

Extruded snacks from industrial by-products: a review

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Accepted Version

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Grasso, S. (2020) Extruded snacks from industrial by-products: a review. *Trends in Food Science & Technology*, 99. pp. 284-294. ISSN 0924-2244 doi: <https://doi.org/10.1016/j.tifs.2020.03.012> Available at <https://centaur.reading.ac.uk/89591/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.tifs.2020.03.012>

Publisher: Elsevier

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Extruded snacks from industrial by-products: a review

Abstract

Background

Within the context of circular economy, there is an emergent need to convert food processing by-products into useful ingredients, thanks also to the recent technological advances in processing techniques. Extruded cereal-based snacks are popular products, however many snacks on the market are currently high in salt, fat and sugar, with an overall low nutritional value.

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



1 Extruded snacks from industrial by-products: a review

2 Dr Simona Grasso

3 School of Agriculture, Policy and Development, University of Reading, PO Box 237, Earley Gate, Reading,

4 RG6 6AR, UK. (Tel.: +44 1 18 378 6576; fax: +44 1 18 935 2421)

5 simona.grasso@ucdconnect.ie

6

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27 extruded snacks from by-products should be more multidisciplinary, covering technical, sensory,
28 consumer, economic and sustainability aspects.

29

30 1. Introduction

31 The UK retail value sales of crisps, savoury snacks and nuts was estimated at £3.9 billion in 2017 and it is
32 forecasted to reach £4.8 billion in 2022. Crisps and crisp-style snacks are a UK staple, being eaten
33 frequently and as part of lunch, with 90% of households consuming them (Mintel, 2018b). According to
34 a recent UK survey (Mintel, 2018a), 96% of people snack (based on 2000 internet users aged 16+) and
35 69% of those who snack do so at least once a day (based on 1923 internet users aged 16+ who eat
36 snacks). The same survey reports that about 39% of people who snack look for healthy products all or
37 most of the time when choosing a snack (based on 1923 internet users aged 16+ who eat snacks). Also
38 52% of people think that snacks made with pulses are healthier than potato-based snacks (based on
39 1852 internet users aged 16+)(Mintel, 2018b). This increase in health consciousness is also backed up by
40 public health campaigns and improved nutritional guidelines. In January 2018, Public Health England
41 launched the first Change4Life campaign around children's snacking, encouraging parents to look for
42 100 calorie snacks, two a day max, in order to cut children's sugar intake, which is three times more

43 than recommended (UK Government, 2018). In 2015, the Scientific Advisory Committee on Nutrition
44 brought the recommended daily intake of fibre to 30 grams, while the average intakes in adults are
45 around 18g of fibre daily (SACN, 2015). The European Food Safety Authority (EFSA) currently allows
46 “source of fibre” and “high fibre” nutritional claims on packaging for foods containing respectively at
47 least 3% or at least 6% fibre (EFSA, 2012).

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

53 According to a recent report by WRAP (2017), in 2015 the UK manufacturing sector was the main supply
54 chain producer of food waste (which includes both wasted food and inedible parts), with 1.85 million
55 tonnes of food waste produced, a 9% increase compared to the 1.7 million tonnes estimated in the
56 previous 2016 WRAP report. Of this amount, almost 1 million tonnes were estimated to be edible parts.
57 Economic and environmental motives have brought increasing demand for the conversion of food
58 processing by-products into useful products, thanks also to the recent technological advances in
59 processing techniques (Maskan & Altan, 2016) and methodologies, such as the 5-Stage Universal
60 Recovery Process, where by-product processing progresses from the macroscopic (I) to the
61 macromolecular level (II) and then to the extraction of specific micro-molecules (III), to end with the
62 purification (IV) and encapsulation of the target ones (V)(Galanakis, 2012). The extrusion process is
63 versatile, highly productive, low-cost, energy efficient and lacks of effluents (Maskan & Altan, 2016),
64 therefore it is ideal to incorporate food industry by-products into novel snacks. Extrusion consists in

65 forming and shaping a dough-like material by forcing it through a restriction called the die. This
66 technology is used extensively by the cereal-processing industry, converting cereal flours by kneading,
67 cooking, forming and texturizing, to produce ready-to-eat food products such as noodles and pastas,
68 breakfast cereals, baby foods and snack foods (Bouvier & Campanella, 2014). Extruded snacks can be
69 divided into different categories, however for the purpose of this review we will focus only second and
70 third generation snacks. Directly expanded snacks (also called second generation snacks or collets)
71 include the majority of extruded snacks, such as puffed snacks. These products can then be seasoned,
72 baked or fried (Hui & Sherkat, 2005). Indirectly expanded snacks (also called third generation snacks or
73 half products) are mixed during the extrusion process, dried into a shelf-stable form (pellets) and then
74 expanded using frying, hot air or microwaving at a later stage (Van der Sman & Broeze, 2014). Typical
75 starch sources for both directly and indirectly expanded snacks are corn, potato, rice and wheat (Bouvier
76 & Campanella, 2014). The resulting snack products are usually high in starch and dense in energy, but
77 poor in nutritional value, in terms of micronutrients, proteins and fibre (Brennan, Derbyshire, Tiwari, &
78 Brennan, 2013). Food industry by-products could be used to add value to extruded snacks, as shown in
79 articles summarised by recent reviews (Obradović, Babić, Šubarić, Ačkar, & Jozinović, 2014; Offiah,
80 Kontogiorgos, & Falade, 2018; Quiles, Campbell, Struck, Rohm, & Hernando, 2018).

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

84 Recently food industry by-products have been used in extrusion processes. Some examples of non-
85 puffed snack applications include breakfast cereals made with carambola seeds (Borah, Mahanta, &
86 Kalita, 2016), crackers made with by-products from Roselle processing (Ahmed & Abozed, 2015), gluten-

87 free pretzels made with brewer's rice flour (Paykary, et al., 2016) and breadsticks made with
88 substandard bread (Vanshin, Vanshina, & Erkaev, 2017). Food by-products have been used as sources of
89 fibre, protein and antioxidants. New dietary fibre sources derived from fruit and vegetable by-products,
90 can be added to food products as cheap and low-calories bulking agents to partially replace flour, fat or
91 sugar (O'Shea, Arendt, & Gallagher, 2012). We will now discuss extruded snack applications of food by-
92 products such as pomace and bagasse from fruit and vegetables, bran and spent grains from cereals,
93 oilseed cakes and whey from dairy (categorised as per Figure 1).

94 2. Pomace

95 2.1. Apple

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

101 Extruded snacks with corn (10%), sorghum flour (70-90%) as an under-utilised cereal, and apple pomace
102 (10-30%) as industrial waste were developed by Lohani and Muthukumarappan (2017). The authors
103 used natural fermentation followed by hydrodynamic cavitation with the aim to improve the total
104 phenolic content and antioxidant activity (to compensate the loss during extrusion) as well as to
105 improve total dietary fibre in the final product. Hydrodynamic cavitation is a novel technology consisting
106 in the formation and collapse of microbubbles over a short time, releasing high energy and resulting in
107 high localised pressures and temperatures, which has been used in food sterilization, microbial cell
108 disruption, water disinfection and wastewater treatment (Gogate, 2011). Similarly, the cavitations and

109 disrupting properties of ultrasound waves (Galanakis, 2013) have been used to enhance extraction of
110 anthocyanins and beta-carotene from grape seeds, citrus and pomegranate peels (Ghafoor, Choi, Jeon,
111 & Jo, 2009; Pan, Qu, Ma, Atungulu, & McHugh, 2012). Pan, et al. (2012) reported that pulsed ultrasound
112 assisted extraction also provided similar antioxidant yield in pomegranate peel, but 50% energy saving
113 compared to conventional ultrasound-assisted extraction. Extrusion cooking with higher apple pomace
114 content (30%), low temperature (80 °C) and screw speed (100 rpm), increased the total phenolic content
115 and antioxidant activity of the final product. After extrusion, starch digestibility and dietary fibre content
116 increased. Paraman, Sharif, Supriyadi, and Rizvi (2015) also used apple pomace (22-28%) in the
117 manufacture of extruded snacks, together with another waste stream product, concentrated liquid
118 whey (20% total solids), instead of water. The authors used supercritical fluid extrusion, a novel
119 extrusion technology where supercritical CO₂ is used as an expansion agent instead of steam, which has
120 the advantages of keeping the temperature below 100 °C, have low energy input and better control on
121 the expansion compared to steam (Manoi & Rizvi, 2010). The authors claim that the high-temperature
122 (130-200 °C) and high shear (150-300 rpm) used on previous extrusion studies with pomace, invariably
123 lead to the loss of both sensory and nutritional quality. Thanks to the more gentle supercritical fluid
124 extrusion process used in this experiment, 84% of the total phenolic compounds and 74% of total
125 antioxidants present in the original apple pomace were retained in the final product. By incorporating
126 22% pomace (containing 83% fibre on a dry basis), the fibre content in the final product increased from
127 0.8 g/100 g of control extrudates to 14 g/100 g product, which would allow for a “high fibre” nutritional
128 claim according to EFSA (2012), as it contains more than 6% fibre.

129 Reis, Rai, and Abu-Ghannam (2014) developed rice-wheat based extruded snacks using apple pomace at
130 different inclusion levels (10-30%). Extruded products with apple pomace incorporation showed a
131 decrease in protein and starch contents and an increase in total dietary fibre compared to control. The

132 addition of apple pomace significantly increased the phenolic compounds in the extrudates compared to
133 control, however the recoveries of phenolic compounds went down as the apple pomace incorporation
134 went up. According to the authors this might be due to polymerisation which affected the extractability
135 of phenolic compounds, therefore the more phenolic compounds were incorporated, the higher the
136 polymerisation. No sensory analyses were carried out as part of these studies.

137 Freeze-dried apple pomace at 5-10% inclusion in corn snacks was used by O'Shea, Arendt, and Gallagher
138 (2014). Extrudate characteristics, such as expansion ratio, bulk density, porosity and volume, were
139 analysed. Optimal apple pomace inclusion was found to be 7.7%, while high die head temperatures and
140 high screw speeds were found to be detrimental to the quality of the extrudates. No nutritional or
141 sensory analyses were carried out in this study.

142 Drozd, et al. (2014) produced extruded con-based snacks with 10-20% apple pomace or rosehip
143 pomace. Corn-rosehip pomace snacks had higher polyphenols content and antioxidant activity than
144 corn-apple pomace snacks. A ten member panel carried out sensory evaluation showed that the
145 addition of pomace to extrudates resulted in progressively lower evaluation of some attributes,
146 however overall the sensory properties of corn-pomace extrudates were acceptable, scoring 3.5-4 in 1-
147 5 scales.

148 2.2. Carrot

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

152 Kaisangsri, et al. (2016) developed corn starch extrudates with carrot pomace at 5, 10 and 15%. Higher
153 levels of pomace inclusion were associated with a decrease in expansion compared to a pomace-free
154 control, similar to other fibre-enrichment studies (Nascimento, Calado, & Carvalho, 2017; Oliveira, et al.,
155 2015). The β -carotene content reduced significantly after extrusion, however the higher the carrot
156 pomace inclusion, the lower the β -carotene retention in the final product. The authors claim that at the
157 lowest carrot pomace inclusion of 5%, the β -carotene might have been more protected from thermal
158 degradation, compared to higher inclusion levels of 10 and 15%.

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

166 Alam, Kumar, and Khaira (2015) developed extruded snacks using rice flour (60-80%), red lentil flour (10-
167 30%) and 10% carrot pomace, using a Box-Behnken design. Optimal extrusion parameters were
168 obtained with an 80:10:10 rice flour/lentil flour/carrot pomace powder formulation, however no
169 nutritional or sensory analyses were carried out. In a similar study by the same group (Alam, Pathania,
170 Kumar, & Sharma, 2015) extruded snacks using broken rice flour, chickpea flour, carrot pomace powder
171 and cheese powder in the proportion of 75:11.25:11.25:2.5 were developed. The authors investigated
172 the effects of different types of packaging during a six-month room temperature shelf life. After

173 manufacture, the extrudates evaluated by ten semi-trained panellist using nine-point hedonic scales,
174 scored high for overall acceptability.

175 2.3. Cherry

176 Cherry pomace is the residue left from cherries after juice extraction (Luca, Cilek, Hasirci, Sahin, &
177 Sumnu, 2013). Nawirska and Kwaśniewska (2005) reported that the total dietary fibre content in cherry
178 pomace is 71.44%, consisting of pectin (1.51%), hemicellulose (10.7%), cellulose (18.4%), and lignin
179 (69.4%).

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

191 2.4. Pineapple

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

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

201 2.5. Berries

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

206 2.5.1. *Blackcurrant*

207 Mäkilä, et al. (2014) developed snacks using the residues from blackcurrant juice production at 30%
208 inclusion. Two types of press residues were used: residues from conventional enzymatic pressing (where
209 the fruit is treated with pectinase before pressing) and residues from non-enzymatic juice pressing. The
210 two types of residues were added to a base of either barley, oat or oat bran, for a total of six
211 treatments. Sensory evaluation, consisting of hedonic scales and preference ranking, was carried out by

212 seventy-seven participants on all the samples. Extrudates made with untreated blackcurrant were the
213 most preferred and had higher liking scored compared to pectin-treated extrudates. The authors
214 concluded that the conventional enzymatic press residue may lack the wanted flavour unique to berry
215 material, therefore the fresher berry taste and colour of non-enzymatically processed press residue
216 might be better suited for extrusion application.

217 2.5.2. Bilberry

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

234 2.6. Tomato

235 Tomatoes are commonly transformed in soup, ketchup, juice and paste, which generates huge amounts
236 of by-products and wastes, accounting for 40% of the total fresh weight of the tomatoes (Anal, 2017).

237 The dry tomato pomace contains on average 44% seeds and 56% pulp and skins (Singh & Bawa, 1998).

238 Devi, Kuriakose, Krishnan, Choudhary, and Rawson (2016) developed corn flour (40-60%) and rice flour
239 (30-40%) extruded snacks with dried and milled tomato peel (5-30%) or seed (2.5-5%) powder. Sensory
240 analysis indicated that tomato pomace could be incorporated into extrudates up to 30%. Optimization
241 using D-optimal mixture design suggested that the best extruded product formulation with high
242 desirability was the one consisting of 40% corn flour, 30% rice flour, 25% milled tomato peel and 5%
243 tomato seed powder.

244 3. Bagasse

245 3.1. Cassava

246 Cassava bagasse, the solid residue leftover from the cassava starch industry, is usually disposed of in
247 water course or left in ditches. Similarly to many other food industry by-products, cassava bagasse has a
248 high moisture content (85%), which causes fermentation, therefore drying needs to happen during
249 production (Fiorda, Soares, da Silva, de Moura, & Grossmann, 2015). Fiorda, et al. (2015) studied the
250 effects of moisture and extrusion temperature on the quality of extruded snacks made with cassava
251 starch and dehydrated cassava bagasse in a 70:30 ratio. The authors concluded that higher expansion
252 and intermediate specific volume were obtained in intermediate conditions of extrusion temperature
253 (104.1 °C) and moisture (16%).

254 3.2. Citrus fruits

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

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

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

265 Ruiz-Armenta, et al. (2018) developed corn snacks using the industry by-product (bagasse) of naranjita
266 fruit (*Citrus mitis B.*) at 1.12-11.88% inclusion. This by-product of the juice industry is generally
267 discarded, although it contains excellent amounts of dietary fibre, carotenoids and flavonoids (Delgado-
268 Nieblas, et al., 2017). Sensory evaluation of the snacks was performed by thirty non-trained panellists.
269 The optimal processing conditions were found to be at 125°C extrusion temperature and 8.03% bagasse
270 content, at which levels the product was low in fat (lipids = 1.58%) and a source of fibre (crude fibre =
271 5.38). It is worth pointing out that the authors only measured the crude fibre and not the total dietary
272 fibre. It has been recognized for many years (Cummings, 1973) that the crude fibre method
273 underestimates the total amount of fibre in the product, therefore it is likely the total dietary fibre in
274 the snacks would have been higher than the amount reported by the authors.

275 4. Cereals

276 4.1. Brewer's spent grain

277 Brewer's spent grain is the main by-product of the brewing industry representing around 85% of the
278 total by-products generated (Reinold, 1997). Malted barley or other cereal grains are milled and mixed
279 with water to produce the wort, the liquid fermentation medium to produce beer, while the leftover
280 insoluble fraction of the malted barley is referred to as brewer's spent grain (Anal, 2017). Rich in dietary
281 fibre (about 70%), protein (about 20%) and minerals such as silicon, phosphorus and calcium, it is
282 commonly used as animal feed (Mussatto, Dragone, & Roberto, 2006; Mussatto, 2014). The dietary fibre
283 of brewer's spent grain consists of mainly water insoluble fibre (lignin and cellulose constitute about 37-
284 45% brewer's spent grain dry weight) with a smaller contribution of non-cellulosic polysaccharides,
285 (mostly arabinoxylans, about 22-28% of brewer's spent grain dry weight) while β -glucans represent less
286 than 1% as they are hydrolysed during wort production (Mussatto, et al., 2006). Before it can be used in
287 foods, brewer's spent grain needs to be dried as the high moisture and fermentable sugars content
288 make is susceptible to bacterial proliferation (Mussatto, et al., 2006). After drying, the brewer's spent
289 grain can be turned into flour, although its use has some limitations due to its flavour and brownish
290 colour (Mussatto, et al., 2006). Spent grain accounts, on average, for 31% of the original malted barley
291 weight (Townesley, 1979). Annually, around 3.4 million tonnes of brewer's spent grain are produced
292 within the European Union, with Germany contributing with approximately 2 million tonnes (Steiner,
293 Procopio, & Becker, 2015).

294 Brewer's spent cassava, a by-product of beer produced with cassava flour, has not received much
295 attention. Ha, Nga, Phu, Anh, and Tosch (2014) developed corn-rice snacks using brewer's spent cassava
296 flour (4-8%). A 4% brewer's spent cassava inclusion caused no significant changes on the extrudate's

297 expansion and density, however no nutritional or sensory analyses were carried out on the final
298 product. Reis and Abu-Ghannam (2014) developed extruded products using blends of rice flour and
299 wheat semolina in a ratio of (2:1) with different proportions of brewer's spent grain (10-40%). Straight
300 after extrusion and drying, the extrudates were ground, therefore expansion and density of the final
301 products are unknown. Although no sensory analyses were carried out, adding brewer's spent grain
302 increased the phenolic content and the antioxidant properties compared to control and 20-40%
303 inclusions produced "high fibre" extrudates (>6% fibre). Adding brewer's spent grain did not lower the
304 glycaemic index of the extruded snacks, probably due to other factors preventing a steeper decrease,
305 such as the increase in starch digestibility. Kirjoranta, Tenkanen, and Jouppila (2016) used 10% of
306 brewer's spent grains to produce barley-based snacks with various combinations of barley flour, barley
307 starch, corn starch and whey protein isolate (20% of solids). All recipes containing brewer's spent grains
308 were "high fibre" (10-17%) and recipes containing whey protein isolates and starches expanded well.
309 However, the authors did not carry out any sensory evaluations and did not produce a control to refer
310 the results to. Finally, Nascimento, et al. (2017) developed extruded broken rice snacks with brewer's
311 spent grain at 15% or 30% inclusion. Adding brewer's spent grains produced denser and less expanded
312 extrudates compared to control. No nutritional or sensory analyses were carried out on the final
313 products, with the study focussing on the physical properties of the puffed snacks.

314 4.2. Rice

315 4.2.1. Broken rice

316 When rice is milled from whole rice grains into polished rice, about 30% of white rice breaks (Kadan,
317 Bryant, & Miller, 2008). Broken kernels that are less than three quarters of the original grain's length are
318 considered broken rice (Courtois, Faessel, & Bonazzi, 2010). Broken rice is currently used as animal feed,

319 in pet foods and to make beer (Paranthaman, Alagusundaram, & Indhumathi, 2009). Broken kernels
320 have a nutritive value similar to polished rice and are available at relatively lower cost (Dar, et al., 2014),
321 therefore its transformation into higher value products would be desirable.

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

326 4.2.2. *Rice bran*

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

337 De-oiled rice bran was used by Sharma, Srivastava, and Saxena (2016, 2017). The authors developed
338 recipes containing 10% corn flour, 55-75% rice flour and 15-35% de-oiled rice bran. Using a numerical
339 multi-response optimization technique, optimum conditions were obtained with 72% rice flour and 18%
340 de-oiled rice bran inclusion, however no nutritional or sensory analyses were carried out on the

341 extrudates. Wang, Fu, et al. (2017) developed snacks using rice starch with 10% of stabilized rice bran
342 and investigated the changes in gelatinization and retrogradation properties after extrusion. The
343 authors did not measure expansion or density of the pellets, nor did they conduct nutritional or sensory
344 analyses. No recent articles on the sensory quality of snacks with rice bran were found, however
345 Sekhon, Dhillon, Singh, and Singh (1997) used rice bran (both full fat and defatted) to manufacture
346 extruded snacks and carried out sensory analysis with a 6-person panel using 9-point hedonic scales. The
347 authors concluded that full-fat rice bran could not be used in the production of extruded snack foods
348 due to the dark color, oily appearance and unacceptable taste, while snacks prepared from blends
349 containing up to 10% defatted rice bran were nearly comparable to control snacks in sensory terms.
350 Rafe, Sadeghian, and Hoseini-Yazdi (2017) investigated the effects of stabilisation through extrusion on
351 rice bran, concluding that extrusion lowered the protein and vitamin E content, but improved the
352 colour, enhanced the dietary fibre and lowered the phytic acid content. This suggests that extruded rice
353 bran could be successfully exploited as an ingredient in a variety of food formulations.

354 4.3. Corn bran

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

358 Ogunmuyiwa, et al. (2017) used corn bran at 10% to 80% inclusion in extruded snacks made with starch
359 (10-80%) and bambara nut flour (10-80%), an underutilized indigenous legume of African origin. Corn
360 bran contained 10% protein, 14% fat, 59% carbohydrate and 35% fibre, while bambara nut contained
361 carbohydrates (60%), proteins (21%), fat (5%), and 20% protein. The total dietary fibre in all treatments

362 was above 7%, therefore the extrudates can be considered to be “high fibre”. No sensory analyses were
363 carried out as part of this study.

364 4.4. Wheat bran

365 The bran portion of wheat accounts for most of the micronutrient, phytochemical and fibre content of
366 the grain (Anal, 2017). Some wheat milling by-products are used for breads, breakfast cereals and ‘all-
367 bran’ breakfast extruded products, however bran is also currently used as livestock feed or disposed of
368 in landfills (Anal, 2017; Hossain, et al., 2013). Wheat bran represents 14-19% of the wheat grain (Maes &
369 Delcour, 2002) and it contains about 47% of fibre (Kamal-Eldin, et al., 2009). The wheat production in
370 2016 was 881 million tonnes (FAO, 2018), with about 123-167 million tonnes being bran (14-19% of the
371 total).

372 Fleischman, et al. (2016) investigated the effects of supplementing antioxidant-rich coloured brans
373 (12.5-37.5%) into extruded wheat snacks, focussing on the physical and antioxidant properties of the
374 extrudates. The authors found that the higher the fibre inclusion, the denser the extrudates and the
375 lower the expansion ratios, similarly to other recent studies (Nascimento, et al., 2017; Oliveira, et al.,
376 2015). Extrusion likely split polyphenolic compounds into smaller molecular species, creating a loss of
377 antioxidant activity in control, white and red bran treatments. However, the purple bran treatment did
378 not have a decrease in Trolox Equivalents after extrusion, probably thanks to the activation of several
379 antioxidants during through non-enzymatic browning reactions. The nutritional content of the
380 extrudates and their sensory properties were not investigated in this study.

381 Oladiran and Emmambux (2017) investigated the effects of extrusion and the incorporation of wheat
382 bran at 10 and 20% addition levels on the quality of extrudates made with blends of raw cassava and
383 defatted toasted soy flour in a 65:35 ratio. Wheat bran addition significantly reduced the expansion

384 compared to control, however both levels of inclusion still showed expansion ratios above 3, with 3
385 being generally accepted for expanded snacks (Korkerd, Wanlapa, Puttanlek, Uttapap, & Rungsardthong,
386 2016). Extrusion increased the soluble dietary fibre and a decreased the insoluble dietary fibre content.
387 The process of extrusion has been previously reported to alter the molecular structure of fibre and
388 increase the amount of soluble fibre in extrudates (Brennan, et al., 2013).

389 4.5. Rye bran

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

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

403 4.6. Oat

404 4.6.1. *Oat bran*

405 Oat bran is a major by-product obtained during processing of oat products (Zhang, Liang, Pei, Gao, &
406 Zhang, 2009). It contains about 24% protein and 72% fibre (Krishnan, Chang, & Brown, 1987) of which 6-
407 9% is β -glucan (Gibinski, 2008). Adding oat bran in extruded products has been associated with
408 decreased expansion and increased hardness (Lobato, Anibal, Lazaretti, & Grossmann, 2011), however
409 up to 18% bran produced well expanded snacks if a high starch ingredient such as corn is used as the
410 main carrier matrix (Rzedzicki, Szpryngiel, & Sobota, 2000).

411 Makowska, Polcyn, and Chudy (2015) developed extruded corn snacks using oat, wheat or rye bran at
412 20% or 40% inclusion. All products had a total fibre content above 6%, therefore they would qualify for a
413 "high fibre" claim, and had a fat content below or equal to 3%, therefore they could be labelled as "low
414 fat". The 20% oat bran extrudates expanded the most, however all extrudates expanded well (expansion
415 ratio of 3 or above). A trained ten member panel used a nine-point scale to assess all samples on
416 porosity, crispiness, colour, taste as well as overall desirability of the products. Results show that oat
417 bran at 20% inclusion was the most desirable extrudate (7.3 out of 9), 40% rye and 40% wheat scored
418 lowest (3 and 2.8 out of 9 respectively), while 20% wheat and 40% oats were borderline acceptable (4.6
419 and 5 out of 9 respectively).

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

425 4.6.2. *Residual oat flour*

426 Residual oat flour is a by-product in the production of beta-glucan concentrate (Betaven), obtained
427 without chemicals by micronization and air separation of oat aleurone particles (Gumul, Ziobro,
428 Gambus, & Nowotna, 2015). Gumul, et al. (2015) developed corn-based snacks with 5-20% of residual
429 oat flour. The residual oat flour contained mainly starch (57%), followed by 12% protein, 8% fat, and
430 5.6% total dietary fibre (of which 2.1% soluble and 3.5% insoluble). Sensory analysis was carried out on
431 all samples by twelve panellists described as having “established sensory sensitivity”, using 1-5 scales to
432 evaluate shape and appearance, consistency, structure and flavour. Extrudates with 10% residual oat
433 flour received the highest scores. This treatment, which according to its nutritional composition can be
434 considered “low in fat” and a “source of fibre”, also exhibited the highest expansion and lowest density
435 of all treatments.

436 5. Oilseed by-products

437 Oil seeds provide edible oil like cottonseed, sesame, peanut, soybean, rapeseed and sunflower (Anal,
438 2017). By-products of the oilseed industry, such as defatted flours, represent an important source of
439 highly digestible proteins, but they are exclusively used as animal feed (Bhise, Kaur, Manikantan, &
440 Singh, 2015). The defatted cake left after oil production represent 35% of the initial oil seed weight in
441 the case of soybean, 45% in the case of cotton seed and 50% in the case of peanut (Anal, 2017).
442 Recently Bhise, et al. (2015) extruded flour from defatted sunflower into a textured defatted sunflower
443 meal, which could be used as an alternative protein source. Wastewater from oil production, such as
444 olive mill wastewater, is rich in polyphenols which have been used as antimicrobial agents in bread
445 (Galanakis, Tsatalas, Charalambous, & Galanakis, 2018a), as UV filters in sunscreens (Galanakis, Tsatalas,

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

448 5.1. Cottonseed

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

457 5.2. Flaxseed

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

467 on the type and composition of flaxseed used, the level of addition and the product subjected to
468 fortification.

469 5.3. Soybean

470 Olusegun, Stephen, Folasade, and Oladejo (2016) developed snacks using cassava and partially defatted
471 soybean flours (46% protein, 8% fat, 2% fibre) at 10-30% inclusion, concluding that a 20% inclusion was
472 optimal for trypsin inhibitor reduction and for sensory evaluation of crispness carried out by fifteen
473 untrained panellists. It is possible that higher levels of inclusion of soy flour in the study by Olusegun, et
474 al. (2016), compared to the optimal 10% of defatted flaxseed meal inclusion found by Ganorkar, et al.
475 (2016), might be due to the lower fibre content in the soy flour used (2% vs 29%), which might have
476 caused less disruption in the matrix.

477 5.4. Hemp

478 Jozinović, Ackar, et al. (2017) developed corn snacks with added defatted hemp cake (5-10%), a by-
479 product of hemp oil production (fibre 60% and protein 34%). The hemp cake was completely defatted
480 prior to extrusion (fat 0.5%), using supercritical CO₂ extraction. Optimum extrusion conditions were
481 reached with a temperature in the extruder ejection zone of 150 °C, a moisture content of 15% and a
482 defatted hemp cake addition of 5%. The authors reported a decrease in the expansion ratio and an
483 increase in bulk density and hardness with increasing hemp cake content. This might be related to the
484 high fibre content or to the unknown particle size of the by-product. The authors did not carry out any
485 nutritional or sensory analyses on the extrudates.

486 5.5. Sesame seed

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

502 6. Whey

503 Whey is a by-product of the dairy industry, which is generated during the manufacture of cheese,
504 yogurts and other dairy products (Anal, 2017). About nine pounds of whey are generated for each
505 pound of cheese produced (Paraman, et al., 2015). Whey proteins have a higher biological value than
506 casein and soy proteins (Chandrasekaran, et al., 2012). Whey can be filtered into whey protein
507 concentrate (WPC) with protein content 35-85% or it can be filtered further to produce whey protein

508 isolate (WPI) with protein content above 90% (Anal, 2017). Currently, whey protein products are widely
509 available in the market as flavoured shakes, protein bars and dietary supplements and extruded snacks
510 may help to further minimise whey disposal problems (Yadav, Anand, & Singh, 2014).

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

516 Yadav, et al. (2014) incorporated 2.5-7.5% WPC into pearl millet expanded snacks. Whey protein at 7.5%
517 resulted in harder and less expanded extrudates and optimal quality was reached with 5% WPC
518 addition. The protein content increased significantly from 8.2% in the control to 13.3% and the calcium
519 content doubled from 24.5 in the control to 54.3 mg 100 g with incorporation of WPC at 7.5% level. Fifty
520 untrained panellist evaluated the samples using nine-point hedonic scales. The overall quality score
521 decreased with increase in WPC levels, but samples with 5% inclusion received acceptable scores of
522 7.5/9.

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

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

540 7. Coconut and cocoa

541 7.1. Coconut haustorium

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

546 Arivalagan, et al. (2018) developed extruded snacks using coconut haustorium, an under-utilised spongy
547 tissue formed during coconut germination. Compared to the rice-maize control, adding 20-30% of
548 coconut haustorium decreased the fat content and increased the protein content. The 10-30% addition
549 resulted in a significant increase in micronutrient content (potassium, magnesium, manganese, iron and
550 zinc), while a 20-30% addition resulted in a significant decrease in calcium content. Sensory analysis,

551 carried out with a semi-trained panel of six people, showed that up to 20% coconut haustorium
552 inclusion improved the product's sensory properties compared to control.

553 7.2. Cocoa bean shell

554 Cocoa products are produced from dried and fermented cocoa beans, and cocoa shells are one of the
555 by-products of cocoa beans, together with cocoa pod husk and cocoa mucilage (Panak Balentić, et al.,
556 2018). Cocoa bean shells are disposed of as waste, however they contain approximately 40% dietary
557 fibre (Redgwell, et al., 2003). Cocoa shells represent 10-14% of the bean weight and they are separated
558 from the nib (which continues for further processing), after whole bean roasting (Beckett, Fowler, &
559 Ziegler, 2017). In 2016 approximately 4.5 million tonnes of cocoa beans were produced (FAO, 2018),
560 therefore an estimated 450-630.000 tonnes of cocoa shells were produced, a large environmental load if
561 not further exploited.

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

567 8. Mixes of more than two by-products

568 Korkerd, et al. (2016) developed corn-based snacks containing 20% of defatted soya meal, germinated
569 brown rice and mango peel fibre mixed in different proportions. The authors carried out a sensory
570 evaluation with thirty untrained panellists on five out of the thirteen formulations and without using
571 control as a reference. The five formulations selected exhibited expansion ratio higher than 3.0 (as

572 generally accepted for expanded snack food) and total dietary fibre of 10% or higher. Increasing the
573 protein and fibre content in the product resulted in decreased expansion ratio and extrusion cooking
574 resulted in the conversion of insoluble to soluble fibre, balancing the two types of fibre.

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

589 Recently Ačkar, et al. (2018) used brewer's spent grain, sugar beet pulp and apple pomace at 5%-10%-
590 15% inclusion to produce corn snacks. To the mixtures with brewer's spent grain and sugar beet pulp,
591 0.5% or 1% of pectin was added, while since apple pomace is already naturally rich in pectin (11-22% in
592 dry matter (Gullón, Falqué, Alonso, & Parajó, 2007)), no extra pectin was added to it. The authors
593 decided to add pectin because this compound has been reported to reduce the fracture of cell walls, by

594 increasing the extensibility and resulting in porous products (Yanniotis, Petraki, & Soumpasi, 2007).
595 Results show that the expansion ratio decreased proportionally to the amount of added by-products
596 probably due to the reduced starch content. The impact was highest with brewer's spent grain addition
597 (highest in protein and fat, lowest in starch) and lowest for apple pomace (lowest in protein and fat,
598 highest in starch). Expansion improved with increasing pectin inclusion. Sensory analysis was carried out
599 by ten trained panellists, who assessed external appearance (uniformity, colour), structure (porosity,
600 crispness), consistency (chewing), odour, flavour and overall quality using hedonic scales. Sensory
601 evaluation was done on the samples with the best physical properties: control sample (corn), all apple
602 pomace samples, brewer's spent grains and sugar beet pulp samples with 1% of added pectin. Results
603 show that the more expanded products received better sensory scores, with pectin inclusion showing
604 potential to reduce cell wall fracture in snacks made with food by-products.

605 9. Future research challenges

606 The future of extruded snacks with food by-products will most likely rely on the use of novel
607 technologies that will limit heat damage during extrusion with temperatures not far from 100 °C, such as
608 supercritical fluid extrusion which we have seen applied on apple pomace (section 2.1). A thorough
609 review by Balentić, et al. (2017) on the use of supercritical CO₂ extrusion concluded that this technology
610 not only has nutritional advantages (because it preserves heat-labile compounds and avoids the
611 formation of undesirable compounds at high processing temperatures), but it also allows energy
612 savings, which is favourable in sustainability terms. Another technological challenge relies on the drying
613 of the food by-products soon after processing to reach shelf stable conditions in an economical manner,
614 while preserving the valuable heat-labile compounds. Some interesting emerging technologies in food
615 drying are radio frequency drying, that evaporates the water in situ at relatively low temperatures (i.e.

616 <80 °C) and electro osmotic dewatering, that allows a reduction of energy consumption up to two thirds
617 compared to traditional thermal processes (Galanakis, 2013). The percentage of by-product inclusion
618 also requires further investigation. Recent articles have highlighted that trying to add more is not
619 necessarily better, as smaller by-product inclusions might produce better results in terms of
620 antioxidants' retention as seen in apple, carrot and cherry pomace (sections 2.1-2.3). However if smaller
621 amounts of by-product are included in extruded snacks, it could be argued that the final product might
622 not be as environmentally "sustainable" or might not have many other added benefits, such as
623 nutritional enhancement in terms of fibre or protein. The scientific contribution of future studies should
624 therefore be targeted to a specific and measureable added value in the final product, whether this
625 might be environmental, nutritional, economical or a combination of these.

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

634 Extruded snacks are not the only baked goods where by-products are being included. The incorporation
635 of fruit and vegetable by-products in bakery foods such as breads, cakes and cookies has been reviewed
636 by Gómez and Martínez (2018). The authors found that in general in cakes and biscuits higher levels of
637 flour replacement can be reached compared to breads (flour replacement $\geq 30\%$ in cakes and $\geq 15\%$ in

638 cookies vs on average $\leq 10\%$ in bread). The authors explain that cakes and cookies better tolerate larger
639 amounts of fruit and vegetable by-products compared to breads, since lipids and sugar may mask bitter
640 flavors, there is no requirement for a gluten network and there is a lower flour fraction in the overall
641 recipe. While extruded snacks are more complex to manufacture compared to breads, cookies and
642 cakes, promising results have been reported in the present review with the use of several by-products
643 even at inclusion levels around 30%.

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

651 The current research in this field seems to be focussed mainly on reformulation strategies rather than
652 sensory or consumer aspects, with only twenty of the forty-eight articles surveyed for this review
653 attempting to evaluate the sensory quality of the new recipes. However, the sensory quality of novel
654 foods is an essential pre-requisite which might determine whether or not a new product survives in a
655 very competitive market. This gap needs to be addressed and hopefully future research will focus on the
656 sensory characterisations of novel snacks made with food industry by-products as well as on the
657 consumer attitudes towards these new products. Of particular importance would be the study of the
658 relationship between the food industry by-products and their snack carrier matrix, to understand
659 whether some combinations of by-products and snack matrix would be preferred over others by

660 consumers. Another important point that should be explored further is the effect of information on
661 consumers' willingness to pay or to buy for snacks made with industry by-products. This would help to
662 understand whether a statement on a product's label about the presence of a by-product ingredient
663 would have an effect on how the overall product is perceived by consumers. For example Cheng, Bekhit,
664 Sedcole, and Hamid (2010) tested the effect of health benefit information on the acceptability of tea
665 infusions made from grape skins generated from wine processing waste. Information on the health
666 benefits of the tea infusion samples significantly increased the sensory scores of the infusions (overall
667 acceptability, overall aroma, flavor, aftertaste) and increased consumers' purchase intention by 29%.
668 Recently Aschemann-Witzel and Peschel (2019) used an experimental survey design among 491 Danish
669 consumers to investigate how consumers react to food products based on ingredients previously wasted
670 in the supply chain. The hypothetical product tested was a soy based cocoa-flavoured drink, containing
671 potato protein from by-products, and presented with or without communication on the sustainability
672 benefit. Results were promising, showing that communication improved attitudes towards the potato
673 drink. More consumer attitudes studies on by-products using different food matrices and types of
674 information should be tested, to get a deeper understanding on this topic.

675 With a lot of research focusing on the development of extruded snacks made with food by-products, it
676 might be worth mentioning here that one of such product has already entered the market. In 2018, a
677 company called Planetarians (www.planetarians.com) launched a snack made from sunflower oil cake.
678 The snacks are made using steam explosion to puff the fibre, while high pressure and temperature are
679 used to cook and sterilize the feed grade ingredient. Their packaging claims that a 43 gram serving
680 provides 12 grams of protein, 11 grams of fibre and 1 gram of fat (in percentage 29% protein, 27% fibre
681 and 2.3% fat), which would make the product "high protein", "high fibre" and "low fat" in the EU (EFSA,
682 2012). The product, marketed as "clean label", contains only sunflower oil cake, potato starch,

683 sunflower oil and natural seasoning. The company claims that their test sales of sunflower chips on
684 Amazon during the 2018 spring brought in £29K in sales, with a 69% average monthly growth rate. It is
685 encouraging to see an example of the successful entry to market of a snack made with industrial by-
686 products using a novel technology and hopefully there will be many more to come in the near future.
687 This company is now determined to push their defatted sunflower seed flour ingredient in the market to
688 test different food applications. In 2015 the products derived from food by-products were still rather
689 limited and across the globe only 35 companies with related products were identified by Galanakis
690 (2015). However, it is quite likely that since then many more might have entered the market due to the
691 growing interest in the food by-product area.

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

695 Acknowledgements

696 This research did not receive any specific grant from funding agencies in the public, commercial, or not-
697 for-profit sectors.

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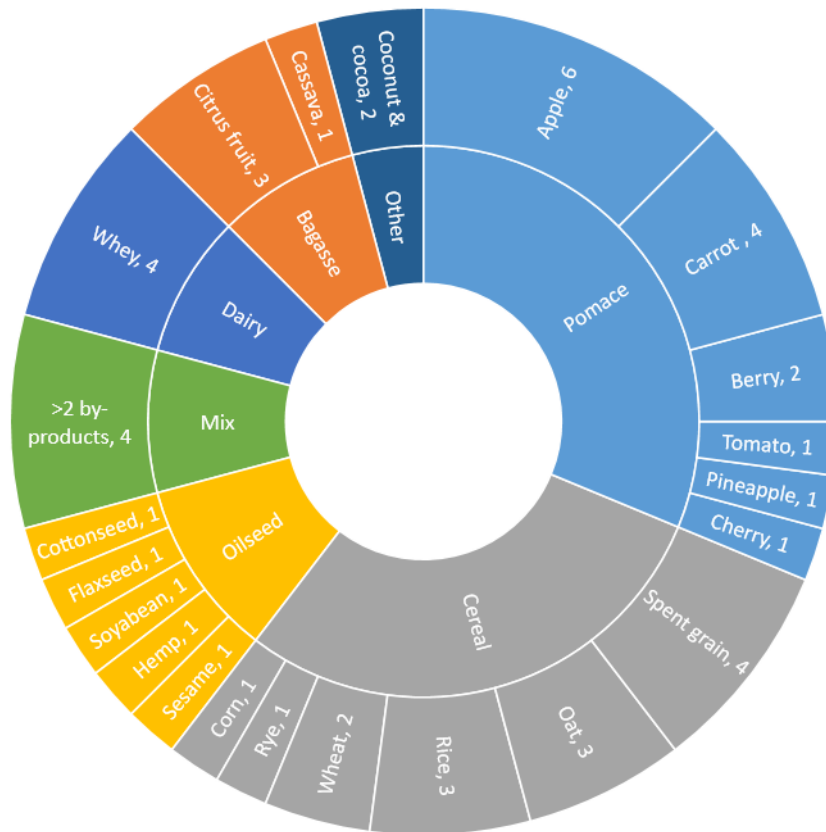


Figure 1. Categories and number of articles published on extruded snacks with by-products in 2014-18.