From Underutilized Side-Streams to Hybrid Food Ingredients for Health

M. Nikinmaa, E. Nordlund, K. Poutanen, and N. Sozer
VTT Technical Research Centre of Finland Ltd., Espoo, Finland[1]

ABSTRACT

Growing global populations and limited resources require more sustainable use of food crops. Lifestyle-related health problems, such as obesity and type 2 diabetes, are also an increasing problem in many parts of the world. Major agricultural side-streams, such as cereal bran, oil-press residues and pomace, are currently used predominantly for feed and fuel. However, they have the potential to be sustainable sources of healthy proteins, fibers, and bioactive compounds for human consumption if challenges related to flavor and texture are overcome. Novel processing methods are needed to create healthy and palatable ingredients from agricultural side-streams. From economic and sustainability perspectives, these methods must be energy and water efficient. Dry-milling and dry-fractionation are energy-lean methods that can be used to produce value-added hybrid ingredients from side-streams. These ingredients may be processed further using bioprocessing, thermomechanical processing, or other methods to improve their applicability in food products.

One of the striking global challenges that will increasingly affect the food ecosystem is population growth. According to a modest estimate, the global population will approach 9.5 billion in 2050 and 12.3 billion by 2100 (16). At the same time, there is a global decline in available agricultural land due to urbanization and unsustainable farming practices. Presently, an estimated 36% of arable land is used for agriculture (6), but this figure includes forested areas and urban environments, which means that any increase in urban environments will invariably lead to decreases in land available for agriculture. At the same time, there are growing concerns about lifestyle-related health problems (e.g., obesity and type 2 diabetes) in industrialized countries.

The Importance of Side-Streams as Future Sources of Food Ingredients

Agricultural food side-streams offer a large source of fiber, protein, and bioactive compounds. This article covers the prospects for utilizing major agricultural side-streams in food ingredients. For cereals, the focus is on bran and brewer's spent grain, while other side-streams examined are oilseed press cakes and fruit pomaces. The common feature of these underutilized process streams is that their efficient utilization could provide various nutritional, sustainability, and economic benefits.

Cereal bran is a major source of side-streams (Table I). The global annual production of wheat bran is ~90 million tonnes (40), which contains ~13.5 million tonnes of protein. However, most of the wheat bran produced is used for feed or is incinerated. Wheat bran also contains other healthy components, such as dietary fiber (~50 g/100 g) and phytochemicals (up to 360 µg of total phenolic acids/g and 0.7 µmol total carotenoids/g) (11,53). Rice is another example of a major cereal from which large amounts of underutilized side-streams are formed during processing. Of the ~740 million tonnes of paddy rice produced annually, ~30% is side-stream products. Rice bran makes up 8% (60 million tonnes) of these side-streams (4). If a daily intake requirement of 50 g of protein is assumed, the amount of protein obtained from wheat and rice brans combined would satisfy the protein needs of well over 1 billion people.

Barley is the fourth largest cereal crop by volume, after wheat, rice, and maize (14). The major barley processing side-stream is brewer's spent grain from beer production (Table I), with ~30 million tonnes produced annually (29). Brewer's spent grain, in addition to bran and remnants of endosperm material, contains the barley husk, which has high quantities of protein (23%), arabinoxylans, cellulose, and lignins, as well as a relatively high lipid content (29).

Press cakes obtained from oilseed pressing are another major source of agricultural side-streams. The largest oilseed crops are soybean, sunflower seed, and rapeseed (34). In 2014 total rapeseed production was 75 million tonnes, from which 26 million tonnes of oil was extracted. Roughly 49 million tonnes of side-streams containing ~18 million tonnes of protein were produced (Table I). The press cakes of all three oilseeds mentioned are high in fiber and protein. Sunflower seed press cake contains 31–40% protein, with fiber making up most of the remainder (50); rapeseed press cake and soybean meal contain 36 and 45% protein, respectively (13,35).

Fruit pomaces obtained from fruit juice processing are good sources of dietary fiber. In 2010 the global production of apple pomace was estimated to be 3.6 million tonnes (36). In addition to dietary fiber, fruit pomaces are rich in polyphenols, such as flavonoids and tannins (3,17). A wide range of health benefits, including antitumor, antipathogen, and gut health-promoting effects have been attributed to these compounds (12,32). In addition, some berry pomaces are also good sources of protein (e.g., strawberry pomace contains 17% protein) (17).

Depending on the material in question, there are a variety of challenges related to the use of side-streams as food sources. Microbial growth during cultivation and storage is generally concentrated in the outer layers of the plant material (e.g., bran,

Table I. Approximate protein quantities in certain major side-streams (global production)

Side-Stream	Approximate Quantity Produced (million tonnes)	Protein Content (%)	Approximate Protein Quantity in Side-Stream (million tonnes)
Wheat bran	90	15	13.5
Rice bran	60	15	7.5
Brewer's spent grain	30	23	6.9
Rapeseed press cake	49	36	18

[1] VTT Technical Research Centre of Finland Ltd., Tietotie 2, Espoo, FI-02044 VTT, Finland.

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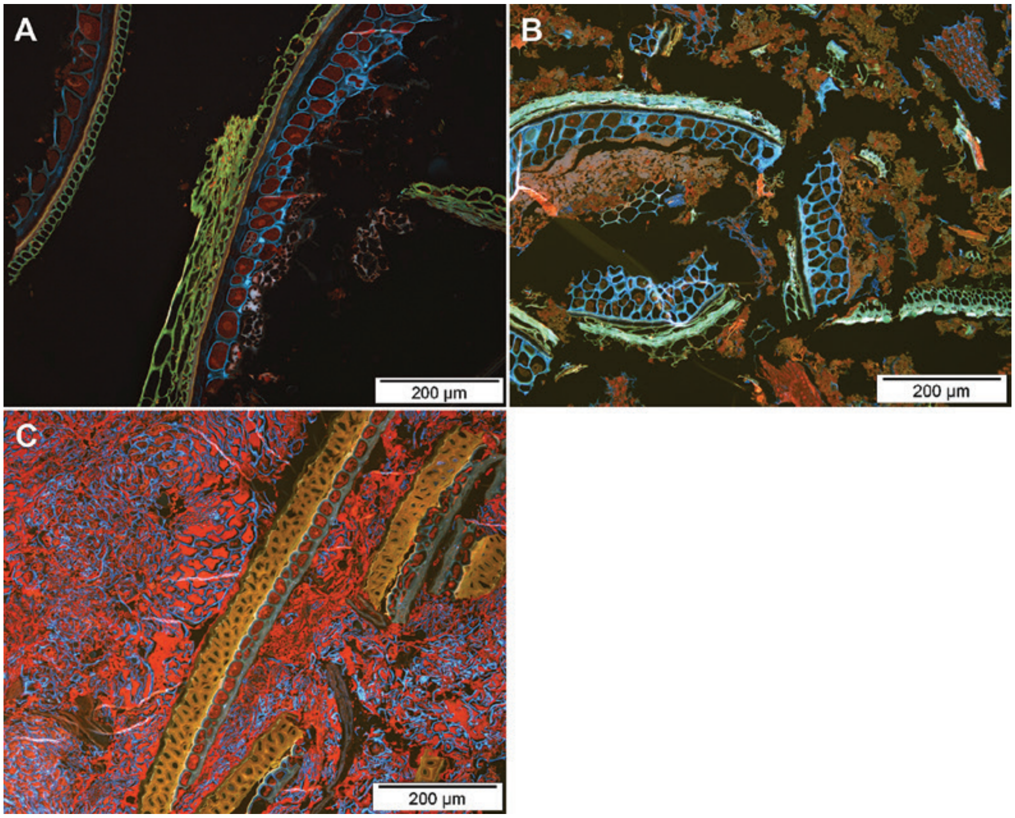

Fig. 1. Micrographs of wheat bran (**A**), brewer's spent grain (**B**), and rapeseed press cake (**C**) stained with Calcofluor and acid fuchsin to show protein (red) and fibers (blue or brown/green); starch remained unstained. Protein in wheat bran is located mainly inside aleurone cells, whereas protein in brewer's spent grain is located in both aleurone and endosperm cells.

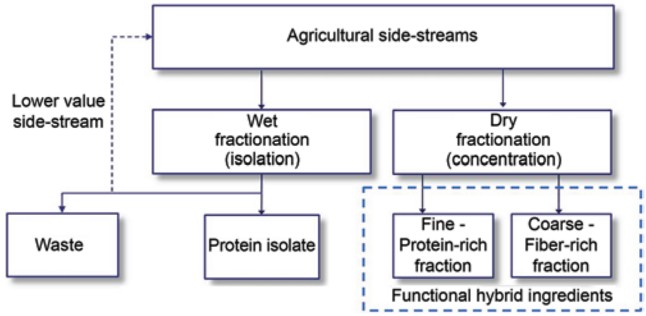

Fig. 2. Side-stream utilization routes.

husk, fruit skin, etc.), which are often present in side-streams. This means that microbes such as mycotoxins may be concentrated in side-streams. Thus, proper handling of side-streams and rigorous testing are needed to ensure that the materials are safe for consumption. Additionally, side-streams such as rice bran may contain high amounts of lipids and lipolytic enzymes, which lead to the formation of rancid oxidation products. Consequently, stabilization by heat treatment or fat extraction, for example, is required prior to utilization in food products. A common feature among all of the plant side-streams discussed here is that they are high in dietary fiber, which may present structural, textural, and sensory challenges for food applications despite their health benefits. In many cases, including brewer's spent grain, wheat bran, and rapeseed press cake, protein is tightly entrapped within the cell matrix, which makes its separation from the cell matrix challenging (Fig. 1). Astringent or bitter compounds are also frequently present in these side-streams, which complicates their utilization as food ingredients (e.g., rapeseed sinapine). Despite these challenges, with suitable processing these underutilized agricultural side-streams can be converted into health-promoting protein, dietary fiber, or hybrid ingredients for use in food products, which will not only increase global food system sustainability, but also create new business ecosystems.

Protein Ingredients

Replacing animal proteins with their plant-based counterparts would be beneficial from both a nutritional and sustainability standpoint. High intake of red meat, in particular, is associated with increased risks of certain cancers (5). Production of animal proteins also requires more energy input, generates higher levels of greenhouse gas emissions, and requires greater freshwater consumption than production of plant proteins (45). Increased food system sustainability could be achieved through reduced meat consumption and more efficient use of plant protein-rich side-streams.

Proteins can be isolated from side-streams using several different traditional aqueous extraction methods (e.g., alkaline, acid, alcohol, salt), depending on the characteristics and location(s) of proteins within the raw material matrix, or concentrated using dry-fractionation methods (Fig. 2). Both aqueous extraction and dry-fractionation methods have advantages and disadvantages. Dry-fractionation requires less energy input, and most of the proteins remain in their native forms. However, because the method is based on particle size and density, other components will always be present, limiting the extent of concentration. It is possible to isolate proteins using certain aqueous processing steps; however, wet-fractionation is energy intensive and requires expensive drying and filtration operations. Often these processes can also induce changes in protein structure and, in turn, functional properties (47).

To improve extraction yields from wet extraction, enzyme-aided processes have been developed. Alkaline or salt extraction yields for rapeseed press cake have been improved by utilizing cell wall-hydrolyzing enzymes, for example. Pectinase treatment has been shown to improve the extraction of rapeseed protein from press cake by 29–42% (43). In addition, recovery of bioactive peptides from rapeseed press cake has been demonstrated using protease hydrolysis (41).

To enable the use of proteins from underutilized side-streams, several technological (e.g., restricted solubility and foaming properties), nutritional (e.g., antinutritional factors), and sensory (e.g., bitterness, astringency) challenges must be overcome. High phytate content, a phosphorus storage molecule found in plants, is a complicating factor that affects both the solubility and bioavailability of proteins (9). Phytate contents of 58 mg/g for rice bran, 25–58 mg/g for wheat bran, and 43 mg/g for sunflower seed press cake have been reported (15,27). In addition to affecting protein solubility, phytate also limits the bioavailability of proteins and chelates minerals, which can lead to iron deficiency. Phytate can be reduced by phytase enzymes or fermentation, but the benefits need to be weighed against the fact that phytate has also been shown to have potential anticancer properties (48). Protein functional properties and solubility can be improved by partial hydrolysis with proteases, such as deamidation with glutaminase (21). In addition, functional properties of plant proteins (e.g., gelling and foaming) can also be improved by treatment with cross-linking enzymes such as transglutaminases or tyrosinase (7,31). For example, the colloidal stability of rapeseed proteins have been improved by transglutaminase treatment (35).

Fiber Ingredients

Cereal brans and berry press cakes are good sources of dietary fiber. Dietary fiber has been associated with a wide range of positive health effects, such as improved cardiovascular health and reduced risk of certain cancers, obesity, and type 2 diabetes (28). Despite their positive health effects, fiber intakes are below recommended levels in many areas of the world (8,25), in part due to the use of refined flours from which the bran has been removed.

As proteins, dietary fibers can also be concentrated using methods such as sieving or air classification. With air classification dietary fiber generally is concentrated into the coarse fraction, while residual starch and other endosperm materials are recovered in the fine fraction. Another more novel method is electrostatic separation, in which the material is finely ground and then separated based on differences in electrical charge (positive, negative, neutral) (19). Currently fiber ingredients are most often produced using wet processes, such as acid extraction with alcohol precipitation (pectin); gelatinization and retrogradation, possibly coupled with enzymatic treatment (resistant starch); and sodium hydroxide or peroxide treatment (oat fiber) (10).

Enrichment of foods through the addition of dietary fiber from side-streams (e.g., bran) is tempting because it would significantly improve their nutritional value. Unfortunately, high (insoluble) dietary fiber content is associated with reduced palatability, including reduced softness and volume in breads or reduced expansion in extrudates, leading to coarse mouthfeel, as well as hard and dense structures (18). This is due to the effects of dietary fiber on water dynamics, viscosity, and elasticity and its physical disruption of bubble formation in extruded foods (42,52). There are various strategies that can be employed to reduce the negative effects of incorporating dietary fiber in foods. Acidification during fermentation activates endogenous enzymes, and the microbes themselves may produce hydrolytic enzymes that can solubilize bran and improve its function in the food matrix (23). Use of hydrolytic enzymes is based on the same principle; for example, xylanase treatment has shown potential for improving the structure of foods that are high in dietary fiber. In extrusion, bioprocessed rye brans enzymatically treated or fermented with *Weissella confusa* provide improved expansion and texture (30,46). Of the oilseeds, soybean fiber has been examined for dietary fiber enrichment of extrudates (22), but use of rapeseed or sunflower seed fiber in foods appears to be rare.

Physical disruption of dietary fiber ingredients may also have a positive effect in certain applications; for example, fine milling of wheat bran has been shown to improve the texture of crackers and biscuits that are high in dietary fiber (49,51), as well as extrudates (2). The effect of steam explosion on the applicability of wheat bran alone and in combination with enzyme treatment has been studied in bread baking. A positive effect on both bread volume and texture was obtained only for bran samples treated with enzymes after steam explosion (1).

In high-moisture systems, wet grinding and microfluidization have been identified as methods that can improve the dispersion stability of bran suspensions (44). Microfluidization has also been used as a pretreatment for bran in cake-baking applications, resulting in firmer and wetter cakes (26).

It should be noted that the coarse, dietary fiber-rich cereal grain fraction from dry-fractionation generally also has a high protein content, because most of the aleurone layer, which has a high protein content, is still present (Fig. 1). The next section focuses on combinations of different components (i.e., "hybrid ingredients").

Hybrid Ingredients

Efficient use of food resources and avoiding food waste are becoming increasingly important. Isolation of components is not always practical, however, due to energy-intensive extraction processes, which may also cause unwanted modifications in the functionality of the component of interest (e.g., denaturation of proteins). Foods are composite, multimaterial matrices in which the main structural polymers are carbohydrates, proteins, and dietary fiber. Each of these components provides synergistic technological, nutritional, and sensory functionalities. Therefore, an agile, processed, sustainable food ingredient would preferably be a hybrid that can deliver multiscale functionalities, such as protein–dietary fiber (e.g., case bran) or protein–carbohydrate (e.g., case protein concentrates). A complex mixture of nutrients can also have synergistic effects in human health: for example, a high dietary fiber ingredient may also be a source of protein and bioactive compounds. At the same time, hybrid ingredients would also enable use of more of the raw side-stream materials and minimize production of waste streams.

Agricultural side-streams such as cereal brans could be considered hybrid ingredients if their applicability can be improved. For example, rye bran contains ~19% protein and 40–45% dietary fiber and is high in bioactive compounds. (33). This means it can be utilized for both protein and fiber fortification. As an example, a recent study used bioprocessing of bran as a pretreatment prior to extrusion. This enabled incorporation of 40% bran in the extrudate, which led to the development of a product high in dietary fiber that is also a source of protein (30). Furthermore, in cases where the mostly insoluble components of bran can be removed (e.g., by air classification) the soluble fractions of fiber and protein in bran can be increased, with subsequent improvement in the technological, functional, and nutritional properties of bran.

In addition to protein- and fiber-rich ingredients, side-streams show potential as hybrid ingredients that contain both dietary fiber and bioactive components. The press cakes from fruit and berry processing are especially good candidates to deliver dietary fiber and bioactive compounds in a hybrid ingredient. For example, fine-milled and microwave-assisted air-dried bilberry press cakes (10 and 25%) have been added to whole grain rye flour in extrusion (20). The bilberry press cake addition enhanced phenolic content and resulted in palatable healthy snacks, particularly at the 10% addition level. Similarly, application opportunities for fruit pomace have been found for fiber and phenolic enrichment of a wide variety of bakery and snack products, ranging from cakes to crackers and extrudates, in which the bioactive compounds also retain their structure (39). In addition, studies have been performed to investigate ways in which the availability of bioactive compounds in different materials, such as berry press cakes and rye bran, can be increased. Fermentation of berry press cake with lactic acid bacteria modified the bioactivity of cloudberry press cake (38), whereas bioprocessing with enzymes increased the antimicrobial and antioxidant activity of bilberry press cake (37). In the former, the anti-inflammatory effects of the press cakes increased, and in the latter case, anthocyanins were released through the enzymatic action: both effects were due to the release of different phenolic compounds from the matrix. Puupponen-Pimiä et al. (37) also showed that it is possible to use dry-fractionation to obtain fractions from press cake with different bioactivities, such as increased anti-inflammatory effects in the coarse fraction and increased antimicrobial effects in the fine fraction. For rye bran, increased bioavailability of ferulic acid, which has a demonstrated antioxidant effect, was achieved by bioprocessing with a ferulic acid esterase enzyme and yeast compared with native rye bran. Bioprocessing increased the free ferulic acid in rye bran from 4 to 20% (24).

Conclusions

Most underutilized agricultural side-streams are good sources of dietary fiber, proteins, and/or bioactive compounds that could be upgraded as health-promoting food ingredients. Efficient valorization of natural resources requires development of agile process technologies that can be used to deliver multifunctional properties to a food matrix through hybrid ingredients. Dry-milling and subsequent dry-fractionation technologies are water- and energy-lean technologies that can be used to produce multicomponent hybrid ingredients (e.g., protein–fiber, protein–starch, fiber–starch, fiber–bioactives). In addition, some researchers are focusing on improving the applicability of hybrid ingredients through bioprocessing (microbial and enzymatic processes), thermal and/or high pressure processing, and particle engineering (homogenization, microfluidization). For example, defatted oat or barley protein concentrate, which contains native starch as a major component, can be utilized in food applications where the gelatinization of starch can be exploited for structure formation or stabilization. Similarly, rice or wheat bran protein concentrates with high amounts of insoluble dietary fiber can be incorporated into high-protein, high-fiber foods as a single ingredient.

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Markus Nikinmaa holds an M.S. (technology) degree and is a research scientist on the VTT Food Solutions team. He is currently working on his doctoral dissertation related to utilizing bioprocessing and fractionation for production of healthy, palatable high-fiber foods.

Emilia Nordlund holds a D.S. (technology) degree and is the research team leader of the VTT Food Solutions team. She is working on food ingredient development and especially on the use of enzymes as a tool to improve plant-based ingredient functionality and applicability. Within the framework of VTT's Food Economy 4.0 program, she is developing ways to support healthy eating via new food delivery and eating concepts.

Kaisa Poutanen holds a D.S. (technology) degree. She is a research professor in food technology at VTT Technical Research Centre of Finland and an invited honorary doctor in food sciences at the University of Helsinki. She has an extensive track record connecting food technology and nutrition sciences. Her research is on the development and nutritional physiology of healthy plant-based foods and concepts, with a focus on cereal foods, dietary fiber, and protein. She has vast experience in interdisciplinary international research leadership, such as the EU Healthgrain project (2005–2010) and is currently the coordinator of the EU BBI PROMINENT project on valorization of proteins from wheat processing side-streams. She leads the focus area "Food Economy 4.0" at VTT, which is aimed at a new sustainable food ecosystem in the digital era to deliver ingredients, foods, concepts, and services to facilitate healthy eating.

Nesli Sozer holds a D.S. (technology) degree in food technology and food engineering. Nesli is a principal investigator at VTT Technical Research Centre of Finland Ltd. and a docent at Helsinki University in food technology. She has expertise in food material science and food ingredient/product design. Recently, she has been working on hybrid protein cereal and legume ingredients with multifunctionalities using biological and mechanical processes. She has been the project manager of EU-SUSFOOD Eranet OATPRO (www.oatpro.eu), focusing on valorization of oat proteins, and led the Nordic Innovation-funded project FUNPRO (Food bUsiness from Nordic Plant pROtein), the aim of which was to identify novel fractionation and functionalization methods for oat, barley, and rapeseed proteins that would enable their use as food ingredients. She is leading the Agile Food Manufacturing Technologies efforts under the Food Economy 4.0 focus area at VTT.

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