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REVIEW ARTICLE

Cereal by-products as an important functional ingredient: effect of processing

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Abstract Cereal is a staple food and major nutrition source throughout the world. The cereal bran obtained from milling as by-product contains multiple benefits and health-promoting components such as dietary fiber, minerals, vitamins, polyphenols, and phytosterols. However, these by-products are usually undervalued and used in animal feed. To increase the functional and food value, processing techniques linked to improving nutritional characteristics, sensory properties and reducing the inhibitory factors have been developed. These processing techniques include mechanical, enzymatic and thermal processing. It aims to improve the functional properties, enhance the extractability of beneficial food ingredients, reduce the complex structure of the bran and improve solubility, decrease the content of inhibitory factors and improve the bio-accessibility of micronutrients. This review highlights the various technological interventions and application of appropriate processing techniques to process cereal bran for the isolation of functional food ingredient and thus utilizing the nutritious by-product of cereal processing industry.

Keywords By-products · Processing · Functional properties, food ingredients

Introduction

Cereal is a member of the grass family (Gramineae) cultivated for the edible components of its grain or the kernel. Strictly speaking, it is a caryopsis which is composed of the fruit coat (pericarp) and a seed. The fruit coat adheres tightly to the seed coat surrounding the remainder of the seed consisting of germ and endosperm. The aleurone layer lies next to the pericarp. This layer is rich in protein and minerals. The endosperm is the large central portion of the kernel made up mostly of starch, and the germ/embryo is the small structure at the lower end of the kernel (Delcour and Hoseney 2010).

There are many different types of cereals grown worldwide, each sharing some structural similarities. It is grown in large quantities due to its importance as an economic commodity and providing food and energy worldwide more than any other type of crop. Due to this, cereal grains are also known as staple crops. Not only cereal processing forms a large and important part of the food production chain, they provide versatile and essential nutrients to numerous populations. Cereal grains are easy to store once their enzymatic activity is in check and may be used to produce a myriad of food products (Tsadik and Emire 2015; Amadou et al. 2013).

Cereal grains are usually milled to remove the fibrous bran, during milling, bran which is separated from the starchy endosperm of the grain is a major by-product. Although the micronutrients are generally present in higher concentrations in the outer part of the grain it is often undervalued and used as animal feed (Slavin et al. 2001; Hemery et al. 2011a). The term "bran" is usually applied to the outer layers of the grain and its composition depends widely on the grain type, kernel size, shape, and maturity, size of the germ, thickness of the pericarp, duration and

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condition of grain storage, conditioning process of the grain before milling, during milling and the milling machinery used (Alan et al. 2012; Zitterman 2003). In wheat grain milling, the bran obtained is about 15% with composite multi-layered materials like outer and inner pericarp, testa, hyaline layer, aleurone layer and part of starchy endosperm residue (Hemery et al. 2011a, b) and in barley the milling by-product yield is approximately 30–40% (Marconi et al. 2000). However, various studies show the utilization of cereal bran in food products, the level of incorporating the bran as such is very low (5–10%) due to the negative effects on overall acceptability of the product. The world production of rice bran is increasing annually but only part of the production is employed to extract rice bran oil or utilized in animal feed only an insignificant amount is used as food additives. Similarly, ragi seed coat is underutilized milling by-products and its extract has potential application as health-promoting ingredients in functional foods. With the increasing concern about the safety of synthetic antioxidant usage, natural antioxidants from plant extracts as an alternative has become a rage. Consequently, rice bran extract has been proven as an effective natural preservative in various food systems (Min et al. 2011). Likewise, other valuable food ingredients with specific health benefits are also abundantly present in the by-product of cereal industry which can be extracted from a low-cost material. Hence, the present review focuses on some of the potential food ingredients present naturally in cereal bran and the various technological treatments that are employed to enhance the functional properties and reduce the inhibitory factors.

Food ingredients from cereal by-products and their benefits

Cereal bran is a nutritional storehouse of the grains. The Chemical composition of cereal bran is highly complex and the multiple beneficial effects of cereal bran could be exploited by incorporating into the daily diet (Charalampopoulos et al. 2002). Besides regular nutrients like protein, vitamins, minerals, and fats, it contains many bioactive compounds such as dietary fiber, phytosterols, polyphenols and phenolic acids which may provide a wide spectrum of biological activities and other health benefits as seen among populations consuming diets based on cereal grains (Patel 2012; McKevith 2004). Functional foods and functional food ingredients are flourishing in the market due to consumers demand for healthier foods. The health benefits associated with dietary fiber from cereal bran is resulting in it being used virtually in all types of food products (Gualberto et al. 1997). However, selecting a good source becomes complicated due to their varied physicochemical properties (Rosell et al. 2009).

Dietary fiber

Dietary fiber is one of the major phytochemicals present in cereal bran. The substantial research carried out over the last three decades supports the beneficial role of dietary fiber in human health (Rosell et al. 2009). Dietary fiber can be divided into two categories based on its water solubility-soluble fiber and insoluble fiber. Soluble fibre has high water holding capacity, high viscosity and property to reduce glycemic response and plasma cholesterol, it has the ability to form gels and/or act as emulsifiers, has neither bad texture nor bad taste and is easy to incorporate into processed foods and drink without affecting the overall sensory quality of the product. Good source of soluble fibers is marine algae, fruits, vegetables, cereal bran (especially oats and barley), psyllium seeds, legumes etc. The water-soluble fraction of the dietary fiber consists mainly of non-starch polysaccharides like beta-glucans and Arabinoxylan or pentosans (Sidhu et al. 2007; Elleuch et al. 2011; Sharif et al. 2013). Another important industrial by-product is Brewers' spent grain (BSG) a by-product of the brewing industry, it is the solid fraction of barley malt left over after the production of wort. It has 20% protein and 70% dietary fiber (Stojceska et al. 2008).

Beta-glucans

The main focus of Beta-glucans in the diet has been on the attenuation of the postprandial blood glucose and insulin, and the ability to lower blood lipids, especially serum total and LDL-cholesterol, assuming that both these effects have long-term health benefits (Wood 2007). Beta-glucans are the predominant components of cell walls of cereal grains such as barley and oats (Brennan and Clearly 2005). It is a linear unbranched polymer molecule containing the β-(1–4) and (1–3) linkages units of glucopyranosyl. It is highly soluble and loses its regularity upon dissolving in water (Havrlentova et al. 2011; Sidhu et al. 2007; Liu 2007). The composition of (1–3, 1–4)-β-$_{\mathrm{D}}$-glucan or commonly referred to as β-glucan in cereal bran ranges from 1% in wheat, 3–7% in oats and 5–24% in barley (Skendi et al. 2003; Marconi et al. 2000). Barley β-glucans is reported to exhibit several health benefits such as reduction in blood cholesterol and glucose, maintaining the body weight by increasing the satiety value all of which helps in controlling heart disease and diabetes in the long run (Baik and Ullrich 2008). Soluble fiber is known to decrease, postprandial blood glucose, insulin and serum cholesterol levels in humans. Having said that, in a clinical study with oats extract, a beverage containing about 80% (dry weight basis) of β-glucan was used to study glycemic response to an oral glucose dose of 50 g. As the β-glucan level in the drink increased, the more desirable flattened response relative to the glucose control with β-glucan was observed (Wood 2002). In another study, barley β-glucans was evaluated in a trial in which hypercholesterolemic men (mean LDL 4.01 mmol/L) consumed varying amounts of soluble fiber (0·4, 3 and 6 g). Test foods contained brown rice/whole wheat (low soluble fiber), a half barley and a half brown rice/whole wheat (medium soluble fiber) or barley alone (high soluble fiber). Total and LDL-cholesterol values decreased in all three diets but were significantly lower in the high-soluble fiber diet. Mean LDL particle number was also recorded to be lowest in high-soluble fiber diet, reflecting a greater anti-atherogenic effect (Smith and Tucker 2011). The water solubility index of β-glucan is higher than its counterpart Arabinoxylan in barley and oats, forming a viscous solution. High molecular weight β-glucans (9000 Da) forms hard gel whereas lower molecular weight (0.4–2 million Da) forms a soft gel. Low molecular weight β-glucan can be obtained by subjecting the bran to enzymatic hydrolysis (Beer et al. 1997).

The Food and Drug Administration (FDA) claimed the daily effective dose of β-glucan for average cholesterol reduction is 3 g. Although a dose–response is not well established, the consumption of 3 g soluble fiber per day from either 3 apples or 3 bowls of oatmeal could decrease total cholesterol by ~ 2%. These data were obtained from 23 studies that had used > 10 g dietary fiber per day. The average cholesterol reduction from the study was 4.4%. It is noteworthy that the test samples used in the meta-analysis were intact whole oats and oat bran (Wood 2007).

Arabinoxylan

Arabinoxylan is a non-starch structural polysaccharide which forms part of the cell wall in grains. Arabinoxylans consists of a linear chain backbone of β-D-xylopyranosyl (Xylp) residues linked through (1–4) glycosidic linkages. The nutritional values of arabinoxylans have not been investigated to the same extent as those of β-glucans. However, recent studies revealed that it has positive effects on fecal fermentation, production of short-chain fatty acids, reduction of serum cholesterol and improved absorption of calcium and magnesium (Izydorczyk and Dexter 2008; Beliaderis 1995). The pre-eminent sources of arabinoxylans have been identified in the bran of the main cereals such as rye, barley, oat, wheat, rice, sorghum, and finger millet and other non-cereal sources like pangola grass, bamboo shoots and rye grass (Izydorczyk and Dexter 2008; Prashanth and Muralikrishna 2014).

It is reported that about 95% of grain phenolic compounds are linked to cell wall polysaccharides otherwise indicated as dietary fiber-phenolic compounds (DF-PC) where the phenolic compounds are covalently bound to polysaccharides through ester bonds. Ferulic acid is bound to the arabinoxylans via the acid group acetylating the primary hydroxyl at the C5 position of α-L arabinofuranose residues (Vitaglione et al. 2008). When different molecular weight arabinoxylans from cereal bran were used to study the effect of soluble polysaccharides on bread making quality, it was observed that the arabinoxylans maximally increased the loaf volume. On the other hand, due to their higher moisture content, the arabinoxylan-fortified bread exhibited a greater rate of starch retrogradation as assessed by calorimetry (Beliaderis 1995).

The physicochemical properties of arabinoxylans for example viscosity, gelation potential, intermolecular association, and conformation are dependent on the amount and molecular size. Structure–property relationships of arabinoxylans have been established in the model and actual food systems. Wheat and rye bran arabinoxylans exhibited as an important functional ingredient in baked products affecting the mechanical properties of dough, as well as the texture and other end-product quality characteristics (Izydorczyk and Dexter 2008).

Polyphenols

Polyphenols are a secondary metabolite of plant and frequently termed as phytochemicals that typically provide protection to plants against ultraviolet light, pathogens, and predators by acting as phytoalexins or by increasing the food astringency, thus making the food rather unpalatable. They also protect the grains from plague and preharvest seed germination (Manach et al. 2004; Cukelj et al. 2015). The chief reason for the interest in recognizing polyphenols as a functional food ingredient is because of the synergistic antioxidative action prevents numerous diseases associated with oxidative stress and neurodegenerative diseases, they possess nutraceutical potential as anti-inflammatory, anticarcinogenic, antimicrobial, anti-diarrheal, antiulcer, and anti-cardiovascular activity. This bioactive compound is mainly present in the outer layers of cereal bran (Sidhu et al. 2007; Gorinstein et al. 2007; Chandrasekara and Shahidi 2010). Besides, polyphenols are also useful in the managing of several physiological disorders such as diabetes mellitus, hypertension, hypercholesterolemia, prevention of oxidation of low-density lipoproteins (LDLs) and also improvement of overall gastrointestinal health (Banerjee et al. 2012).

Polyphenols may be classified into different groups as a function of the number of phenol rings that they contain and of the structural elements that bind these rings to one another. Divisions are thus made between the phenolic acids, flavonoids, stilbenes, and lignans (Manach et al. 2004; Sidhu et al. 2007). Phenolic acids and flavonoids are largely present in cereals in the free and conjugated forms, these compounds are most significantly found in the aleurone layer of the grains (Banerjee et al. 2012). Phenolic acids like ferulic acid from corn bran can be used as a natural source of vanillin production. It can be synthesized by chemical treatment (alkaline solution) where the feruloylated oligosaccharides convert into free ferulic acid and upon further enzyme treatment converts to vanillic acid and subsequently into vanillin (Piironen et al. 2009). Brewers' spent grain is also rich in phenolic compounds particularly ferulic acid and p-coumaric acid, it can be incorporated in bakery items and ready to ear snacks where the organoleptic properties are controlled (McCarthy et al. 2013).

Phytosterol

Phytosterols are a collective term for plant sterols and stanols, having a similar structure to cholesterol, differing only in the side chain groups (Liu 2007). Cereals are one of the main dietary sources of natural phytosterols and their conjugates like squalene, tocopherol, campesterol, sitosterol, and stigmasterol. Cereal grains such as rice, corn, wheat, and rye are a good source of phytosterols. This bioactive compound is accumulated in the bran and germ fraction of the grains (Jiang and Wang 2005; Nurmi et al. 2012). Many low valued cereal by-products contain a significant amount of phytosterols that could become potential sources of health-enhancing food ingredient (Jiang and Wang 2005; Wanyo et al. 2014).

The importance of phytosterols is based on their proven blood cholesterol-lowering ability and other suggested health benefits, e.g., anti-carcinogenic, anti-inflammatory, free radical scavenging activity etc. Phytosterols compete with cholesterol for micelle formation in the intestinal lumen and inhibit cholesterol absorption (Pradeep et al. 2014; Liu 2007). Plant sterols inhibit the biliary cholesterol absorption from the small intestine, which could be attributed to its superior solubility properties than cholesterol. The daily consumption requirement is not known but an essential daily intake of 1–2 g is recommended. A 6-week, randomized, double-blind, non-cross-over trial study showed that serum cholesterol was significantly decreased ($P \leq 0.05$) by 8.3 ± 2.4% and 13.0 ± 1.8% in groups consuming rice bran and oat bran respectively, but there was no change in the third group consuming rice starch (placebo) (Sidhu et al. 2007).

Micronutrients

Nutritional quality of food is a fundamental property in maintaining overall health. Because nutritional well-being is a sustainable force for health and development and maximization of human genetic potential (Saleh et al. 2013). Nutrients from cereal grains constitute the major source of dietary nutrients in the world. Millets like ragi, little millet, proso millets and pearl millet are unique among the cereals due to their richness in minerals and phytochemical content (Amadou et al. 2013; Ross et al. 2014). However, the bioavailability of divalent minerals such as iron, zinc, calcium, magnesium is low, because of the formation of an insoluble complex with food components such as phytic acid (Coulibaly et al. 2011). Phytic acid forms a stable phytate complex due to strong negative charges under gastrointestinal conditions inhibiting the activity of phytase enzymes. Sometimes phytic acid may also bind to proteins resulting in inhibition of α-amylase which in turn leads to decreased starch digestibility (Lee et al. 2015). But with right amount and method of processing this anti-nutritional activity could be reduced or prevented altogether. Bran fractions produced from milling which is composed of pericarp, aleurone, sub-aleurone layer and germ contains a substantial amount of nutrients like Vitamin E, thiamine, potassium, calcium, magnesium and iron. This brightens the prospects of utilization of these milling by-products as a functional ingredient for human consumption (Sharif et al. 2013; Gualberto et al. 1997).

Effect of processing on the functional food ingredient

Food value and functional value are the two important characteristics of food which improve the efficiency of market value in consumers (Aryee and Boye 2015). To increase the functional and food value of cereal bran, processing techniques linked to improving nutritional characteristics, sensory properties and convenience are developed. Several traditional household food processing and preparation methods similarly can be used to enhance the bioavailability of micronutrients and other phytochemicals from cereal bran. These processing techniques include thermal processing, mechanical processing, soaking, fermentation, and germination/malting. These techniques aim to increase the physicochemical accessibility of micronutrients, decrease the content of anti-nutrients, such as phytates and increase the content of compounds that improve bioavailability (Saleh et al. 2013; McKevith 2004; Amadou et al. 2013).

Milling

Milling can be principally described as grinding, sifting, separation, and regrinding. These steps are repeated to extract particular parts of the grain like endosperm and obtain bran as a by-product. Fiber, Vitamins, and minerals are mostly concentrated in the outer bran and aleurone layers of the grain, so final nutrient content will depend on the extent to which these layers were removed during processing (McKevith 2004). In the current scenario of rice milling technology, rice bran from different layers of the kernel caryopsis can be removed and phytochemical contents of each of these fractions can vary widely, for example, the γ-oryzanol concentration was seen highest in the outer bran layer (Lerma-García et al. 2009). The effects of milling on nutritional contents of millet grains and their milling fractions have been studied by a number of researchers. In one study, milling of pearl millet grains was found to reflect a change in gross chemical composition (Saleh et al. 2013).

Fractionation of the grain during milling rather than the milling process itself is important from a nutritional perspective (MacEvilly 2003). Wheat and corn milling by-products released from milling industry was processed using ball milling technique which reduced the particle size and improved the solubility of the bran fiber by rapidly inducing fractures in the cell wall of aleurone layer. Extensive laboratory scale ball milling treatment increased the untreated wheat bran water extractable arabinoxylans from 4 to 61% of the treated wheat bran arabinoxylans. This bran fraction was incorporated in bakery item as a value-added product as well as tea substitute (Tsadik and Emire 2015; Schramm et al. 2007; Alan et al. 2012).

Fractionation

Different layers of wheat bran and rice bran exhibit various health-promoting compounds. These layers of bran could be fractionated into purified fractions, undesirable to desirable, which can either be used as a food ingredient by including in human food products or contribute as starting material for additional processing and extraction of bioactive compounds (Hemery et al. 2011a). Fractionation process can be carried in many ways like dry, wet and micro-fractionation. Dry-fractionation processes have been developed to enhance the usage of all the different parts of the wheat grain (Gul et al. 2015; Hemery et al. 2007) and corn (Thakur et al. 2015). Debranning by dry fractionation allows the removal of the most peripheral bran layers before milling, and to obtain bran rich in aleurone layer. This promising process has successfully been used to produce aleurone-rich fractions from medium-ground wheat bran but at very low yields (5–10%) (Bohm et al. 2003; Stone and Minifie 1988). Not only removal of bran but the dry milling of corn to obtain the different fractions in three corn types by Thakur et al. (2015) revealed that there are changes in both the physical and chemical compositions at different reduction stages which allows the fractions to find a place of application in the food industry be it flour, flakes or extruded products. In the near future, dry fractionation processes could be improved to produce higher yields of wheat bran fractions displaying higher phytochemical composition (Hemery et al. 2011a). On the other hand, supercritical carbon dioxide fractionation is also used and has been reported to be effective than dry fractionation and wet fractionation processes (Gul et al. 2015).

The application of micro-fractionation in food research revealed that the reduction of the particle size of various fiber-rich plant materials modifies the structure, surface area and functional properties of the particles. Chau et al. (2007) and Wu et al. (2007) hypothesized that subjecting plant insoluble fibre to different treatments like ball milling, jet milling, high-pressure micronization resulted in the rearrangement of fibres from insoluble to a soluble form, which improved their physicochemical properties and put forth a favourable effect on improving intestinal function and general health as seen in in vivo studies.

Rice bran fractionation by successive sieving on the basis of particle size can improve the quality of the crude rice bran which allows for the selective use of portions of the bran layer containing a higher amount of components of interest with respect to the overall bran layer average and least processing of bran required to obtain those components. The result from a study showed that oryzanol (32.3%) and protein (1381 ± 0.47–1515 ± 0.38 mg/100 g) were found to be highest in the outer portion of the rice bran layer also known as fibrous bran, while rice bran polysaccharide components (61.5 ± 0.01–90.2 ± 0.35 mg/100 g) was found to be the highest in the inner portion of the bran layer. The bran obtained from long grain rice varieties subjected to polishing for 10 s each was reported to contain a higher concentration of vitamin E (21.82 ± 18.62–22.99 ± 8.39 mg/100 g) and oryzanol (184.6 ± 248.32–251.62 ± 255.61 mg/100 g) (Bhatnagar et al. 2014; Schramm et al. 2007) (Table 1).

Fermentation and enzymatic treatment

Fermentation is a common traditional method of food preservation where modern preservation method is seldom used. It helps to preserve many food products, provides a wide variety of flavors, and significantly improves the nutritional properties of the raw material. Fermentation and enzymatic hydrolysis are promising techniques that can be used as single or in combination with other techniques

Table 1 Processing techniques to improve nutritional characteristics, sensory properties, and convenience of cereal by-products

Processing technique	Improvement/benefit	References
Fractionation by milling		
(i) Dry fractionation (ultra-fine grinding)	Decrease in particle size (40 µm) improves the nutritional potential by increasing the solubility or release of bioactive compounds	Hemery et al. (2011a), Bohm et al. (2003), Stone and Minifie (1988), Schramm et al. (2007)
	Controlled milling time (10 s) improves the vitamin E and oryzanol concentration in rice bran by 22 and 31%	
(ii) Supercritical carbon dioxide fractionation	Improve shelf life of rice bran by reducing free fatty acids and prevents the loss of bioactive components in rice bran oil by 50%	Dunford and King (2000)
(iii) Micro fractionation and high pressure micronization	Change in physicochemical properties by redistribution of insoluble to soluble dietary fiber fractions and starch digestibility in wheat	McAllister and Sultana (2011), Wu et al. (2007), Chau et al. (2007)
Fermentation and enzymatic treatment	Provides optimum pH for enzymatic degradation of phytates and tannins thus increasing the soluble iron, zinc, and calcium several folds in millets. Reduction in polyphenols (11–22%) and Flavonoids (40–51%) in pearl millet bran	Coulibaly et al. (2011), Kohajdová and Karovičová (2007), Blandino et al. (2003), Jha et al. (2015)
	Improves in vitro starch digestibility (86%) by increasing soluble solids and the synthesis of certain amino acids and B vitamins in millets	Saleh et al. (2013), Delcour et al. 2012, McKevith (2004)
	Bioprocessing of wheat bran can produce cinnamoyl-oligosaccharides having potential prebiotic properties	Mussatto and Mancilha 2007, Charalampopoulos et al. (2002)
	The β-glucan from oat bran can selectively support the growth of lactobacilli and bifidobacteria	
Germination or malting	In vitro starch and protein digestibility improved by 14–26% and 86–112% respectively in different millets	Saleh et al. (2013)
	Increased extractability and bio-accessibility of calcium, iron, and zinc in finger millet seed coat was 68, 23, 75 g/100 g	Krishnan et al. (2012)
	Significant reduction in phytates (30–80%) and polyphenols (14–42%) and increased HCl extractable major and minor minerals during germination (2–6 days) in pearl millet	Abdelrahaman et al. (2007)
	Folate and easily extractable phenolic acids increased in rye bran	Liukkonen et al. (2003)
	Significant improvement in γ- aminobutyric acid (GABA) by 2–3%, oryzanol (168 ± 1.0–377 ± 1.0 mg/100 g), dietary fiber, ferulic acid in rice bran	Pradeep et al. (2014), Patil and Khan (2011)
Heat treatment		
(i) Hydrothermal treatment	Increased shelf life by denaturing lipases	Thanonkaew et al. (2012), Slavin et al. (2001), Pradeep et al. (2014), Krishnan et al. (2012)
	Reduction in phytate by 46–77%. Improved zinc bioaccessibility from 23 g/100 g in native to 47 g/100 g in treated finger millet seed coat	
(ii) Extrusion	Increased crude fat (18.7–31.1 mg/100 g), total tocotrienol (15.58 ± 6.07–22.77 ± 12.07 mg/100 g) and vitamin E (27.40 ± 2.89–32.0 ± 11.26 mg/100 g) content in rice bran	Cheftel (1986), Gualberto et al. (1997), McKevith (2004)
	Improve texture and palatability, low cost, decrease insoluble dietary fiber in extruded oats, rice and wheat bran by 17.74, 7.46 and 5.1%	
	Increase soluble dietary fiber in oats, rice and wheat extruded by 36.81, 22.77 and 9.95%	

(Saleh et al. 2013). Fermentation is one of the processes that decrease the levels of anti-nutrients in food grains by providing optimum pH conditions for enzymatic degradation of phytic acid present in cereal bran as complexes with polyvalent cations (iron, zinc, calcium). Reduction in phytates increase the availability of soluble minerals by several folds, increase the activity of other phenolic compounds, protein availability, in vitro protein digestibility, nutritive value, taste, and aroma (Coulibaly et al. 2011; Kohajdová and Karovičová 2007).

Natural fermentation leads to decrease in the level of carbohydrates as well as non-digestible poly- and oligosaccharides but the increase in total soluble solids, synthesis of certain amino acids and the availability of vitamin B group improved. Fermentation of cereals by lactic acid bacteria has been reported to increase free amino acids and their derivatives by proteolysis and/or by metabolic synthesis (Coulibaly et al. 2011; Delcour et al. 2012; McKevith 2004). Cereal bioprocessing through enzymatic reactions or through fermentation can also produce a large range of oligosaccharides with potential prebiotic properties by enhancing the growth of lactic acid bacteria. β-gluco-oligosaccharides can be produced by enzymatic hydrolyzation of oat bran β-D-glucan, by the action of endo-β-glucanase II enzyme (Mussatto and Mancilha 2007; Charalampopoulos et al. 2002). Few studies on the use of corn bran or corn fiber as starting material for the enzymatic production of Xylo-oligosaccharides, a partially hydrolyzed water-soluble xylan fragment, revealed that 250–450 g/100 g of available heteroxylan may be released from the starting material with xylanase treatments (Rose et al. 2009).

Germination or malting

The primary step of germination is soaking the grains and is usually done at room temperature. Soaking allows the grain to reach a moisture content favorable for respiratory and metabolic activities, mobilize primary and secondary metabolite thereby allowing germination (Coulibaly et al. 2011). Owing to the changes brought about by germination in the brown rice, there was increased protein, ash, essential amino acids and some polyphenols content in all the five cultivars that was analysed (Pal et al. 2016). It has been found that the in vitro extractability and bio-accessibility of minerals such as calcium, iron, and zinc were increased in finger millet and pearl millet by germination due to increase in phytase activity which resulted in lowering the phytate in sprouts (Abdelrahaman et al. 2007). In the meantime, the changes in nutrient contents of grains after germination can be attributed to the utilization by growing sprouts (Saleh et al. 2013). Krishnan et al. (2012) reported that finger millet seed coat matter from malted finger millet exhibited the highest calcium bio-accessibility (170 ± 4.2 mg/100 g). During 6 days germination of rye at 25° C, the amount of folate and easily-extractable phenolic acid compounds increased whereas only small changes in tocopherol, tocotrienols, sterols, lignans were observed (Liukkonen et al. 2003). It induces metabolic changes, such as hydrolyzation of starch in the endosperm into sugars by α-amylase and proteins into amino acids, especially glutamic acid, which is converted to γ-aminobutyric acid (GABA) by the action of glutamate decarboxylase in germinated brown rice (Pal et al. 2016). Germinated rice bran showed significant improvement in GABA by 2−3%, dietary fiber, ferulic acid and oryzanol (25.66–39.66%) (Pradeep et al. 2014) (Table 1). Whereas the GABA content in germinated brown rice was reported to have increased up to 99.85% (Pal et al. 2016).

Heat treatment

Hydrothermal treatment

Hydrothermal treatment is a process to optimize the physical modification of biochemical compounds without destroying its nature. The limited application of rice bran in food products is basically due to its rapid deterioration by enzymatic activity (lipase and lipoxidase). Rice bran with extended shelf-life can be obtained by various heat treatments. Heat treatment in the presence of moisture (steaming, parboiling) is effective in permanently denaturing lipases and pressurized heating (autoclave) will reduce the heating time and so will reduce the destruction of bioactive compounds in rice bran. The crude fat content of rice bran from 3 rice varieties that was hydrothermally treated increased up to 40% and this was subsequently followed by the increase of total tocotrienols and vitamin E by 32% and 15% (Thanonkaew et al. 2012; Pradeep et al. 2014). Hydrothermally treated millet seed coat from finger millet exhibited higher (51.06%) zinc bioaccessibility (Krishnan et al. 2012) (Table 1).

Extrusion

Extrusion-cooking is a versatile and efficient industrial technology, used for texturizing, improving the functionality of food ingredients and to increase the variety of commodities over a wide range of moisture, shear, pressure, time and temperature conditions. Extrusion also permits the utilization and co-processing of various cereal by-products for the increased beneficial effect of nutrients like protein and starch digestibility, to the preparation of low-cost, nutritionally enriched and/or balanced foods and feeds (Cheftel 1986). Extrusion process brought about the decrease in insoluble dietary fiber content of oats, rice, and wheat bran up to 18% and increase the general soluble fiber content to 37%. This was due to the effect of screw speed during extrusion and the strain of shear stress caused on the fibre macromolecules resulting in breakage of chemical bonds resulting in smaller particles which are soluble. The lower the extrusion speed (50 maximum rotations per minute) more favorable was the outcome (Gualberto et al. 1997; McKevith 2004) (Table 1). Meanwhile, the chemical and structural changes induced by thermomechanical treatment during extrusion determines the quality of the

Table 2 The yield of cereal by-products, their bioactive contents, properties and application

By-products	Yield (%)	Functional ingredients/ Bioactive components (g/100 g)	Properties	Application	References
Rice bran Rice germs	20 7–10 (of commercial rice bran)	Phenolic acid (0.21), Total vitamin E (31.90–42) γ-oryzanol (381–591) Total phytosterol (0.45)	Anti-oxidant Anti-inflammatory	Rice bran oil Dietary fiber source in bakery products	Friedman 2013, Min et al. 2011, Bhatnagar et al. 2014, Jiang and Wang 2005
Wheat bran	15 (bran) 5–10 (aleurone rich fraction of bran)	Dietary fiber (0.44) β-glucan (1–1.5) Total phytosterol (0.12)	Improves intestinal health Antioxidant bulkiness	Bakery products such as biscuit, muffin Tea/coffee substitute from wheat bran	Hemery et al. 2011a, Bohm et al. 2003, Stone and Minifie 1988, Alan et al. 2012, Skendi et al. 2003, Jiang and Wang 2005
Corn bran Corn fibre	6–7 8–11	Total phytosterol (0.03) Total phenol (5.50) Cellulose (20)	Anti-oxidant Anti-microbial Preservative Natural food additive	Cellulosic fiber gel (commercially available as Z-Trim) Cellulose fiber gum Corn fiber oil	Rose et al. 2009, Jiang and Wang 2005
Barley bran	30–40	β-glucan (5–24) Dietary fiber (0.02)	Hypocholesterolemic Lower glycemic response	Functional food ingredient in making pasta/noodles, ready to eat extruded snack	Skendi et al. 2003, Marconi et al. 2000, Alan et al. 2012
Oats bran	34.1–43.4	Dietary fiber (0.02) β-glucan (3–7) total phytosterol (0.15)	Hypocholesterolemic Lower glycemic response Anti-inflammatory Bulkiness	Film forming hydrocolloid, edible/ biodegradable food packaging material	Alan et al. 2012, Skendi et al. 2003, Jiang and Wang 2005
Finger millet seed coat	15–20	Calcium (792–983 mg/100 g) Iron (8.2–10.9 mg/100 g) Zinc (2.6–2.8 mg/100 g) Dietary fiber (39.50–48.74) Polyphenols (≥ 70)	Plant source of minerals Anti-oxidant and anti-radical activity Anti-microbial for food preservation	Functional food ingredient in cereal-based foods	Malleshi 2003, Krishnan et al. 2012, Banerjee et al. 2012
Proso millet bran	19–24	Crude fat (12.74)	–	–	Lorenz and Dilsaver 1980

end products. These changes also provides better understanding and aids in refining the process to obtain quality extruded products (Thakur et al. 2017). Extrusion did not seem to affect the bound phenolics content in the corn extrudates as high concentrations were recorded by Thakur et al. (2017). This proves that there was enhancement of the antioxidant and anthocyanins in the end product (Table 2).

Conclusion

Cereal bran a major by-product of milling industry is a storehouse of various components with potential health benefits which can be exploited as food ingredients. The review clearly establishes that the low-cost by-product can be effectively processed by various processing techniques such as fractionation by milling to reduce the particle size which increased the solubility of dietary fiber. Not only did the enzymatic and thermal treatments used on the by-products improved the functionality, digestibility, it enhanced the extractability of minerals and phytonutrients as well. Similarly, the reduction in anti-nutritional factors was observed. The heat treatment also improved the shelf stability of the cereal bran oil content by stabilizing and/or inactivating the lipase enzymes. Keeping in mind the effective processing techniques specific to each component of the cereal bran, processed cereal by-products can be successfully incorporated into conventional food products that deliver nutrition, bioactive compounds, shelf stability and convenience at low cost.

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