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Potential nutritional and functional improvement of extruded breakfast cereals based on incorporation of fruit and vegetable by-products - a review

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Abstract

Background

There is a need to improve the nutritional and functional characteristics of breakfast cereal products (BCP) consumed worldwide, namely by increasing the content and diversity of dietary fibre and enrichment in micronutrients and bioactive compounds. Considering the high amounts of fruit and vegetable by-products (FVB) generated by industrial processing, the associated environmental issues but also their richness in nutrients and phytochemicals, FVB show great potential for incorporation in BCP, thus improving the nutritional and functional aspects of these products.

Scope and Approach

The transformation of FVB into flours/powders results in added-value ingredients rich in fibre and bioactive compounds (e.g., phenolic compounds, carotenoids, prebiotics). The extrusion processing (used to produce BCP) is an affordable technique that uses flours as raw material. This work reviews extrusion processing to produce BCP supplemented with FVB powders and discusses the main effects on the final products associated with composition and processing characteristics. Additionally, advantages and challenges of introducing FVB powders into BCP are also reviewed and discussed.

Key Findings and Conclusions

The use of the FVB flours to create richer BCP in several types of fibre and phenolic compounds appears to be a promising strategy to create nutritionally valuable BCP. By simultaneously valorising FVB, this strategy also contributes positively to the food system sustainability from a circular economy point of view. The use of FVB flours may improve fibre, micronutrient, and bioactive compounds content. High fibre content reduces texture quality of products, but extrusion processing allows to adjust production variables to overcome the potential decrease in sensory quality.

Keywords: ready-to-eat cereals, high-density nutrient foods, dietary fibre, bioactive compounds, extrusion

List of abbreviations:

BCP – Breakfast cereal products; BD – Bulk density; DF – Dietary fibre; EI – Expansion index; FVB – Fruits and vegetable by-products; IDF - Insoluble dietary fibre; PS – Particle size; RTEC – Ready-to-eat cereals; SDF – Soluble dietary fibre; TDF – Total dietary fibre; WAI – Water absorption index; WSI – Water solubility index

1 - Introduction

Fruits and vegetable by-products (FVB) include peels, stems/cores, leaves, pomaces, unripe and/or damaged or “ugly” fruits and vegetables that are generated during processing from post-harvest up to the retail level, which means these by-products are able to be collected and valorised under a circular economy approach. A recent report from Food and Agriculture Organization of the United Nations (FAO) and the United Nation Environment Programme estimates that 14% of the food produced is lost from post-harvest up to, but not including, the retail level (FAO, 2019). The higher levels of losses pertain to fruits and vegetables given their perishable nature, in this case, the loss percentage rises to 20% along the supply chain but excluding retail level (FAO, 2019), *i.e.*, losses happen mainly at the harvest and producer stages of the supply chain (FAO, 2020). Other studies indicate that processed fruits and vegetables generate around 50% of by-products (peels, stems/cores, leaves, pomaces) (Gómez & Martinez, 2018; Virk & Sogi, 2004). Currently, the European commission is targeting to “halve per capita global food waste at the retail and consumer levels of reducing food loss along production and supply chains (including post-harvest losses) by 2030” (FAO, 2019), which is reflected in the Sustainable Development Goal Target 12.3.

These by-products have several high-value compounds, namely bioactive compounds with advantageous antioxidant and antimicrobial activities (Trigo, Alexandre, Saraiva, & Pintado, 2019). FVB have also a considerable amount of fibre, containing approximately 30% to 90% of dry weight (Elleuch et al., 2011) being often used to increase dietary fibre (DF) content of food products (Shirazi, Koocheki, Milani, & Mohebbi, 2020; Stojceska, Ainsworth, Plunkett, & İbanoğlu, 2010). The importance of to increase DF content in foods is related to the fact that the DF intake amount is under the recommendations in EU countries (Stephen et al., 2017) and the USA (Hoy & Goldman, 2014) - recommendations (adequate intake) for average population total fibre intake are >25 g/day in Europe (ESFA, 2010) and 25 (females) or 38 g/day (males) in USA (Institute of Medicine, 2001).

So, several strategies have been used to FVB valorisation. They can be transformed into powders (flours) to be used as ingredients or into extracts rich in bioactive compounds (e.g., phenolic compounds, carotenoids), to be applied as antioxidants and preservatives, contributing to reduce lipid oxidation and microbial growth, consequently increasing product shelf-life, with potential applications in areas such as animal products, dairy products, beverages, and bakery products (Gómez-García, Campos, Oliveira, et al., 2021). Other possible characteristics of these by-products that can potentially improve nutritional aspects and the chemical, physical or microbiological stability of food products remain poorly studied.

On the other hand, BCP represents a class of food products with a determining role in the current human diet, namely in certain age groups and societies, while presenting well-identified nutritional deficiencies (*e.g.,* higher intakes of total sugar, low intake of soluble DF and bioactive compounds). In fact, due to their acceptability and wide dissemination in the human diet, BCP offers great potential for improvement and development of formulations that correspond to high nutrient density foods.

Aspects of concern, and already addressed in different studies, are the physical form of the by-products and the processes used for their incorporation into cereals, maintaining the product's stability and consumer's acceptability, and minimizing any detrimental effect on the properties of the compounds of interest present in the by-products. We will give particular relevance to these aspects in this review. For the incorporation of FVB into BCP, FVB has been transformed into powders or flours to replace part of the cereal flour in extruded BCP (Borah, Mahanta, & Kalita, 2016; Kaisangsri et al., 2016; Kothakota, Jindal, & Thimmaiah, 2013). Extrusion processing is indeed the most applicable for this purpose (Alam, Kaur, Khaira, & Gupta, 2016; Altan & Maskan, 2011), and therefore our focus will be mainly on extruded ready-to-eat BCP. Flours from FVB have been blended with cereal flours to produce other cereal-based food products, with improved nutritional and functional properties, including bread and cakes (Eshak, 2016; Fendri et al., 2016; Jeddou et al., 2017), biscuits (Ferreira et al., 2015; Nassar, AbdEl-Hamied, & El-Naggar, 2008), pasta (Ajila, Aalami, Leelavathi, & Rao, 2010), and cereal bars (Damasceno et al., 2016; Ferreira et al., 2015; Marques et al., 2015), but these products will not be further explored in the present review.

In this review we will provide an updated and critical discussion on the current knowledge regarding the health and technological-related potential of FVB powders to be applied in ready-to-eat cereals (RTEC). First, BCP market and current consumer demand are briefly analysed. Second, the need to improve the nutritional and functional characteristics of most BCPs currently consumed is discussed. Then, production processes are reviewed, focusing on the extrusion approach, and the effects of extrusion on the key compounds (nutrients, bioactive compounds) present in the FVB. Finally, a critical review on the advantages and challenges of introducing FVB powders into extruded BCP regarding consumer acceptance is provided.

2 - Breakfast cereal products (BCP) - market value, consumption, and consumer's demand

Priebe & McMonagle (2016) divided BCP into two groups: i) cooked cereals (as porridge); ii) RTEC or "cold" BCP (as corn flakes and muesli). BCP segment represented a revenue of up to US$62,763 million worldwide in 2020 with an expected annual (2020-2025) growth of 4.1% (Statista, 2020). Considering different world regions, North America generates the most revenue *per capita*, followed by Europe and Asia (Figure 1A). Per country, USA generates the most total revenue (US$20,186 million), followed by China and France (Figure 2A). The average consumption of BCP per capita stands at 1.6 kg worldwide in

2020 (Statista 2020), but there is a wide dispersion of values, namely for different regions of the world. Consumption is highest in North America, followed by Europe (Figure 1B). Per country, the higher consumption per capita is found in France (15.7 kg/capita), followed by the United States (8.7 kg/capita) and the United Kingdom (8.5 kg/capita) (Figure 2B). It is worth mentioning that for regions of the world where the lowest consumption rates are currently occurring, these are also the regions for which the annual (2020-2025) growth for the BCP market is expected to be significantly higher, with anticipated growths of around 11 and 8%, for Africa and Asia, respectively (Figure 1C) (Statista 2020).

BCP are indeed an important component of breakfast worldwide. Commonly, approximately half of the population consume BCP in developed countries, mainly children. Just a brief reference to some quantitative data, considering different regions and age groups as examples. In Australia, 49% of 2 to 18 years old choose BCP for breakfast, from which 62% exclusively consume minimally pre-sweetened BCP (Fayet-Moore, McConnell, Tuck, & Petocz, 2017). In Belgium, the BCP consumption is also highest amongst children (6-9 years) and lowest among adults (Vermote, Bonnewyn, Matthys, & Vandevijvere, 2020). In the United Kingdom, among low-income populations, approximately 80% of children, 58% of women and 49% of men consume BCP (Holmes, Kaffa, Campbell, & Sanders, 2011). In both Spain (van den Boom et al., 2006) and Portugal (Marktest, 2015), about half of the population consume BCP, mainly among children/adolescents – in Portugal, about 66% of children/adolescents consumed RTEC for breakfast (Rito et al., 2019). In USA, only about 36% of children consume RTEC (Smith et al., 2019).

Whole grain fortified RTEC can thus play an increasingly important dietary role and contribute to a diet rich in several under-consumed nutrients of public health concern, as advocated by the 2015–2020 Dietary Guidelines for Americans (Department of Health and Human Services & Department of Agriculture, 2015).

Besides the scientific evidence supporting the need for a healthier diet and the general nutrition recommendations worldwide, consumers' lifestyle and growing health awareness (Betoret, Betoret, Vidal, & Fito, 2011) boost changes in food formulation by the food industry, including in the production of BCP. Attributes such as low-calorie content, namely low-carbohydrate foods and high fibre, are increasingly valued by the consumer and associated with healthier food products. Market studies verified that labelling statements on foods increases its prices, especially for carb-conscious labelling statements. Still, producers do not need to use health claims or indicate a direct link between low-carbohydrate diets and health benefits. Simple labelling statements related to whole grain and sugar content (no sugar added and less sugar) labelling statements had a positive effect on RTEC prices, as well as fat content (fat-free, low-fat, or absence of a specific fat) and salt content (low salt, no salt, and no salt added) related statements, as demonstrated by the study of Muth et al. (2013) performed with consumers and retail data across the United States. A study comparing consumer reaction towards fibre-enriched cereals, calcium-enriched fruit juice, and omega-3 enriched spread, performed among Belgium consumers, showed a clear preference for fibre-enriched cereals (Verbeke, Scholderer, & Lähteenmäki, 2009).

3 - Benefits *versus* needed improvements in breakfast cereal products

BCP plays a significant role in a healthy diet, contributes to meeting nutrient recommendations, and help to reduce the risk of several diseases. Compared with other breakfast options, BCP provides improved nutrient intake at breakfast, indirectly contributing to the increase in the frequency and quantity of ingested milk/yoghurt and fruits (Michels et al., 2016; Zhu et al., 2019). Previous systematic reviews demonstrated that the daily consumption of BCP at breakfast is associated with a healthier lifestyle and well-being feeling (for additional information regarding target populations, daily dosages and specific health benefits, which departs from the focus of the present review, the reader is advised to consult the following papers as representative examples: Giménez-Legarre, Miguel-Berges, Flores-Barrantes, Santaliestra-Pasías, & Moreno, 2020; Priebe & McMonagle, 2016 and Williams, 2014).

Health benefits of BCP are mainly related to the intake of dietary fibre, thus contributing to fill a general insufficient fibre intake, in relation to the recommended doses (USDA, 2021). The American Association of Cereal Chemists (AACC) and the Australia-New Zealand Food Authority (ANZFA) proposed a comprehensive definition of DF: "Dietary fibre is the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. Dietary fibre includes polysaccharides, oligosaccharides, lignin, and associated plant substances. Dietary fibres promote beneficial physiological effects including laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation." (Institute of Medicine, 2001) (For additional information on fibre definitions and related issues, please see reference Stephen et al., 2017). Typically DF can be divided in two categories: i) Insoluble dietary fibre (IDF), consisting in water-insoluble/less fermented fibres such as cellulose, hemicellulose, and lignin; and ii) Soluble dietary fibre (SDF), consisting in water-soluble/well and more readily fermented fibres, as gums, pectins, and some hemicelluloses such as water-soluble arabinoxylans and soluble β-glucans (Dhingra, Michael, Rajput, & Patil, 2012). IDF and SDF present different health benefits due to their mechanism of action in the human body. Especially for SDF, its health benefits are closely related to the influence on the intestinal microbiome, that are nowadays known to play a significant role in hosts health (Duda-Chodak, Tarko, Satora, & Sroka, 2015).

Despite the proven health benefits of BCP and their correlation with DF content, there is still a need to increase the fibre content and fibre diversity in BCP. The current BCP has limited fibre types, mainly maize, oat, and wheat bran, which correspond to 1.2 to 15 g of fibre/100 g of product (Stephen et al., 2017). Very few BCP have a fibre content above 20% (Vin et al., 2020), which could be explained by the difficulty of achieving acceptable sensory quality and overcome the technological problems in incorporating high amounts of fibre in BCP. Thereby, current BCP provide mainly IDF which is the main DF present in cereals grains. On the other hand, FVB flours are a good source of SDF, as described below in section 4.1.

Nutritional imbalances associated with BCP intake have been identified mainly related to sugar and salt content. For example, 84.6% of the RTEC consumed in Portugal were non-compliant according to WHO-Europe nutrient profile model (WHO, 2015) for sugar content; thus, children taking RTEC presented a 5% and 26% higher energy and sugar intake, respectively, than the children that did not consume RTEC (Rito et al., 2019). Children consuming RTEC in USA showed diets with a similar energy intake but higher intake of carbohydrates, despite the lower fat intake and the higher intake of vitamins, than children not consuming RTEC (Smith et al., 2019). Despite some controversies in literature, excessive sugar and sodium intakes associated with RTEC are still of concern, especially among children and adolescents (Chepulis, Everson, Ndanuko, & Mearns, 2020; Goglia et al., 2010; Mesana et al., 2018; Priebe & McMonagle, 2016; Schwartz, Vartanian, Wharton, & Brownell, 2008).

According to the identified nutritional deficiencies, several nutritional improvements have been proposed for specific market contexts, namely reducing sugar, fat and sodium and increasing fibre contents (Chepulis et al., 2020). Compared with Canada, UK, New Zealand, and Australia BCP markets, the USA is the country requiring more the improving of BCP nutritional values. New Zealand and Australia presented the best BCP nutritional profiles (Chepulis et al., 2020). Among these and Latin America countries, the UK was the country where the BCP contained less sugar, which can be attributed to the UK voluntary sugar reduction programme (Garcia et al., 2020). The impact of this program shows how consumers' palate can be educated to consume healthier products.

BCP were usually composed of refined flours, mainly wheat, rice, and corn. However, given the consistent demonstration of the whole grain health benefits and consequent consumer demand for low-carb products, some of the major companies in the BCP market have been replacing some refined flour with whole-grain flour. The American Society for Nutrition concluded that "consumption of cereal fibre or mixtures of whole grains and bran is modestly associated with a reduced risk of obesity, type 2 diabetes, and cardiovascular disease" (Cho, Qi, Fahey, & Klurfeld, 2013). However, the studies about the benefits of whole-grain intake in disease risk reduction are not conclusive when whole-grain does not include added bran (Ye, Chacko, Chou, Kugizaki, & Liu, 2012), which shows the importance of fibre content for health benefits. Similarly, Priebe and McMonagle (2016) and Williams (2014) concluded that only high-fibre or whole-grain BCP has beneficial roles in type 2 diabetes, hypertension, and cardiovascular disease.

There are thus important driving factors for the nutritional improvement of these products, including consumer demands, which justify the growing acceptance by the industry for changes in formulation and production that could meet these objectives. On the other hand, there is an opportunity window for the use of FVB, not only as a DF source but also of other important nutrients (e.g., vitamins, minerals), simultaneously offering economic advantages in the fortification of BCP.

4 - Fruit and vegetable by-products (FVB) in extruded ready-to-eat cereals products

4.1. Representative sources of FVB and relevant composition

Harvesting, post-harvest handling and the processing of fruits and vegetables generate substantial amounts of by-products. These essentially include pulp residues, peels, stalks, and seeds. Many of them can represent an environmental problem, but they can also be important sources of nutrients and bioactive compounds, including minerals, vitamins, dietary fibre, phenolic compounds (phenolic acids, flavonoids, tannins), prebiotic oligosaccharides and carotenoids (Gómez & Martinez, 2018; Santos, Lopes da Silva, & Pintado, 2022).

As mentioned above, the wasted quantities of these by-products are, in many cases, very high (in the order of tens of million tons per year). The growing interest in the isolation, characterization, and application of FVB has been reflected in many studies on this subject (Elleuch et al., 2011; Kowalska, Czajkowska, Cichowska, & Lenart, 2017; O'Shea, Arendt, & Gallagher, 2012; Sharma et al., 2016; Trigo et al., 2019). Here, in the context of the present review, we only discuss representative examples of these by-products, taking into account the diversity among fruits and vegetables and especially FVB flours that have been applied into extruded BCP, and their constituents with attractive characteristics from the nutritional and/or functional point of view.

FVB can also be an important source of minerals and, therefore, potentially useful for BCP mineral supplementation. Table 1 shows some representative values in comparison with the mineral content typically found in cereals' flours.

Being a source of DF has been recognized as one of the most useful nutritional advantages of these by-products (Santos et al., 2022). Additionally, the presence of significant amounts of bioactive compounds such as polyphenols, which are often found linked to DF components, further enhances the potential nutritional benefits of these by-products. Table 2 shows examples of DF amounts and other high-value compounds present in representative FVB.

Although, to our knowledge, there are no studies that evaluate and compare the possible different bioavailability of different bioactive compounds when present in diverse FVBs, it is important to emphasize the synergistic effect between DF and phenolic compounds, which increases the potential health benefits of FVB flours (Santos et al., 2022). In the free and soluble conjugated forms, phenolics are absorbed in the upper gastrointestinal tract (stomach and small intestine), providing health benefits such as inhibition activities against oxidation of cholesterol and liposomes (Acosta-Estrada et al., 2014), while the bound forms have chemopreventive activity against colon cancer as they are transported throughout the gastrointestinal tract and released in the colon where the microflora metabolise DF (Acosta-Estrada et al., 2014).

4.2. BCP enriched in FVB - Production process

The transformation of FVB into ingredients that are easy to handle, assuring the preservation of their desired properties, is an essential step to guarantee their valorisation. FVB are typically characterised by high water content and high-water activity, often associated with a high amount of cellular damage and thus undesired enzymatic activity (e.g., polyphenol oxidase activity causing browning and off-flavor development, lipoxygenase activity causing destruction of essential fatty acids and vitamin A, or ascorbic acid activity causing loss of vitamin C). Therefore, FVB are naturally susceptible to biochemical and microbiological deterioration. Drying and their subsequent transformation into flour will thus be the most obvious technology, and it is indeed the most used, allowing the decrease in water activity, the inactivation of unwanted enzymes and the reduction of microbial growth. However, it will be essential to ensure that the temperatures reached do not cause undesirable changes in thermolabile constituents such as vitamins and bioactive compounds. This can allow for suitable storage and use as ingredients for BCP supplementation. Another important aspect may be related to the flour particle size. Smaller particle size will obviously be related to a larger surface area, a characteristic that may influence the stability of FVB, the mixing and dispersion of FVB flour within the matrix of the final food product, and the digestibility, absorption or gastrointestinal transit of the compounds of interest. Processing conditions used to obtain flours from FVB have been recently reviewed (Santos et al., 2022) and will not be further discussed in the present review.

FVB, when transformed into powders/flours, can be used to create extruded products with improved nutritional profile, namely, decreased carbohydrate content and increased content of total dietary fibre (TDF) and bioactive compounds (Oliveira, Marques, Kwiatkowski, Monteiro, & Clemente, 2013; Santos et al., 2020; Shirazi et al., 2020). Several variables associated with the extrusion process may influence the final characteristics of the extruded products incorporating FVB (Alam et al., 2016). The quality of the final product can be managed by controlling the processing conditions such as die head temperature, feed rate, screw speed and moisture (Altan, McCarthy, & Maskan, 2008; Santos et al., 2020). In this section, studies comprising the inclusion of FVB flours, powders, or extracts into extruded BCP will be reviewed, focusing on the production methods.

Several methods produce BCP, but it is only possible to include FVB when they are dehydrated in the form of powders and resort to extrusion processing, i.e., creating extruded RTE cereals (not flakes). This type of BCP is produced by mixing the ground ingredients, adding water to produce a paste, cooking the mixture, shaping the product, cooling and drying. This process is usually conducted in an extruder machine. Extrusion is a low cost, high-temperature, short-time process where the mixture is plasticized at high-temperature, pressures, and shear. Further discussion on extrusion cooking is out of the scope of the present review. Still, the reader can find additional information on several bibliographic sources, including the works of Guy (2003), Johnson (2003), and more recently Moscicki (2016), Rosentrater and Evers (2018), Alam et al. (2016) and Offiah, Kontogiorgos, and Falade (2019). Shortly, extrusion processing includes conveying, mixing, and compressing moist powders through a barrel with a screw into a small opening of a defined shape called die. During this continuous and constant rate process, the pressure increases with the compression along the barrel, thus allowing to form doughs from a minimum amount of moisture mixtures. This process has several key features such as a) feeding system (devices that supply the raw material into the barrel); b) design of the screw system (single or twin) and its barrel; c) dimensions and the number of dies (Alam et al., 2016; Guy, 2003).

The general process mostly used when producing BCP with by-products is summarized in the flow chart represented in Figure 3. Prior to extrusion, the ingredients are mixed thoroughly. When the extruder has no feed moisture, water is added during ingredients mixing to a known moisture level. The mixture is left to stabilize usually at 4 °C stored in closed bags or containers for 24 hours (Drożdż et al., 2014; Fleischman et al., 2016; Kaisangsri et al., 2016; Singha & Muthukumarappan, 2018; Stojceska, Ainsworth, Plunkett, İbanoğlu, & İbanoğlu, 2008; Wang et al., 2017). Then, the blend is fed into the extruder and heated above starch gelatinisation temperature leading to a cooked product (Foschia, Peressini, Sensidoni, & Brennan, 2013). Some typical extrusion temperatures and moisture contents used to prepare supplemented extruded cereal products and already reported in the literature are shown in Table 3.

After extrusion, the extrudates are cooled down or may previously need a drying step if the moisture level is above 10% (Mäkilä et al., 2014). Drying conditions will be particularly critical for maintaining some of the nutritional and functional characteristics of these products. There is a great diversity of these conditions, already reported in the literature (Table 3). Besides, the general purpose of reducing water activity and improving biochemical and microbiological stability, drying may also improve texture attributes, as observed, for example, for corn-mango peel extrudates that showed decreasing hardness and increasing crispiness, after drying at 105 °C for 2 h (Mazlan et al., 2019).

Water can also be removed by frying, although this is more applied in snacks than BCP (Moscicki, 2016). Dar, Sharma, and Kumar (2014b) evaluated the effect of frying at different temperatures and times on the characteristics of rice/carrot pomace extrudates. As expected, changes in the colour of the final product were observed, but also an increase in oil absorption with increasing temperature and time of frying. Despite the additional changes during storage, the product was still considered sensory acceptable.

After drying, usually, samples are cooled and stored at room temperature. Several packages have been used, such as low-density polyethene bags (Borah et al., 2016); multiple layer laminate PA/PE with 40 cc/m2/day oxygen penetration bags (Mäkilä et al., 2014; Santos et al., 2020); polypropylene plastic bags (Uline Poly Bags, S-1255); polythene bags (Kumar, Sarkar, & Sharma, 2010) and sometimes the package is simply described as sealed plastic bags (Shi et al., 2017).

4.3. BCP enriched in FVB - Composition in bioactive compounds

In this section, molecular changes affecting bioactive compounds present in the FVB ingredients or in the cereal flour components caused by the extrusion process are reviewed. These changes may positively or negatively affect the characteristics of the final products. Most available information is related to phenolic compounds. Table 4 summarises those studies, including relevant results related to technological attributes and sensory properties of the final products, which necessarily reflect on the acceptability by consumers and will be further discussed in the following sections of the present work.

The incorporation of FVB into BCP typically increases its fibre content and related health benefits. Despite that, the elevated temperatures and the mechanical disruption that are achieved during extrusion may lead to a reduction in the content of minerals, vitamins (ascorbic acid, retinol, tocopherols) and carotenoids (β-carotene, lutein, zeaxanthin) mainly due to undesirable chemical reactions (Cueto, Farroni, Schoenlechner, Schleining, & Buera, 2017; Dar, Sharma, & Kumar, 2014a; Dewanto, Wu, & Liu, 2002; Johnson, 2003; Kaisangsri et al., 2016), the antioxidant activity often increases due to the release of molecules with higher antioxidant capacity, such as phenolic compounds (Acosta-Estrada, Gutiérrez-Uribe, & Serna-Saldívar, 2014), or due to production of Maillard reaction products that possess additional reducing capacity (White, Howard, & Prior, 2010). Extrusion cooking also promotes the release of other molecules (xylooligosaccharides, fructans, raffinose, stachyose) that have prebiotic activity and can contribute to cancer and cardiovascular diseases prevention (Fardet, 2010; Ou & Sun, 2014).

Despite the fact that cereals are richer in bound phenolics (52-88%), FVB flours are also rich in bound phenolic compounds (7-76%) (Dewanto et al., 2002). Bound phenolics are mainly released in the colon through fermentation by gut microbiota, limiting its health benefits, which are mainly related to a chemopreventive activity against colon cancer. However, the extrusion cooking used to produce BCP promotes the release of these bound phenolics from the fibres (Rochín-Medina et al., 2012), thus allowing its absorption in the stomach and/or in small intestine increasing its range of health benefits, such as inhibition activities against oxidation of LDL cholesterol and liposomes (Acosta-Estrada et al., 2014). The liberation of bound phenolics may occur through the breakdown of both cellular constituents or ester linkages between the phenolic compounds and cell wall components.

One can expect that the thermal conditions associated with the extrusion process will also cause the release of the phenolic compounds related to these mixtures' cereal components. Dewanto et al. (2002) demonstrated that thermal processing (115 °C, 25 min) of sweet yellow maize significantly increased total phenolics, ferulic acid content, and total antioxidant activity. The application of heat treatment at 160 °C for 1 h on maize bran allowed the solubilization of 80% of ferulic acid also in the form of feruloylated oligosaccharides (Saulnier, Marot, Elgorriaga, Bonnin, & Thibault, 2001). *trans*-Ferulic acid is the main phenolic compound in cereals. Heat treatments release the ferulic acid mainly as solubilized feruloylated oligosaccharides with higher antioxidant activity than free ferulic acid (Siyuan, Tong, & Liu, 2018), especially the 6-O feruloyl-glucosides (Kylli et al., 2008). These oligosaccharides inhibit glycation related to radical scavenging and iron-chelating activities, they also act as prebiotics as they stimulate the growth of *Bifidobacterium bifidum*, and protect the gastrointestinal, respiratory and urogenital tracts from infection (Ou & Sun, 2014).

Worth mentioning that extrusion may have different effects on different phenolic compounds, related to the different thermal sensitivity of these compounds and due to the different degree of bonding to other system constituents. Therefore, anthocyanins, being more heat-sensitive, are more easily lost. Normally extrusion leads to a decrease in their content as for the anthocyanins, unlike, for example, flavonols which are more thermostable, in addition to being more extensively linked to cell wall constituents, so their content in the final products is often increased as a result of extrusion (White et al., 2010). The degree of polymerization of procyanidins and thus their bioavailability and bioactivity may also be affected by extrusion. White at al. (2010) showed that for mixtures of cranberry pomace and corn starch, extrusion leads to depolymerization of procyanidins, consequently increasing the amounts of low molecular weight compounds. Since low molecular weight procyanidins (monomers, dimmers) show much higher absorption rates than larger ones (Donovan et al., 2002), extrusion cooking may have important consequences on improving procyanidins' absorption and thus their potential health benefits, due to the depolymerization effect.

From what has already been discussed, we can assume that two most important factors influence the extrusion effects on the content and bioavailability of phenolic compounds: their thermal sensitivity and consequent level of thermal degradation, the type and intensity of their binding to other constituents of the system or among themselves.

The extent to which these compounds are released from the bonds they establish with the fibre constituents will depend on the conditions used during extrusion, and so different extrusions conditions differently affect the phenolic content and antioxidant activity (Table 4). Therefore, it is not surprising that different results have been reported, probably associated with different processing conditions and the effect of those conditions on the breakdown or formation of bonds between phenolic compounds and other food constituents. For example, the study of O˝zer, Herken, Güzel, Ainsworth, and İbanoğlu (2006) showed that extrusion processing at 110 °C (screw speed 220-240 rpm, moisture content 11-15%) of a mixture containing chickpea, corn, oat, corn starch, carrot powder and ground raw hazelnut, did not change the total phenolic compounds concentration (which corresponds to the free phenolic compounds). On the other hand, the total phenolic content may not be proportional to the FVB flour addition to the food products due to increasing polymerization of these compounds, as suggested by Reis and Abu-Ghannam (2014) on the incorporation of apple pomace into rice-wheat based extrudates. Clearly, the extrusion conditions must be carefully studied and optimized to allow the liberation of the bound phenolic compounds and thus benefit from their advantageous properties when they are free/bioavailable in the final product, concurrently avoiding their unwarranted thermal degradation.

As mentioned above, the incorporation of FVB into BCP *per si* typically increases the fibre content of the final products. However, extrusion can also reduce the content of insoluble dietary fibre (IDF) and increase soluble dietary fibre (SDF). This effect has been observed, for example, for orange pulp flour extrudates, especially for higher barrel temperatures (Larrea, Chang, & Martínez Bustos, 2005), and for bamboo shoots flour extrudates (Ge et al., 2017). The most accepted explanation is based on the degradation of insoluble fibre components, including cleavage of 1,4 carbon-oxygen bonds and formation of new anhydro-glucose linkages (Ge et al., 2017), due to the combination of intense instantaneous heat energy and other forces occurring during extrusion (cavitation, friction, and impact compression), thus increasing SDF content at the expense of decreasing IDF. Under conditions that may lead to more extensive degradation, such as higher barrel temperatures and lower moisture contents, even the TDF may decrease, due to a more pronounced fragmentation and solubilisation of polysaccharides (Larrea et al., 2005). The influence of the extrusion conditions on the fibre content and on other product characteristics is typically a multivariate problem. Therefore, as expected, not only the barrel temperatures have a significant influence, but also the feed moisture and screw speed, this last directly related to the sample residence time while inside the extruder, can affect both the IDF and SDF contents (Table 4).

Given the heterogeneous and complex composition of each IDF and SDF, it is to be expected that extrusion conditions may affect each component differently, thus leading to complex and sometimes apparently contradictory effects. While the IDF content may decrease due to the aforementioned thermal degradation, an increase in the relative content of SDF due to starch gelatinization during extrusion and further retrogradation during cooling, and the formation of resistant starches has also been reported (Elleuch et al., 2011; Stojceska, et al., 2010). In fact, the high temperature and high-pressure conditions achieved during extrusion can affect polysaccharides profile once they can break physical bonds and new structures can be formed by changes in the carbohydrate components and proteins (Ying et al., 2017).

The soluble sugar content may increase due to fibre degradation (Saulnier et al., 2001), one possible consequence of the extrusion conditions, with relevant importance for the nutritional value of these products. This aspect has not yet been sufficiently clarified and clearly deserves further studies.

4.4. Technological challenges to improve texture, sensory characteristics and consumer acceptance

This section reviews relevant technological challenges associated with the production methods used to obtain BCP supplemented with FVB. Physical characteristics, composition and added amount of the FVB powders influence extrudates' physical properties and structure that reflect on texture and, consequently, on product sensory characteristics and consumer acceptance.

As mentioned above, among the physical properties of the FVB powders, the particle size (PS) of the flour is one of the most relevant characteristics to be considered. The study of Wang et al. (2017) on corn starch-cherry pomace extrudates demonstrated that smaller particle sizes (< 125 μm) lead to higher expansion of the extrudates (higher expansion index (EI)), an effect that was more pronounced for the higher tested proportions of added FVB.

Regarding compositional effects and levels of FVB inclusion, the greater challenge of introducing FVB powder into extruded products is related to the consequent increase of the DF content. Typically, high fibre content has a detrimental effect on the texture of extruded products, decreases EI and increases bulk density (BD), which is also related to a lower starch concentration due to the increase in fibre content (Table 4). SDF may have positive or negative effects. It can decrease hardness by acting as a lubricant, producing crispier rather than harder textures, and can enhance elastic properties through an anisotropic process (alignment of the soluble fibres in an axial direction as a result of the extrusion process); however, if too much fibre is present, the sectional structure expansion is limited decreasing expansion. Also, the absorption of water in the melt decreases the amount of vaporised water (steam), which would lead to nucleation and expansion, thus resulting in lower EI (O'Shea, Arendt, & Gallagher, 2014). Consistently, the addition of FVB powders results in a reduction of EI (Table 4). If higher starch contents characteristically result in higher EI, as starch is responsible for the puffiness in the final products (Selani et al., 2014), the opposite is true when the relative proportion of fibre increases.

Fleischman et al. (2016) produced extruded products with several brans (white, red and purple) at different levels of waxy-pen flour replacement (12.5, 25 and 37.5%). The higher concentration of bran caused the lower EI and the highest density values. The product with the higher starch content (purple bran products) expanded more than the other products. O'Shea et al. (2014) found that increased apple pomace powder content in an extruded snack resulted in decreased EI and hardness. Similar effects on EI were reported by Wang et al. (2017) for high levels of added FBV (15 wt.%), but these authors also showed that cherry pomace added at lower levels (5 wt.%) and especially with small particle sizes (< 500 μm) could enhance expansion during extrusion, probably related to a uniform distribution of fibre within the starch matrix, originating higher expansion levels.

In general, several mechanisms may be responsible for the effects on texture observed for different amounts of fibre, namely the main effect of decreasing EI (Borah et al., 2016; dos Santos et al., 2019; O'Shea et al., 2014). In summary, the following effects resulting from an increase in the relative amount of fibre (typically FVB added within the range 0 to 20%, corresponding to a TDF increase in the extruded products that can be up to 14 g/100 g product, depending of amount and type of added FVB - for specific values please see table 4 and cited studies) have been proposed:

i) Increasing extensional viscosity thus decreasing elastic properties and consequently reducing affinity between starch and IDF;
ii) Diluting starch content and consequently reducing its swelling capacity;
iii) Modification of the glass transition temperature of the melt due to absorption of water.
iv) Fibres adhering to the bubble structure leading to cell puncturing hampering gas bubbles to expand and thus reducing cell extensibility.
v) Adhesion of partially molten starch granules to the cellulosic wall, forming complexes of cellulose, gelatinized starch, and cellular protein which difficult the expansion.

The final effects necessarily result from a complex set of factors. Santos et al. (2020) proposed that cooking the fruits before by-product flour production results in a pre-gelatinization of the starch that in turn reduces mechanical shear in the extrusion process resulting in reduced EI. Notwithstanding, the study of dos Santos, Caliari, Soares, Viana, and Leite (2015) showed that the lower amount of carbohydrates (namely starch) has a greater influence on decreasing EI than the higher fibre content. The incorporation of 10% of jabuticaba peel powder (31% of TDF, mainly IDF) in corn-based extruded BCP increased EI and decreased BD (also increased water solubility index (WSI), decreased hardness and increased the crispiness of the products (Table 4)) (Oliveira, Alencar, & Steel, 2018), which may be due to the relatively high concentration of starch in this fruit powder. Contrarily, the same study showed that wheat based extruded BCP presented lower EI, higher hardness and lower crispiness, which demonstrates the importance of the functional properties of the cereal component for the final product characteristics. In fact, corn starch is unique for providing highly expanded and porous extrudates (Owusu-Ansah, van de Voort, & Stanley, 1984). Incorporation of fibre-rich FVB into starchy cereal flours may also have an important effect on the nutritional aspects of these products, namely by decreasing the degree of starch gelatinization and *in vitro* starch digestibility, as observed for barley–grape pomace extrudates (Altan et al., 2009a).

Extrudates' bulk density (BD), another physical parameter of interest, is closed related to the expansion characteristics of these products. As expected, BD increases as a result of decreasing EI, but other factors can also influence, namely the water absorption capacity of the different constituents of the system; it has been shown, for example, that high amounts of fibre and sugars that can absorb water lead to an increase in the density of the final product (Selani et al., 2014).

The composition of FVB and cereal flours, namely starch and fibre contents, also influences water absorption index (WAI) (Table 4). WAI measures the amount of water absorbed by the constituents of the system; given the predominance of starch in the constitution of cereal flours and its relatively high-water absorption ability, WAI is strongly dependent on the relative amount of this constituent. Necessarily, an increase in the relative amount of fibre will cause a dilution of the remaining components and a decrease in the concentration of starch; hence, as expected and already reported, adding FVB to cereal flours to produce extruded products usually leads to a decrease in WAI, associated with an increase in fibre (Altan et al., 2009a; Santos et al., 2020; Wang et al., 2017). Besides the dilution effect, competition for available water will also have an important role on many of the final extrudate properties. In fact, other studies have shown that different effects can also be obtained, namely a non-significant effect on WAI or even an increase resulting from FVB addition to cereal extrudates, which can be explained by the significant contribution of fibre to WAI, mainly the SDF component (Kaisangsri et al, 2016; Selani et al., 2014).

For the products under discussion, WSI is related to the amount of soluble components during extrusion and is used as an indicator of dextrinization, which generates smaller and more water-soluble molecules (Ding, Ainsworth, Plunkett, Tucker, & Marson, 2006). It generally decreases with the incorporation of FVB powders (Table 4) due to the dilution of starch or other constituents that can be degraded, generating more water-soluble molecules (Selani et al., 2014; Wang et al., 2017).

As discussed before, different extrusion conditions (Table 3) have been used to obtain extrudate BCP supplemented with FVB, including different extruder designs, moisture feed contents and extrusion temperatures, and those conditions necessarily influence the final products' textural characteristics (Table 4). Extrusion is indeed a multivariate process that can be optimized to achieve the desired characteristics for the final products. Furthermore, the strategies followed for drying the extrudates (post-drying conditions, Table 3) will also significantly influence the final properties of these products.

Different effects on texture are expected as a result of the variation in the diversity of parameters involved and interactions among variables, thus requiring a careful interpretation of the results already reported in the literature.

Extrudates' characteristics such as hardness, density, porosity and WAI are affected not only by the relative amount of added FVB but also by moisture content, temperature and screw speed (Altan et al., 2008; Kumar et al., 2010; O'Shea et al., 2014; Santos et al., 2020; Stojceska et al., 2008; Wang et al., 2017).

Mazlan et al. (2019) reported a significant effect on the maximum mixing torque by a negative linear relationship between barrel temperature and screw speed. The same study showed that increasing the temperature and screw speed increased the linear expansion and decreased the hardness of corn-mango peel extrudates. Similar effects of temperature and/or screw speed were reported for rice-pineapple waste pulp extrudates (Kothakota et al., 2013) and for corn starch-cherry pomace extrudates (Wang et al., 2017). Contrarily, O'Shea et al. (2014) showed that decreasing the screw speed and/or decreasing die head temperature resulted in lower BD, higher porosity and higher EI for corn-based extrudates supplemented with apple pomace. Screw speed also influences WAI, which seems to depend on the level of added FVB (Altan et al., 2008, 2009a). Increasing both amount of added FVB and die temperature also increased WAI of barley–tomato pomace extrudates (Altan et al., 2008).

To increase the fibre content in extruded BCP, moisture content can be managed to prevent product characteristics from being negatively affected and thus to improve texture. As well-known, feed moisture plays a key role on texture properties of extruded BCP. Moisture can increase or decrease EI, thus influencing the texture in different ways, depending on blend formulations (Yağci & Göğüş, 2009). The study of Kothakota et al. (2013) on rice-pineapple extrudates showed that increasing levels of moisture resulted in extrudates with lower hardness and lower expansion, yet higher overall consumer acceptability. On the other hand, formulations containing high moisture and high amounts of FVB originated corn-mango peel extrudates with lower EI and higher hardness (Mazlan et al, 2019). In accordance with this study, more desirable texture characteristics, such as higher expansion, lower hardness and adequate lightness, were obtained for corn-peach palm extrudates at low moisture and intermediated amounts of added FVB (Santos et al., 2020)

Besides a concentration effect, water plays an important role in starch functionality, namely on the gelatinization process due to the extrusion thermal treatment and further starch retrogradation. Considering the multicomponent and complex system corresponding to a mixture of cereal flour and FVB, one may expect that the water partition between these components, although difficult to predict, will be decisive for the properties of the final product. Other cereal flour components and fibre polysaccharides are known to influence starch functionality, namely by competing with starch for water affinity, thus lowering water availability for starch gelatinization (Raguzzoni, Delgadillo, & Lopes da Silva, 2016; Santos, Gama, & Lopes da Silva, 2002). Higher hydration levels are expected to promote a complete starch gelatinization, and one may expect that under higher water levels competition for water availability will have a lower effect on the product's final characteristics. Regarding this, although some studies have shown a non-significant effect of adding FBV to cereal flours (Karkle, Keller, Dogan, & Alavi, 2012), the potential effects of adding FVB are likely dependent on a complex set of factors, including the level of moisture (Kaisangsri et al., 2016), FVB composition and proportion in the final mixtures.

The water content also influences the extent of damage to the starch granules and degradation of constituents that normally occurs resulting from the severe thermal and mechanical conditions during extrusion. The increase in feed moisture reduces viscosity and dissipates mechanical energy in the extruder barrel, leading to a greater plasticizing effect, resulting in lower starch dextrinization, and in extrudates with higher density, lower EI and WAI (dos Santos et al., 2019; Santos et al., 2020).

Finally, it is worth noting that different water addition methodologies can also significantly influence the final properties of the extrudates. Karkle et al. (2012) tested the hydration at three points during extrusion (water added into the preconditioner, the extruder or into both locations) and verified that delayed water addition (when added into de extruder) decreased starch gelatinization and promoted broader cell size and cell wall thickness distributions due to poor mixing and hydration at this stage, thus affecting texture and digestibility of the extrudates.

Other promising strategies worth to further studies include the use of supercritical CO_2 instead of steam to improve EI and BD of cereal extruded products supplemented with FVB (Paraman, Sharif, Supriyadi, & Rizvi, 2015).

4.5. Consumer acceptance

This section critically reviews the information available so far regarding the consumer acceptance of the final BCP supplemented with FVB. Table 4 includes relevant results on consumer sensory analysis when available.

As discussed in the previous section, EI and BD affect the texture quality of the BCP and so consumer acceptance. In general, extrudates with high EI and low BD have higher overall acceptability (Kothakota et al., 2013). Regarding sensory aspects and consumer acceptance, the available information about extruded BCP supplemented with FVB is not abundant. Some of the studies conducted regarding incorporating these by-products in other food products can be useful in predicting and planning useful strategies to improve sensory aspects and consumer acceptability towards FVB-BCP. The sensory evaluation has demonstrated that consumer acceptance is not affected until a certain level of fibre content. Sudha, Baskaran, and Leelavathi (2007) evaluated the incorporation of 10, 20 and 30% of apple pomace flour in cakes and showed that the scores for texture, grain, eating quality, and overall quality decreased only at the 30% level. Sensory evaluation of wheat flour-based snacks supplemented with cauliflower by-products showed an up limit of 10% added FVB, above which there was a significant decrease in acceptability (Stojceska et al., 2008). Similarly, biscuits added with white grape pomace powder (10, 20 and 30%) only exhibited different taste and overall acceptance at 30% of pomace powder (Mildner-Szkudlarz, Bajerska, Zawirska-Wojtasiak, & Górecka, 2013), although colour and texture scores were worse for all analysed FVB proportions. High levels of tomato pomace by-products (30%) were also incorporated into extruded snacks without compromising expansion, texture and overall acceptability (Karthika, Kuriakose, Krishnan, Choudhary, & Rawson, 2016). This study also demonstrated that the type of FVB may affect sensory properties and consumer acceptance differently, as it was demonstrated for different levels of added tomato seeds, peels or pomace – for example, in general, higher acceptability was observed for those formulations with high levels of tomato seed flour, despite the higher amount of fibre, probably due to higher fat content of seeds seed, which improved the taste of the final products. Other sensory attributes that reflect on aroma and taste are also important to take into consideration. For example, the study of Cedola, Cardinali, D'Antuono, Conte, and Del Nobile (2020) on the incorporation of olive paste into bread (50%) and pasta (10%) revealed that the characteristics of the products got worse due to the bitter and spicy taste of the added FVB.

BCP produced from rice, passion fruit peels (3%), and whey protein (10%) had a texture score just above 4, which was the acceptance limit on that scale. The authors attributed this score to the lower crunchiness of the product and suggested that "crunchiness can be improved by the reduction of the moisture content in the breakfast cereal" (dos Santos et al., 2019). The effect of moisture on crunchiness is related to its effect on EI, as previously discussed.

Hough, Buera, Chirife, and Moro (2001) verified that the ideal crispiness is different for diverse types of biscuits and crackers. This could be related to consumer familiarity with the products and expected crispiness. BCP is expected to be crunchy; thus, the assumption of low scores for texture being attributed to the lower crunchiness is expected. This study also revealed that crispiness was higher for lower values of water activity and moisture (Hough et al., 2001). It could be interesting to assess if the same is verified for BCP; once the moisture is one of the parameters controlled during extrusion, it could be handled to achieve better crunchiness.

Kumar et al. (2010) verified a similar behaviour for hardness and sensory scores. Both were lower for higher levels of pomace content, moisture and temperature and lower screw speed values. These results reveal that increased hardness results in increased consumer 'liking' (Table 4 for optimal conditions). Similar results were found by Borah et al. (2016) for extrudates of rice, banana flour and carambola pomace flour blends. In this work, the blend products had higher sensory quality scores (approximately 8) than the only-rice extrudate (approximately 7).

Health benefits associated with food products may increase consumers' interest in fibre-rich products, despite some negative effects on texture. A recent study conducted among 1014 Polish consumers showed that health-conscious consumers, consumers that have a higher intake of wholemeal bread and bread with grains, are willing to pay more for bread fortified with fibre (Sajdakowska, Gębski, Żakowska-Biemans, & Jeżewska-Zychowicz, 2019). One may assume that the same would happen for BCP supplemented with fibre-rich FVB. Consumers create habits and familiarity with food products, but as health concerns increases, also increases consumers' awareness of the health benefits of fibre, which can result in increasing acceptance for fibre-fortified food products, as demonstrated by the studies of Sajdakowska et al. (2019) and Concha-Meyer et al. (2019), the later related to the sensory evaluation and consumer acceptability (231 American consumers, 55% females and 45% males, ages 18 to 70) for bread supplemented with tomato pomace power. The study performed by Yeu, Lee and Lee (2008), based on a total of 120 consumers (38 male and 82 female, 18 to 65 y old), revealed that sensory acceptance of extruded soy-based BCP was lower than selected commercial BCP, but consumer acceptance significantly increased when nutrition and cost information was provided.

5 - Conclusion and future perspectives

The available knowledge here reviewed and discussed is of relevant importance to achieve two objectives of established public interest: 1) The enhancement of the nutritional profile of BCP to promote the improvement of public health; and 2) The need to valorise food by-products within the context of circular economy, thus decreasing the environmental impact of agro-industries.

Several studies demonstrated that incorporation of FVB into BCP could increase the amount of fibre, micronutrients and bioactive compounds in these products. However, in order to the nutritional benefits may be fully exploited, there is a need for adequate control of the characteristics of the constituents and process conditions. The amount of FVB and consequent DF content is one of the main factors affecting texture quality. FVB content generally above 30% results in low sensory scores. However, extrusion technology is a promising technique to incorporate by-products powders into new BCP once several processing conditions may be managed to improve texture quality of the product that is typically compromised by the increase of fibre content. Extrusion processing breaks covalent linkages releasing smaller molecules and phenolic compounds in the free and/or soluble forms, but it can also reduce the amount of free bioactive compounds due to thermal degradation. Thus, to improve bioactivities and bioactive compounds content in BCP, the flours' production process must be as mild as possible to avoid the release of bound phenolic compounds that would probably suffer extensive degradation during extrusion. Yet, BCP with improved nutritional characteristics and satisfactory consumer acceptability will be obtained only through optimization of extrusion conditions. There is still a need for additional knowledge, namely, to produce BCP-FVB extrudates with higher levels (above 30%) of incorporation of by-products, while minimizing the potential disadvantages that would be reflected in the texture of these products and their acceptance by the consumer. Since SDF and IDF have different effects on texture of extrudates, additional studies on the adequate SDF:IDF ratio for better texture quality of the BCP would be also beneficial. Most of the available studies are centred on the physical/technological characteristics of the products. There is also a need for studies addressing the health benefits of consumption of BCP enriched in FVB flours, including the study on the necessary dosage to achieve those health benefits. The subject of consumer acceptance is a weakness in the current knowledge on new food products with by-products ingredients. The development of new food products with FVB will require further studies on sensory evaluation and consumer acceptance.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT author statement

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Figure captions

Figure 1. (A) The average revenue per capita for breakfast cereals products, (B) The average per capita consumption, and (C) the annual expected growth (2020-2025) for the breakfast cereals market, for different world regions (data adapted from Statista, 2020).

Figure 2. (A) The total annual revenue and (B) average per capita consumption of the breakfast cereals segment (2020), for representative countries from different regions around the world (data adapted from Statista, 2020).

Figure 3. Flow chart of extrusion production process and most common conditions described in literature. After cooling, the extrudates may or may not go through a drying step, which has been done following different strategies, including frying the samples.

Table 1 – Macro- and microminerals nutrients present in representative fruit and vegetable by-products, in comparison with the mineral content typically found in cereal flours [a].

Source	Macrominerals (mg/g)				Microminerals (μg/g)				References
	K	Ca	Mg	Na	Fe	Zn	Mn	Cu	
Pineapple - Core - Crowns - Skin	25	2.7	1.2	0.13	43	18	688	15	Brito et al. (2020)
Banana peels	16.3	3.3	--	0.44	1217	1.97	54.7	--	Eshak (2016)
Pomegranate peels	12.9	3.2	0.77	--	86.1	9.2	5.1	--	Topkaya and Isik (2019)
Pea pods	4.1	30.4	5.1	17.4	--	9.2	9.2	1.1	Fendri et al. (2016)
Tomato Pomace	24.5	3.6	2.8	--	130	41.5	40.1	--	Isik and Topkaya (2016)
Onions - Brown skin	4-7	22-31	1.1-1.5	--	120-419	15-22	8.3-25	--	Benítez et al. (2011)
- Top+bottom	11-13	10-16	1.4-1.5	--	427-889	50-54	20-29	--	
Cabbage stalks	95	19	3.3	0.84	42	40	67	2.7	Brito et al. (2020)
Garlic husk	7.0	16.6	2.0	2.0	89	11	17	8.7	Kallel et al. (2014)
Wheat flour [b]	1.1-2.1	0.16-0.29	0.29-0.48	0-0.03	9.1-16	7.8-22	4.9-14	1.4-3.9	USDA (2019)
Whole wheat flour [c]	3.1-5.3	0.33-0.48	1.2-1.5	0.03-0.04	29-45	22-53	28-42	3.7-6.5	
Rice flour [d]	0.3-1.0	0.04-0.12	0.12-0.35	0-0.12	0-7	9.3-15	4.9-14	1.6-3.6	
Whole rice flour [e]	2.5-2.9	0.08-0.14	1.0-1.4	0-0.03	11-22	14-27	24-33	2.5-3.4	
Corn flour [f]	0.90	0.02	0.18	0.01	9.1	3.7	0.56	1.4	
Whole corn flour [g]	3.15	0.07	0.93	0.05	23.8	17.3	4.6	2.3	

[a] All values on dry matter basis (DM); [b] Flour, wheat, all-purpose, unenriched, unbleached; [c] Flour, whole wheat, unenriched; [d] Flour, rice, white, unenriched; [e] Flour, rice, brown; [f] Corn flour, yellow, degermed, unenriched; [g] Flour, Corn flour, whole-grain, yellow. (--) data not available

Table 2 – Dietary fibre and other bioactive compounds present in selected fruit and vegetable by-products [a].

Source	Dietary fibre (g/100 g)		TPC (mg GAE/g)	Examples of identified bioactive compounds	References
	TDF	SDF			
Cabbage stalks	43	4.9	--	Maltooligosaccharides (MOS)	Brito et al. (2020)
Cacao shells	48.1	--	9.5	Polyphenols (catechin, epicatechin, and isoquercetin), flavonoids, tannins	Delgado-Ospina et al. (2021)
Cacao pod husk	35-37	--	5-17		
Carrot pomace	63.5	13.4	--	--	Chau, Chen, and Lee (2004)
	83.9	22.7	--	--	Kırbaş, Kumcuoglu, and Tavman (2019)
	--	--	0.22-0.32	β-carotene; chlorogenic acid, caffeic acid, catechin and epicatechin	Jabbar et al., 2014
Garlic husk	62.2	4.2	12-25	Hydroxybenzoic, *p*-coumaric, coumaroylquinic acids; flavonoids	Kallel et al. (2014)
Olive pomace	35	5.8	37.6	Lutein, luteolin, oleuropein, hydroxytyrosol and tyrosol derivatives, caffeic acid, verbascoside	Balli, Cecchi, Innocenti, Bellumori, and Mulinacci (2021); Sinrod et al. (2019)
Onions - Brown skin	75	5-8	53	Quecetin and isorhamnetin glycosides	Benítez et al. (2011)
- Outer scales	22-31	4-6	20	S-alk(en)yl-L-cysteine sulphoxides	
- Top+bottom	45-67	9	30	fructooligosaccharides (FOS)	
Pea pods	47.3	4.0	4.2	--	Mateos-Aparicio, Redondo-Cuenca, and Villanueva-Suárez (2012)
Broad beans pods	33.7	8.8	30.8	Flavan-3-ols (catechin, epicatechin), flavones (apigenin derivatives) and flavonols (glycosides of quercetin and kaempferol)	Mejri et al. (2018)
Potato peels	28.4-29.7	9.2-10.1	--	--	Jeddou et al. (2017)
	--	--	7.9-8.5	Chlorogenic, caffeic, ferulic and *p*-coumaric acids; glycoalkaloids (α-chaconine, α-solanine), anthocyanins	Albishi, John, Al-Khalifa, and Shahidi (2013); Sampaio et al. (2020)
Tomato pomace	59.9	4.9	4.3	--	Isik and Topkaya (2016)
	--	--	--	Lycopene and β-carotene, vitamin C, quercetin, naringenin, chlorogenic acid, rutin	Yagci, Calıskan, Gunes, Capanoglu, and Tomas (2022)

Apple pomace	65 42	20 --	-- 7.0	Benzoic acids (gallic acid), hydroxycinnamic acids (chlorogenic acid), flavanols (catechin), flavonols (rutin) and chalcones (phloridzin); triterpenic acids (ursolic and oleanolic)	Grigoras, Destandau, Fougère, and Elfakir (2013); Kırbaş et al. (2019); Zlatanović et al. (2019)
Banana peels	11.2	--	29.2	Flavonol glycosides, flavan-3-ols, proanthocyanidins	Eshak (2016); Rebello et al. (2014)
Cherry pomace	37.6	4.2	--	--	Wang et al. (2017)
			14.2	Cyanidin-3-glucosylrutinoside, cyanidin-3-glucoside, cyanidin-3-rutinoside; neochlorogenic acid, catechin, caffeic acid, ferulic acid and *p*-coumaric acid	Yılmaz, Karaaslan, and Vardin (2015)
Cranberry pomace	65.5	5.7	--	Cyanidins, peonidins, myricetins, quercetins, procyanidins (from monomers to nonomers)	White, Howard, and Prior (2010a)
Grape pomace	57.2	5.5	47.6	Flavonols (quercetin derivatives), flavan-3-ols, several anthocyanins and stilbenes	Zhang et al. (2017)
	40	--	2.8	Flavonoids (quercetin, kaempferol), anthocyanins (delphinidin-3-*O*-glucoside, petunidin-3-*O*-glucoside, peonidin-3-*O*-glucoside, malvidin-3-*O*-glucoside (oenin), malvidin-3-*O*(6-*O*-*p*-coumaroyl)glucoside	Balli et al. (2021)
Grape skins (white) Grape skins (red)	17 - 28 51 - 56	0.72-0.84 0.81-1.7	11.6 - 15.8 21.4 - 26.7	Flavanols, proanthocyanidins Anthocyanins, flavanols, proanthocyanidins	Deng, Penner, and Zhao (2011)
Ripe mango peels	64-78	24-28	55-100	Polyphenols, carotenoids, vitamin E and vitamin C	Ajila, Bhat, and Prasada-Rao (2007)
Passion fruit peels	50.8	14.9	--	--	dos Santos et al. (2015)
Pineapple crowns	67	8.7	--	Maltooligosaccharides (MOS)	Brito et al. (2020)
Pineapple peels	8.2	1.4	3.0	Gallic, chlorogenic, cryptochlorogenic, *p*-hydroxybenzoic, 2,5-dihydroxybenzoic, caffeic, and ferulic acids; hydroxytyrosol, syringaldehyde	Campos, Ribeiro, Teixeira, Pastrana, and Pintado (2020)
Wheat flour[b]	2.7-3.4	~0.9	0.03 0.04-0.14	Lutein	USDA (2019) Žilić, Serpen, Akıllıoğlu, Janković, and Gökmen (2012) Vaher, Matso, Levandi, Helmja, and Kaljurand (2010)
Whole wheat flour[c]	8.9-11.4	~3.2	~1.3 0.27-0.46	Ferulic acid, flavonoids, lutein	USDA (2019) Žilić et al. (2012) Vaher et al. (2010)
Rice flour[d]	0.2-0.6	tr.	0-0.1		USDA (2019)

				Phenolic acids (ferulic, *p*-coumaric, sinapinic acids)	Gunaratne, Bentota, Cai, Collado, and Corke (2011) Zhu, Cai, Bao, and Corke (2010)
Whole rice flour[e]	~1.9	tr.	0.2-1		Englyst, Bingham, Runswick, Collinson, and Cummings (1989); Gunaratne et al. (2011)
Corn flour[f]	1.9	--	0.08-1.10	Phenolic acids, flavonoids	USDA (2019)
Whole corn flour[g]	7.3	--			Alcântara et al. (2020); Nikolić et al. (2019)

[a]All values on dry matter basis (DM); [b]Flour, wheat, all-purpose, unenriched, unbleached; [c]Flour, whole wheat, unenriched; [d]Flour, rice, white, unenriched; [e]Flour, rice, brown; [f]Corn flour, yellow, degermed, unenriched; [g] Corn flour, whole-grain, yellow. TDF, total dietary fibre; SDF, soluble dietary fibre; TPC, total phenolic compounds, GAE, gallic acid equivalents; -- data not available.

Table 3 – Typical extrusion temperatures, moisture feed and reported drying conditions for post-extrusion treatment of cereal extrudates containing fruit and vegetable by-products flours.

Samples	Extrusion temperature profiles[a,b]	Moisture content (g/100 g)	Drying conditions	References
Barley flour extrudates supplemented with grape or tomato pomaces	30 | 60 | 100 | 130 | 133 to 167 °C (die)	22	Forced-air drier at 52 °C overnight	Altan et al. (2008); Altan, McCarthy, and Maskan (2009a, 2009b)
Barley flour extrudates supplemented with carrot pomace	120 | 145 | 170 °C	14, 17, 20	--	Shirazi et al. (2020)
Corn breakfast cereals enriched with whole peach palm flour	70 | 100 | 130 | 150 °C	15-23	Continuous rotary dryer at 125 °C (until moisture was lower than 7%)	Santos et al. (2020)
Corn extrudates supplemented with apple pomace flour	75 | 75 | 75 | 90 | 110 °C	No moisture feed	Dual pass dryer at 115 °C for 18 min, with a 7 min cooling step	Karkle et al. (2012)
Corn extrudates supplemented with dehydrated naranjita bagasse	75 | 89.9 to 140.2 | 75 °C	21-33	Under ventilation and controlled temperature (25 °C) for 3 days or moisture 8–12%	Ruiz-Armenta et al. (2018)
Corn extrudates supplemented with mango peel powder	100 | 75 to 175 | 75 to 175 °C	16-22	Air oven at 105 °C for 2 hours until it reached 1.5% moisture content	Mazlan et al. (2019)
Corn extrudates supplemented with pineapple pomace flour	80 | 90 | 140/160 °C	14, 15, 16	Drier at 100 °C for 10 min	Selani et al. (2014)
Corn extrudates supplemented with rosehip or apple pomace powders	130 | 150 | 180 °C	No moisture feed	Air dryer at 25 °C for 48 hours	Drożdż et al. (2014)
Corn-rice extrudates supplemented with tomato by-products flours	30 | 60 | 100 | 140 °C	14	Hot air oven at 50°C until moisture ≤ 4-5%	Karthika, Kuriakose, Krishnan, Choudhary, and Rawson (2016)
Corn starch extrudates supplemented with carrot pomace flour	50 | 100 | 140 | 140 °C	15, 22.5, 30	Convection oven at 45 °C for 18 h	Kaisangsri et al. (2016)
Corn starch extrudates supplemented with cherry pomace	RT[c] | 50 | 100 | 140 | 140 °C	15.5	Convection oven at 45 °C for 18 h	Wang et al. (2017)
Corn starch extrudates supplemented with cranberry pomace	80 | 150/170/190 °C	30	No drying step	White et al. (2010b)
Corn-whole grain wheat extruded breakfast cereals enriched with jabuticaba peel powder	75 | 100 | 100 | 100 °C	16	Drying to 3-4% moisture content	Oliveira et al. (2018)
Extruded breakfast cereals composed by broken rice grains, whey powder, and passion fruit peel flour	40 | 60 | 80 °C	No moisture feed	Oven with circulating air at 80 °C for 1 h	dos Santos et al. (2015)

Rice flour extrudates supplemented with carrot pomace	110 to 130 °C (die temperature)	18-21	Incubator at 60 °C for 12 h	Kumar et al. (2010)
Sorghum flour extrudates supplemented with blueberry juice pomace	160/180/200 °C	No moisture feed	No drying step	Khanal, Howard, Brownmiller, and Prior (2009)
Starch-based extrudates supplemented with apple pomace and other ingredients	~25 °C (through the barrel, supercritical fluid extrusion)	24	Forced air oven at 90 °C to ~5–8% moisture content	Paraman et al. (2015)
Wheat flour-based snacks supplemented with cauliflower by-products	80 | 120 °C	9-11	No drying step	Stojceska et al. (2008)

[a] From the feed zone towards the die; [b] Each temperature corresponds to each individual heating point through the barrel; [c] RT – room temperature; (--) information not provided.

1 Table 4 – Studied extrusion variables *versus* relevant effects on bioactive compounds, technological properties, and sensory quality of the final product.

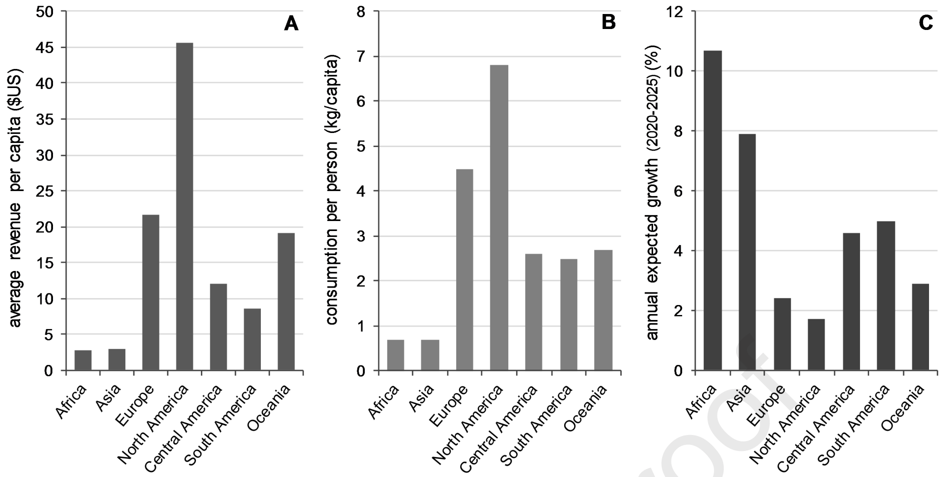
Mixture flours	**Extrusion variables**	**Optimal conditions**	**Relevant results**[a]	**References**
Chickpea + corn + oat + corn starch + carrot + hazelnut	Temperature: 110 °C Screw speed: 220-340 rpm Moisture content: 11-15% By-product content: 10%	Not determined	Antioxidant activity decreased at higher screw speeds, lower moisture content of the feed and lower feed rates. Concentration of total phenolic compounds did not change.	O˝zer et al. (2006)
Barley + tomato pomace	Temperature: 133-160 °C Screw speed: 133-217 rpm Moisture content: 21-22% By-product content: 0, 2, 6, 10, 13%	Not determined	BD, EI and WAI decreased when temperature was increased. Increasing the FVB content decreased WAI and EI but increased BD and product hardness. Decreasing die temperature and/or screw speed increased the product hardness. Sensory quality (colour, texture and flavour) increased with FVB flour content.	Altan et al. (2008)
Wheat flour-based snacks supplemented with cauliflower by-products	Temperature: 120 °C Screw speed: 250-350 rpm Moisture content: 9-11% By-product content: 5, 10, 15, 20%	Not determined	FVB flour decreased EI and WAI and increased BD. Extrusion increased TPC and antioxidant activity.	Stojceska et al. (2008)
Barley + tomato or grape pomace	Temperature: 133-167 °C Screw speed: 133-217 rpm Moisture content: 22% By-product content: 0, 2, 6, 10, 13%	Not determined	WAI decreased with increasing both die temperature and pomace level. Increasing screw speed decreased WAI at low pomace level but increased it at high-pomace level. WSI first increased with increase in temperature up to 150 °C and then decreased. Increasing level of pomace increased WSI. Extrusion decreased antioxidant activity, TPC, and β-glucan content of the extrudates. Increasing levels of FVB flours decreased starch digestibility and increased antioxidant activity.	Altan et al. (2009a, 2009b)
Sorghum + grape by-products	Temperature: 90-190 °C Screw speed: 100-200 rpm Moisture content: 45% By-product content: 30%	Not determined	Extrusion decreased anthocyanins content and increased procyanidin monomer and dimers.	Khanal, Howard, and Prior (2009)
Rice + durum clear + hazelnut + FVB flour [80% orange peel + 10% grape seed + 10% tomato pomace] + sucrose	Temperature: 150-175 °C Screw speed: 200-280 rpm Moisture content: 12-18% By-product content: 3-7%	By-product content: 5-7%	Extrudates with good overall sensory acceptability. Decreasing the temperature or Increasing the moisture content increased EI but showed no effect on hardness. Hardness and crispness were higher for intermediate FVB levels.	Yağci and Göğüş (2009)
Rice + carrot pomace	Temperature: 115-135 °C Screw speed: 270-310 rpm	Temperature: 114 °C Screw speed: 294 rpm	EI increased and BD decreased with the increase in screw speed or die temperature. BD initially increased with FVB proportion and	Kumar et al. (2010)

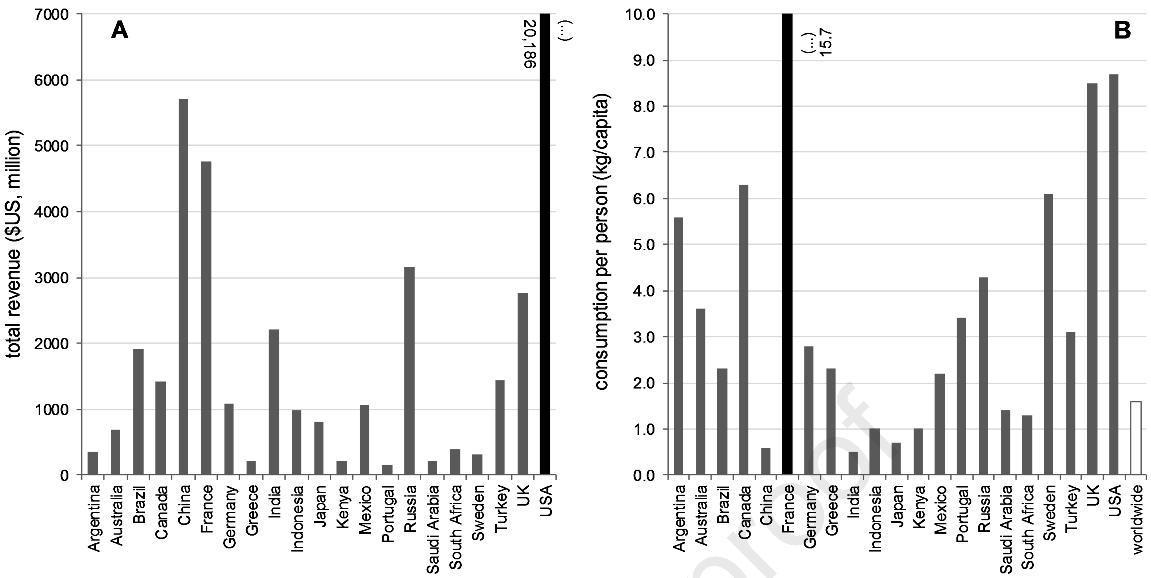
	Moisture content: 18-21% By-product content: 10-30%	Moisture content: 20% By-product content: 12%	then decreased, whereas BD initially decreased with moisture content and then increased. Complex effects of other extrusion parameters on WAI, WSI and hardness. FVB flour increased WAI and decreased WSI, EI and hardness. Sensory quality increased with FVB flour and moisture contents.	
Corn starch + cranberry pomace	Temperature: 190 °C Screw speed: 150-200 rpm Moisture content: 30% By-product content: 30, 40, 50%	Not determined	Extrusion decreased anthocyanin content, but increased flavonols and antioxidant activity. Increased procyanidin monomers and dimers and decreased procyanidin trimers and oligomers. Screw speed had no effect.	White et al. (2010)
Cornmeal + pregelatinized corn starch + apple pomace	Temperature: -- Screw speed: 300 rpm Moisture content: -- By-product content: 0, 17, 22, 28%	--	FVB flour decreased EI and cell size, and increased BD, cell wall thickness and hardness.	Karkle et al. (2012)
Rice + red gram + pineapple waste pulp	Temperature: 120-140 °C Screw speed: 260-340 rpm Moisture content: 16-21% By-product content: 12.5%	Temperature: 132.3 °C Screw speed: 315 rpm Moisture content: 18.5 %	Increasing barrel temperature increased EI, hardness, and WAI, and decreased BD and WSI. Increasing in screw speed resulted in higher EI, lower BD and hardness. Increasing level of moisture decreased EI, BD and hardness, and resulted in higher overall acceptability.	Kothakota et al. (2013)
Rice + Pulse + carrot pomace	Temperature: 120-180 °C Screw speed: 300-500 rpm Moisture content: 14-20% By-product content: 10%	Die temperature: 120 °C Screw speed: 394 rpm Moisture content: 14% By-product content: 10%	Feed moisture and screw speed were the most significant effect variables on all the responses. EI increased with screw speed while BD decreased with the increase of screw speed and increased with feed moisture. WAI decreased with increase in feed moisture. WSI and hardness increased as screw speed and die temperature increased but decreased with increasing feed moisture.	Alam and Kumar (2014)
Rice + Carrot pomace	Temperature: 110-140 °C Screw speed: 310 rpm Moisture content: 19% By-product content: 16.5%	Not determined	Temperature affected sensory parameters (colour, hardness and crispiness) and decreased bioactive compounds content. Increasing temperature affected extrudates' color and decreased crispiness and β-carotene and vitamin C contents.	Dar et al. (2014a)
Corn + apple or roseship pomace	Temperature: 180 °C Screw speed: 180 rpm Moisture content: -- By-product content: 0, 10, 15, 20%	Not determined.	FVB flours increased TPC, antioxidant activity and decreased sensory quality (shape, size, structure, taste and smell).	Drożdż et al. (2014)
Corn + apple pomace	Temperature: 150-200 °C Screw speed: 60-100 rpm Moisture content: 10.5% By-product content: 0, 5, 7.5, 10%	Temperature: 150 °C Screw speed: 69 rpm Moisture content: -- By-product content: 7.7%	EI decreased by increasing screw speed, die temperature or FVB content. BD decreased by increasing screw speed. Porosity decreased as the screw speed or temperature increased. Increasing apple pomace addition significantly decreased hardness.	O'Shea et al. (2014)

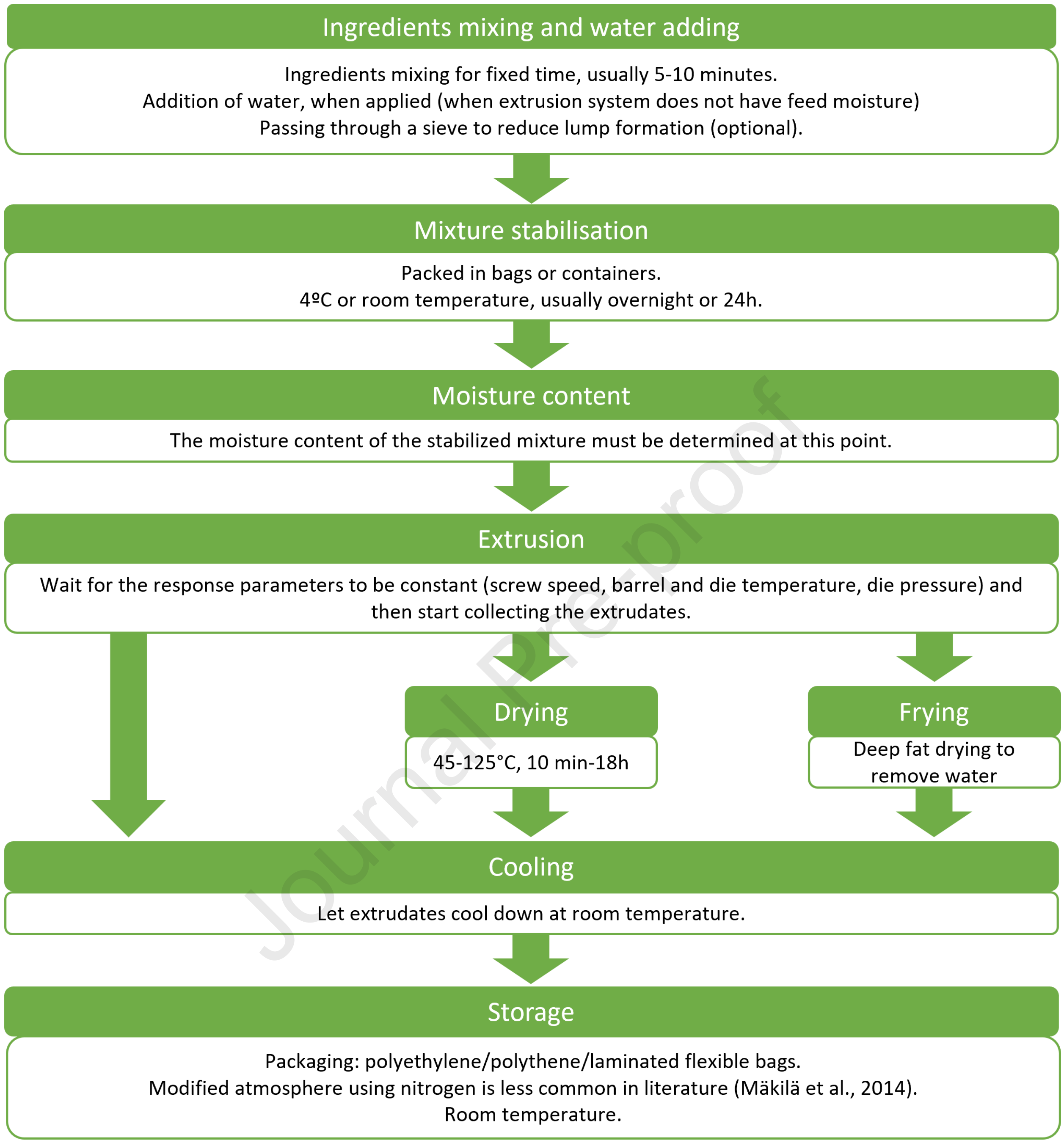
Corn + pineapple whole fruit flour	Temperature: 140-160 °C Screw speed: 220 rpm Moisture content: 14, 15 and 16% By-product content: 10.5 and 21%	Not determined	Increasing FVB flour content decreased EI and WSI and increased BD. Moisture and temperature increased WAI.	Selani et al. (2014)
Pregelatinized corn starch + apple pomace + lecithin + distilled monoglycerides	Temperature: 86 °C Screw speed: 100 rpm Moisture content: 24% By-product content: 0, 22%	Not determined	FVB flour increased TDF, protein, fat, TPC and antioxidants content. Decreased EI and hardness, and increased BD and compressive modulus.	Paraman et al. (2015)
Rice + passion fruit peels + whey protein	Temperature: 80 °C Screw speed: 177 rpm Moisture content: 13% By-product content: 0-3%	Not determined	Addition of passion fruit peels increased ash content and TDF (especially insoluble fiber), and decreased EI and WSI of the final product.	dos Santos et al. (2015)
Low-amylose rice + banana + carambola pomace	Temperature: 90-130 °C Screw speed: 200-400 rpm Moisture content: 9-21% By-product content: 10%	Temperature: 120 °C Screw speed: 350 rpm Moisture content: 12%	Hardness, puncture force and breaking strength decreased as moisture decreased and as barrel temperature increased. BD increased with feed moisture and decreased with the increase in barrel temperature or screw speed. Increase in screw speed and barrel temperature increased expansion. Sensory desirability decreased with decreased screw speed and temperature.	Borah et al. (2016)
Corn + carrot pomace	Temperature: 140 °C Screw speed: 100-250 rpm Moisture content: 15, 22.5, 30% By-product content: 5, 10, 15%	Not determined	Extrusion decreased β-carotene content. With increasing feed moisture or decreasing screw speed, expansion ratio and WSI decreased. At higher levels of moisture, the addition of carrot pomace decreased expansion ratio significantly.	Kaisangsri et al. (2016)
Corn + rice + tomato peel + tomato seed	Temperature: 140 °C Screw speed: 300 rpm Moisture content: 14% By-product content: 0-30%	Not determined	Addition of FVB increased TDF and reduced EI, and affected color, mainly increasing *redness*. Sensory analysis revealed that products were still acceptable with added tomato pomace up to 30%.	Karthika et al. (2016)
Brown rice + pomelo peel	Temperature: 180 °C Screw speed: 200 rpm Moisture content: -- By-product content: 5, 10, 15%	Not determined	FVB flour increased TPC and antioxidant activity of samples. FVB flour decreased EI.	Shi et al. (2017)
Corn + cherry pomace	Temperature: 140 °C Screw speed: 150-250 rpm Moisture content: 15.5% By-product content: 0, 5, 15%	Not determined	FVB flour increased TPC. Extrusion did not affect TPC. Adding cherry pomace significantly decreased WAI and WSI, with smaller particles leading to higher WSI, only decreasing EI at 15% level.	Wang et al. (2017)

Corn + jabuticaba peel	Temperature: 100 °C Screw speed: 325 rpm Moisture content: 16% By-product content: 0, 10%	--	FVB flour increased EI, WSI, crispiness and sensory attributes, and decreased BD and hardness.	Oliveira et al. (2018)
Corn + calamondin bagasse	Temperature: 89.9 °C to 140.2 °C Screw speed: 75 rpm Moisture content: 21-33% By-product content: 1-12%	Temperature: 125 °C Moisture content: 23% By-product content: 8.0%	Highest hardness obtained for low temperatures (<100°C) combined with levels of moisture within the range 21-28%, a response that showed an inverse correlation with EI. EI increased with temperature especially at the lowest moisture content and decreased with fruit bagasse amount. Adding the fruit bagasse increased the carotenoid content of the snacks.	Ruiz-Armenta et al. (2018)
Corn + soy + apple pomace	Temperature: 100-140 °C Screw speed: 100-200 rpm Moisture content: 14-20% By-product content: 0, 5, 10, 15, 20%	Temperature: 140 °C Screw speed: 200 rpm Moisture content: 20% By-product content: --	FVB flour increased BD, TPC and antioxidant activity. Moisture had quadratic influence on WAI and WSI.	Singha and Muthukumarappan (2018)
Corn + mango peels	Temperature: 75-175 °C Screw speed: 76-100 rpm Moisture content: 15.5-21.5% By-product content: 8-33%	Temperature: 144°C Screw speed: 100 rpm Moisture content: 17% By-product content: 17.1%	Increasing moisture and mango peel content decreased EI and increased hardness of extrudates. EI increased as barrel temperature and screw speed increased. Increasing barrel temperature decreased hardness. Post-drying improved the texture.	Mazlan et al. (2019)
Rice + passion fruit peels + whey protein	Temperature: 60-110 °C Screw speed: 250 rpm Moisture content: 10-20% By-product content: 3%	Temperature: 85 °C Moisture content: 15%	38% of consumers had "would probably buy" purchase intention. 13% of consumers had "would certainly buy" purchase intention. Low scores for texture and taste.	dos Santos et al. (2019)
Corn + peach palm	Temperature: 150 °C Screw speed: 180 rpm Moisture content: 15-23% By-product content: 0-50%	Not determined	Decreasing feed moisture resulted in higher expansion and lower hardness. Increasing peach palm flour content decreased WAI, decreased digestible carbohydrates content, increased fat, TDF and carotenoids content.	Santos et al. (2020)
Barley + carrot pomace	Temperature: 120, 145, 170 °C Screw speed: 160 rpm Moisture content: 14, 17, 20% By-product content: 10, 17.5, 25%	Temperature: 143 °C Moisture content: 14% By-product content: 10%	Increasing feed moisture increased hardness and decreased EI. Increasing die temperature decreased hardness, while the expansion ratio increased with increasing the die temperature to up to 145 °C and then decreased. Increasing the carrot pomace content decreased EI and increased hardness. Adding carrot pomace increased soluble dietary fiber.	Shirazi et al. (2020)

[a]Abbreviations used: BD, bulk density; EI, expansion index; FVB, fruit and vegetable by-product; TDF, total dietary fibre; TPC, total phenolic content; TFC, total flavonoids content; WAI, water absorption index; WHC, water holding capacity; WSI, water solubility index. (--) information not provided.


A
average revenue per capita ($US)
50
45
40
35
30
25
20
15
10
5
0
Africa
Asia
Europe
North America
Central America
South America
Oceania
B
consumption per person (kg/capita)
8
7
6
5
4
3
2
1
0
Africa
Asia
Europe
North America
Central America
South America
Oceania
C
annual expected growth (2020-2025) (%)
12
10
8
6
4
2
0
Africa
Asia
Europe
North America
Central America
South America
Oceania


A
total revenue ($US, million)
7000
6000
5000
4000
3000
2000
1000
0
20,186
(…)
Argentina
Australia
Brazil
Canada
China
France
Germany
Greece
India
Indonesia
Japan
Kenya
Mexico
Portugal
Russia
Saudi Arabia
South Africa
Sweden
Turkey
UK
USA
B
consumption per person (kg/capita)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
(…)
15.7
worldwide


Ingredients mixing and water adding
Ingredients mixing for fixed time, usually 5-10 minutes.
Addition of water, when applied (when extrusion system does not have feed moisture)
Passing through a sieve to reduce lump formation (optional).
Mixture stabilisation
Packed in bags or containers.
4ºC or room temperature, usually overnight or 24h.
Moisture content
The moisture content of the stabilized mixture must be determined at this point.
Extrusion
Wait for the response parameters to be constant (screw speed, barrel and die temperature, die pressure) and then start collecting the extrudates.
Drying
45-125°C, 10 min-18h
Frying
Deep fat drying to remove water
Cooling
Let extrudates cool down at room temperature.
Storage
Packaging: polyethylene/polythene/laminated flexible bags.
Modified atmosphere using nitrogen is less common in literature (Mäkilä et al., 2014).
Room temperature.

Nutritional and functional improvement of extruded breakfast cereals based on incorporation of fruit and vegetable by-products - a review

Diva Santos, Manuela Pintado and José A. Lopes da Silva

Highlights

- Food supplementation with fruit and vegetable by-products (FVB) is increasing.
- Breakfast cereals products (BCP) richer in fibre and bioactive compounds can be achieved.
- Incorporation of FVB could lead to BCP with enhanced functional properties.
- Existing challenges regarding texture and consumer acceptance are reviewed and discussed.
- Valorisation of FVB will contribute to a more sustainable food system.