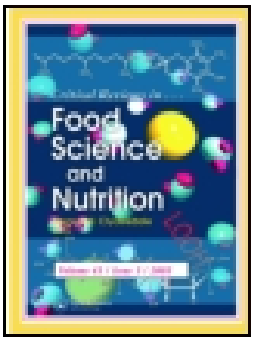

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Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: http://www.tandfonline.com/loi/bfsn20

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To cite this article: Ahmed S. M. Saleh, Peng Wang, Na Wang, Shu Yang & Zhigang Xiao (2017): Technologies for enhancement of bioactive components and potential health benefits of cereal and cereal-based foods: Research advances and application challenges, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2017.1363711

To link to this article: https://doi.org/10.1080/10408398.2017.1363711

Accepted author version posted online: 28 Aug 2017.
Published online: 19 Mar 2018.

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2017.1363711

Technologies for enhancement of bioactive components and potential health benefits of cereal and cereal-based foods: Research advances and application challenges

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ABSTRACT

Cereal grains are a major source of human food and their production has steadily been increased during the last several decades to meet the demand of our increasing world population. The modernized society and the expansion of the cereal food industry created a need for highly efficient processing technologies, especially flour production. Earlier scientific research efforts have led to the invention of the modern steel roller mill, and the refined flour of wheat has become a basic component in most of cereal-based foods such as breads and pastries because of the unique functionality of wheat protein. On the other hand, epidemiological studies have found that consumption of whole cereal grains was health beneficial. The health benefit of whole cereal grain is attributed to the combined effects of micronutrients, phytochemicals, and dietary fibre, which are mainly located in the outer bran layer and the germ. However, the removal of bran and germ from cereal grains during polishing and milling results in refined flour and food products with lower bioactive compounds and dietary fibre contents than those from whole grain. Also, the level of bioactive compounds in cereal food is influenced by other food preparation procedures such as baking, cooking, extrusion, and puffing. Therefore, food scientists and nutritionists are searching for strategies and processing technologies to enhance the content and bioavailability of nutrients, bioactive compounds, and dietary fibre of cereal foods. The objective of this article was to review the research advances on technologies for the enhancement of bioactive compounds and dietary fibre contents of cereal and cereal-based foods. Bioactivities or biological effects of enhanced cereal and cereal-based foods are presented. Challenges facing the application of the proposed technologies in the food industry are also discussed.

KEYWORDS
Cereal foods; dietary fibre; health beneficial; phytochemicals

Introduction

The increasing world population and modernized consumers demands have created a need for the development of new food manufacturing methods that will provide convenient, ready-to-eat, safe, and all-time accessible food products. Food scientists and technologists have greatly contributed to the development of food processing and manufacturing new products (Floros et al. 2010). However, the competitive food market has led to the development of many food products based on appealing taste such as found in ready-to-eat snacks that many people prefer, especially children and young adults. Generally, tasty foods are prepared by the addition of one or more of natural or synthetic food flavours and taste enhancers such as sugars, alternative sweeteners, fat, and sodium. Also, the taste and overall acceptability of food can be enhanced by subjecting the raw materials to certain processing treatments, which may result in the elimination of some portions of the raw materials or modification of physicochemical properties of the end product. Overeating of tasty processed foods and the negative effects of some processing methods on the nutritive value of food as well as many other factors may increase the risk of chronic and food consumption-related diseases (Monteiro et al. 2012). Therefore, the relationship between food and human health has attracted increasing attention from nutritionists, food scientists and technologists, consumers, and governments.

Although many food products from other sources have been developed, cereal grains and their processed foods remain the major sources of the human diet, especially in the developing countries. Today, a wide range of developed cereal and cereal-based foods are available in local markets. However, several epidemiological studies have found a relation between intake of whole cereal grain and reducing the risk of chronic diseases such as cancer, cardiovascular diseases, type II diabetes, and gastrointestinal disorders. Health benefits of whole cereal grain could be attributed to the synergistic effects of micronutrients and phytochemicals such as phenolic acids, sterols, tocols, tannins, and anthocyanins as well as dietary fibre, which are mainly located in the outer bran layer and the germ (Fardet, 2010; Andersson et al., 2014; Kaur et al., 2014; Wang, He, and Chen, 2014;

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Singh et al., 2016a). Phytochemicals of cereal grains possess antioxidant activities and prevent oxidative damage to cellular components such as membranes, proteins, and nucleic acids; therefore reducing the rate of cell death and hence the effects of aging and aging-related diseases (Zhu et al., 2013; Masisi, Beta, and Moghadasian, 2016). Also, several research studies have found that dietary fibre is involved in disease prevention and enhance potential health benefits and technological qualities of cereal and cereal-based foods (Foschia et al., 2013). However, during the preparation and development of cereal food products, cereal grains are subjected to processing treatments such as polishing, milling, extrusion, baking, or cooking that may cause a considerable reduction in the bioactive compounds and dietary fibre contents of processed product compared to whole grain (Ragaee et al., 2014). Therefore, nutritionists and food scientists are searching for strategies and new technologies for the enhancement of micronutrients, bioactive compounds, and dietary fibre contents of processed cereal foods.

Several strategies and processing technologies have been proposed in literature and applied in the preparation of processed cereal foods to deal with deficiencies of nutrients, dietary fibre, and bioactive compounds contents of refined flour and to enrich the end products of cereal and cereal-based foods. Examples of these strategies and technologies such as the supplementation of cereal-based foods with vegetable and fruit ingredients (Gawlik-Dziki et al., 2015; Ahmad et al., 2016b; Bhol, Lanka, and Bosco, 2016; Tańska et al., 2016), legumes and seed ingredients (Rumiyati et al., 2015; Villarino et al., 2015; Mesías et al., 2016; Rizzello et al., 2016), and plant ingredients (Utama-ang et al., 2016; Ruiz-Ruiz et al., 2015). The preparation of cereal foods from whole cereal flours (Khan et al., 2014; Koletta et al., 2014) and cereal composite flours (Angioloni and Collar, 2011; Serpen et al., 2012; Ragaee et al., 2011; Yousif et al., 2012; Koletta et al., 2014; Collar and Angioloni, 2014; Patil et al., 2016) was also applied in research. Processing technologies such as germination, fermentation, and enzymatic treatments have also been recommended for improving the bioaccessibility and bioavailability of nutrients and bioactive compounds of cereal foods (Wang et al., 2014; Singh et al., 2016a). Furthermore, biofortification of crop plants at the source with the implementation of breeding programs and genetic engineering approaches to generate cereal crops rich in bioactive compounds has also been proposed (Zhu et al., 2013). Different methods such as determination of phenolic compounds, carotenes, and dietary fibre contents have been used for evaluation of the enhancement in bioactive compounds contents of cereal foods after application of these strategies and processing technologies. Antioxidant, antimicrobial, and other *in vitro* biological assays have been used for evaluation of the enhancement in bioactivity of cereal and supplemented cereal-based food. Trials for determination of biological effects in animal models and human subjects were also performed. However, challenges facing the application in the food industry are not avoidable and should be considered before recommendation of any strategy or processing technology. Therefore, the objective of this article was to review the advances in research on strategies and processing technologies for the enhancement of bioactive compounds and dietary fibre contents. Bioactivity and biological effects of supplemented or enhanced cereal and cereal-based foods are also presented. Challenges facing the application of strategies and proposed processing technologies in the food industry are also discussed.

The supplementation with fruit and vegetable ingredients

Fruits and vegetables are known rich in bioactive compounds such as phenolic acids, flavonoids, anthocyanins, carotenoids, and vitamins. In addition, there is a large amount of fruit and vegetable by-products such as peels, pulp residues, seeds, and kernels, is produced. The processing by-products also showed a similar or even higher content of phytochemicals and dietary fibre compared with major product of fruit and vegetable processing (Ayala-Zavala et al., 2010; Joshi, Kumar, and Kumar, 2012). Therefore, the supplementation with fruit and vegetable by-products may enhance bioactive compounds of foods such as cereal-based products and help to achieve the recommended intake of dietary fibre and provides a technological bulking (O'Shea, Arendt, and Gallagher, 2012; Rohm et al., 2015).

Ingredients derived from different fruits and vegetables have been used as food supplements and applied in the preparation of different types of cereal-based foods. Generally, fruits and vegetables and their by-products are dehydrated and powdered to be suitable for the use as supplemental ingredients. For example, pre-harvest dropped apples, which were generated from a weather disaster, were ground and subjected to hydrothermal treatment and subsequent fractionation. A dried and powdered fibre-rich fraction was obtained and incorporated into wheat flour and cookies rich in fibre were prepared (Kim et al., 2013). Also, pumpkin (*Cucurbita moschata*) powder, which is known rich in carotenoids, pectin, phenolic compounds, and terpenoids, was added as a supplemental ingredient in the preparation of ready-to-eat extrudates. It was found that acceptable extrudates can be commercially produced with supplementation of corn flour with 19 to 21% pumpkin powder (Hong et al. 2015). In another study, tomato and tomato processing by-products, such as skin and seeds, were found to contain several bioactive compounds, such as ascorbic acid, β-carotene, lycopene, phenolics (total content), and minerals, and also showed 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity (DPPH). The addition of dry tomato by-product at 6% resulted in bread with good sensory characteristics and overall acceptability. However, as the amount of dry tomato by-product increased to 10%, the bread was less acceptable (Nour, Ionica, and Trandafir, 2015). Also, mango processing by-products, such as peels, seeds, and pulp fibre, are considered rich sources of dietary fibre and natural bioactive compounds. Mango pulp fibre, which results from the juice extraction process, was dried and incorporated into wheat flour to prepare muffins. The supplementation with the dried mango pulp fibre was found to increase contents of dietary fibre, total phenolics, β-carotene, and lutein in muffins (Sudha et al., 2015a). The supplementation of gluten-free bread with fruit and vegetable by-products and ingredients has been reviewed by (Capriles and Areas, 2014). On the other hand, cereal-based foods were supplemented with major fruit products such as concentrated juice and jam (Guevara-Arauza et al., 2011; Sun-Waterhouse, Jin, and Waterhouse, 2013).

Dried extracts obtained by organic solvents extraction from fruit and vegetable by-products were also used as supplemental ingredients in the preparation of cereal-based foods. For example, functional cookies accepted by consumers with a radical scavenging activity (DPPH) about 10 times higher than regular cookies were prepared by the addition of microencapsulated grape seed extracts (GSE). The addition of GSE created a flavour profile with attributes like cookies made with whole grain ingredients. Microencapsulating of the GSE helped to reduce their thermal degradation and partially masked their colour (Davidov-Pardo et al., 2012). Studies on the application of wine pomace in preparation of varying types of food such as cereal-based products have been reviewed by Garcıa-Lomillo and Gonzalez-SanJose (2017). The supplementation of biscuit with 1% (w/w) grape leaves, carrot, or turmeric extract was found to be acceptable and showed a higher antioxidant potential (based on the phosphomolybdenum reduction assay) than that of synthetic antioxidants. The antioxidant potential of these extracts could be attributed to the stability during baking. In addition, sensory evaluation revealed that these extracts have no effect on the organoleptic properties of the biscuit (Hefnawy, El-Shourbagy, and Ramadan, 2016). Furthermore, extract derived from pineapple by-product was added to muffins formula and showed lipid oxidation inhibition (Gomez and Pablos, 2016). More studies on the application of fruit and vegetable by-products and ingredients in the preparation of cereal-based foods are presented in Table 1.

Biological effects and potential health benefits of cereal-based foods supplemented with fruit and vegetable ingredients were also evaluated in animal models or human subjects. For example, biological effects of tortillas or bars filled with nopal (prickly pear) fruit jam, supplemented or not with nopal stem dietary fibre, were evaluated in healthy volunteers. The supplementation with nopal increased the fiber and total phenolics content in both tortillas and bars. Lower levels of glucose, total cholesterol, low-density lipoprotein (LDL), and triglycerides were found in plasma after consumption of nopal-supplemented tortilla (Guevara-Arauza et al., 2011). In another study, bread supplemented with grape by-products was found to reduce the negative impact of high-cholesterol/cholic acid diet, total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C), lipid peroxidation, glucose and leptin levels, preventing visceral fat accumulation, increase the high-density lipoprotein cholesterol, and increase the plasma ferric-reducing antioxidant capacity in rats. However, because the control bread (sourdough mixed rye bread) feeding significantly lowered TC, LDL-C and lipid peroxidation compared with high-fat diet, it was suggested that not only grape by-products but also another components in bread were related to lipid metabolism (Mildner-Szkudlarz and Bajerska, 2013). Also, rye bread supplemented with tomato pomace was included into rats' feed high-fat diet. Although the supplemented rye bread has led to a decrease in the atherogenic index of plasma and liver total lipid content, these effects were not significantly higher than those found in the case of rye bread without tomato pomace. These results were attributed to that the influence on lipid metabolism may be related to the ingredients of rye bread rather than the other components of tomato pomace (Bajerska et al., 2015). Furthermore, white bread supplemented with an extract derived from baobab showed a potential to improve the use of insulin in healthy adults (Coe and Ryan, 2016).

Based on the literature reviewed above it can be concluded that the supplementation with fruit and vegetable ingredients may enhance bioactive components and dietary fibre contents as well as bioactivity or biological effects of cereal-based foods. The enhancement is mainly attributed to that the supplemental ingredients contain higher amounts of bioactive compounds and dietary fibre than those of polished cereal grain and refined flour. The level of the enhancement in contents of bioactive compounds and dietary fibre of the end products depends on the type or source of the supplemental ingredient, supplementation level, and the type of the end food product or processing conditions. Generally, the appropriate level of supplementation is recommended depend on the changes in quality and sensory properties of the supplemented food products. However, few studies were performed to determine and verify safety and biological effects of cereal-based foods supplemented with fruit and vegetable ingredients in animal models or human subjects. Also, although a wide range of fruit and vegetable ingredients have been recommended for the use as food supplements, the application in the food industry is limited. Challenges facing the application in the food industry are discussed in a separated section in the end of this review.

The supplementation with plant ingredients and extracts

The plant kingdom is the major source of phytochemicals such as phenolic acids, phytosterols, carotenoids and tocopherols. The extraction, purification, and identification of these compounds from different plants have been a subject of many research studies (Dimitrios, 2006). Plant phytochemicals have attracted increasing attention due to their potent antioxidant properties and their marked effects in the prevention of various oxidative stress associated diseases (Dai and Mumper, 2010). The supplementation with plant-derived ingredients and extracts has been proposed in research for enhancement of bioactive compounds and dietary fibre content of cereal-based foods. Green tea is one of the most plants that have extensively been studied for that purpose. Green tea is popular and commonly used as dietary supplement in the United States (Perumalla and Hettiarachchy, 2011). Also, green tea water extract is a commonly consumed beverage in many areas in the world and has attracted more attention due to potential health benefits. Green tea extract contains several polyphenolic components with antioxidant properties, mainly the flavanol monomers known as catechins. Therefore, green tea extracts can be used in lipid-bearing foods to delay lipid oxidation and to enhance the shelf-life of varying food products (Senanayake, 2013). Extracts derived from varying types of tea have been used as supplemental ingredients in the preparation of cereal-based foods. For example, biscuits were supplemented with green tea extract as a source of tea catechins at amounts of 150, 200, and 300 mg per 100 g of flour. The green tea catechins were relatively stable in the dough and increased as the concentration of extract was increased in the biscuit dough; however

Table 1. Research studies on supplementation of cereal foods with fruit and vegetable ingredients for enhancement of bioactive compounds and dietary fiber contents.

Supplemental ingredient	Cereal food type	Sensory evaluated /highly acceptable or chosen supplemental level	Enhanced bioactive compounds	Enhanced bioactivity and measurements	Dietary fiber content	References
Grape seed powder	Wheat bread	Yes/ 5g/100g flour	Total phenolics content	ND[1]	ND	Hoye and Ross (2011)
Grape by-product	Sourdough mixed rye bread	Yes/up to 6%	Total phenolics content (individual phenolic compounds were also identified)	DPPH[2] and FRAP[3]	+[4]	Mildner-Szkudlarz et al. (2011)
Defatted blackcurrant (DS-BC) and strawberry (DS-ST) seeds	Corn starch based bread	Yes/5% DS-BC or 10% DS-ST	Total phenolics content	ND	+	Korus et al. (2012)
Grape seed flour	Cereal bars	Yes/5%	ND	DPPH	ND	Soto, Brown, and Ross (2012)
Banana pseudo-stem flour	Wheat bread	Yes/10%	Total phenolics content	DPPH and FRAP	+	Ho et al. (2013)
Grape by-products: dried powdered skins (PGP) and freeze-dried extract (EGP)	Wheat/rye bread	Yes/ up to 6% PGP or 1.4% EGP	Total phenolics content (individual phenolic compounds were also identified)	FRAP and varying biological effects in rats	+	Mildner-Szkudlarz and Bajerska (2013)
White grape pomace	Wheat biscuits	Yes/ up to10%	Total phenolics content (individual phenolic compounds were also identified)	DPPH	+	Mildner-Szkudlarz et al., (2013)
Elderberry juice concentrate (EJC)	Wheat pasta	No/ 50 mL diluted EJC per 50 g flour	Total phenolics content (individual phenolic compounds were also identified)	FRAP	+	Sun-Waterhouse et al. (2013)
Grape pomace or seed flour	Wheat cookies	Yes/ 5% (seed flour)	Total phenolics content	DPPH	+	Acun and Gul (2014)
Calamondin fiber extract	Wheat steamed bread	Yes / 3 or 6%	Total phenolics content	DPPH	+	Fu, Shiau, and Chang (2014)
Two types of wine grape pomace	Breads, muffins, and brownies	Yes/ varying levels for different products and pomace type used	Total phenolics content	DPPH	+	Walker et al. (2014)
Blueberry and defatted grape seed powder	Wheat biscuits	Yes/ 5%	Total phenolics content	DPPH	+	Aksoylu, Çagindi, and Köse (2015)
Unripe plantain flour or modified unripe plantain flour	Semolina spaghetti	Yes/ 50 g/100 g	Total phenolics content	ABTS[5] and DPPH	+	Almanza-Benitez et al. (2015)
Plantain peel powder	Wheat cookies	Yes/ 10%	Total phenolics content	DPPH	+	Arun et al. (2015)
Broccoli and olive paste	Corn snacks	Yes/ 4–7% for broccoli and 4–8% for olive paste	Total phenolics content	DPPH	ND	Bisharat et al. (2015)
Onion skin	Wheat bread	No/ 3%	Total phenolics content	Cytostatic and anti-invasive effect on human stomach cancer AGS cells and the ability to inhibit oxidative enzymes	ND	Gawlik-Dziki et al. (2015)
Lemon fiber	Wheat steamed bread	Yes/ 3 or 6 g/100g flour	Total phenolics content	DPPH	+	Fu, Chang, and Shiau (2015)
Defatted baru bowder (Brazilian almond)	Wheat cookies	Yes/ 25g/100g flour	Total phenolics content	ND	+	Pineli et al. (2015)
Date seed powder	Wheat bread	Yes/ up to 10%	Total phenolics content (individual phenolic compounds were also identified)	Nitric oxide radical inhibition, ABTS, DPPH, and FRAP	+	Platat et al. (2015)
Mango processing by-product (peels and pulp residues)	Wheat muffins	Yes/ 50 and 75% of flour/ sugar mixture	Total phenolics content (individual phenolic compounds were also identified)	DPPH and FRAP	+	Ramírez-Maganda et al. (2015)

Papaya pulp flour	Wheat cookies	Yes/ 50%	Total phenolics content	DPPH	+	Varastegani, Zzaman, and Yang (2015)
Date palm kernels (DK) and purple carrots (PC)	Wheat pasta-like product	Yes/ 10%, (4DK:6PC, w/w)	Total phenolics content (individual phenolic compounds were also identified)	ND	+	Abdel-Moemin (2016)
Doum (*Hyphaene thebaica* L.) powder	Wheat bread	Yes/ 15%	Total phenolics content	Reducing power and DPPH	+	Aboshora et al. (2016)
Carrot pomace powder (72 and 120 mesh screen)	Wheat cookies	Yes/ 20% (120 mesh screen)	ND	DPPH	ND	Ahmad et al. (2016b)
Pomegranate whole fruit bagasse powder	Wheat bread	Yes/ 5 and 15 g/100g flour	Total phenolics content	DPPH	+	Bhol, Lanka, and Bosco (2016)
Banana peel powder	Whole wheat bread (chapatti, unleavened Indian flat bread)	Yes / 5–10%	Total phenolics content	DPPH	+	Kurhade et al. (2016)
Apple pomace	Oat flour /potatos starch extruded cereal	No/ 14g/100g of the mixture	Total phenolics content (individual phenolic compounds were also identified)	Lipid oxidation inhibition and DPPH	+	Leyva-Corral et al. (2016)
White, yellow, and red dried onion	Wheat baked rolls	Yes/ 5%	Total phenolics content	DPPH and FRAP	ND	Michalak-Majewska, Sołowiej, and Sławinska (2016)
Raspberry and cranberry pomaces	Wheat muffins	No/10 and 20%	Ellagic acid, flavonols, anthocyanins, tocopherols, and tocotrienols	ND	ND	Mildner-Szkudlarz et al. (2016)
Date fruit fiber concentrates	Wheat muffins	Yes / 2.5–5%	ND	Inhibition capacity of lipid peroxidation and DPPH	+	Mrabet et al. (2016)
Watermelon rind powder	Wheat cookies	Yes/ up to 20%	Total phenolics content	DPPH, FRAP	+	Naknaen et al. (2016)
Boletus edulis flour	Wheat cookies	No/ 30%	Total free and bound phenolic acids (individual phenoilc acids were also identified)	Reducing power and DPPH	ND	Nikolic et al. (2016)
Black carrot dietary fiber concentrate	Rice muffins	Yes/ 6%	ND	ND	+	Singh et al. (2016b)
Dehydrated apple pomace	Wheat buns, muffins, cookies	Yes/ 15 for buns, 30 for muffins, and 20% for cookies	Total phenolics content	Cyto/DNA protective ability and DPPH	+	Sudha et al. (2016)
Fruit pomace from rosehip, rowan, blackcurrant, and elderberry	Cookies	Yes/ 20%	ND	DPPH; but the supplements were ineffective in inhibiting of lipid oxidation	+	Tańska et al. (2016)

*Notes: (1) ND = not determined; (2) DPPH = 2,2-diphenyl-1-picrylhydrazyl radical scavenging assay; (3) FRAP = Ferric-reducing antioxidant power assay; (4) + = indicates an increase in dietary fiber content; (5) ABTS = 2,2-azinobis (3-ethyl-benzothiazoline-6-sulfonic acid radical scavenging assay.

catechins stability was decreased as the baking progressed (Sharma and Zhou, 2011). In another study, bread supplemented with spray dried and freeze dried green tea extract (GTE) encapsulates retained qualities of volume and crumb firmness almost similar to control. Moreover, there was no much difference in the total phenolics content between bread supplemented with encapsulated GTE and bread supplemented with unencapsulated GTE (Pasrija et al., 2015). More applications of tea ingredients and extracts in the preparation of cereal-based foods such as cookies, cake, and cereal breakfast are presented in Table 2.

The addition of 0.02% of rosemary (*Rosmarinus officinalis* L.) or 0.2% of thyme (*Thymus vulgaris* L.) extract in the preparation of cookies was found to be acceptable and reduced the lipid oxidation (Kozłowska et al., 2014). Also, addition of dehydrated curry leaves (*Murraya koeniggi*) and coriander leaves (*Corinadrum sativum*) at the ratio of 1:1 (w/w) to refined wheat flour or a blend of refined wheat flour and whole wheat flour in the preparation of buns improved the protein, dietary fibre, iron and carotenoids contents (Sudha et al., 2014). In another study, an aqueous extract was derived from green coffee beans and chromatographically purified to increase the concentration of hydroxycinnamic acids (HCAs). The purified extract was used to form inclusion complexes of HCAs with β-cyclodextrin (β-CD) and used to supplement six food products including cookies, bread, caramel cottage, mushroom and meat stuffing and nutty filling. Efficiency of the supplementation with hydroxycinnamic acid was found to depend on the conditions of the processing, particularly the high temperature used along with the food product type (Budryn et al. 2016). Furthermore, supplementation of wheat-based cookies with modified and non-modified sugar beet fibres and commercially available dietary fibre enhanced radical scavenging activity (DPPH) and functional characteristics of the formulated cookies (Simovic et al., 2016). Further applications of varying plant ingredients in the preparation of cereal-based foods are presented in Table 2. From the reviewed research studies it can be seen that several extracts and ingredients from different plant sources have been recommended as supplements for enhancement of bioactive compounds and dietary fibre contents of cereal-based foods. However, the major limitation is that biological activities and potential health benefits of cereal-based foods supplemented with plant extracts and ingredients were commonly determined based on in *vitro* assays. Also, challenges facing the application of some recommended plant extracts in the food industry are potential and discussed in this review.

The supplementation with legumes and grain-like seeds

Legumes or pulses are rich sources of protein, carbohydrates, dietary fibre, minerals, and vitamins. In addition, legumes contain several nonnutritive and bioactive compounds such as enzyme inhibitors, lectins, phytosterols, phenolic compounds, and saponins (Singh and Basu, 2012). Also, due to the higher protein and resistant starch contents compared with cereal grains, legumes have a low glycemic index, which generates slow and moderate postprandial glucose and insulin response (Collar et al., 2014). Therefore, the supplementation of cereal-based foods with legume flours and by-products has been a subject of several research studies. For example, a sensory evaluation has indicated that cookies with acceptable physical characteristics and improved nutritional profile can be produced with a partial or complete replacement of the wheat flour by navy bean, pinto bean, green lentil, or commercial yellow pea flour. The legume-supplemented and baked cookies showed higher protein content and radical scavenging activity (DPPH) than those of control (Zucco, Borsuk, and Arntfield, 2011). Also, gluten-free precooked pasta was prepared from the blend of rice and yellow pea flours under optimized conditions of extrusion-cooking. Protein, ash, dietary fibre, and phenolic acids contents were enhanced in the blend due to the rice and yellow pea complementation (Bouasla et al., 2016). Furthermore, tortillas and gluten-free cookies rich in flavonoids, saponins, and anthocyanins were prepared by the addition of ethanolic extract, derived from black beans seed coat, to nixtamalized corn flour at ratio of 3 or 7 g/kg flour (Chávez-Santoscoy et al., 2016). More applications of legume ingredients in the preparation of cereal foods are presented in Table 3. Also, flours and by-products of some grain-like seeds, such as buckwheat, chia, and quinoa, have been used as supplements to enrich some types of cereal-based foods with dietary fibre and bioactive compounds (Table 3).

The enhancement of cereal-based foods supplemented with legumes and seeds is mainly attributed to that the whole grain flour of legume or seed contain higher amounts of bioactive compounds and dietary fibre than those of cereal refined flour. In addition, because they are edible and contain higher content of starch and protein, the supplementation with legume and seed flours may has less influence on the technological quality and sensory properties of cereal-based foods compared with the supplementation with other ingredients such as fruit and vegetable by-products and plant extracts. However, challenges facing the application in the food industry at commercial scale are not avoidable and are discussed in this review.

The supplementation with combination of different ingredients

The supplementation with combination of ingredients from different sources has been applied in research to enhance nutritive value and health promoting components of cereal-based foods. For example, replacement of 22.5 up to 45% of wheat flour by teff, green pea, and buckwheat flours blend provided multigrain bread with superior nutritional composition, higher amounts of total bioaccessible phenolics, higher radical scavenging activity (DPPH), and higher dietary fibre content (Collar et al., 2014). In another study, 20% of wheat flour was replaced by blend of oat bran concentrate, whole oat flour, and finely ground chia seeds in the preparation of cookies. The cookies were recommended a health-promoting functional food because of omega-3 fatty acids of chia seeds and soluble β-glucan of oat products, which are known decrease blood cholesterol and coronary heart disease (Inglett, Chen, and Liu, 2014). The supplementation of pre-gelatinized barley flour with varying amounts of sprouted and roasted faba bean and dried carrot in the preparation of functional cereal-based food, or basso (a traditional food in Ethiopia), increased iron, zinc,

Table 2. Research studies on supplementation of cereal foods with plant ingredients and extracts for enhancement of bioactive compounds and dietary fiber contents.

Supplemental ingredient	Cereal food type	Sensory evaluated /highly acceptable or chosen supplemental level	Enhanced bioactive compounds	Enhanced bioactivity and measurements	Dietary fiber content	References
Dried moringa leaves	Wheat cookies	Yes/ 10%	Total carotenes content	ND[1]	+[2]	Dachana et al. (2010)
Ginger powder	Wheat bread	Yes/ 3%	Total phenolics content	DPPH[3]	ND	Balestra et al. (2011)
Green tea powder	Wheat cookies	Yes/ 1, 2, and 4% (Lower level is preferred)	ND	Reducing power and DPPH	ND	Ahmad et al. (2015b)
Hibiscus sabdariffa by-product	Wheat snack crackers	Yes/ up to 3.75%	Total phenolics content	DPPH	+	Ahmed and Abozed (2015)
Bamboo shoot powder	Wheat biscuits	Yes/ up to 10%	Total phenolics content	DPPH	+	Choudhury et al. (2015)
Bee pollen	Wheat biscuits	Yes/ 5%	Total phenolics content	ABTS[4]	+	Krystyjan et al. (2015)
Green tea, oolong tea, and black tea	Wheat chiffon cakes	Yes/ up to 20%	Total phenolics content	Reducing power and DPPH	ND	Mau et al. (2015)
Stevia rebaudiana extract	Wheat bread	Yes/ 50% of the used sugar replaced with the extract	Total phenolics content	α-amylase and α-glucosidase inhibition, antimicrobial effect, and DPPH	+	Ruiz-Ruiz et al. (2015)
Jambolan fruit pulp (JFP) + xanthan gum (XG)	Rice muffins	Yes/ 30 g GFP + 0.5 g XG/ 100 g rice flour	Total phenolics content	ABTS and DPPH	ND	Singh et al. (2015a)
Normal or dehydrated leaves of dill (*Anethum graveolens*) and fenugreek (*Trigonella foenum-graecum L. Leguminosae*)	Whole wheat paratha, an Indian flat bread	Yes/ 7.5% for the dehydrated leaves and 25% for normal leaves	ß-carotene and total chlorophyll	ND	+	Sudha et al. (2015b)
Alkali-treated moringa leaves flour	Black gram/corn snack	Yes/ 20%	Total phenolics content (individual phenolic compounds were also identified)	ND	+	Devisetti, Sreerama, and Bhattacharya (2016)
Malva aegyptiaca L. leaves	Wheat bread	Yes/ 3%	Total phenolics content	Reducing power and DPPH	ND	Fakhfakh et al. (2017)
Ground green and yellow tea leaves	Wheat cookies	Yes/ Up to 5.5%	Total phenolics content	Lipid fraction oxidative stability, ABTS, DPPH, ORAC[5], and PCL[6]	+	Gramza-Michałowska et al. (2016)
Carob flour	Wheat pasta	Yes/ 1 to 5%	Total phenolics content	ABTS and FRAP[7]	ND	Seczyk, Swieca, and Gawlik-Dziki (2016)
Assam Tea (*Camellia sinesis* Var. *Assamica*) extract powder	Rice flour/ rice bran breakfast cereal	Yes/ 0.5%	Total phenolics content (individual phenolic compounds were also identified)	Lipid oxidation inhibition and DPPH	ND	Utama-ang et al. (2016)

Notes: (1) ND = not determined; (2) + = indicates increased dietary fiber content; (3) DPPH = 2,2-diphenyl-1-picrylhydrazyl radical scavenging assay; (4) ABTS = 2,2-azinobis (3-ethyl-benzothiazoline-6-sulfonic acid radical scavenging assay; (5) ORAC = oxygen radical absorption capacity;(6) PCL = photochemiluminescence assay for measuring superoxide anion radical scavenging activity; (7) FRAP = Ferric-reducing antioxidant power.

Table 3. Research studies on incorporation of legume and grain-like seed ingredients for enhancement of bioactive compounds and dietary fiber contents.

Supplemental ingredient	Cereal food type	Sensory evaluated /highly acceptable or chosen supplemental level	Enhanced bioactive compounds	Enhanced bioactivity and measurements	Dietary fiber content	References
Buckwheat flour	Wheat/ginger nut biscuits	Yes/ 40%	Total phenolics content (rutin and quercetin contents were also determined)	β –carotene bleaching inhibition, Reducing power, and DPPH[1]	+[2]	Filipčev et al. (2011)
Marama bean flour	Sorghum meal porridges	No/ 30%	Total phenolics content	ABTS[3]	ND[4]	(Kayitesi et al. (2012)
Green gram flour	Wheat cookies	Yes/ 40%	ND	ND	+	Rajiv et al. (2012)
Germinated lupin flour	Wheat cookies	Yes/ Up to 50%	ND	ND	+	Obeidat et al. (2013)
Buckwheat flour and bran	Wheat spaghetti	No/ 10 to 40 g/100 g	Total phenolics content (individual phenoilc compounds were also identified)	DPPH and ORAC	ND	Biney and Beta (2014)
Roselle seed powder	Wheat cookies	Yes/ 20%	Total phenolics content	DPPH	+	Nyam et al. (2014)
Chickpea, lentil, and bean flour	Wheat bread	Yes/15%	ND	DPPH	+	Rizzello et al. (2014)
Buckwheat flour	Dark and white wheat breads	No/10, 20, 30 and 50%	Total phenolics content (rutin and quercetin were also determined)	The inhibitory effect against glycation end-products (AGEs)	ND	Szawara-Nowak et al. (2014)
Tartary buckwheat sprouts flour	Wheat steamed bread	Yes/ 8%	Total phenolics content (individual phenoilc compounds were also identified)	ABTS, DPPH, and β-carotene bleaching inhibition	ND	Xu et al. (2014)
Germinated Australian sweet lupin flour	Wheat muffin	No/ Up to 8%	Total phenolics content, Campesterol, Stigmasterol, and β-sitosterol	DPPH	ND	Rumiyati et al., (2015)
Australian sweet lupin flour	Wheat bread	No/ 20%	Total phenolics content and total carotenoids (individual carotenoids were also identified)	DPPH	+	Villarino et al. (2015)
Lima bean and cowpea protein hydrolysates	Wheat pasta (extruded product)	No/ 5% and 10%	Protein hydrolysates	Angiotensin converting enzyme inhibition and ABTS	ND	Drago et al. (2016)
Chia flour	Wheat biscuits	No/ 5, 10, 15, and 20%	Total phenolics content (individual phenoilc acids were also identified)	ABTS, DPPH, ORAC[5], and FRAP[6]	+	Mesías et al. (2016)
Germinated horse gram flour	Wheat bread	Yes/ Up to 6%	Total phenolics content	DPPH	+	Moktan and Ojha (2016)
Quinoa sourdough	Wheat bread	Yes/ 20%	Total phenolics content	DPPH	+	Rizzello et al. (2016)
Buckwheat flour	Dark and white wheat breads	No/ 10, 20, 30 and 50%	Total phenolics content	ABTS and PCL[7]	ND	Szawara-Nowak et al. (2016)

Notes: (1) DPPH = 2,2-diphenyl-1-picrylhydrazyl radical scavenging assay; (2) + = indicates increased dietary fiber content; (3) ABTS = 2,2-azinobis (3-ethyl-benzothiazoline-6-sulfonic acid radical scavenging assay; (4) ND = not determined; (5) ORAC = oxygen radical absorption capacity; (6) FRAP = Ferric-reducing antioxidant power; (7) PCL = photochemiluminescence assay for measuring superoxide anion radical scavenging activity.

and the total carotenoids of the blend (Neme, Bultosa, and Bussa, 2015). Furthermore, the supplementation of semolina with varying amounts of amaranth seed flour or dried amaranth leaves or blend of both increased total phenolics content, dietary fibre content, radical scavenging activity (DPPH and ABTS), and ferric-reducing antioxidant power (FRAP) of pasta. However, a significant loss in the phenolics content and antioxidant potential was observed after cooking. The loss in phenolics could be explained by that the amaranth starch is more water soluble than wheat starch because of the very small size of the amaranth starch granules and this has led to leaching of bioactive compounds from the food matrix during cooking process (Cardenas-Hernandez et al., 2016). Also, pasta consisted of 20 g groundnut meal, 30 mL capsicum juice and about 89.99 g refined wheat flour has been prepared. The supplementation with groundnut meal and capsicum juice improved protein content, total phenolics content, and radical scavenging activity (DPPH) of pasta (Mridula et al., 2016).

In the preparation of ready-to-eat snacks, 20% of corn grits was replaced by rich sources of protein and dietary fibre from food processing by-products including defatted soybean meal, germinated brown rice meal, and mango peel fibre. Incorporation of these ingredients with corn grit increased total dietary fibre, total phenolics, and radical scavenging activity (DPPH) of the snack products (Korkerd et al., 2016). In another study, ready-to-eat breakfast cereal extrudates rich in dietary fibre and minerals was prepared by extrusion cooking of blend consisted of low-amylose rice flour, seeded banana (*Musa balbisiana*, ABB), and carambola (*Averrhoa carambola* L.) pomace at blending mass ratio of 65:25:10; respectively (Borah, Mahanta, and Kalita, 2016). Based on literature, it can be concluded that the supplementation with combination of ingredients from different sources may improve potential health benefits of cereal-based foods. However, controlling of the quality and sensory properties of cereal-based food consists of ingredients from different sources is not easy because different materials have varying functional properties. Therefore, optimization process and sensory test should be performed before recommendation of combined ingredients for the use as food supplements.

Application of cereal composite flours, whole grain flour, and cereal by-products

Because of the increasing world population and the rapid rise of wheat, rice, and corn prices, the development of new cereal food products using cereal composite or multi-grain flours and whole grain flour is attracting much attention from scientists and governments, especially in the developing countries. In addition to the reduction of wheat and rice importation and saving foreign currency, using cereals composite also improve the nutritive value and potential health benefits of cereal-based foods compared with those prepared from the refined flour or single grain (Noorfarahzilah et al., 2014). Several types of cereal foods were successfully prepared from cereals composite flours or combined cereal grains. For example, multigrain bread was prepared from varying combinations of wheat flour with flours of other cereals such as barley, oat, rye, sorghum, corn, and finger millet (Angioloni and Collar, 2011; Serpen, Gokmen, and Mogol, 2012; Ragaee et al., 2011; Yousif, Nhepera, and Johnson, 2012; Koletta et al., 2014; Collar and Angioloni, 2014; Patil et al., 2016). Pasta with higher cooking quality and sensorial acceptability was prepared by incorporation of whole sorghum flour at incorporation level of 30% with durum wheat flour (Khan et al., 2014). Also, cookies were prepared after partial replacement of refined wheat flour with whole barley flour (Sharma and Gujral, 2014) or sorghum and millet flours (Pasha et al., 2015). Furthermore, it was found that biscuits with substantial levels of magnesium, iron, zinc and high-fibre can be developed from whole grain sorghum and pearl millet composited with defatted soy flour, with or without sourdough addition (Omoba et al., 2015).

Generally, cereal foods prepared from multigrain flours were found to contain higher contents of bioactive compounds such as phenolics and dietary fibre compared to those prepared from refined wheat flour only. The higher phenolics content and antioxidant capacity of multigrain foods could mainly be attributed to the replacement of wheat refined flour with whole grain flour in multigrain combinations. The whole grain flour contains the aleurone of bran, which is rich in minerals, protein and certain bioactive components such as ferulic acid, and it was suggested a critical grain constituent for health effects such as protecting against obesity, diabetes, cardiovascular diseases, hypertension and certain cancers (Fardet, 2010; Lillioja et al., 2013; Andersson et al., 2014). Also, Maillard reaction products, result during baking at high temperature, may have synergistic antioxidant activity and their formation was found to depend on cereal type in multigrain combination (Serpen et al., 2012).

Cereal processing by-products have also been suggested as functional food ingredients by a number of research studies. A large amount of cereal grain bran, especially wheat, corn, and rice, is produced during milling. Cereal bran is considered a cheap and abundant source of dietary fibre, minerals, vitamins, phenolic acids, and phytosterols and has been applied as food supplement in the preparation of varying types of foods including cereal-based foods (Rose, Inglett, and Liu, 2010; Onipe, Jideani, and Beswa, 2015). Recently, bran of different wheat varieties was incorporated into wheat flour at levels of 0%, 12.5%, 25%, and 37.5% in the preparation of extruded snacks. The incorporation of purple and red wheat bran enhanced the oxygen radical absorption capacity (ORAC) of the prepared snacks and was suggested as functional food ingredients (Fleischman et al., 2016). Also, consuming of pasta enriched with antioxidants extracts derived from durum wheat bran showed an antioxidant effect in human subjects (Laus et al. 2017). Cereal processing by-products other than bran were also applied in the preparation of cereal-based foods to enhance nutrients, bioactive compounds, and dietary fibre contents. For example, finger millet coat that results from milling, malting, and decortications of millet grains in developing countries, was found to contain high dietary fibre, minerals, and total phenolics contents. Based on sensory evaluation of biscuit, it was suggested that 10% of biscuit flour can be replaced by native and hydrothermally processed finger millet coat or 20% by malted millet coat (Krishnan et al., 2011). In another study, incorporation of a food additive consisting of 80% nejayote solids, a wastewater results from the alkaline-cooking of maize during tortilla industry, and 20% gluten at level of 9.0% into wheat flour improved the dietary fibre content, free ferulic acid content, and oxygen radical absorption capacity (ORAC) of bread (Acosta-Estrada et al., 2014). Furthermore, varying types of barley wort, an intermediate product of beer brewing, was used as water alternative in bread making and resulted in an increase in the total phenolics content of the bread (Baiano et al., 2015). More applications of cereal composite flours, whole grain flours, and cereal by-products in the preparation of cereal-based foods are presented in Table 4. However, although the preparation of multigrain and whole grain food products has potential health beneficial and can promote utilization of cereal grains other than wheat, the negative changes in technological qualities and consumer acceptability of products produced from gluten-free grains and whole grain flour are a key challenge facing the application in the food industry.

Processing technologies

The influence on bioactive compounds content, dietary fibre content, and bioactivity of cereal grains and cereal-based foods were found to depend on some factors such as type of the end product and conditions of processing as well as other postharvest handling and treatments conditions (Ragaee, Seetharaman, and Abdel-Aal, 2014; Gong et al., 2017). Processing methods, such as germination, fermentation, and enzymatic treatments were found to enhance bioaccessibility and bioavailability of bioactive compounds such as phenolics (Wang et al., 2014; Singh et al., 2016a). Therefore, by choosing an appropriate processing method and optimizing of processing and postharvest handling conditions, bioactive compounds and bioactivity of cereal foods can be enhanced or preserved.

Soaking and germination

A number of research studies have found that soaking and germination of cereal grains may enhance the content of nutrients, bioactive compounds, and bioactivity. For example, the nutritive value, total phenolics content, dietary fibre content, and radical scavenging activity (DPPH) of the wheat flour were improved with the increase in germination time of wheat grains (Hung, Hatcher, and Barker, 2011, 2012, 2015). Higher total phenolics and γ-oryzanol contents were found after soaking of glutinous rice in media contains 3% NaCl (Thammapat, Meeso, and Siriamornpun, 2015). In another study, germination of brown rice for 48 h resulted in bread with higher content of protein, lipids, γ-aminobutyric acid, and total phenolics; and showed higher oxygen radical absorption capacity (ORAC). In addition, the germination reduced phytic acid content and glycemic index (Cornejo et al., 2015). Also, β-d-glucan obtained from germinated barley showed higher antioxidant potential (Reducing power, metal chelating activity, DPPH, and FRAP) compared to that obtained from the unprocessed barley. The increase in antioxidant activity of germinated barley was attributed to the breakdown and degradation of polysaccharides due to increased action of enzymes activated during germination process that has led to the exposure of their hydroxyl groups and decreasing the intramolecular hydrogen bonding (Ahmad et al. 2016a). Antioxidant properties of malt and how they are influenced by individual constituents of barley and the malting conditions has been reviewed by (Carvalho, Goncalves, and Guido, 2016). Also, the germination improved bioactive compounds and bioactivity of other cereal grains such as sorghum (Garzon et al., 2016), corn (Paucar-Menacho et al., 2016), and millet (Sharma, Saxena, and Riar, 2016). Generally, the enhancement in content of bioactive compounds during germination is attributed to enzymatic release of bound phenolics as well as to glycosylation reactions. Therefore, soaking and germination have been recommended to improve the nutritional quality and potential health benefits of cereal grains and cereal-based foods.

Some research studies were performed to evaluate biological effects of soaked and germinated cereal grains in animal models and human subjects. For example, the blood cholesterol of rats could be significantly modulated by using the pregerminated brown rice in feed diet compared to the ungerminated one. The effect of germinated rice was attributed to that the germination has led to an increase in bioactive components; thereby providing more efficient functional diet with blood cholesterol lowering effect (Roohinejad et al., 2010). In another study, brown rice and germinated brown rice improved glycemia and kidney hydroxyl radical scavenging activities and prevented the deterioration of total antioxidant status in type 2 diabetic rats. In addition, germinated brown rice preserved liver enzymes as well as serum creatinine (Imam et al., 2012). Furthermore, total soluble phenolics content and oxygen radical absorption capacity (ORAC) of barley and wheat were found to increase by the addition of tea catechin during soaking. Also, rat intestinal α-glucosidase, maltase, and sucrase inhibitory activities of barley were found to improve with the increase in tea catechin concentration from 0.1 to 0.5% during soaking (Zhou et al., 2013). On the other hand, a comparison was made between malted and non-malted wholegrain wheat to determine the differences in the polyphenol content and biological effects. The results showed that although malted wheat has showed significant higher total phenolics content and radical scavenging activity (DPPH), no significant differences were found in biological effects between malted and non-malted wheat after daily intake for 4 weeks by overweight/obese adults (Nelson et al., 2016). Therefore, more studies for verifying health beneficial of germinated cereal grains in animal models and human subjects are needed. Also, research for studying the suitability of germinated cereal grains for the application in the preparation and development of high quality and acceptable cereal-based foods is needed.

Fermentation

Microbial fermentation has been recommended for preparation of food supplements rich in antioxidant phenolic compounds from different agricultural and food sources (Dey et al., 2016). Also, in the preparation of cereal-based foods such as breads and cakes, cereal flour dough is subjected to a fermentation process in the presence of yeast. Fermentation in presence of Lactic acid bacteria, or sourdough fermentation, is also applied and recommended for preparation of functional cereal foods (Arendt, Moroni, and Zannini, 2011; Coda et al., 2014). For example, sourdough-fermented bread, prepared from whole meal and white wheat and rye flours, was found to contain higher contents of free ferulic acid, proteins, tocochromanols, and oxidized products of fatty acids than those of yeast-

Table 4. Research studies on application of cereals composite flour, whole grain flour, and cereal byproducts for preparation of cereal foods with enhanced contents of bioactive compounds and dietary fiber.

Supplemental ingredient	Cereal food type	Sensory evaluated /highly acceptable or chosen supplemental level	Enhanced bioactive compounds	Enhanced bioactivity and measurements	Dietary fiber content	References
Barley flour	Wheat Cookies	Yes/ 30%	Total phenolics content	ABTS[1]	+[2]	Gupta, Bawa, and Abu-Ghannam (2011)
Defatted rice bran	Wheat Bread	Yes/ up to 15%	ND[3]	Lipid oxidation inhibition	+	Sairam, Krishna, and Urooj (2011)
Barley hull and flaxseed hull extracts	Chinese wheat steamed bread	No/ 1g/100g	Total phenoilcs content (individual phenolic acids were also identified)	DPPH[4] and ORAC[5]	ND	Hao and Beta (2012)
wholegrain "white" sorghum flour or "red" sorghum flour	Wheat bread	Yes/ 40%	Total phenolics content	DPPH	+	Yousif, Nhepera, and Johnson (2012)
High β-glucan barley	Wheat bread	Yes/ 40%	Bioaccessible phenolics content (individual phenolic compounds were also identified)	DPPH	+	Collar and Angioloni (2014)
Wholegrain rye flour, wholegrain barley flour, and oat flakes meal	Wheat bread	Yes/ 60%	Total phenolics content	ND	+	Koletta et al. (2014)
Whole barley flour	Wheat cookies	Yes/ Up to 25%	Total phenolics content	Metal chelating activity, reducing power, and DPPH	ND	Sharma and Gujral (2014)
Stabilized rice bran	Wheat bread	Yes/ up to10%	Total phenolics content (individual phenolic acids were also identified) and vitamin E compounds (tocopherols and tocotrienols)	DPPH and FRAP[6]	+	Irakli, Katsantonis, and Kleisiaris (2015)
Little millet flour	Wheat bread	Yes/ 30%	ND	ND	+	Mannuramath, Yenagi, and Orsat (2015)
Extruded finger millet flour	Wheat bread	Yes/ 20g/100g	Total phenolics content	FRAP	ND	Patil et al. (2016)
Black rice	Wheat chiffon cake	Yes/ up to 60%	Total phenolics content	DPPH	ND	Mau et al. (2017)

Notes: (1) ABTS = 2,2-azinobis (3-ethyl-benzothiazoline-6-sulfonic acid radical scavenging assay; (2) + = indicates increased dietary fiber content; (3) ND = not determined; (4) DPPH = 2,2-diphenyl-1-picrylhydrazyl radical scavenging assay; (5) ORAC = oxygen radical absorption capacity; (6) FRAP = Ferric-reducing antioxidant power assay.

fermented bread. In addition, total antioxidant activity (based on cupric reducing antioxidant capacity CUPRAC assay) of sourdough-fermented bread, defined as the sum of lipophilic and hydrophilic compound activities, was found significantly higher than that of yeast-fermented bread (Konopka et al., 2014). Also, yeast fermentation of brown rice flour, at moderate acidity and optimized time and temperature, has significantly increased the levels of protein, total ash, insoluble and soluble fibre, minerals, total phenolics, resistant starch, riboflavin, pyridoxine, nicotinic acid, γ-tocotrienol, δ-tocotrienol, and ferric-reducing antioxidant power (FRAB). However, the contents of γ-oryzanol, γ-tocopherol, α-tocopherol, phytic acid, amylose and total starch were reduced (Ilowefah et al., 2015). In another study, varying enhancement in levels of nutrients, total phenolics, and antioxidant potential (based on reducing power, ferrous ion chelating ability, scavenging ability on superoxide anion radical, and DPPH assays) were found after solid-state fermentation of wheat, rice, oat, corn, millet, broomcorn millet and sorghum by basidiomycete *Agaricus blazei* Murrill (Zhai, Wang, and Han, 2015). Furthermore, the replacement of sodium salt by potassium salt and 21% of wheat flour by whole meal wheat sourdough improved γ-aminobutyric acid and peptide content of wheat bread. In addition, angiotensin converting enzyme I (ACE) inhibition and oxygen radical absorption capacity (ORAC) of peptide fraction derived from sourdough-fermented bread were significantly higher than control (Peñas et al., 2015).

Recently, metabolomics approach was applied to improve sensorial and functional properties of wheat fermented foods through selection of optimal flour-microbial strain combinations. A large set of metabolites, including volatile compounds, phenolic acids, and flavonoids, was taken into consideration and radical scavenging activity (ABTS) was determined. The increase in these sensorial and health promoting compounds was found to depend on microbial strains and wheat variety (Ferri et al., 2016). Also, different varieties of barley were fermented with the aid of a number of bacterial strains, mainly belong to *Lactobacillus reuteri*. The results revealed that bioactive compounds such as γ-aminobutyric acid, 1,3-propanediol, and histamine can be improved by choosing an appropriate bacterial strain and substrate (Pallin et al., 2016). On the other hand, although a significant increase was happened in total carotenoids and vitamin C contents of maize flour as a result of fermentation, a reduction in radical scavenging activity (ABTS and DPPH) was found (Oladeji, Akanbi, and Gbadamosi, 2017). The enhancement in bioactive compounds such as phenolics during fermentation of cereal flour is attributed to the action of native flour enzymes and microbial enzymes. Also, the presence of water and oxygen during fermentation promote a series of simultaneous reactions, including hydrolysis, oxidation, polymerization, and degradation of sensitive molecules, which affect the structure and solubility of bioactive compound (Konopka et al., 2014). From results of research, it can be concluded that the enhancement of bioactive compounds and bioactivity of cereal fermented-foods depends on fermentation conditions, microbial type, and cereal grain species or flour source. Therefore, by optimization of fermentation conditions and choosing an appropriate microbial strain, bioactive compounds and potential health benefits of cereal-based foods can be improved. However, research studies on animal models and human subjects are needed to evaluate the safety and biological effects of cereal-based foods fermented with different microbial strains. Also, research for extraction of safe ingredients rich in bioactive compounds by fermentation of different agricultural and plant materials for the use as cereal-based food supplements is needed.

Enzymatic treatments

Health benefits of whole cereal grain consumption are attributed to the micronutrients, bioactive compounds, and fibres located in the outer bran layer. Therefore, the liberating of bioactive compounds from bran matrices by enzymatic treatments has been studied and recommended to enhance their level in cereal-based foods (Wang et al., 2014). At present time, there is increasing interest in the application of cell wall degrading enzymes to mobilize the bioactive molecules from bran of grains and enhance their level in cereal flour (Singh et al., 2015b; Singh et al., 2016a). For example, the treatment with cellulase was found to enhance total phenolics content and antioxidant potential (based on ABTS, DPPH, FRAB, and protection against protein oxidation assays) of oat bran (Chen et al., 2016). In another study, physicochemical properties, total free/ bound phenolics, and antioxidant potential (based on ABTS, DPPH, and FRAB assays) of hulled and whole rice were improved with the increase in the concentration of the added thermostable α-amylase up to 6% (db of starch) during extrusion (Xu et al., 2015).

Few studies were performed to evaluate the biological effects of enzymatically treated cereal ingredients in animal models. For example, the structure of wheat aleurone layer was modified either by dry-grinding or by enzymatic treatments with xylanase alone or in combination with feruloyl esterase. The modified wheat aleurone fraction has altered metabolism of aleurone derived phenolic acids and other phytochemicals excreted in the urine of diet-induced obese mice (Pekkinen et al., 2014). In another study, the impact of long-term feeding with intact and enzymatically treated rye bran on the urinary phytochemical profile of mice was determined. Urinary excretion of varying betaines was found, including proline betaine, alanine betaine, valine betaine, phenylalanine betaine, pipecolic acid betaine, and trigonelline, but not glycine betaine. Furthermore, enzymatic treatment may have improved the bioavailability of rye-derived phytochemicals, as a higher increase in ferulic acid and benzoxazinoid metabolites was observed in the urine of mice fed with the enzymatically treated rye bran than the intact one (Pekkinen et al., 2015). Therefore, enzymatic treatment can be considered an effective method for liberating of bioactive compounds from cereal bran and other plant sources for obtaining food supplements. However, the application of enzymatic processing of whole cereal flours and cereal-based foods in the food industry facing some technological challenges such as the negative changes in quality and texture of the end products.

Other processing technologies and optimization of processing conditions

In addition to processing methods mentioned above, other processing methods have been applied and optimized to facilitate the release and increase the accessibility of bound phenolics and other bioactive compounds in cereal grains and cereal processed foods. For example, considerable changes in the benzoxazinoid contents, phytochemicals that exhibited potential health benefits, were found after milling, soaking, and boiling of three rye-based breakfast cereals. The changes in these bioactive compounds were found to depend on processing method and food type or cereal grain processing fraction (Tanwir et al., 2013). Also, higher contents of phenolic acids, flavonols, total anthocyanins, as well as ferric-reducing antioxidant power (FRAB) were retained in pigmented and non-pigmented whole meal rice after risotto cooking compared to the boiling method (Zaupa et al., 2015). In another study, air classification technology was successfully used for the preparation of coarse fractions with higher β-glucans content, total free and bound phenolics content, and radical scavenging activity (ABTS and DPPH) compared to the whole meal of barely (Gómez-Caravaca et al., 2015). Recently, the stone milling process of durum wheat was found to preserve more healthy compounds, such as total fibre, carotenoids, and anthocyanins, compared with roller-milling. However, anthocyanins and carotenoids were significantly reduced after drying process of pasta prepared from the resulting flour with respect to the pasteurization process involved in fresh pasta production (Ficco et al., 2016). Furthermore, ecological nixtamalized noodle prepared from maize has showed superior physicochemical properties and total phenolic content as well as antioxidant potential (based on ferric reducing power, metal chelating capacity, inhibition of lipid peroxidation capacity, and ABTS assays) compared to traditional nixtamalized noodle. Thus, ecological nixtamalization was suggested to be employed as pre-treatment in developing of whole grain maize based functional foods (Das, Bhattacharya, and Singh, 2017).

Processing technologies such as high hydrostatic pressure and extrusion cooking were also suggested for enhancement of bioactive compounds in cereal foods. For example, higher contents of total phenolics, γ- aminobutyric acid, arabinoxylan, and γ-oryzanol were found in the germinated rough rice after high hydrostatic pressure treatments. In addition, phytic acid was found to decrease with the increase in pressure level up to 100 MPa (Kim et al., 2015). Also, an increase in total phenolics, anthocyanins, and oxygen radical absorption capacity (ORAC) of black rice bran was found after extrusion process; while all were significantly reduced in polished and brown rice after same process (Ti et al., 2015). In another study, incorporation of extruded finger millet flour has improved quality, total phenolic content, and ferric reducing antioxidant power (FRAP) of wheat bread compared to the incorporation of native finger millet (Patil et al., 2016). The increase in the phenolic compounds could be attributed to that the high temperature during extrusion is known to release the bound phenolics from the cellular matrix, resulting in increased extractability of free phenolics (Nayak et al., 2011). Also, there is increased probability for formation of Maillard reaction products during extrusion, which are known to have reducing properties (Sharma and Gujral, 2011). For example, Maillard reaction products derived from biscuits showed antioxidant, antihypertensive, and prebiotic effects in Wistar rats (Patrignani, Rinaldi, and Lupano, 2016). Furthermore, higher antioxidant capacity (based on metal chelating activity, reducing power, ABTS, DPPH, and FRAP assays) was found for microwave processed barley compared to that of the unprocessed. The enhancement in antioxidant activity of the microwave processed barley was attributed to the breakage of polysaccharides chain due to microwave heating, that can expose more hydroxyl groups for free radical scavenging (Ahmad et al. 2016a).

Optimization of processing and postharvest treatment conditions could also improve nutritional and bioactivity of cereal food products. For example, higher lipids oxidative stability (evaluated by determination of volatile compounds and the loss of tocopherols and tocotrienols) was found for coarse rye bran when extruded at low water content, 13 or 16%, and the higher stability was connected with a higher formation of Maillard reaction products, which could act as antioxidants (Moisio et al., 2015). Also, storage of wheat grains under appropriate conditions may help in the control of lutein esterification and improve the stability and retention of carotenoids content (Mellado-Ortega and Hornero-Méndez, 2017). In a recent study, sun drying was found superior compared to hot air drying in preserving the anthocyanins, γ-oryzanols, and vitamin E contents of glutinous black rice (Norkaew et al., 2017). In another study, wheat flour and other fractions rich in bioactive compounds could be produced by optimization of the roller milling and pearling fractionation process (Giordano et al., 2017). Furthermore, optimized process of hydrothermal autoclaving has significantly decreased phytic acid content; however increased dietary fibre content, total phenolic content, and radical scavenging activity (DPPH) of wheat and rice bran (Özkaya et al., 2017). Therefore, choosing an appropriate processing technology and optimization of processing and storage conditions may result and enhancement and preservation of bioactive compounds in cereal and cereal-based foods.

Cereal breeding programs and genetic engineering

Content of bioactive compounds was found to depend on the breeding environment, maturity, and genotype of cereal grain. For example, contents of the 5-n-alkylresorcinol, a group of phenolic lipids synthesized as secondary metabolites in the outer parts of cereal grain, was significantly influenced by the growing environment and the genotype of durum wheat (Bellato et al., 2013). In another study, a decrease in vitamins, β-carotene, and γ-tocotrienol contents was found with the advancement of rice grain maturing. Therefore, immature rice grain was suggested as a good source of bioactive compounds compared with matured grain (Ji et al., 2013). Varying total phenolics and carotenoids contents as well as varying levels of radical scavenging activity (ABTS) were found among Chinese wheat varieties (Dong-yun et al., 2014). Also, lutein, lutein esters, tocochromanols (vitamin E), alkylresorcinols, and steryl ferulates were quantified in whole grain flours of 75 genotypes of 5 *Triticum* species grown in four different environments. The concentrations of these compounds were found to depend on grain genotype (Ziegler et al., 2015, 2016). Furthermore, the polyphenol profile (total polyphenols content and individual phenolic acids) and antioxidant capacity (based on ABTS and FRAP assays) of 12 Argentinean wheat varieties were also found to depend on wheat genotype and the growing environment (Podio et al., 2017). In addition to breeding of certain genotype, may the enhancement of bioactive compounds content of cereal crops can be achieved by genetic manipulation or biofortification (Mellado-Ortega and Hornero-Mendez, 2015). Also, it was demonstrated that improved understanding of the genetics and biochemistry pathways of lutein esterification can be a useful approach for optimizing the retention of lutein during the storage, handling, and processing of wheat (Ahmad et al., 2015a). However, it has been reported that biofortification of plants with antioxidants by modulating endogenous metabolic pathways to increase the production of specific antioxidants without affecting plant growth and development and without collateral effects on other metabolic pathways is a key challenge (Zhu et al., 2013).

Challenges facing the application in the food industry

Food quality and consumer acceptability challenges

From the reviewed literature, it can be observed that several strategies and processing technologies for the enhancement of bioactive compounds and dietary fibre contents of cereal and cereal-based foods have been proposed and applied in research. However, the application of some processing technologies in the food industry at commercial scale is limited. The limited application in the food industry can be attributed to a number of challenges. An important challenge that commonly found in research is the negative changes in sensory characteristics such as taste, colour, and texture of cereal foods after supplementation with natural sources rich in bioactive compounds and dietary fibre (Foschia et al., 2013; Noorfarahzilah et al., 2014; Heinio et al., 2016). The influence on technological and sensory characteristics of supplemented product mainly depends on source, composition, and amount of supplemental ingredient. Also, the level of bioactive compounds and the influence on quality characteristics was found to depend on type of the end product and processing conditions.

The changes in taste and colour of cereal foods supplemented with natural sources of bioactive compounds and dietary fibre could be attributed to the naturally bitter or astringent taste of bioactive compounds such phenolics (Heinio et al., 2016). Also, the processing at high temperature such as baking, extrusion, and puffing with the presence of natural supplements such as fruit and vegetable by-products, plant ingredients and extracts, whole grain flour, and cereal by-products may result in significant changes in taste and colour of the end products compared with products prepared from the refined flour only. The changes in taste and colour can be attributed to that these supplements contain high amounts of high-temperature sensitive compounds such as pigments, tannins, phenolics, sugars, free amino acids, and vitamins. Under high temperature, these compounds are degraded or involved in non-enzymatic browning reactions such as oxidation and Maillard reaction and produce reaction products and flavour active substances, which may contribute to dark colour and bitter or astringent taste of the end product (Ellouze-Ghorbel et al., 2010; Arun et al., 2015). Furthermore, overall acceptability of cereal foods supplemented with natural sources of bioactive compounds and dietary fibre was found to be influenced by the storage time depend on the type of supplemental ingredients (Aksoylu et al., 2015).

The special texture and volume of cereal foods such as breads mainly depend on formation of the wheat gluten network and the ability to hold the gas produced by yeast during fermentation. However, most of the natural supplements proposed in research are gluten-free and may contribute to reduced volume and weak texture of the enriched products compared with baked products prepared from refined flour only (Arun et al., 2015). The texture and technological properties of cereal-based foods other than bakery products such as pasta, breakfast cereals, and children cereal-based formula depend on starch/protein and other components matrix. For example, the incorporation of buckwheat flour resulted in pasta with reduced swelling capacities due to the low content of starch and the loss of starch granules and phenolics through leaching during cooking as a result of poorly formed gluten networks (Biney and Beta, 2014). Also, a loss in total phenolics content was found after cooking of pasta supplemented with amaranth flour and could be explained by that the amaranth starch is more water soluble than wheat starch because of the very small size of the amaranth starch granules and this has led to leaching of bioactive compounds from the food matrix during the cooking process (Cardenas-Hernandez et al., 2016). Moreover, some recommended supplements such as fruit and vegetable by-products and plant extracts are free or contain very low amount of starch and protein. Therefore, the addition of these ingredients to cereal and cereal-based foods may result in unfavorable technological and eating qualities of the end products. Also, the texture, volume, and other sensory characteristics of cereal-based foods were found to depend on the source, type (soluble and insoluble), and particle or molecular size of supplemented dietary fibres (Gómez et al., 2010; Robin, Schuchmann, and Palzer, 2012; Foschia et al., 2013). Generally, the addition of insoluble fibre to cereal-based foods was found to result in a higher reduction in the volume and expansion of end products than that of the soluble fibre. The differences in expansion volume of the supplemented products could be attributed to the differences in water absorption capacity and viscoelastic properties between the soluble and insoluble fibres (Brennan, Monro, and Brennan, 2008).

Volume, texture, and taste of fermented and baked products are also influenced by the sufficiency of the fermentation process and production of the gas and flavour substances during the fermentation. However, bioactive extracts and plant ingredients are known possess antimicrobial activity. Therefore, the addition of bioactive compounds rich ingredients such as organic solvent extracts of fruit and vegetable by-products and plants in the preparation of cereal-based foods can partially inhibit the activity of yeast or bacterial strain and lead to insufficient fermentation. For example, declined lightness, more astringent taste, and reduced volume of bread were found with the increase in the supplemental amount of green tea extract (Wang et al. 2007). The reduced volume of green tea extract supplemented bread was attributed to the partial inhibition of yeast activity and the reduced gas production during fermentation. Also, physicochemical interactions among components of supplemented ingredient and the protein and starch of flour that influence the formation of protein network and the expansion during processing are expected.

Although most of research studies have performed a sensory test and the supplemented products were found to be acceptable at certain supplemental levels, the testing in the laboratory is not enough indicator of high consumer preference at commercial scale. In most cases, the sensory evaluation in research laboratories of institutes is carried by untrained and limited number of people. However, for food companies and manufacturers in a high competitive market and modernized society, the food taste and consumer acceptability of a product are the most important factors because high consumers' acceptability indicates high food buying and profits. Therefore, cereal-based foods supplemented with natural sources of dietary fibre and bioactive compounds should pass taste and sensory test with a larger and trained population to be considered in the food industry.

Food health claims and safety challenges

A major challenge facing the application of supplemental ingredients recommended in research in the cereal-based food industry at commercial scale is that there is a lack of high quality scientific evidence about health beneficial of the supplemented products. In most of the reviewed research studies, the potential health beneficial, such as antioxidant activity, of the supplemented cereal-based foods was evaluated based on in *vitro* assays. However, the findings of the in *vitro* and in *vivo* studies are not always consistent (Nelson et al., 2016). Also, in some studies, no significant differences were found in biological effects between supplemented and un-supplemented cereal-based foods in rats (Mildner-Szkudlarz and Bajerska, 2013; Bajerska et al., 2015). In addition, although bioactive compounds content was increased after fermentation of maize flour, a reduction in radical scavenging activity (ABTS and DPPH) was found (Oladeji, Akanbi, and Gbadamosi, 2017). Therefore, before recommendation of any functional or supplemented food with health claims, the biological effects should be verified in animal models and human subjects. Another important challenge is that there is no enough high-quality scientific evidence about safety of natural supplements and supplemented cereal-based foods recommended in research. For example, chemical safety and composition of some recommended ingredients such as fruit and vegetable by-products and plant extracts are not well studied. Some extracts and by-products such as peels and seeds may contain components possess toxic activity or digestion discomforts in the human body at a specific concentration or with long term consumption. Another important issue is that during the growing in the field, fruits and vegetables may be treated with pesticides and their by-products, such as peels and pomace may contain a high amount of pesticide residues compared with the pulp or major processing products. In addition, agricultural by-products applied in research, such as fruit and vegetable by-products and other derived ingredients, may be prepared in laboratory in a limited amount and used as food supplements. However, the situation for the by-products discarded from the food processing industry is different because they are discarded in large amounts and usually mixed with water and other pollutants, which need several cleaning, preparation, and preservation treatments to be safe and suitable for the use as food supplements.

Also, the processing of cereal-based foods supplemented with natural sources rich in phenolic compounds, sugars, and amino acids at high temperature such as baking may produce an amount of potentially harmful substances, such as hydroxymethylfurfural and Maillard reaction products (Navarro and Morales, 2017). Therefore, before recommendation of any natural supplement for the enhancement of bioactive compound and fibre contents of cereal-based food, it is necessary to consider and study their role in the formation of potentially harmful compounds under different processing conditions. Furthermore, some fruit and vegetable ingredients such as juice and powders are rich sources of nutrients and micronutrients, such as monosaccharides, vitamins, and minerals, which make them an ideal medium for growth of microorganisms compared with cereal pure products. Therefore, the supplementation with these ingredients may result in a reduction in shelf-life of cereal food products and further preservation treatments will be needed. Also, different unwanted compounds with toxic effects may be produced during fermentation of agricultural or food matrix with microbial strains to produce bioactive compounds rich extract (Dey et al., 2016). Furthermore, the presence of some antinutrients, which reduce protein digestibility and micronutrient bioavailability, in recommended phenolics-rich ingredients such as legumes, whole cereal grains, and cereal bran contributes to their limited use in food formulations. Another issue is that some people have an allergy and digestive discomfort to some recommended ingredients such as legumes. Therefore, extensive in vivo and toxicological research studies are essential before the application of bioactive compounds rich sources in the food industry.

Cost-effectiveness challenges

A number of cost-effectiveness challenges are facing the application of proposed strategies and processing technologies in the food industry. The high consumers' preferences of basic, tasty, and single source food products as well as the lack of consumers' knowledge about the relationship between food composition and well-being are a key challenge for commercialization of fibre and bioactive compounds enriched cereal-based formulations. Another important challenge is that the higher price or preparation cost of some ingredients recommended in research such as juice or powder of fruits and vegetables, by-products and plant extracts, and legumes compared with cereal grains and cereal flours. In addition, a consistent supply of safe and ready-to-use functional food supplements for the industrial use may need special technology and manufacturing lines expansion that will increase the cost of the whole manufacturing process and the end products. Also, the added-value of the potential application of food processing by-products in the food industry should be compared with that of other potential applications such as biomass (Padam et al., 2014), livestock feed production (Kasapidou, Sossidou, and Mitlianga, 2015), organic fertilizers, and biofuel industries that are mainly depend on the by-products discarded from the agricultural and food industry. Therefore, the cost-effectiveness of the end products and the whole process of functional food manufacturing should be considered because cereal and cereal-based foods are the major source of the daily diet of larger populations, especially in the developing countries.

Conclusions and future perspectives

Several strategies and technologies for the developing of functional cereal-based foods with enhanced contents of bioactive compounds and dietary fibre have been proposed and applied in research. Generally, the proposed technologies were based on the supplementation of cereal-based foods with natural sources rich in fibre and bioactive compounds such as fruit and vegetable by-products, plant ingredients and extracts, whole cereal grain and cereal by-products, whole legume, and whole grain-like seeds. However, although the supplementation of cereal-based foods with several functional ingredients from natural sources has been successfully applied in research, the application of some strategies and technologies in the food industry is limited and facing a number of technological challenges. Also, there is a lack of high-quality scientific evidences about safety and health promoting effects of recommended functional supplements and supplemented cereal-based foods in animal models or human subjects. Therefore, before recommendation of a strategy for the supplementation of cereal-based foods with natural sources, factors such as safety, health effects, shelf-life, and cost-effectiveness of the end products should be considered and verified in future research. In addition, future studies should focus on improving the sensory attributes and the end supplemented products should pass taste and consumers acceptability testing with trained and larger population to be considered for the application in the food industry. Designing of programs for improving consumers' knowledge about functional and health promoting foods are also necessary.

Acknowledgment

This work was supported by National Spark Program of Ministry of Science and Technology, China (2015GA650007). The first author (Ahmed S. M. Saleh) gratefully appreciates the research fellowship supported by the Chinese Ministry of Science and Technology within Talented Young Scientist Program (EG-16-004).

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