour, 2002) and it contains about 47% of fibre (Kamal-Eldin, et al., 2009). The wheat production in 2016 was 881 million tonnes (FAO, 2018), with about 123-167 million tonnes being bran (14-19% of the total).

Fleischman, et al. (2016) investigated the effects of supplementing antioxidant-rich coloured brans (12.5-37.5%) into extruded wheat snacks, focussing on the physical and antioxidant properties of the extrudates. The authors found that the higher the fibre inclusion, the denser the extrudates and the lower the expansion ratios, similarly to other recent studies (Nascimento, et al., 2017; Oliveira, et al., 2015). Extrusion likely split polyphenolic compounds into smaller molecular species, creating a loss of antioxidant activity in control, white and red bran treatments. However, the purple bran treatment did not have a decrease in Trolox Equivalents after extrusion, probably thanks to the activation of several antioxidants during through non-enzymatic browning reactions. The nutritional content of the extrudates and their sensory properties were not investigated in this study.

Oladiran and Emmambux (2017) investigated the effects of extrusion and the incorporation of wheat bran at 10 and 20% addition levels on the quality of extrudates made with blends of raw cassava and defatted toasted soy flour in a 65:35 ratio. Wheat bran addition significantly reduced the expansion compared to control, however both levels of inclusion still showed expansion ratios above 3, with 3 being generally accepted for expanded snacks (Korkerd, Wanlapa, Puttanlek, Uttapap, & Rungsardthong, 2016). Extrusion increased the soluble dietary fibre and a decreased the insoluble dietary fibre content. The process of extrusion has been previously reported to alter the molecular structure of fibre and increase the amount of soluble fibre in extrudates (Brennan, et al., 2013).

4.5. Rye bran

Rye bran contains most of the dietary fibre and phytochemicals of rye, with 41–47% dietary fibre including arabinoxylan (20–25%) and β-glucan (3.5–5.3%), 13–28% starch and 14–18% protein (Kamal-Eldin, et al., 2009).

Alam, et al. (2014) used rye bran with different particle sizes to develop extruded snacks. The rye bran used contained 13-14% protein, 1.6-2% fat, 38-44% starch and 27-30% fibre, of which 21-26% was insoluble and 5-5.5% was soluble. Total dietary fibre of extrudates was 28-32%, therefore the snacks can be considered “high fibre” (fibre above 6%), however no sensory analyses were carried out on the extrudates. Extrusion processing did not have a significant effect on soluble fibre content but the insoluble dietary fibre content increased by extrusion perhaps due to the formation of resistant starch. Decreasing the particle size improved the crispiness of rye bran extrudates by increasing expansion, air cell size and porosity with reduced hardness. Kallu, Kowalski, and Ganjyal (2017) in a later study investigating the effects of cellulose fibre particle size on expansion, also confirmed that the smaller fibre particle size resulted in extrudates with higher expansion ratio.

4.6. Oat

4.6.1.Oat bran

Oat bran is a major by-product obtained during processing of oat products (Zhang, Liang, Pei, Gao, & Zhang, 2009). It contains about 24% protein and 72% fibre (Krishnan, Chang, & Brown, 1987) of which 6-9% is β-glucan (Gibinski, 2008). Adding oat bran in extruded products has been associated with decreased expansion and increased hardness (Lobato, Anibal, Lazaretti, & Grossmann, 2011), however up to 18% bran produced well expanded snacks if a high starch ingredient such as corn is used as the main carrier matrix (Rzedzicki, Szpryngiel, & Sobota, 2000).

Makowska, Polcyn, and Chudy (2015) developed extruded corn snacks using oat, wheat or rye bran at 20% or 40% inclusion. All products had a total fibre content above 6%, therefore the would qualify for a "high fibre" claim, and had a fat content below or equal to 3%, therefore they could be labelled as "low fat". The 20% oat bran extrudates expanded the most, however all extrudates expanded well (expansion ratio of 3 or above). A trained ten member panel used a nine-point scale to assess all samples on porosity, crispiness, colour, taste as well as overall desirability of the products. Results show that oat bran at 20% inclusion was the most desirable extrudate (7.3 out of 9), 40% rye and 40% wheat scored lowest (3 and 2.8 out of 9 respectively), while 20% wheat and 40% oats were borderline acceptable (4.6 and 5 out of 9 respectively).

Dar, Sharma, and Nayik (2016) developed extruded snacks using wheat, rice and oat brans individually and in combination (W:R:O at 2:1.5:1.5) at 10, 20 and 30% level of supplementation to rice flour. The six-month shelf life study showed a decrease in the total phenolic content and antioxidant activity and an increase in moisture content, water activity and free fatty acid. No expansion, density, nutritional or sensory analyses were carried out.

4.6.2. Residual oat flour

Residual oat flour is a by-product in the production of beta-glucan concentrate (Betaven), obtained without chemicals by micronization and air separation of oat aleurone particles (Gumul, Ziobro, Gambus, & Nowotna, 2015). Gumul, et al. (2015) developed corn-based snacks with 5-20% of residual oat flour. The residual oat flour contained mainly starch (57%), followed by 12% protein, 8% fat, and 5.6% total dietary fibre (of which 2.1% soluble and 3.5% insoluble). Sensory analysis was carried out on all samples by twelve panellists described as having "established sensory sensitivity", using 1-5 scales to evaluate shape and appearance, consistency, structure and flavour. Extrudates with 10% residual oat flour received the highest scores. This treatment, which according to its nutritional composition can be considered "low in fat" and a "source of fibre", also exhibited the highest expansion and lowest density of all treatments.

5. Oilseed by-products

Oil seeds provide edible oil like cottonseed, sesame, peanut, soybean, rapeseed and sunflower (Anal, 2017). By-products of the oilseed industry, such as defatted flours, represent an important source of highly digestible proteins, but they are exclusively used as animal feed (Bhise, Kaur, Manikantan, & Singh, 2015). The defatted cake left after oil production represent 35% of the initial oil seed weight in the case of soybean, 45% in the case of cotton seed and 50% in the case of peanut (Anal, 2017). Recently Bhise, et al. (2015) extruded flour from defatted sunflower into a textured defatted sunflower meal, which could be used as an alternative protein source. Wastewater from oil production, such as olive mill wastewater, is rich in polyphenols which have been used as antimicrobial agents in bread (Galanakis, Tsatalas, Charalambous, & Galanakis, 2018a), as UV filters in sunscreens (Galanakis, Tsatalas,

& Galanakis, 2018) and as natural preservatives in oils and meat products (Galanakis, 2018; Galanakis, Tsatalas, Charalambous, & Galanakis, 2018b), but no extrusion applications are reported.

5.1. Cottonseed

Jáquez, et al. (2014) produced corn-based extruded snacks using glandless cottonseed meal (nutritional composition not provided) at 5-98% inclusion, with optimal level found to be at 10%. The authors studied the microstructure of the extrudates, so the effects of cottonseed meal addition on expansion, density and sensory quality were not investigated as part of this study. The optimal treatment with 10% cottonseed meal had 6% fat and almost 13% protein, while the commercial snacks used as a reference had 26-32% fat and 6-7% protein. The authors report that as the cottonseed inclusion increase, the surface of extrudates became rougher, lumpier and more disrupted, suggesting that this might affect consumer's acceptance.

5.2. Flaxseed

Ganorkar, Patel, Shah, and Rangrej (2016) developed rice-corn snacks where rice flour was substituted with 7.5–20 % defatted flaxseed meal flour (29% fibre, 28% protein and 2% fat). Ten semi trained panellist evaluated the overall acceptability of the extrudates, with results showing a decrease in overall acceptability score as the defatted flaxseed meal inclusion level increased. This was related by the authors to the decreased expansion ratio and increased hardness caused by the defatted flaxseed meal addition. The optimum conditions for maximum acceptability of extruded product were found to be with 10% defatted flaxseed meal incorporation, which is in accordance with the previous study using cottonseed meal. Mercier, et al. (2014) reviewed that cereal product fortification with flaxseed generally has a negative impact on sensory attributes, however sensory quality and consumer acceptance depend on the type and composition of flaxseed used, the level of addition and the product subjected to fortification.

5.3. Soybean

Olusegun, Stephen, Folasade, and Oladejo (2016) developed snacks using cassava and partially defatted soybean flours (46% protein, 8% fat, 2% fibre) at 10-30% inclusion, concluding that a 20% inclusion was optimal for trypsin inhibitor reduction and for sensory evaluation of crispness carried out by fifteen untrained panellists. It is possible that higher levels of inclusion of soy flour in the study by Olusegun, et al. (2016), compared to the optimal 10% of defatted flaxseed meal inclusion found by Ganorkar, et al. (2016), might be due to the lower fibre content in the soy flour used (2% vs 29%), which might have caused less disruption in the matrix.

5.4. Hemp

Jozinović, Ackar, et al. (2017) developed corn snacks with added defatted hemp cake (5-10%), a by-product of hemp oil production (fibre 60% and protein 34%). The hemp cake was completely defatted prior to extrusion (fat 0.5%), using supercritical CO_2 extraction. Optimum extrusion conditions were reached with a temperature in the extruder ejection zone of 150 °C, a moisture content of 15% and a defatted hemp cake addition of 5%. The authors reported a decrease in the expansion ratio and an increase in bulk density and hardness with increasing hemp cake content. This might be related to the high fibre content or to the unknown particle size of the by-product. The authors did not carry out any nutritional or sensory analyses on the extrudates.

5.5. Sesame seed

The production of sesame oil creates a sesame oil cake by-product similarly to other oilseeds, which is often used as an alternative to fish meal (Anal, 2017). Mechanically extracted sesame seed meal contains 44.4% crude protein, 7.8% crude fibre, 11.1% residual crude lipid and 12.4% ash on a dry matter basis, while the solvent extracted meal contains 48.5% crude protein, 10.1% crude fibre, 2.6% residual crude lipid and 12.6% ash (Feedipedia, 2015). Sisay, Emire, Ramaswamy, and Workneh (2018) developed snacks with wheat (38–100%), tef (8-35%), sesame protein concentrate (2.5-25%) and tomato powder (1.2-5%). The sesame protein concentrate (59% protein) was obtained after defatting the hulled sesame seeds, using an aqueous-alcohol process to remove the soluble sugar fraction. The sesame protein concentrate contributed to elevate the protein and simultaneously lower the carbohydrate content of the extruded products. Sensory analysis, carried out by thirty panellists (described as “well-informed”) using nine-point hedonic scales, showed that products with tef, sesame protein concentrate and tomato powder had similar sensory scores to control. Samples with almost 10% sesame protein concentrate received significantly higher acceptability scores for colour compared to other inclusion levels. This 10% inclusion levels is in accordance with the optimal 10% inclusion level of defatted flaxseed meal found by Ganorkar, et al. (2016).

6. Whey

Whey is a by-product of the dairy industry, which is generated during the manufacture of cheese, yogurts and other dairy products (Anal, 2017). About nine pounds of whey are generated for each pound of cheese produced (Paraman, et al., 2015). Whey proteins have a higher biological value than casein and soy proteins (Chandrasekaran, et al., 2012). Whey can be filtered into whey protein concentrate (WPC) with protein content 35-85% or it can be filtered further to produce whey protein isolate (WPI) with protein content above 90% (Anal, 2017). Currently, whey protein products are widely available in the market as flavoured shakes, protein bars and dietary supplements and extruded snacks may help to further minimise whey disposal problems (Yadav, Anand, & Singh, 2014).

Extruded corn snacks with 10-40% WPC inclusion were developed by Yu, et al. (2017). Expansion ratio increased at lower WPC inclusion (10-20%) and decreased with WPC content above 20%. Increasing levels of WPC resulted in snacks with darker colours. The temperatures tested were 130˚C and 150˚C, with increasing temperatures resulting in lower expansion ratios. No nutritional or sensory analyses were carried out.

Yadav, et al. (2014) incorporated 2.5-7.5% WPC into pearl millet expanded snacks. Whey protein at 7.5% resulted in harder and less expanded extrudates and optimal quality was reached with 5% WPC addition. The protein content increased significantly from 8.2% in the control to 13.3% and the calcium content doubled from 24.5 in the control to 54.3 mg 100 g with incorporation of WPC at 7.5% level. Fifty untrained panellist evaluated the samples using nine-point hedonic scales. The overall quality score decreased with increase in WPC levels, but samples with 5% inclusion received acceptable scores of 7.5/9.

Fernandes, Madeira, Carvalho, and Pereira (2016) developed extruded corn snacks with 5-34% WPC inclusion where the extrusion temperatures were kept at a maximum of 100 ˚C. The authors concluded that up to 17% inclusion produced pellets with good expansion, while pellets with 5% of WPC had higher acceptance than the standard samples without whey protein according to ninety-five untrained consumers. A consumer preference map was used in this study, together with Check All That Apply questionnaires (CATA).

Makowska, Cais-Sokolinska, Waskiewicz, Tokarczyk, and Paschke (2016) developed extruded corn snacks containing 3-10% of nano-filtered spray-dried whey powder. When the whey powder content was 10%, acrylamide content increased above permitted levels, snacks became dark and sensory scores were low as assessed by a panel of one hundred and ten consumers. However adding 3-5% of whey powder produced acceptable extrudates. The extrusion temperatures reached were high (140 to 180 ˚C), therefore it is possible that lower extrusion temperatures would have resulted in improved sensory scores, lower acrylamide formation and higher whey inclusion levels. From the above findings it seems that on average a 5% whey powder inclusion produced acceptable extrudates, but acrylamide formation needs to be monitored and at such low inclusion level it is debatable whether there is an environmental advantage (i.e. amount of by-product valorised) or nutritional advantage (i.e. protein content) when adding whey to extruded snacks.

7. Coconut and cocoa

7.1. Coconut haustorium

Coconut haustorium (*Cocos nucifera L.*), is a spongy tissue which forms during the germination of coconut, rich in dietary fibre, iron, phenolics, and antioxidants (Manivannan, et al., 2018). It is estimated that 2-3% of the total coconut production is left to germinate, for reasons related to the harvesting cycle, long storage and scarcity of labour (Manivannan, et al., 2018).

Arivalagan, et al. (2018) developed extruded snacks using coconut haustorium, an under-utilised spongy tissue formed during coconut germination. Compared to the rice-maize control, adding 20-30% of coconut haustorium decreased the fat content and increased the protein content. The 10-30% addition resulted in a significant increase in micronutrient content (potassium, magnesium, manganese, iron and zinc), while a 20-30% addition resulted in a significant decrease in calcium content. Sensory analysis, carried out with a semi-trained panel of six people, showed that up to 20% coconut haustorium inclusion improved the product's sensory properties compared to control.

7.2. Cocoa bean shell

Cocoa products are produced from dried and fermented cocoa beans, and cocoa shells are one of the by-products of cocoa beans, together with cocoa pod husk and cocoa mucilage (Panak Balentić, et al., 2018). Cocoa bean shells are disposed of as waste, however they contain approximately 40% dietary fibre (Redgwell, et al., 2003). Cocoa shells represent 10-14% of the bean weight and they are separated from the nib (which continues for further processing), after whole bean roasting (Beckett, Fowler, & Ziegler, 2017). In 2016 approximately 4.5 million tonnes of cocoa beans were produced (FAO, 2018), therefore an estimated 450-630.000 tonnes of cocoa shells were produced, a large environmental load if not further exploited.

Jozinović, Panak Balentić, et al. (2017) produced corn snack products enriched with cocoa shells. They added milled shells to corn grits in 5%, 10%, and 15% dry matter, and extruded in a laboratory single-screw extruder. Resistant starch, starch damage, polyphenol content and antioxidant activity were measured. The authors concluded that cocoa shells can be successfully employed as nutritional fortification agent, although no sensory analyses were carried out as part of this study.

8. Mixes of more than two by-products

Korkerd, et al. (2016) developed corn-based snacks containing 20% of defatted soya meal, germinated brown rice and mango peel fibre mixed in different proportions. The authors carried out a sensory evaluation with thirty untrained panellists on five out of the thirteen formulations and without using control as a reference. The five formulations selected exhibited expansion ratio higher than 3.0 (as generally accepted for expanded snack food) and total dietary fibre of 10% or higher. Increasing the protein and fibre content in the product resulted in decreased expansion ratio and extrusion cooking resulted in the conversion of insoluble to soluble fibre, balancing the two types of fibre.

Alam, Pathania, and Sharma (2016) developed extruded snacks using a combination of four food by-products: broken rice (65-85%), defatted soybean flour (7.5-17.5%), carrot pomace powder (3.75-8.75%) and cauliflower trimmings powder (3.75-8.75%). Sensory evaluation was carried out by ten semi-trained panellists using a nine-point hedonic scale and the highest overall acceptability was at 125 ˚C die temperature, 400 rpm screw speed and 65 g/100 g rice flour. At the same conditions but higher temperature of 175 ˚C, the overall acceptability was lower, showing a direct association of temperature with the acceptability of the product. In terms of nutritional composition, substituting rice flour with defatted soybean flour in the formulation increased the overall protein content (10-14%). The fibre content increased in extrudates with increased carrot pomace and cauliflower trimmings, but it was not higher than 2.46%, therefore the extrudates would not qualify as a source of fibre, for which at least 3% of fibre content is needed. Singha and Muthukumarappan (2017) investigated extruded snacks with apple pomace (5-20%), defatted soy flour (30-45%) and corn grits (50%) under several different process conditions, however no quality, nutritional or sensory analyses were carried on the extrudates as part of the study.

Recently Ačkar, et al. (2018) used brewer's spent grain, sugar beet pulp and apple pomace at 5%-10%-15% inclusion to produce corn snacks. To the mixtures with brewer’s spent grain and sugar beet pulp, 0.5% or 1% of pectin was added, while since apple pomace is already naturally rich in pectin (11-22% in dry matter (Gullón, Falqué, Alonso, & Parajó, 2007)), no extra pectin was added to it. The authors decided to add pectin because this compound has been reported to reduce the facture of cell walls, by increasing the extensibility and resulting in porous products (Yanniotis, Petraki, & Soumpasi, 2007). Results show that the expansion ratio decreased proportionally to the amount of added by-products probably due to the reduced starch content. The impact was highest with brewer's spent grain addition (highest in protein and fat, lowest in starch) and lowest for apple pomace (lowest in protein and fat, highest in starch). Expansion improved with increasing pectin inclusion. Sensory analysis was carried out by ten trained panellists, who assessed external appearance (uniformity, colour), structure (porosity, crispness), consistency (chewing), odour, flavour and overall quality using hedonic scales. Sensory evaluation was done on the samples with the best physical properties: control sample (corn), all apple pomace samples, brewer's spent grains and sugar beet pulp samples with 1% of added pectin. Results show that the more expanded products received better sensory scores, with pectin inclusion showing potential to reduce cell wall fracture in snacks made with food by-products.

9. Future research challenges

The future of extruded snacks with food by-products will most likely rely on the use of novel technologies that will limit heat damage during extrusion with temperatures not far from 100 ˚C, such as supercritical fluid extrusion which we have seen applied on apple pomace (section 2.1). A thorough review by Balentić, et al. (2017) on the use of supercritical CO_2 extrusion concluded that this technology not only has nutritional advantages (because it preserves heat-labile compounds and avoids the formation of undesirable compounds at high processing temperatures), but it also allows energy savings, which is favourable in sustainability terms. Another technological challenge relies on the drying of the food by-products soon after processing to reach shelf stable conditions in an economical manner, while preserving the valuable heat-labile compounds. Some interesting emerging technologies in food drying are radio frequency drying, that evaporates the water in situ at relatively low temperatures (i.e.

<80 °C) and electro osmotic dewatering, that allows a reduction of energy consumption up to two thirds compared to traditional thermal processes (Galanakis, 2013). The percentage of by-product inclusion also requires further investigation. Recent articles have highlighted that trying to add more is not necessarily better, as smaller by-product inclusions might produce better results in terms of antioxidants' retention as seen in apple, carrot and cherry pomace (sections 2.1-2.3). However if smaller amounts of by-product are included in extruded snacks, it could be argued that the final product might not be as environmentally "sustainable" or might not have many other added benefits, such as nutritional enhancement in terms of fibre or protein. The scientific contribution of future studies should therefore be targeted to a specific and measureable added value in the final product, whether this might be environmental, nutritional, economical or a combination of these.

One issue not discussed in the present review concerns the economic sustainability of snacks produced with food by-products. While each of the by-products mentioned in the text does represent an environmental challenge of its own, the use of some by-products in extrusion could be more justified than others. Factors such as the environmental impact of the by-product, the ease and energy requirements of its processing, its current uses, its seasonality and its behaviour in extrusion application, should all be considered together in a more holistic approach. The formulations of extruded snacks with by-products developed by future scientists should be justified by all of these factors, rather than in isolation and as a pure publication exercise.

Extruded snacks are not the only baked goods where by-products are being included. The incorporation of fruit and vegetable by-products in bakery foods such as breads, cakes and cookies has been reviewed by Gómez and Martinez (2018). The authors found that in general in cakes and biscuits higher levels of flour replacement can be reached compared to breads (flour replacement ≥30% in cakes and ≥15% in cookies vs on average ≤10% in bread). The authors explain that cakes and cookies better tolerate larger amounts of fruit and vegetable by-products compared to breads, since lipids and sugar may mask bitter flavors, there is no requirement for a gluten network and there is a lower flour fraction in the overall recipe. While extruded snacks are more complex to manufacture compared to breads, cookies and cakes, promising results have been reported in the present review with the use of several by-products even at inclusion levels around 30%.

The particle size of the by-product added also requires some attention, as higher by-product additions might be possible if the by-product added has a smaller particle size and therefore might disrupt the starch matrix less, as seen in rye bran, section 4.5. In this regard, the use of modern encapsulation techniques such as nano-emulsions could help to achieve droplets of 10-100 nm, ensuring physical stability and increased bioavailability in the final product (Choi, Kim, Cho, Hwang, & Kim, 2011), although the cells membrane permeability of nano-materials and their effect on biological matrices still remain unknown (Galanakis, 2013).

The current research in this field seems to be focussed mainly on reformulation strategies rather than sensory or consumer aspects, with only twenty of the forty-eight articles surveyed for this review attempting to evaluate the sensory quality of the new recipes. However, the sensory quality of novel foods is an essential pre-requisite which might determine whether or not a new product survives in a very competitive market. This gap needs to be addressed and hopefully future research will focus on the sensory characterisations of novel snacks made with food industry by-products as well as on the consumer attitudes towards these new products. Of particular importance would be the study of the relationship between the food industry by-products and their snack carrier matrix, to understand whether some combinations of by-products and snack matrix would be preferred over others by consumers. Another important point that should be explored further is the effect of information on consumers' willingness to pay or to buy for snacks made with industry by-products. This would help to understand whether a statement on a product's label about the presence of a by-product ingredient would have an effect on how the overall product is perceived by consumers. For example Cheng, Bekhit, Sedcole, and Hamid (2010) tested the effect of health benefit information on the acceptability of tea infusions made from grape skins generated from wine processing waste. Information on the health benefits of the tea infusion samples significantly increased the sensory scores of the infusions (overall acceptability, overall aroma, flavor, aftertaste) and increased consumers' purchase intention by 29%. Recently Aschemann-Witzel and Peschel (2019) used an experimental survey design among 491 Danish consumers to investigate how consumers react to food products based on ingredients previously wasted in the supply chain. The hypothetical product tested was a soy based cocoa-flavoured drink, containing potato protein from by-products, and presented with or without communication on the sustainability benefit. Results were promising, showing that communication improved attitudes towards the potato drink. More consumer attitudes studies on by-products using different food matrices and types of information should be tested, to get a deeper understanding on this topic.

With a lot of research focusing on the development of extruded snacks made with food by-products, it might be worth mentioning here that one of such product has already entered the market. In 2018, a company called Planetarians (www.planetarians.com) launched a snack made from sunflower oil cake. The snacks are made using steam explosion to puff the fibre, while high pressure and temperature are used to cook and sterilize the feed grade ingredient. Their packaging claims that a 43 gram serving provides 12 grams of protein, 11 grams of fibre and 1 gram of fat (in percentage 29% protein, 27% fibre and 2.3% fat), which would make the product "high protein", "high fibre" and "low fat" in the EU (EFSA, 2012). The product, marketed as "clean label", contains only sunflower oil cake, potato starch, sunflower oil and natural seasoning. The company claims that their test sales of sunflower chips on Amazon during the 2018 spring brought in £29K in sales, with a 69% average monthly growth rate. It is encouraging to see an example of the successful entry to market of a snack made with industrial by-products using a novel technology and hopefully there will be many more to come in the near future. This company is now determined to push their defatted sunflower seed flour ingredient in the market to test different food applications. In 2015 the products derived from food by-products were still rather limited and across the globe only 35 companies with related products were identified by Galanakis (2015). However, it is quite likely that since then many more might have entered the market due to the growing interest in the food by-product area.

In the future, to increase the chances of success in the competitive snack market, it will be important to support new snacks with multidisciplinary teams to provide not only the adequate technologies and reformulation strategies, but also the supporting sensory testing and consumer insights.

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References

Ačkar, Đ., Jozinović, A., Babić, J., Miličević, B., Panak Balentić, J., & Šubarić, D. (2018). Resolving the problem of poor expansion in corn extrudates enriched with food industry by-products. *Innovative Food Science & Emerging Technologies*, *47*, 517-524.

Ahmed, Z. S., & Abozed, S. S. (2015). Functional and antioxidant properties of novel snack crackers incorporated with Hibiscus sabdariffa by-product. *Journal of Advanced Research*, *6*, 79-87.

Alam, M. S., Kumar, S., & Khaira, H. (2015). Effects of extrusion process parameters on a cereal-based ready-to-eat expanded product formulated with carrot pomace. *Cereal Foods World*, *60*, 287-295.

Alam, M. S., Pathania, S., Kumar, S., & Sharma, A. (2015). Studies on storage stability of carrot pomace-chickpea incorporated rice based snacks. *Agricultural Research Journal*, *52*, 73-79.
Alam, M. S., Pathania, S., & Sharma, A. (2016). Optimization of the extrusion process for development of high fibre soybean-rice ready-to-eat snacks using carrot pomace and cauliflower trimmings. *LWT*, *74*, 135-144.
Alam, S. A., Järvinen, J., Kirjoranta, S., Jouppila, K., Poutanen, K., & Sozer, N. (2014). Influence of particle size reduction on structural and mechanical properties of extruded rye bran. *Food and Bioprocess Technology*, *7*, 2121-2133.
Anal, A. K. (2017). *Food processing by-products and their utilization*: John Wiley & Sons.
Arivalagan, M., Manikantan, M. R., Yasmeen, A. M., Sreejith, S., Balasubramanian, D., Hebbar, K. B., & Kanade, S. R. (2018). Physiochemical and nutritional characterization of coconut (Cocos nucifera L.) haustorium based extrudates. *LWT*, *89*, 171-178.
Aschemann-Witzel, J., & Peschel, A. O. (2019). How circular will you eat? The sustainability challenge in food and consumer reaction to either waste-to-value or yet underused novel ingredients in food. *Food Quality and Preference*, *77*, 15-20.
Balentić, J. P., Ačkar, Đ., Jozinović, A., Babić, J., Miličević, B., Jokić, S., Pajin, B., & Šubarić, D. (2017). Application of supercritical carbon dioxide extrusion in food processing technology. *Gas*, *10*, 0.1.
Beckett, S. T., Fowler, M. S., & Ziegler, G. R. (2017). *Beckett's industrial chocolate manufacture and use*: John Wiley & Sons.
Bhise, S., Kaur, A., Manikantan, M., & Singh, B. (2015). Development of textured defatted sunflower meal by extrusion using response surface methodology. *Acta Alimentaria*, *44*, 251-258.
Borah, A., Mahanta, C. L., & Kalita, D. (2016). Optimization of process parameters for extrusion cooking of low amylose rice flour blended with seeded banana and carambola pomace for development of minerals and fiber rich breakfast cereal. *Journal of Food Science and Technology-Mysore*, *53*, 221-232.
Bouvier, J.-M., & Campanella, O. H. (2014). *Extrusion processing technology: Food and non-food biomaterials*: John Wiley & Sons.
Brennan, M. A., Derbyshire, E., Tiwari, B. K., & Brennan, C. S. (2013). Ready-to-eat snack products: the role of extrusion technology in developing consumer acceptable and nutritious snacks. *International Journal of Food Science & Technology*, *48*, 893-902.
Chandrasekaran, M., Nout, M. J. R., & Sarkar, P. K. (2012). *Valorization of food processing by-products*. Boca Raton, FL: CRC.
Chau, C.-F., & Huang, Y.-L. (2003). Comparison of the chemical composition and physicochemical properties of different fibers prepared from the peel of Citrus sinensis L. Cv. Liucheng. *Journal of Agricultural and Food Chemistry*, *51*, 2615-2618.
Cheng, V. J., Bekhit, A. E.-D. A., Sedcole, R., & Hamid, N. (2010). The Impact of Grape Skin Bioactive Functionality Information on the Acceptability of Tea Infusions Made from Wine By-Products. *Journal of Food Science*, *75*, S167-S172.

Choi, A.-J., Kim, C.-J., Cho, Y.-J., Hwang, J.-K., & Kim, C.-T. (2011). Characterization of capsaicin-loaded nanoemulsions stabilized with alginate and chitosan by self-assembly. *Food and Bioprocess Technology*, *4*, 1119-1126.

Cortez, R. O. N., Gomez-Aldapa, C. A., Aguilar-Palazuelos, E., Delgado-Licon, E., Rosas, J. C., Hernandez-Avila, J., Solis-Soto, A., Ochoa-Martinez, L. A., & Medrano-Roldan, H. (2016). Blue corn (Zea mays L.) with added orange (Citrus sinensis) fruit bagasse: novel ingredients for extruded snacks. *CyTA-Journal of Food*, *14*, 349-358.

Courtois, F., Faessel, M., & Bonazzi, C. (2010). Assessing breakage and cracks of parboiled rice kernels by image analysis techniques. *Food control*, *21*, 567-572.

Cummings, J. (1973). Dietary fibre. *Gut*, *14*, 69.

Dar Aamir, H., Sharma Harish, K., & Kumar, N. (2014). Effect of frying time and temperature on the functional properties of carrot pomace, pulse powder and rice flour–based extrudates. In *International Journal of Food Engineering* (Vol. 10, pp. 139).

Dar, A. H., Sharma, H. K., & Kumar, N. (2014). Effect of extrusion temperature on the microstructure, textural and functional attributes of carrot pomace-based extrudates. *Journal of Food Processing and Preservation*, *38*, 212-222.

Dar, B., Sharma, S., & Nayik, G. A. (2016). Effect of storage period on physiochemical, total phenolic content and antioxidant properties of bran enriched snacks. *Journal of Food Measurement and Characterization*, *10*, 755-761.

Delgado-Nieblas, C. I., Zazueta-Morales, J. J., Ahumada-Aguilar, J. A., Aguilar-Palazuelos, E., Carrillo-López, A., Jacobo-Valenzuela, N., & Telis-Romero, J. (2017). Optimization of an air-drying process to obtain a dehydrated naranjita (Citrus Mitis B.) pomace product with high bioactive compounds and antioxidant capacity. *Journal of Food Process Engineering*, *40*, e12338.

Devi, B., Kuriakose, S., Krishnan, A., Choudhary, P., & Rawson, A. (2016). Utilization of by-product from tomato processing industry for the development of new product. *Journal of Food Processing and Technology*, *7*.

Đilas, S., Čanadanović-Brunet, J., & Ćetković, G. (2009). By-products of fruits processing as a source of phytochemicals. *Chemical Industry and Chemical Engineering Quarterly/CICEQ*, *15*, 191-202.

Drozdz, W., Tomaszewska-Ciosk, E., Zdybel, E., Boruczkowska, H., Boruczkowski, T., & Regiec, P. (2014). Effect of apple and rosehip pomaces on colour, total phenolics and antioxidant activity of corn extruded snacks. *Polish Journal of Chemical Technology*, *16*, 7-11.

Duxbury, D. (1988). Fiber intake, labeling boosted by FASEB and NFPA. *Food processing*, *49*, 37-44.

EFSA. (2012). EU Register on nutrition and health claims. In.

FAO. (2018). FAOSTAT Statistics Database – Agriculture. http://www.fao.org/faostat/en/#data/QC.

Feedipedia. (2015). Animal feed resources information system. In.

Fernandes, A. F., Madeira, R. A. V., Carvalho, C. W. P., & Pereira, J. (2016). Physical and sensory characteristics of pellets elaborated with different levels of corn grits and whey protein concentrate. *Ciência e Agrotecnologia*, *40*, 235-243.

Fiorda, F. A., Soares, M. S., da Silva, F. A., de Moura, C. M. A., & Grossmann, M. V. E. (2015). Physical quality of snacks and technological properties of pre-gelatinized flours formulated with cassava starch and dehydrated cassava bagasse as a function of extrusion variables. *LWT-Food Science and Technology*, *62*, 1112-1119.

Fleischman, E. F., Kowalski, R. J., Morris, C. F., Nguyen, T., Li, C., Ganjyal, G., & Ross, C. F. (2016). Physical, textural, and antioxidant properties of extruded waxy wheat flour snack supplemented with several varieties of bran. *Journal of Food Science*, *81*, E2726-E2733.

Galanakis, C. M. (2012). Recovery of high added-value components from food wastes: conventional, emerging technologies and commercialized applications. *Trends in Food Science & Technology*, *26*, 68-87.

Galanakis, C. M. (2013). Emerging technologies for the production of nutraceuticals from agricultural by-products: A viewpoint of opportunities and challenges. *Food and Bioproducts Processing*, *91*, 575-579.

Galanakis, C. M. (2015). *Food waste recovery: processing technologies and industrial techniques*: Academic Press.

Galanakis, C. M. (2018). Phenols recovered from olive mill wastewater as additives in meat products. *Trends in Food Science & Technology*, *79*, 98-105.

Galanakis, C. M., Tsatalas, P., Charalambous, Z., & Galanakis, I. M. (2018a). Control of microbial growth in bakery products fortified with polyphenols recovered from olive mill wastewater. *Environmental Technology & Innovation*, *10*, 1-15.

Galanakis, C. M., Tsatalas, P., Charalambous, Z., & Galanakis, I. M. (2018b). Polyphenols recovered from olive mill wastewater as natural preservatives in extra virgin olive oils and refined olive kernel oils. *Environmental Technology & Innovation*, *10*, 62-70.

Galanakis, C. M., Tsatalas, P., & Galanakis, I. M. (2018). Phenols from olive mill wastewater and other natural antioxidants as UV filters in sunscreens. *Environmental Technology & Innovation*, *9*, 160-168.

Ganorkar, P. M., Patel, J. M., Shah, V., & Rangrej, V. V. (2016). Defatted flaxseed meal incorporated corn-rice flour blend based extruded product by response surface methodology. *Journal of Food Science and Technology-Mysore*, *53*, 1867-1877.

Ghafoor, K., Choi, Y. H., Jeon, J. Y., & Jo, I. H. (2009). Optimization of ultrasound-assisted extraction of phenolic compounds, antioxidants, and anthocyanins from grape (Vitis vinifera) seeds. *Journal of Agricultural and Food Chemistry*, *57*, 4988-4994.

Gibinski, M. (2008). Beta-glukany owsa jako skladnik zywnosci funkcjonalnej. *Żywność Nauka Technologia Jakość*, *15*, 15-29.

Gogate, P. R. (2011). Hydrodynamic cavitation for food and water processing. *Food and Bioprocess Technology*, *4*, 996-1011.

Gómez, M., & Martinez, M. M. (2018). Fruit and vegetable by-products as novel ingredients to improve the nutritional quality of baked goods. *Critical reviews in food science and nutrition*, *58*, 2119-2135.

Gullón, B., Falqué, E., Alonso, J. L., & Parajó, J. C. (2007). Evaluation of apple pomace as a raw material for alternative applications in food industries. *Food Technology and Biotechnology*, *45*, 426-433.

Gumul, D., Ziobro, R., Gambus, H., & Nowotna, A. (2015). Usability of residual oat flour in the manufacture of extruded corn snacks. *CyTA-Journal of Food*, *13*, 353-360.

Ha, P., Nga, L. H., Phu, T. V., Anh, T. K., & Tosch, W. (2014). Development of method to produce snacks supplemented with brewer's spent cassava. In *2nd International Conference on Food and Agricultural Services* (Vol. 77, pp. 44-48).

Höglund, E., Eliasson, L., Oliveira, G., Almli, V. L., Sozer, N., & Alminger, M. (2018). Effect of drying and extrusion processing on physical and nutritional characteristics of bilberry press cake extrudates. *LWT*, *92*, 422-428.

Hossain, K., Ulven, C., Glover, K., Ghavami, F., Simsek, S., Alamri, M., Kumar, A., & Mergoum, M. (2013). Interdependence of cultivar and environment on fiber composition in wheat bran. *Australian Journal of Crop Science*, *7*, 525.

Hui, Y. H., & Sherkat, F. (2005). *Handbook of food science, technology, and engineering-4 Volume set*: CRC press.

Jáquez, D. R., Casillas, F., Flores, N., Cooke, P., Licon, E. D., Soto, A. S., González, I. A., Carreón, F. O. C., & Roldán, H. M. (2014). Effect of glandless cottonseed meal content on the microstructure of extruded corn-based snacks. *Advances in Food Sciences*, *36*, 125-130.

Jozinović, A., Ackar, D., Jokic, S., Babic, J., Panak Balentic, J., Banozic, M., & Subaric, D. (2017). Optimisation of extrusion variables for the production of corn snack products enriched with defatted hemp cake. *Czech Journal of Food Sciences*, *35*, 507-516.

Jozinović, A., Panak Balentić, J., Ačkar, Đ., Babić, J., Pajin, B., Miličević, B., Guberac, S., & Šubarić, D. (2017). Cocoa husk application in enrichment of extruded snack products. In *Fourth International Congress on Cocoa Coffee and Tea Book of Abstracts*. Turin.

Jung, J., Cavender, G., & Zhao, Y. (2015). Impingement drying for preparing dried apple pomace flour and its fortification in bakery and meat products. *Journal of food science and technology*, *52*, 5568-5578.

Kadan, R. S., Bryant, R. J., & Miller, J. A. (2008). Effects of milling on functional properties of rice flour. *Journal of Food Science*, *73*, E151-E154.

Kaisangsri, N., Kowalski, R. J., Wijesekara, I., Kerdchoechuen, O., Laohakunjit, N., & Ganjyal, G. M. (2016). Carrot pomace enhances the expansion and nutritional quality of corn starch extrudates. *LWT - Food Science and Technology*, *68*, 391-399.

Kallu, S., Kowalski, R. J., & Ganjyal, G. M. (2017). Impacts of cellulose fiber particle size and starch type on expansion during extrusion processing. *Journal of Food Science*, *82*, 1647-1656.

Kamal-Eldin, A., Lærke, H. N., Knudsen, K.-E. B., Lampi, A.-M., Piironen, V., Adlercreutz, H., Katina, K., Poutanen, K., & Åman, P. (2009). Physical, microscopic and chemical characterisation of industrial rye and wheat brans from the Nordic countries. *Food & Nutrition Research*, *53*, 1912.

Kirjoranta, S., Tenkanen, M., & Jouppila, K. (2016). Effects of process parameters on the properties of barley containing snacks enriched with brewer's spent grain. *Journal of Food Science and Technology-Mysore*, *53*, 775-783.

Korkerd, S., Wanlapa, S., Puttanlek, C., Uttapap, D., & Rungsardthong, V. (2016). Expansion and functional properties of extruded snacks enriched with nutrition sources from food processing by-products. *Journal of Food Science and Technology-Mysore*, *53*, 561-570.

Krishnan, P., Chang, K., & Brown, G. (1987). Effect of commercial oat bran on the characteristics and composition of bread. *Cereal Chemistry*, *64*, 55-58.

Kryževičiūtė, N., Kraujalis, P., & Venskutonis, P. R. (2016). Optimization of high pressure extraction processes for the separation of raspberry pomace into lipophilic and hydrophilic fractions. *The Journal of Supercritical Fluids*, *108*, 61-68.

Lobato, L., Anibal, D., Lazaretti, M., & Grossmann, M. (2011). Extruded puffed functional ingredient with oat bran and soy flour. *LWT-Food Science and Technology*, *44*, 933-939.

Lohani, U. C., & Muthukumarappan, K. (2017). Effect of extrusion processing parameters on antioxidant, textural and functional properties of hydrodynamic cavitated corn flour, sorghum flour and apple pomace-based extrudates. *Journal of Food Process Engineering*, *40*, 15.

Luca, A., Cilek, B., Hasirci, V., Sahin, S., & Sumnu, G. (2013). Effect of degritting of phenolic extract from sour cherry pomace on encapsulation efficiency—production of nano-suspension. *Food and Bioprocess Technology*, *6*, 2494-2502.

Maes, C., & Delcour, J. (2002). Structural characterisation of water-extractable and water-unextractable arabinoxylans in wheat bran. *Journal of cereal science*, *35*, 315-326.

Mäkilä, L., Laaksonen, O., Ramos Diaz, J. M., Vahvaselkä, M., Myllymäki, O., Lehtomäki, I., Laakso, S., Jahreis, G., Jouppila, K., Larmo, P., Yang, B., & Kallio, H. (2014). Exploiting blackcurrant juice press residue in extruded snacks. *LWT - Food Science and Technology*, *57*, 618-627.

Makowska, A., Cais-Sokolinska, D., Waskiewicz, A., Tokarczyk, G., & Paschke, H. (2016). Quality and nutritional properties of corn snacks enriched with nanofiltered whey powder. *Czech Journal of Food Science*, *34*.

Makowska, A., Polcyn, A., & Chudy, S. (2015). Application of oat, wheat and rye bran to modify nutritional properties, physical and sensory characteristics of extruded corn snacks. *Acta scientiarum polonorum. Technologia alimentaria*, *14*.

Manivannan, A., Bhardwaj, R., Padmanabhan, S., Suneja, P., Hebbar, K., & Kanade, S. R. (2018). Biochemical and nutritional characterization of coconut (Cocos nucifera L.) haustorium. *Food Chemistry*, *238*, 153-159.

Manoi, K., & Rizvi, S. S. H. (2010). Physicochemical characteristics of phosphorylated cross-linked starch produced by reactive supercritical fluid extrusion. *Carbohydrate Polymers*, *81*, 687-694.

Maskan, M., & Altan, A. (2016). *Advances in food extrusion technology*: CRC press.

Mercier, S., Villeneuve, S., Moresoli, C., Mondor, M., Marcos, B., & Power, K. A. (2014). Flaxseed-enriched cereal-based products: A review of the impact of processing conditions. *Comprehensive Reviews in Food Science and Food Safety*, *13*, 400-412.

Mintel. (2018a). Consumer snacking, UK, May 2018. In.

Mintel. (2018b). Crisps, savoury snacks and nuts - UK, January 2018. In.

Mussatto, S., Dragone, G., & Roberto, I. (2006). Brewers' spent grain: generation, characteristics and potential applications. *Journal of cereal science*, *43*, 1-14.

Mussatto, S. I. (2014). Brewer's spent grain: a valuable feedstock for industrial applications. *Journal of the Science of Food and Agriculture*, *94*, 1264-1275.

Nascimento, T. A., Calado, V., & Carvalho, C. W. P. (2017). Effect of brewer's spent grain and temperature on physical properties of expanded extrudates from rice. *LWT - Food Science and Technology*, *79*, 145-151.

Nawirska, A., & Kwaśniewska, M. (2005). Dietary fibre fractions from fruit and vegetable processing waste. *Food Chemistry*, *91*, 221-225.

O'Shea, N., Arendt, E. K., & Gallagher, E. (2012). Dietary fibre and phytochemical characteristics of fruit and vegetable by-products and their recent applications as novel ingredients in food products. *Innovative Food Science & Emerging Technologies*, *16*, 1-10.

O’Shea, N., Arendt, E., & Gallagher, E. (2014). Enhancing an extruded puffed snack by optimising die head temperature, screw speed and apple pomace inclusion. *Food and Bioprocess Technology*, *7*, 1767-1782.

Obradović, V., Babić, J., Šubarić, D., Ačkar, Đ., & Jozinović, A. (2014). Improvement of nutritional and functional properties of extruded food products. *Journal of Food & Nutrition Research, 53*.

Offiah, V., Kontogiorgos, V., & Falade, K. O. (2018). Extrusion processing of raw food materials and by-products: a review. *Critical reviews in food science and nutrition*, 1-60.

Ogunmuyiwa, O. H., Adebowale, A. A., Sobukola, O. P., Onabanjo, O. O., Obadina, A. O., Adegunwa, M. O., Kajihausa, O. E., Sanni, L. O., & Keith, T. (2017). Production and quality evaluation of extruded snack from blends of bambara groundnut flour, cassava starch, and corn bran flour. *Journal of Food Processing and Preservation*, *41*, 7.

Oladiran, D. A., & Emmambux, N. M. (2017). Effects of extrusion cooking and wheat bran substitution on the functional, nutritional, and rheological properties of cassava-defatted toasted soy composite. *Starch-Starke*, *69*, 9.

Oliveira, C. T., Gutierrez, É. M. R., Caliari, M., Monteiro, M. R. P., Labanca, R. A., & Carreira, R. L. (2015). Development and characterization of extruded broken rice and lupine (Lupinus albus). *American Journal of Plant Sciences*, *6*, 1928.

Olusegun, A., Stephen, A., Folasade, B., & Oladejo, D. (2016). Effect of extrusion conditions on cassava/soybean extrudates. *MOJ Food Processing & Technology*, *3*, 237-245.

Pan, Z., Qu, W., Ma, H., Atungulu, G. G., & McHugh, T. H. (2012). Continuous and pulsed ultrasound-assisted extractions of antioxidants from pomegranate peel. *Ultrasonics sonochemistry*, *19*, 365-372.

Panak Balentić, J., Ačkar, Đ., Jokić, S., Jozinović, A., Babić, J., Miličević, B., Šubarić, D., & Pavlović, N. (2018). Cocoa shell: a by-product with great potential for wide application. *Molecules*, *23*, 1404.

Paraman, I., Sharif, M. K., Supriyadi, S., & Rizvi, S. S. H. (2015). Agro-food industry byproducts into value-added extruded foods. *Food and Bioproducts Processing*, *96*, 78-85.

Paranthaman, R., Alagusundaram, K., & Indhumathi, J. (2009). Production of protease from rice mill wastes by Aspergillus niger in solid state fermentation. *World Journal of Agricultural Sciences*, *5*, 308-312.

Paykary, M., Karim, R., Saari, N., Sulaiman, R., Shekarforoush, E., & Aghazadeh, M. (2016). Optimization of leavening agents in extruded gluten-free brewer's rice hard pretzel using response surface methodology. *Journal of Food Process Engineering*, *39*, 610-624.

Pitts, K. F., McCann, T. H., Mayo, S., Favaro, J., & Day, L. (2016). Effect of the sugar replacement by citrus fibre on the physical and structural properties of wheat-corn based extrudates. *Food and Bioprocess Technology*, *9*, 1803-1811.

Quiles, A., Campbell, G. M., Struck, S., Rohm, H., & Hernando, I. (2018). Fiber from fruit pomace: A review of applications in cereal-based products. *Food Reviews International*, *34*, 162-181.

Rafe, A., Sadeghian, A., & Hoseini-Yazdi, S. Z. (2017). Physicochemical, functional, and nutritional characteristics of stabilized rice bran form tarom cultivar. *Food science & nutrition*, *5*, 407-414.

Redgwell, R., Trovato, V., Merinat, S., Curti, D., Hediger, S., & Manez, A. (2003). Dietary fibre in cocoa shell: characterisation of component polysaccharides. *Food Chemistry*, *81*, 103-112.

Reinold, M. R. (1997). Manual prático de cervejaria. *São Paulo: Aden*.

Reis, S. F., & Abu-Ghannam, N. (2014). Antioxidant capacity, arabinoxylans content and in vitro glycaemic index of cereal-based snacks incorporated with brewer's spent grain. *LWT - Food Science and Technology*, *55*, 269-277.

Reis, S. F., Rai, D. K., & Abu-Ghannam, N. (2014). Apple pomace as a potential ingredient for the development of new functional foods. *International Journal of Food Science and Technology*, *49*, 1743-1750.

Ruiz-Armenta, X. A., Zazueta-Morales, J. d. J., Aguilar-Palazuelos, E., Delgado-Nieblas, C. I., López-Diaz, A., Camacho-Hernández, I. L., Gutiérrez-Dorado, R., & Martínez-Bustos, F. (2018). Effect of extrusion on the carotenoid content, physical and sensory properties of snacks added with bagasse of naranjita fruit: optimization process. *CyTA - Journal of Food*, *16*, 172-180.

Rzedzicki, Z., Szpryngiel, B., & Sobota, A. (2000). Estimation of some chosen physical properties of extrudates obtained from corn semolina and oat bran mixtures. *International Agrophysics*, *14*, 233-240.

SACN. (2015). Scientific Advisory Committee on Nutrition-Carbohydrates and Health. *England PH, editor*.

Sekhon, K., Dhillon, S., Singh, N., & Singh, B. (1997). Functional suitability of commercially milled rice bran in India for use in different food products. *Plant foods for human nutrition*, *50*, 127-140.

Selani, M. M., Brazaca, S. G. C., dos Santos Dias, C. T., Ratnayake, W. S., Flores, R. A., & Bianchini, A. (2014). Characterisation and potential application of pineapple pomace in an extruded product for fibre enhancement. *Food Chemistry*, *163*, 23-30.

Sharma, R., Srivastava, T., & Saxena, D. C. (2016). Development of nutritious snack from rice industry waste using twin screw extrusion. In T. Srivastava, S. Rani & S. Kakkar (Eds.), *4th International Conference on Advancements in Engineering & Technology* (Vol. 57). Cedex A: E D P Sciences.

Sharma, R., Srivastava, T., & Saxena, D. C. (2017). Effects of different process and machine parameters on physical properties of rice flour, corn flour and deoiled rice bran extruded product. *Current Nutrition & Food Science*, *13*, 219-226.

Singh, D., & Bawa, A. (1998). Dehydration of tomato processing waste. *Indian Food Packer*, *52*, 26-29.

Singha, P., & Muthukumarappan, K. (2017). Effects of processing conditions on the system parameters during single screw extrusion of blend containing apple pomace. *Journal of Food Process Engineering*, *40*.

Sisay, M. T., Emire, S. A., Ramaswamy, H. S., & Workneh, T. S. (2018). Effect of feed components on quality parameters of wheat–tef–sesame–tomato based extruded products. *Journal of food science and technology*, *55*, 2649-2660.

Steiner, J., Procopio, S., & Becker, T. (2015). Brewer's spent grain: source of value-added polysaccharides for the food industry in reference to the health claims. *European Food Research and Technology*, *241*, 303-315.

Townsley, P. (1979). Preparation of commercial products from brewer's waste grain and trub [Protein flours]. *Technical Quarterly Master Brewers Association of America*.

UK Government. (2018). Public Health England launches Change4Life campaign around children's snacking. In.

Van der Sman, R., & Broeze, J. (2014). Effects of salt on the expansion of starchy snacks: a multiscale analysis. *Food & function*, *5*, 3076-3082.

Vanshin, V. V., Vanshina, E. A., & Erkaev, A. V. (2017). Food by-products as a source of raw materials for the production of extruded products. *Izvestiya Vuzov-Prikladnaya Khimiya I Biotekhnologiya*, *7*, 137-144.

Wang, P., Fu, Y., Wang, L., Saleh, A. S. M., Cao, H., & Xiao, Z. (2017). Effect of enrichment with stabilized rice bran and extrusion process on gelatinization and retrogradation properties of rice starch. *Starch - Stärke*, *69*, 1600201.

Wang, S., Kowalski, R. J., Kang, Y., Kiszonas, A. M., Zhu, M.-J., & Ganjyal, G. M. (2017). Impacts of the particle sizes and levels of inclusions of cherry pomace on the physical and structural properties of direct expanded corn starch. *Food and Bioprocess Technology*, *10*, 394-406.

Warren, B. E., & Farrell, D. J. (1990). The nutritive value of full-fat and defatted Australian rice bran. I. Chemical composition. *Animal Feed Science and Technology*, *27*, 219-228.

WRAP. (2017). Courtauld 2025 signatory data report: 2015 and 2016. In. Banbury.

Yadav, D. N., Anand, T., & Singh, A. K. (2014). Co-extrusion of pearl millet-whey protein concentrate for expanded snacks. *International Journal of Food Science & Technology*, *49*, 840-846.

Yanniotis, S., Petraki, A., & Soumpasi, E. (2007). Effect of pectin and wheat fibers on quality attributes of extruded cornstarch. *Journal of Food Engineering*, *80*, 594-599.

Yu, C., Liu, J. F., Tang, X. Z., Shen, X. C., & Liu, S. W. (2017). Correlations between the physical properties and chemical bonds of extruded corn starch enriched with whey protein concentrate. *Rsc Advances*, *7*, 11979-11986.

Zhang, M., Liang, Y., Pei, Y., Gao, W., & Zhang, Z. (2009). Effect of process on physicochemical properties of oat bran soluble dietary fiber. *Journal of Food Science*, *74*, C628-C636.

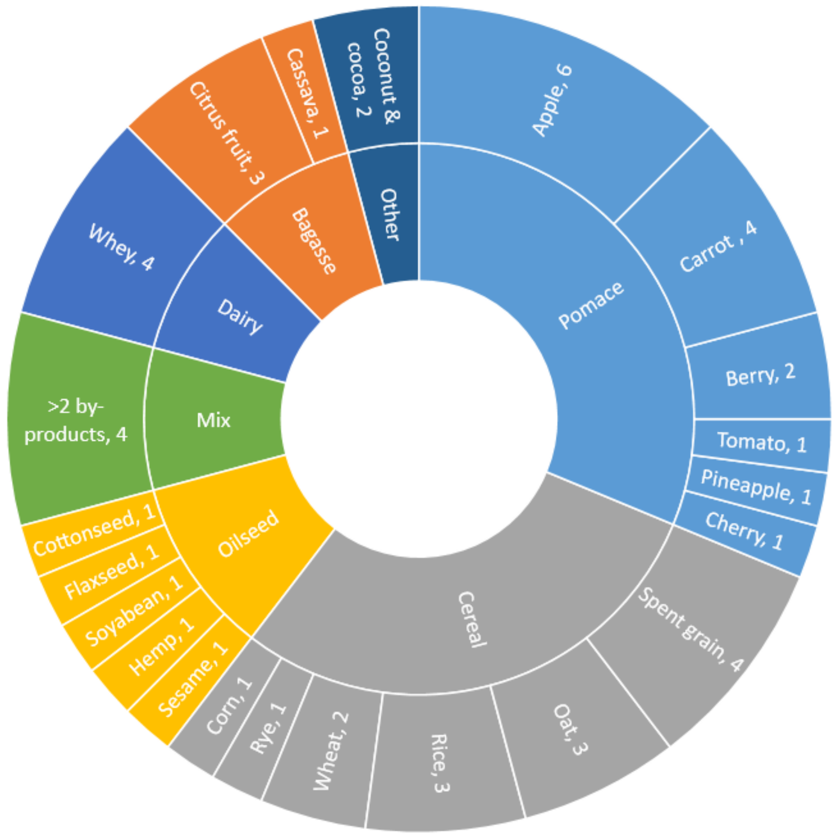

Figure 1. Categories and number of articles published on extruded snacks with by-products in 2014-18.