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REVIEW

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ABSTRACT

Cereal β-glucan describes a group of soluble dietary fiber primarily found in barley and oats. It is characterized by the mixed occurrence of β-(1,3) and β-(1,4) bonds between the glucose monomers, forming long polysaccharide chains with unique properties. Alongside their technological benefits, they exhibit a number of health–beneficial properties. Nevertheless, β-glucan applications as nutraceutical food ingredient, are rarely utilized. The changes in physicochemical (molar mass, solubility and viscosity) and health–beneficial (glycemic control, lowering of blood glucose) properties during food processing and storage are a major drawback. The understanding of the complex mechanisms behind the health benefits of β-glucan is still incomplete. In contrast to original believes, it becomes evident from recent literature, that physiological properties are not only based on the dose administered. A more thorough view on the molecule and its structure–size–function relationship is required to understand the impact of molar mass, molar ratio, solubility and viscosity. Therefore, this review evaluates the recent scientific data to identify β-glucan key properties responsible for the nutraceutical function in the final product. This provides a guideline for future research which characteristics need careful monitoring and preservation throughout processing and help to fully utilize cereal β-glucan as nutraceutical ingredient.

Introduction

In recent decades, the relationship between dietary habits and human health has become widely recognized due to extensive investigations (Hassani, Procopio, and Becker 2016). In combination with the increasing prevalence for obesity, high blood pressure, coronary heart disease and other chronic diseases, the desire for foods with health-endorsing properties has increased drastically. The use of such functional foods presents a safe way to prevent and treat various diseases. It was shown, that a consumer's decision to buy a certain product is strongly related to the advertised health effects of the product (Loebnitz and Grunert 2018). As a consequence, food industries worldwide are increasingly looking for possibilities to incorporate constituents with health-endorsing effects into their products.

One prime candidate to exploit for the production of nutraceutical foods are cereals. They are a widespread crop throughout large parts of the world and important part of the human diet. Cereal grains account for over 50% of the plant derived energy intake and are the most consumed staple food worldwide (Bader Ul Ain et al. 2018). The most abundant cereals in human diet include wheat, rye, barley, sorghum and oat, among others. However, it is predominantly the endosperm that is used for the production of foods. Outer layers of the kernels, such as the bran, are often removed during milling and only used as animal feed. However, numerous studies linked the health-endorsing

effects of wholegrain products to the bran (Hollmann and Lindhauer 2005; Singh, Liu, and Vaughn 2012; Du, Zhu, and Xu 2014; Wolever et al. 2018). The primary group of components responsible are nonstarch polysaccharides summarized as dietary fibers. It has been proposed by researchers that the incorporation of dietary fiber can result in more healthy, low-calorie, cholesterol-lowering, fat-free foods (Elleuch et al. 2011). This has led to a dramatic increase in wholegrain products available on the market (Wang et al. 2020). Nowadays, approximately half of the foods available on the market contain dietary fiber, with cereals being the main source of origin (Macagnan, da Silva, and Hecktheuer 2016). Nonetheless, the average daily intake remains below the recommendation (Vasquez Mejia, de Francisco, and Bohrer 2020).

Cereals contain a variety of dietary fibers, with β-glucans (BG) being among the most intensely studied, due to their technological and physiological properties (Bader Ul Ain et al. 2018). For foods allowing a consumption of at least 3 g barley or oat BG per day (0.75 g/serving) the European Food Safety Authority (EFSA) and the American Agency for Food and Drug Administration (FDA) have permitted the assignment of several health claims (Åman 2006; EFSA 2011; FDA 2008). Beneficial effects associated with BG intake include decreased serum lipid concentration, lowered blood pressure, attenuated blood glucose level, reduced bowel transit time and increased stool bulk (El Khoury et al. 2012; Wang et al. 2014; Whitehead et al. 2014). In addition, cereal BGs

Table 1. Characteristics of beta-glucans from the most relevant cereal sources.

Cereal	Beta-glucan content [%]	Molar mass [kg mol^{-1}]	Molar ratio [β-(1,3)-cellotriosyl/ β-(1,3)-cellotetrasyl]	References
Oat	3.0–7.0	400–2500	1.5–2.3	Beer et al. (1997), Cui and Wood (2000), Izydorczyk and Dexter (2008)
Barley	5.0–11.0	400–2500	2.3–3.4	Beer et al. (1997), Cui and Wood (2000), Izydorczyk and Dexter (2008)
Wheat	approximately 0.5	209–416	3.0–4.5	Cui and Wood (2000), Lazaridou and Biliaderis (2007), Izydorczyk and Dexter (2008)
Rye	approximately 2.0	up to 1130	2.4–2.7	Beer et al. (1997), Lazaridou and Biliaderis (2007), Wood (2010)

exhibit a variety of technological properties, such as gel forming and increased viscosity, which can also improve the technological properties of the product (López-Vargas et al. 2013). Consequently, the application of cereal derived BG, appears as a great opportunity regarding food functionality and consumer health improvement. There are also several alternative BG sources, such as mushrooms, yeast and some bacteria. But despite sharing the same principle structure, they present different physicochemical and physiological properties (Zhu, Du, and Xu 2016). Thus, the scientific data presented in this review will focus only on cereal BG, while BGs from other sources are reviewed elsewhere.

Despite the proven health-promoting properties of cereal BG, its potential as nutraceutical ingredient is heavily underutilized (Din et al. 2018). Often it is only incorporated into foods products for technological benefits, i.e., as thickener in beverages. As a consequence, products containing enough BG to grant a health claim or general health benefit for the consumer are rare. The reasons behind are manifold. The overall low concentration in the kernel is among the major drawbacks. Thus, simple use of wholegrain products usually does not provide high enough levels of BG. The production of a concentrate is usually cost intensive, has low efficiency and induces structural changes, often resulting in the loss of the desired physiological effects (Yoo, Ko, and Chung 2020).

Furthermore, the mechanisms determining the health promoting effects of cereal BG are still not fully understood (Henrion et al. 2019). The results reported on the efficiency of BG preparations are inconsistent due to the highly complex interactions between several factors, such as BG molar mass, viscosity, solubility, molar ratio and surrounding food matrix, among others. Since most studies only examine the impact of one factor, without giving exact and comparable information regarding the others, understanding of the demands for the ideal preparation for maximum functionality is still incomplete (Henrion et al. 2019).

Therefore, this review was conducted in order to summarize recent research activities on cereal BG. Special attention was given to the newest advances in extraction, functionality, mode of action and changes upon food application. Based on this information, perspectives for future research were identified, in order to fill existing knowledge gaps regarding the specific use of BG as nutraceutical ingredient. This will help to identify the ideal processing of BG, from extraction until consumption by the consumer, to ensure highest nutraceutical functionality for every application.

Availability and structure

BG can be found in various cereals with highest concentrations present in barley and oat, but to a lower extent also in wheat, rye and rice grains (Bader Ul Ain et al. 2018; Vasquez Mejia, de Francisco, and Bohrer 2020). The characteristics of BG from the most relevant cereal sources are summarized in Table 1. Depending on the cultivar, variety and location of growth, the BG content of cereals can vary substantially. For barley, oats, rye and wheat, concentration ranges of $5 - 11\%$, $3 - 7$, 2 and $<0.5\%$ are reported (Cui and Wood 2000; Herrera et al. 2016; Nishantha et al. 2018). In addition to containing the highest amounts of BG, the health claims permitted by ESFA and FDA only apply to BG originating from oats (OBG) or barley (BBG) (Åman 2006; EFSA 2011). Consequently, they have received the most research attention among all cereal derived BG and are the main focus of this review.

Numerous varieties of barley were analyzed for their BG content, with generally highest contents present in waxy and hull-less varieties (Ehrenbergerova et al. 2008; Wiege et al. 2016). It was also found that wild barley generally contains higher levels of BG compared to domesticated varieties (Nishantha et al. 2018). Warm and dry conditions during flowering increase the BG content of waxy–barley varieties, whereas it is decreased as a result of very wet conditions (Ehrenbergerova et al. 2008). Consequently, careful consideration of both, barley cultivar and growth location are essential, to ensure grains, rich in high quality BBG.

A screening of different oat (*Avena sativa*) varieties regarding their BG content revealed only very little variation (Shewry et al. 2008). Similar results were reported by other researchers, finding only small variations in BG content and quality for different oat varieties and growth locations (Redaelli et al. 2013; Sikora et al. 2013). In contrast, Andersson and Börjesdotter (2011) reported that BG content is heavily influenced by the variety, while the molecular size is much more dependent on the climate conditions on the
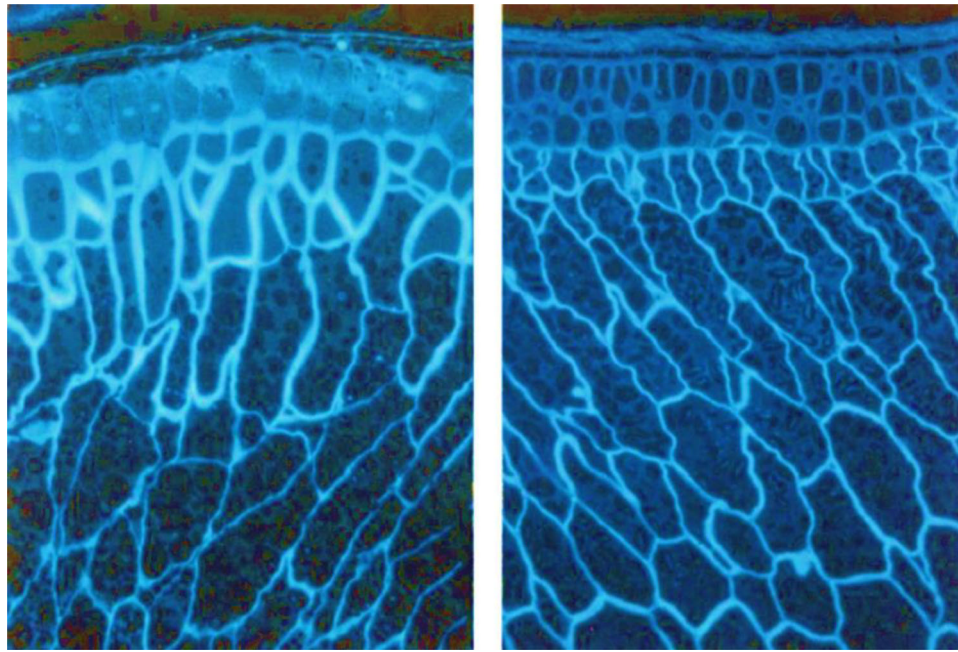
Figure 1. Distribution of β-glucan in oat (left) and barley (right) kernels, visualized by staining with calcofluor. The micrograph images show the pericarp and aleurone layer at the top. In oat, the majority of the β-glucan is located in the subaleurone layer, while barley shows a more even distribution (Tosh 2013).

field. From the data available, a high likelihood for the possibility of selective breeding aiming at high BG contents can be concluded (Shewry et al. 2008). However, the primary objective of current oat breeding programs is the increase of protein content, rather than dietary fiber and BG in particular (Sunilkumar et al. 2017). Yet another factor to consider is the distribution of BG throughout the grain, which is very inhomogeneous. Highest concentrations are present in the aleurone and subaleurone layers, as well as the cell walls of endosperm cells (Burton, Collins, and Fincher 2009; Sibakov et al. 2014; Wiege et al. 2016). Distribution of BG throughout barley and oat kernels is shown in Figure 1 (adapted from Tosh 2013). From these images it is clearly visible, that highest contents are located in the outer layers. Hence, focusing on the bran as source for BG appears as the best approach.

In addition to the BG content, the molecular structure is an important consideration for potential sources of BG with optimal nutraceutical properties. Despite some variations, a general structure for cereal BG was identified and is shown in Figure 2 (adapted from Vasanthan and Temelli 2008). The BG molecule is described as a polysaccharide consisting of numerous D-glucose monomers linked together via β-glycosidic bonds. The most characteristic structural feature of cereal BG is the mixed occurrence of β-(1,3)- and β-(1,4)-glycosidic bonds between the D-glucose monomers (Hu et al. 2015). In contrast, BG from other origins, such as yeast or bacteria, contain β-(1,3)-glycosidic and β-(1,6)-glycosidic bonds, resulting in different properties (Zhu, Du, and Xu 2016). Most frequently found are subunits of three to four β-(1,4) linked D-glucose monomers, forming cellotriosyl (DP3) and cellotetraosyl (DP4) oligosaccharides. However, few oligosaccharide subunits consisting of up to 14 monomers were detected via high performance liquid chromatography (HPLC) also (Izydorczyk, Macri, and

MacGregor 1998; Tosh 2004). The individual subunits are connected by β-(1,3) linkages, forming long linear polysaccharide chains with a fibrous structure (Driscoll et al. 2009). Furthermore, the ratio between cellotriosyl and cellotetraosyl units (molar ratio), after breaking the β-(1,3) glycosidic bonds, was found to be very specific for different cereals. Thus, it can be used as a tool to identify the cereal from which a given BG molecule originates (Lazaridou and Biliaderis 2007). For BBG the molar ratio commonly found ranges from $2.3 - 3.4$, while OBG was reported with a lower molar ratio of $1.5 - 2.3$. On the other hand, wheat has a characteristically higher molar ratio of $3 - 4.5$ (Izydorczyk and Dexter 2008). It also has to be considered, that the molar ratio is heavily influenced by the genotype and environmental conditions. In that regard, it was found by several researchers that waxy barley genotypes produce BG with higher molar ratio $(3.1 - 3.2)$ compared to other genotypes $(2.5 - 3.1)$ (Wood et al. 2003; Izydorczyk and Dexter 2008).

Properties

The main reason behind the attractiveness of cereal BG as food additive originates from the combination of all the functional properties of food hydrocolloids, such as emulsification, thickening, stabilizing and gelation, with the health promoting properties of dietary fibers (Lazaridou and Biliaderis 2007; Jayachandran et al. 2018). Therefore, this section will explore recent research data on BBG and OBG physicochemical and physiological properties. This information will help to identify characteristics, which need most careful monitoring, to ensure optimal functionality for every application.
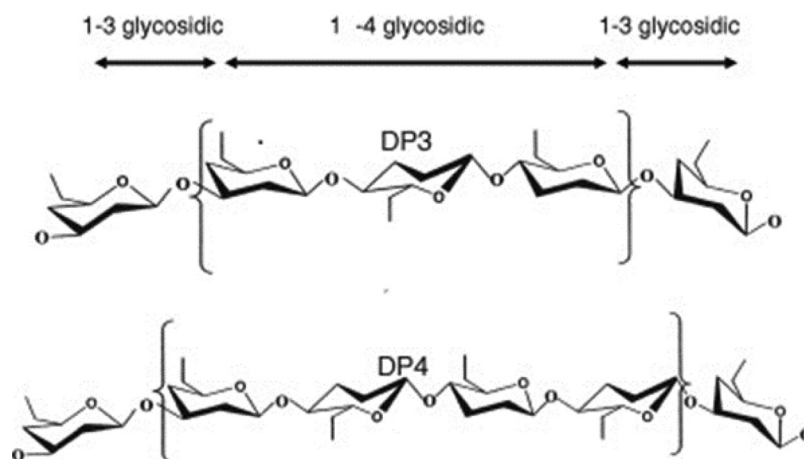
Figure 2. Molecular structure of cereal β-glucans, adapted from Vasanthan and Temelli (2008). D-Glucose monomers are linked by β-(1,4) links to subunits of a) cellotriosyl units (DP3) and b) cellotetraosyl units (DP4), which are terminated by β-(1,3) links on both ends.

Physicochemical properties

From a technological point of view, the physicochemical properties of BG are an important parameter to consider for industrial applications. Molecular structure, size, solubility and viscosity are the most relevant parameters determining the product quality and are also closely linked to the physiological properties of BG. The molar mass is commonly described as the most important attribute regarding both, the origin and the properties of cereal BG. According to the existing literature, the molar mass of BG obtained from oats, barley, wheat and rye ranges between 35 and 3.100, 31 and 2.700, 209 and 416 and 21 and 1.100×10^3 g/mol, respectively (Lazaridou and Biliaderis 2007). A number of external factors, including environmental conditions, β-glucanase activity, processing and storage conditions, as well as the method of extraction and purification were also found to have an impact on the molar mass (Lazaridou and Biliaderis 2007; Regand et al. 2011). Routinely, only BG content and molar mass are considered when discussing the use for technological or nutraceutical benefits. However, this section will identify further key characteristics which need consideration.

Molar ratio

The molar ratio (DP3/DP4 ratio) has a direct influence on the functional properties of the BG molecule. Cellotetraosyl and longer subunits are mainly responsible for the gel forming and high viscosity properties. The cellotriosyl units show responsible for stronger bonds between the individual BG chains (Ryu et al. 2012). A comparative study, using the same extraction procedure on a high BG barley mutant and the corresponding barley mother resulted in substantial differences in solubility. The authors concluded that these differences originate from the differences in molar ratio between the high BG mutant and its mother (Mikkelsen et al. 2013). Similar results were reported by Håkansson, Ulmius, and Nilsson (2012), who found that BG preparations with a high molar ratio are less soluble. The reason behind is the higher amount of cellotriosyl units, causing a very tight packing of the BG chains. Thus, the water

molecules have less space to interact with the BG, resulting in reduced solubility (Håkansson, Ulmius, and Nilsson 2012). In accordance with the lower molar ratio reported for OBG (1.5–2.3) compared to BBG (2.3–3.4), a generally better solubility of OBG is evident from the research data available (Lazaridou and Biliaderis 2007; Izydorczyk and Dexter 2008). The molar ratio is also heavily influenced by cultivar and environmental conditions. It was shown among Canadian oat varieties, that both factors have a strong influence on the molar ratio and therefore should be considered carefully when selecting grains for specific BG applications (Mikkelsen et al. 2013; Herrera et al. 2016).

A recent study provided evidence, that BG with higher molar ratio (DP3/DP4) is more resistant against wheat β-glucanase (De Arcangelis et al. 2019). These results provide a potential way to estimate and control the fate of BG during food processing with regards to enzymatic degradation. Application of BG in products, such as breads, has traditionally proven difficult, due to the enzymatic activity in the added flour (Andrzej et al. 2020; Skendi et al. 2010). The selective application of high molar ratio BG could potentially provide a valid solution, although reduced solubility needs to be considered as well. To date, the study of De Arcangelis et al. (2019) is the only investigation of enzymatic resistance in relation to BG molar ratio, hence leaving several knowledge gaps to fill for future research. Current knowledge on the relation between molar ratio and functionality is very limited and requires further exploration.

Studies on the structure–function relationship of cereal BG regarding their molar ratio are still rare. However, the few reports available clearly show the relevance of DP3/DP4 ratio for the technological and physiological functionality of BG. Thus, future research needs to explore this factor further, in order to fully evaluate it.

Solubility

Among the most important physicochemical properties of BG is the solubility, as it determines the extractability and possible applications. Despite the shared general molecular structure among all cereal BGs, there are significant

differences in solubility. These originate primarily from the variation in the molar ratio, as discussed in Section 3.1.1.

Furthermore, it was reported that BG solubility is also heavily influenced by its intermolecular aggregation states and high-level structure (Zhao et al. 2020). Thus, exogenous physical treatment, even without modification of the molecular structure, can have an impact on the BG solubility and the associated physiological properties. Håkansson, Ulmius, and Nilsson (2012) demonstrated, that extracted BBG dissolves in water on a molecular level. In contrast, OBG samples dissolved as aggregates only. A study conducted on the aggregation properties of BBG and OBG revealed loosely and highly aggregated structures for both types of BG (Zielke, Stradner, and Nilsson 2018; Zielke, Lu, and Nilsson 2019). Some aggregates formed by BBG were very dense, sphere shaped and well defined (Zielke, Lu, and Nilsson 2019). To date, this is the only report on such well-defined and distinct BG aggregates. For high molecular weight BG species, the formation of microgel-like aggregates when dissolved in water was reported and suggested to have a positive effect on the cholesterol lowering properties of BG (Zielke, Stradner, and Nilsson 2018).

In order to improve BG applicability, some studies investigated the environmental conditions facilitating highest solubility. Best results were reported at approximately 55 °C (Vasquez Mejia, de Francisco, and Bohrer 2020). Unfortunately, the extractability of the main contaminants of BG extracts, namely starch and other polysaccharides, is also favored under such conditions (Zielke et al. 2017; Harasym et al. 2019). It was further reported that the solubility of BG can be increased by chemical modification. The addition of carboxyl (COO$^-$) or sulfite (SO$_3^{2-}$) groups significantly improved solubility in water (Elleuch et al. 2011). Interestingly, limited depolymerization of the polysaccharide increased its solubility in water and the solution stability (Gamel et al. 2014). But depolymerization to a molecular weight as low as 130,000 g/Mol resulted in a 50% reduced solubility (Tosh et al. 2008). In order to improve solubility, controlled depolymerization using acid or enzymatic treatment was studied. As a result, BG preparations with adjusted solubility were produced (Sibakov et al. 2013). There is also evidence that moisture present during processing of BG fortified food products promotes depolymerization (Mäkelä, Brinck, and Sontag-Strohm 2020). Also, microwave treatment or germination (24 h) prior to the BG extraction of barley grains were reported to improve extractability, as well as nutraceutical properties of BBG (Ahmad et al. 2016). However, it is crucial to carefully control the time of germination, since a previous study by Hübner et al. (2010) reported substantial decrease in BBG and OBG as a result of germination for 48–116 h.

In contrast, reducing the molecular weight of OBG by subjecting oat–bran muffins to repeated freeze–thaw cycles resulted in a substantial decrease in solubility (Lan-Pidhainy et al. 2007). However, the study failed to examine the exact reasons behind the decreased solubility. Based on the results of El Khoury et al. (2012), freeze–thaw cycles cause a reduced linearity of the polysaccharide chain, resulting in

lower solubility. Further evidence of decreasing BG solubility due to processing was provided by Moriartey, Temelli, and Vasanthan (2010), who reported decreasing solubility as a result of fermentation of a bread dough. Furthermore, the authors concluded that the reduced solubility leads to a reduced viscosity, which can compromise the physiological properties of the BG.

Traditionally, BG solubility was considered a key factor for the health-endorsing properties. These were believed to originate only from the formation of a highly viscous solution in the gastric system. But in light of a recent study, there is evidence that solubility has a lower impact on the health-endorsing properties of BG than originally believed. Instead it appears that also insoluble BG exhibits nutraceutical traits, although these are believed to rely on different mechanisms (Li et al. 2020). However, further research on the nutraceutical properties and mechanisms determining these is required, to extend the knowledge and confirm the findings of Li et al. (2020). Also, the understanding of the formation of aggregates and the resulting implications on solubility need further understanding. Independent from the importance of BG solubility for its physiological effects, it plays a major role in BG extraction and food applications. The targeted use of depolymerization, to adjust technological and physiological properties appears as a promising approach for future research. Better understanding of the behavior of BG in solution will allow the development of more efficient extraction methods, in turn making cereal BG a more accessible and valuable ingredient for food industries.

Viscosity

The formation of a highly viscous solution is considered of high importance for both, technological relevance and physiological benefit. The viscosity of a BG solution is primarily determined by two factors, namely the molecular weight distribution and the concentration in solution, which is limited by the BG solubility (Lan-Pidhainy et al. 2007; Moriartey, Temelli, and Vasanthan 2010). In addition, the viscosity of BG preparations can vary greatly depending on cultivars and environmental conditions (Herrera et al. 2016).

Investigations on the viscosity of crude and purified BG extracts from oats and barley in relation to concentration, shear rate and temperature were conducted by Mikkelsen et al. (2010). The authors found significant differences between BBG and OBG. While BBG was characterized as low-viscosity BG exhibiting Newtonian flow behavior, OBG behaved as shear-thinning high-viscosity BG. The viscosity of OBG solutions was found to be approximately 100-fold compared to BBG at similar concentration. These findings are in correlation with the stronger affinity of OBG toward the formation of micro-gel structures (Zielke, Stradner, and Nilsson 2018).

Investigations on the impact of the dissolution temperature on the gelling properties of OBG and BBG at low concentrations (1 and 1.5%) revealed that no gelation occurred at 85 °C (Mäkelä et al. 2017). The viscosity is independent from the content and composition of starch and α-dextrin

impurities in the extract but can be complemented by the presence of mucin (Mikkelsen et al. 2010; Yuan, Ritzoulis, and Chen 2019). The authors further found the ideal gelation temperature for OBG and BBG at 37 and 57 °C, respectively. The viscosity of a BG extract obtained from pasta was increased as a result of cooking prior to extraction (De Paula et al. 2017). However, the authors found no correlation between viscosity and BG content.

Oxidatively treated BG was found to gel at the same temperatures but produced weaker gels (Mäkelä et al. 2017). The reason behind is in the degradation of the polymer by oxidizing reagents, such as hydrogen peroxide or ascorbic acid (Makela, Sontag-Strohm, and Maina 2015). The oxidation of BBG, using hydrogen peroxide was also described as a useful tool to modulate and improve the viscosity alongside other functional properties of BG extracts (Lee et al. 2016). As such it is a cost-effective, highly efficient (compared to enzyme treatment), food grade approach to modify BG and make it more accessible for industrial applications in the food industry. However, in particular under elevated temperature, oxidation can lead to a complete depolymerization. Therefore, conditions have to be adjusted carefully in order to maintain the desired functional properties of the BG preparation (Faure et al. 2014).

There are controversial conclusions regarding the importance of molar mass for the viscosity of BG solutions. Some authors found, that the molecular weight is in direct correlation with the apparent viscosity of a BG solution (Mikkelsen et al. 2010; Gamel et al. 2014; Mäkelä, Brinck, and Sontag-Strohm 2020). This explains the lower viscosity of extracts obtained through the use of digestive enzymes, leading to partially degraded BG. According to Mäkelä, Brinck, and Sontag-Strohm (2020) this could compromise the physiological properties of BG. Other researchers proposed, that the product of molar mass and soluble BG is in direct correlation with the viscosity (Tosh et al. 2008; Brummer et al. 2012). As a consequence, a reduction in molar mass due to enzymatic activity or other events does not necessarily cause a decrease in viscosity and the connected physiological properties. However, it also should be considered, that a reduction in apparent viscosity can improve the handling and processing ability for industrial applications. Hence, further research should aim toward the comprehensive understanding of the structure–size–function relationship of BG. Only then it will become possible to develop BG preparations combining health-endorsing properties and good processability to utilize cereal BG to the highest extent.

In addition to the technological considerations, the viscosity of BG solutions, forming during passage through the gastrointestinal tract needs to be considered as well. It is among the most important properties, as it was identified as the primary reason behind the health endorsing properties (Mäkelä, Brinck, and Sontag-Strohm 2020). Differences between BBG and OBG regarding the intestinal viscosity were reported by a recent *in vivo* study (Leuzinger, Steingotter, and Nystrom 2018). Using MRI technology, the authors reported higher intestinal viscosity after consumption of BBG meal compared to OBG meal. They attributed these results to the structural differences between BBG and OBG. Also, impurities in the extract were considered as possible influence on the results. Both BG samples resulted in substantially higher intestinal viscosity compared to the control glucose solution.

Further evidence suggests, that products containing BG from dry processing result in higher extractability and viscosity upon passage through a gastrointestinal model (Mäkelä, Brinck, and Sontag-Strohm 2020). Regand et al. (2011) reported, that enhancing the content of soluble BG increased the in vitro viscosity during passage of the gastric system. As a result, the starch digestibility was lowered leading to a reduced glycemic response. On the other hand, a recent study on the incorporation of BG into bread products found the viscosity independent from the reduction in glycemic response after in vitro digestion (Rieder et al. 2019). Despite the need for further verification of these results, they raise questions about the importance of viscosity for the health-endorsing effects of BG. This is of particular interest, since for most industrial applications, the high viscosity of BG makes it more difficult to handle and process. Hence, the application of a BG preparation with low viscosity, yet apparent health-endorsing properties would be ideal and greatly increase the industrial use of cereal BG at concentrations permitting a health claim.

While viscosity of BG solutions plays an important role regarding the technological and physiological properties, attributes determining viscosity and its role upon passage through the human gastrointestinal system is not fully understood. Approaches, such as oxidation and modification are useful tools to adjust the solubility and resulting viscosity but are underutilized due to knowledge gaps in structure–size–function relationship of BG.

Health-endorsing properties

Alongside the technologically valuable physicochemical properties discussed in the previous section, cereal BG is known for its health-endorsing properties. The health benefits associated with the regular consumption of cereal BG are summarized in Figure 3. The most investigated benefits include lowering of plasma cholesterol, reduction of the glycemic response and weight management (Ahmad et al. 2012; Daou and Zhang 2012; El Khoury et al. 2012). Furthermore, they act as prebiotics by promoting the development of a health–beneficial gut microbiota (Thondre, Ryan, and Henry 2011). Based on the scientific evidence, the EFSA and FDA have permitted the use of health claims, regarding the cholesterol lowering and control of glycemic response exhibited by BBG and OBG, if food products contain sufficient amounts (Åman 2006; EFSA 2011; FDA 2008). However, it was summarized in the review by Wood (2004), that only concentration is insufficient as factor to evaluate the efficiency of health-endorsing effects of cereal BG. More in-depth characterization of the polymer is required, in order to accurately determine health benefits of BG-containing products. To this end, the following section will evaluate
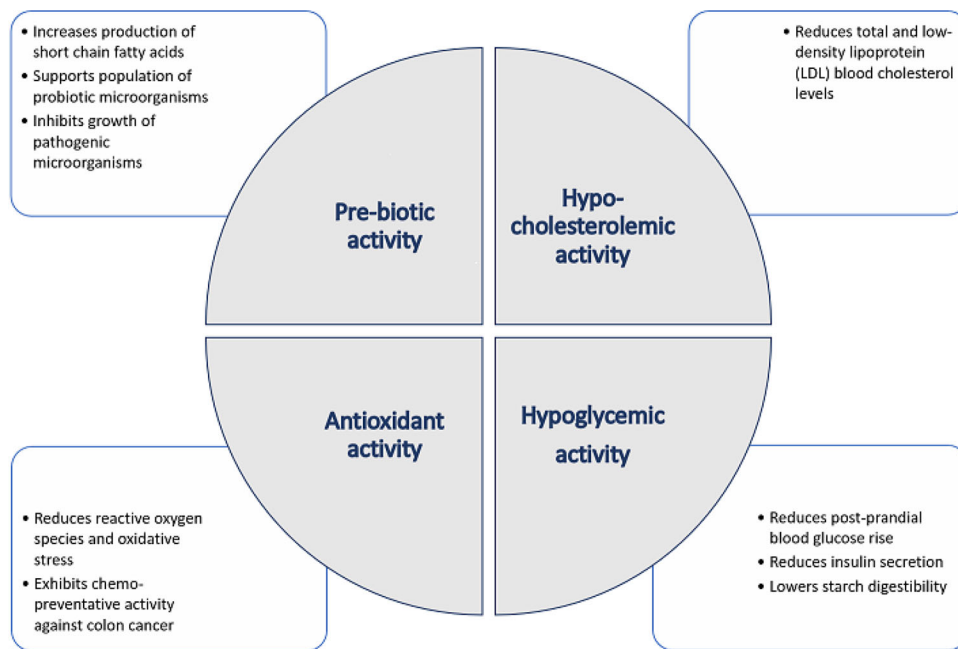
Figure 3. Health benefits associated with the regular ingestion of cereal beta-glucans.

research findings regarding health-endorsing properties of BG and explore the mechanisms behind to utilize BBG and OBG more efficiently as nutraceutical food ingredients.

Glycemic control

The reduction of the glycemic response after consumption of food (glycemic control) is among the most intensely studied and well documented properties of cereal BG. This effect has been investigated in numerous animal and human studies using model food systems. For instance, the comparison of oat bran containing breakfast oats with conventional breakfast oats was demonstrated by Wolever et al. (2018). The addition of bran, equal to 1.6 g of OBG was sufficient for a 20% decrease in peak glucose rise. Similar results became evident in several other studies (Dong et al. 2011; Thondre, Shafat, and Clegg 2013; Cassidy, McSorley, and Allsopp 2018; Rieder et al. 2019; Li et al. 2020). Based on such scientific evidence, for foods containing at least 4 g BBG or OBG per 30 g available carbohydrates, the EFSA has approved a health claim for lowering blood glucose response (EFSA 2011). A recent meta-analysis of cereal BG consumption also concluded that consumption of BG significantly decreases body weight and body mass index (Rahmani et al. 2019). The authors attributed both effects to the reduced glycemic response. However, the study further found no evidence of BG reducing waist circumference or energy intake. Interestingly, consumption of at least 4 g BG per day even results in an increased energy intake. Hence, a reduced digestion efficiency due to the presence of the undigestible BG is evident.

There is evidence, that increasing molar weight and/or viscosity of BG improves the postprandial glucose regulation, indicating that this effect is based on the formation of a high viscosity gel in the intestine (Joyce et al. 2019). Digestible saccharides embedded in this gel are, due to the

resistance of BG against the human digestive enzymes, less accessible (Regand et al. 2011; Zhang, Luo, and Zhang 2017). As a result, the gastric emptying and thus the delivery of chyme to the intestine are delayed. The reduced starch digestibility, as a consequence of the high intestine viscosity, was described by Regand et al. (2011). This effect is based on three mechanisms, namely the restricted access of digestive enzymes upon passage through the intestine, reduced mixing of the luminal content and slower glucose transport to reach the absorbing surface (Henrion et al. 2019). In addition, BG was also found to inhibit the metabolism of glucose and the activities of digestive enzymes, such as α-glycosidase during passage through the digestive system (Dong et al. 2011), further contributing to a reduced glucose response. In consequence, these effects result in a slower, steadier introduction of glucose into the blood stream, leading to lower insulin concentrations. The authors drew a direct correlation between an increase in BG molar mass and glycemic control as a result of the increased intestine viscosity. These findings were confirmed in a later study, reporting that postprandial peak glucose levels show an inverse correlation to the $\log_{10}$[viscosity] after consumption of oat bran cereals (Brummer et al. 2012). However, the molecular size of the BG present was found to be insignificant with regards to the glycemic control.

To date, there are still contradicting reports regarding the importance of molar mass. Some researchers found a high molar mass and viscosity as essential parameters for nutraceutical properties, such as glycemic control (Regand et al. 2011; Sibakov et al. 2014). In contrast, a recent study reported no differences in the control of blood glucose and cholesterol lowering between hydrolyzed (approximately 10,000 g/Mol) and native (1,000,000 g/Mol) BBG in mice (Mio et al. 2020). It was demonstrated that the radiation induced depolymerization of OBG only has minor influences on the biological properties, while enhancing the

technological usability (Hussain, Rather, and Suradkar 2018). Therefore, a controlled depolymerization was suggested, in order to improve the industrial handling. Extraction techniques, such as milling and freeze milling, subcritical water, acid- and enzyme hydrolysis, and thermal treatment are proposed, in order to reduce BG molar mass and therefore increase its field of applications and extraction efficiency (Harasym, Suchecka, and Gromadzka-Ostrowska 2015).

Another vital factor for the ability of BG to control the glucose response is the solubility. It was demonstrated that BG molecules have to be free and able to interact with their surroundings (Kwong et al. 2013). Hence, the application of BG gel was not found to reduce the glycemic response significantly. A model to characterize the efficiency in glycemic response was based on the correlation between peak blood glucose rise and the product of molecular weight and soluble BG content (Tosh et al. 2008). The study determined the peak blood glucose rise after consumption of oat bran muffins (containing 8 g BG/serving) and found a reduction by 44% compared to the whole wheat control muffins. This is further supported by the studies of Lan-Pidhainy et al. (2007) and Rieder et al. (2019), that the glycemic index is in a reverse relationship with the amount of soluble BG consumed during a meal. Moreover, the authors found, that viscosity after in vitro digestion is not related to any of the parameters for postprandial glycemic response. Instead, the positive effects are attributed to the interaction with the mucosa, the higher water content and a reduced gastric emptying due to the presence of BG in the intestinal system (Rieder et al. 2019).

In the light of recent studies (Hussain, Rather, and Suradkar 2018; Mio et al. 2020), the original believes, that BG molar mass and viscosity play an essential role in the control of glucose response, require some reevaluation. The reason behind the contradicting results discussed here is most likely in the limitations of the studies investigating the impact of BG molar mass on the glucose response. They often contain a number of variables, which are likely to have substantial impact on the outcome. For instance, the comparison of low- and high molar mass BG regarding the glucose release in the gastric system concluded the inefficiency of low-molar mass BBG due to the inability to delay starch digestion but failed to provide values of molar mass for all BG sources investigated (Thondre and Henry 2011). Further studies of Regand et al. (2011) and Thondre, Shafat, and Clegg (2013) compared the effects of low- and high-molar mass BG, but unfortunately applied different amounts of BG in their studies. Since it is generally accepted, that the concentration of BG has some influence on the functional properties, these results are only of limited value. Hence, it is still not possible to draw definitive conclusions on the ideal molar mass of BG for the most efficient glycemic control. Further complications arise from the modifications the BG-molecule undergoes during food processing, extraction, analysis and the influence of the surrounding food matrix, to determine the molecular weight objectively.

With the increasing knowledge about parameters with impact on the physiological properties, future research has to take care of carefully controlling these. This appears as necessary improvement in order to produce comparable results, which will allow to draw definitive conclusions on the mechanisms of BG glycemic control. Using this increased knowledge would allow for more efficient application as nutraceutical ingredient.

Cholesterol lowering

Another well studied health-promoting property of BBG and OBG is the ability to lower blood cholesterol levels. While high-density lipoprotein (HDL) cholesterol remains unaffected by BG, the reduction in low-density lipoprotein (LDL) cholesterol, an important marker for the risk of cardiovascular diseases, is recognized (Nakashima et al. 2018). The generally accepted mechanism behind is based on the formation of a highly viscous gel inside the human intestine. The gel interacts with the bile acids present in the gastric system, preventing their re-adsorption and thus promotes the de novo synthesis of such acids (Nakashima et al. 2018; Thandapilly et al. 2018). Since cholesterol is used for the bile acid synthesis, its concentration decreases. Gunness et al. (2016) characterized the impact of BG on the bile acids in the intestine. They found alterations in the acid profile, reduced circulation levels, a reduced ability to diffuse across the terminal ileum and a reduced adsorptive surface area on the microvilli in the jejunum. In this context, the blood cholesterol lowering capacity was found to be in good correlation with the viscosity of the BG extract (Gamel et al. 2014). Further evidence for the mechanism behind the cholesterol lowering properties of BG is provided by numerous animal and human studies, which are comprehensively reviewed by Joyce et al. (2019). Based on this data, the EFSA and FDA have concluded, that the regular consumption of at least 3 g of OBG or OBG/BBG per day is required in order to achieve a substantial cholesterol lowering effect (EFSA 2011; FDA 2008). As a consequence of the lowered cholesterol, the risk of coronary heart disease is reduced also (EFSA 2011; FDA 2008). However, appropriate investigation of this effect is challenging, since it requires 5–6 weeks of high BG diet (Henrion et al. 2019). Over such a long time it has proven difficult to accurately control the diet of the subjects in order to rule out any interferences. Furthermore, using the BG content as the only parameter to warrant a health claim is insufficient based on the results found in literature. Instead, molar mass, solubility and viscosity should be considered also when discussing the cholesterol lowering properties of BG.

Regarding the importance of BG molar mass on the cholesterol lowering properties, controversial results can be found. It was demonstrated that BG with low molar mass is far less efficient in cholesterol reduction compared to higher molar mass BG (2,210,000 g/Mol) when used as supplement in breakfast cereals (Wolever et al. 2010). As a consequence, for the consumption of cereal BG as functional ingredient, a molar mass of 210,000 g/Mol or greater was recommended by the authors. The comparison of wholegrain oats granola with no-wholegrain oats granola showed the total and LDL cholesterol lowering effects of wholegrain oats, primarily

attributed to the presence of BG in the bran (Connolly et al. 2016). Likewise, the comparison of high- and low-molar mass BG revealed significantly better cholesterol reduction for higher molecular weights (Frank et al. 2004; Wang et al. 2016). Unfortunately, these reports failed to determine the exact molar mass of the BG preparations used, making a comparison with other results difficult. A meta-analysis conducted by Whitehead et al. (2014) only examined reports of OBG with a molar mass determined to >100,000 g/Mol. However, due to the lack of a standard method for determination of BG molar mass, some of the results included might be inaccurate. A substantial reduction in LDL cholesterol and total cholesterol was found as a result of the regular consumption of at least 3 g OBG per day. Furthermore, no changes in HDL cholesterol or triglycerides could be determined. Biörklund et al. (2005) determined the cholesterol lowering effect of BG fortified dinks only in a dose dependent manner, without determining the molar mass. The authors found a reduction in LDL and total cholesterol from the drink containing 5 g BG but not the one with 10 g. This was attributed to the faster degradation during storage of higher concentrated solutions, ultimately indicating the importance of high molar mass.

On the other hand, fruit juices supplemented with 5 g of low molar mass OBG (70,000–80,000 g/Mol), consumed daily for 5 weeks were demonstrated to lower the LDL cholesterol significantly (Naumann et al. 2006). These results are supported by an animal study on hamsters, which found no difference between BBG with 175,00 g/Mol and 1,000,000 g/Mol regarding the reduction of non-HDL cholesterol (Wilson et al. 2004). Keenan et al. (2007) reported no difference between low molar mass BBG and high molar mass BBG at a dose of 3 g/day for reduction of LDL cholesterol. Interestingly, at a dose of 5 g/day, an LDL cholesterol reduction of 15 and 13% was found for high and low molar mass BBG, respectively (Keenan et al. 2007).

To date, there is no clear answer regarding the importance of molar mass on the cholesterol lowering properties of cereal BG. It was further proposed by Naumann et al. (2006), that the baseline level of LDL and total cholesterol of the test subjects plays an essential role. While there is some evidence supporting this hypothesis (Ripsin et al. 1992), the meta-analysis conducted by Brown et al. (1999) found no relation between baseline cholesterol level and efficiency of reduction by BG. Overall, the importance of baseline cholesterol levels on the rate of reduction by BG is rarely investigated and remains unclear. The surrounding food matrix is another considerable influence for both BG molar mass and behavior in the gastric system. It is remarkable, that studies which found little or no impact of the molar mass on the cholesterol lowering applied BG in a liquid matrix. In contrast, studies which determined the molar mass as crucial factor used solid foods. This observation is supported by the conclusions of a recent review article (Grundy et al. 2018). It is stated, that the efficiency of BG cholesterol lowering capacity is generally lower but more consistent in liquid foods compared to solid and semisolid foods (Grundy et al. 2018). The authors further reported a trend of refined BG extracts being less efficient compared to whole oat bran (at equal levels of BG) due to synergistic effects with other oat constituents (Grundy et al. 2018). However, it needs to be mentioned that this can often result in technological and/or sensorial compromised products, since relatively high amounts of oat bran are required to achieve physiological benefits.

Further aspects to consider in relation to the health-endorsing properties of BG include the increased population of microorganisms beneficial for the human gastrointestinal health, namely lactic acid and Bifido bacteria. The ability of selected strains of lactic acid bacteria present in the human intestine to lower cholesterol levels is well documented (Lim, Kim, and Lee 2004; Tsai et al. 2014; Shehata et al. 2016). To this end, the consumption of whole oat granola was reported to result in the stimulation of probiotic bacteria, responsible for the cholesterol reduction (Connolly et al. 2016). The importance of the solubility, and in turn also viscosity, of BG for the cholesterol lowering properties is not fully understood yet. While only soluble BG can form a viscos gel in the intestine, the probiotic activity is primarily based on the fermentability of BG by cholesterol lowering strains of lactic acid bacteria. In this regard, soluble and insoluble fractions of OBG were investigated for their impact on blood cholesterol and lipid levels in mice. In contrast to traditional believes, also the insoluble fraction was able to reduce LDL-cholesterol, while increasing HDL-cholesterol (Li et al. 2020). This is the first report of an increase in HDL-cholesterol alongside the LDL cholesterol reduction resulting from the consumption of cereal BG. If further investigations can provide more insight to the mechanisms behind the cholesterol lowering properties, in particular of insoluble BG, this could allow a broader field of application of BG as nutraceutical ingredient.

Careful revision of the scientific evidence regarding the LDL and total cholesterol lowering properties of cereal BG clearly shows that consideration of BG content alone is insufficient. In order to determine the health-endorsing properties of BG, molar mass, solubility and surrounding food matrix have a substantial impact. Due to the varying study designs and analytical methods applied to characterize the BG applied, the results of different studies are difficult to compare. For instance, BG with a molar mass of 200,000 g/Mol might be considered as high molar mass in one study (Naumann et al. 2006) but as low molar mass in another (Wilson et al. 2004). Adding the differences in molar mass, depending on the method of extraction and analysis used, this makes it nearly impossible to draw conclusions across different studies. However, there is a general trend toward better cholesterol lowering properties of high molar weight BG. Regarding the minimum weight required, further investigations are necessary. The apparent need for higher molar mass in solid food products has to be considered as well.

Others

Alongside the intensely studied lowering of blood cholesterol and glycemic response, there is some evidence for further benefits from the regular consumption of cereal BG. Effects

discussed include probiotic activities in the intestine and cancer prevention, among others. This section is to summarize the limited scientific data available and identify future research interests.

Pre- and probiotic effects are attributed to the consumption of cereal BG. The most commonly accepted mechanism behind is based on the BG providing a fermentable substrate for the bacteria, promoting their growth and population. Substances, such as bile acids, which are metabolized alongside the BG polysaccharide support the bacterial development further (Joyce et al. 2019). As a by-product of the bacterial metabolism, an increase in short chain fatty acid (SCFA) content (primarily propionic acid) in the intestine was found in various animal and human studies (Alvaro et al. 2008; Miyamoto et al. 2018; Thandapilly et al. 2018; Yau et al. 2020). Health–beneficial lactic acid and bifido bacteria were found to be particularly promoted by the availability of fermentable BG (Jayachandran et al. 2018; Sanders et al. 2019). As a consequence, the gut microbiota is altered toward more prominent populations of beneficial bacteria. At the same time, adverse microorganisms, such as the pathogenic *Candida glabrata* are found to be eliminated due to the ingestion of BG (Charlet et al. 2018). The recent research activities on this topic were comprehensively reviewed by Joyce et al. (2019). Other discussed effects of BG on the gut microbiota include the promotion of production of exopolysaccharides and the microbial cholesterol assimilation.

Furthermore, polyphenols are often bound to BG and released upon bacterial fermentation. These can act as antioxidants and free radical scavengers, inducing further health promoting effects (Jayachandran et al. 2018). This antioxidant activity was reported to be significantly higher for BBG compared to OBG (Nakashima et al. 2018). There is further evidence, that BG is incorporated in the circulatory system and/or stimulates the human antioxidant system. As a result, the antioxidant activity is evident in internal organs beyond the gastric system (Nakashima et al. 2018). The antioxidant and anticancer activity of BG was found to be in direct correlation to the molar mass (Błaszczyk et al. 2015; Henrion et al. 2019). To date, the antitumor activity is mainly studied for mushroom BG (Nakashima et al. 2018). Preventative properties of cereal BG against colon cancer are discussed but only few relevant studies have been conducted so far. A recent study on waxy winter barley indicated chemopreventative potential of in vitro fermented raw and roasted flakes (Schlormann, Atanasov, et al. 2020). The authors attributed this primarily to the inhibitory and apoptotic properties investigated on LT97 cells. In addition, the SCFA concentrations generally increased, with particular shift toward butyric acid, while levels of ammonia decreased significantly (Schlormann, Atanasov, et al. 2020). Interestingly, it was found that OBG with lower molar mass has higher anticancer activity, compared to high molar mass (Choromanska et al. 2015). Hence, fermentation of BG can increase the activity. Similar results were reported upon application of the same study design on raw and roasted oat flakes (Glei et al. 2020). Both studies give evidence to the

chemopreventative effects of cereal BG against colon cancer, which remained unaffected by roasting of the cereal flakes. Instead, the immune stimulation induced by BG is strongly dependent on the type of linkage, degree of branching and solubility (Soltanian et al. 2009). High solubility was identified as a particularly important parameter for the immune stimulation by cereal BG. However, studies on the anticancer and antioxidant properties of BG are still very rare, thus leaving substantial knowledge gaps. Future research needs to explore these more complex effects of a high BG diet more thoroughly to provide a comprehensive understanding and allow for full utilization.

Extraction

Based on the numerous desirable properties, BG is considered a very valuable ingredient for many applications. Due to the naturally low concentration of BG in cereals, a wide range of applications as health-endorsing product requires the extraction and concentration of BG prior to use (Vizhi and Many 2014). Extraction procedures are generally grouped in one of two categories, carried out in dry or wet conditions (Benito-Román, Alonso, and Lucas 2011). In order to avoid undesirable alterations during extraction and concentration, the conditions need careful adjustment and monitoring. This is not only regarding extraction yield and cost efficiency, but also taking the possible changes in physicochemical and physiological properties of OBG and BBG into account (Kaur et al. 2019). Only then, the desired effects for both, product quality and consumer health endorsement are achievable. The scientific literature on the extraction of oat and barley BG was thoroughly reviewed some years ago by Vasanthan and Temelli (2008). Therefore, this section will focus primarily on recent research advances to help identify the ideal method to access cereal BG.

Dry extraction

Dry processes aim primarily toward the selective milling of barley or oats. As shown in Figure 1, the highest BG concentrations are present in the bran fractions, which can be separated during the milling process. The biggest advantage of dry extraction techniques is the absence of potentially hazardous chemicals during the extraction process. However, due to the need of several consecutive cleaning and concentration steps this method is highly cost-intensive, while still yielding comparatively low BG concentrations (Benito-Román, Alonso, and Lucas 2011). In addition, defatting of the samples before dry extraction is necessary in order to obtain best results (Benito-Román, Alonso, and Lucas 2011; Sibakov et al. 2014; Vasquez Mejia, de Francisco, and Bohrer 2020). From selective milling, BG concentrations of approximately 12% from barley and 17% from oats, can be obtained (Malkki et al. 2004; Benito-Román, Alonso, and Lucas 2011; Wiege et al. 2016).

Although researchers obtained BG also from other sources, such as the endosperm cell walls (Kanauchi and Bamforth 2001), these approaches are much less popular.

Table 2. Commercially available β-glucan preparations with extraction method, source cereal and selling company, adapted from Vasanthan and Temelli (2008).

Company	Source	Process	Trade name
Natraceutical Canada	Barley and oat	Semi-alcoholic enzymatic	Viscofiber® (up to 65%)
GTC Nutrition, USA	Oat	Aqueous	OatVantage™ (up to 54%)
Cargill Inc., USA	Barley	Aqueous	Betafiber™ (up to 70%)
GraceLinc Ltd, New Zealand	Barley	Aqueous	Glucagel™ (up to 75%)
Van Drunen Farms, USA	Oat	Aqueous thermomechanical	Nutrim™ (up to 6%)
Danisco, USA	Oat	Aqueous enzymatic	Oatrim™ Trimchoice™ (up to 25%)
Crea Nutrition Inc., USA	Oat	Milling and air classification	Oatwell™ BG3™ (up to 22%)

This is mainly due to the option of using the inner parts of the grain, i.e. the endosperm, for further purposes. In particular for oats, but to some extent also for barley, the bran is removed to avoid interference during downstream processing and used as animal feed (Slavin, Jacobs, and Marquart 2000). The use of bran with less than 20% BG is not suitable for most applications aiming at noteworthy health benefits. The total amount of bran needed would significantly compromise the product quality and sensory profile (Du, Zhu, and Xu 2014). The technological shortcomings of bran constituents other than BG, such as insoluble fibers, usually cannot be compensated for. It further has to be considered that using only the BG rich parts of the barley or oat grains equals a substantially increased use of raw material, with only approximately 30% of the barley and 21% of the oat kernel used for BG fortification (Malkki et al. 2004; Wiege et al. 2016). As a result, selective milling is commonly used only in combination with subsequent wet extraction techniques to obtain sufficiently high concentrated and pure BG extracts (Ahmad et al. 2012).

Only very limited research investigating advanced techniques of dry extraction and purification has been conducted so far. The use of ultrafine grinding and electrostatic separation was shown to result in an extract containing 56% OBG (Sibakov et al. 2014). The industrial relevance of this approach is still very limited, due to the cost-intensity of the process. Also, defatting of the sample prior to extraction remains a noteworthy drawback. However, as an emerging technology, electrostatic separation could in future turn into a much more feasible process, offering an interesting alternative for BG extraction. The future perspectives of electrostatic separation were extensively reviewed by Laigle and Barakat (2017).

To date, the most common way to fortify food products with cereal BG is the addition of bran obtained from selective milling. However, this approach is not suitable for all kinds of food, i.e. liquids. It further requires the addition of high amounts of oat or barley bran in order to achieve significant health benefits. Hence, the final product often has compromised sensory or technological quality or does not contain enough BG to qualify as functional food (Heiniö et al. 2016). Future research should dedicate more efforts into the development of novel and advanced dry extraction techniques to allow for easier incorporation of cereal BG.

Wet extraction

Wet extraction procedures are usually based on the solubility of cereal BG in hot water with subsequent precipitation in ethanol. They are more popular than dry extraction techniques, primarily due to the higher BG contents and purity achievable. Also, further purification of high BG fractions obtained from dry processes is often carried out (Vasanthan and Temelli 2008). As shown in Table 2, most commercially available BG extracts were obtained by wet extraction procedures and can contain up to 75% of cereal BG (Vasanthan and Temelli 2008). The main impurities present in such extracts are starch and proteins (Zielke et al. 2017; Harasym et al. 2019). Further purification would require the use of hydrolytic enzymes and substantially increase the extraction costs (Kivelä et al. 2012; Limberger-Bayer et al. 2014). Instead, BG-rich fractions obtained from dry milling or the raw extract are commonly used for food products.

As summarized by Vasquez Mejia, de Francisco, and Bohrer (2020), there are numerous factors impacting the efficiency of the BG extraction process. These include the solvent, temperature, pH, time, particle size and fat content of the sample, among others. An early study investigating the ideal condition for the extraction of BBG was conducted by Temelli (1997). Best results in terms of foam yield, purity, foam stability and whippability were reported for pH 7 at 56 °C, using hot water and alcohol for the extraction. The method was later adapted by Liu (2014) in order to study the effect of defatting and centrifugal force on the extraction efficiency. Centrifugation on defatted samples was found to increase the BG yield from 46 to 51% at a centrifugation speed of 1000 g. An investigation on the ideal extraction parameters for BBG from different varieties using hot water determined the ideal particle size to 100 μm. In addition, a solvent–flour ratio of 5 and stirring at 1000 rpm for 3 h at 55 °C, pH 7 resulted in the highest BG yield (Benito-Román, Alonso, and Lucas 2011). The authors further demonstrated that such conditions result in highest BG yield, regardless of the composition of the barley extracted. Similar parameters were reported by Gangopadhyay et al. (2015), who carried out the extraction at pH 8 to inactivate the endogenous β-glucanases and prevent depolymerization of the polysaccharide. After 4 h of extraction, they obtained an extract yield of 81% for BBG with a molecular weight of 351,000 g/Mol.

A comparison between novel extraction approaches, namely accelerated solvent extraction (ASE), ultrasound, microwave assisted and the conventional reflux extraction of BG produced highest yields from the ASE (Du, Zhu, and Xu 2014). The extraction was carried out in subcritical water at 70 °C and a pressure of 10 MPa. The authors concluded, that ASE using subcritical water has the potential for industrial BG extraction. At the same time, ASE presents a

number of advantages, such as an environmentally friendly extraction and solvent system, shorter extraction times and reduced extraction discrimination, compared to conventional systems (Sun et al. 2012; Du, Zhu, and Xu 2014). However, before industrial establishment of BG extraction using ASE is possible further optimization is required. To this end, Yoo, Ko, and Chung (2020) reported on the importance of accurately controlling the extraction time to prevent excessive depolymerization and subsequent loss of functional properties. Other parameters to adjust include the particle size and solvent pH, among others (Du, Zhu, and Xu 2014; Yoo, Ko, and Chung 2020)

As mentioned before, the ideal extraction conditions for BG also provide a suitable solvent for starch and proteins, the main impurities in BG raw extracts (Zielke et al. 2017; Harasym et al. 2019). Since enzymatic purification is too cost-intensive for food applications, some researchers have started to investigate alternative purification techniques. First studies using high pressure and supercritical fluids (Benito-Román, Alonso, and Cocero 2013a) or ultrasound (Benito-Román, Alonso, and Cocero 2013b) were conducted but are still insufficiently developed. When Zielke et al. (2017) applied heat-stable α-amylase during the aqueous extraction, only degraded starch occurred as impurity in the raw extract, while molecular weight and size of OBG and BBG were preserved. In particular, the absence of covalently bound proteins without application of proteinases is noteworthy. Further investigations should be conducted to clarify if an extract of similar quality can be produced without use of any enzymatic hydrolysis.

Future investigations should aim to produce BG extracts as a more cost-effective solution for nutraceutical foods. Using conventional extraction methods, water or weak alkaline solutions are the most preferable in order to obtain a low-cost, high yield extract of cereal BG with a high molar mass (Maheshwari, Sowrirajan, and Joseph 2017). However, emerging novel technologies, such as ASE, should be more intensely investigated also. Finding optimum conditions to facilitate a rapid extraction with minimal impurities will be essential to utilize the full potential of cereal BG as nutraceutical ingredient.

Food applications

The application of cereal BG is desirable for a broad range of food products, due to the combination of both, health promoting and technological properties. However, since extraction, handling and fate during upstream processing impose a number of challenges the use, in particular as health-endorsing ingredient, is still limited. This section is aiming to evaluate reports on the use of BG as functional ingredient in order to identify present achievements and future challenges to utilize the health-endorsing properties of BG better.

BG is routinely used in liquid food matrices, such as beverages, sauces and soups. However, this is primarily for its emulsifying and thickening properties but usually not as nutraceutical ingredient (Zhang et al. 2018; Karp, Wyrwisz,

and Kurek 2019). Karp, Wyrwisz, and Kurek (2019) also stated, that the high viscosity and difficult industrial handling can limit the usefulness of BG for the beverage industry. This is a particular problem when sufficient concentrations for health-promoting properties are applied. Various different commercially available BG preparations were studied by Lyly et al. (2003) for their suitability in beverage products. The authors reported, that higher processed BG with lower molar mass is more suitable, since it has less impact on the product viscosity. For the development of a cereal beverage, substitution of 0, 0.3, 0.5 and 0.7% of pectin with BBG was investigated. While all beverages showed microbial stability over 12 weeks and an acceptable color, a substantially increased viscosity was evident for the drinks containing 0.5% and 0.7% BBG (Temelli, Bansema, and Stobbe 2004). However, the trained sensory panel rated all the BG beverages as acceptable. Another study, aiming at the production of a cereal based fermented beverage, investigated the combination of OBG with lactic acid bacteria (LAB) (Angelov et al. 2006). The authors reported no changes to the content of BG throughout the 8 h fermentation period and subsequent storage. Also, high viability and activity of the LAB was evident. On the downside however, the drinks contained only up to 0.36% of OBG. In order to exhibit physiological benefits this would require a minimum consumption of approximately 800 mL of the drink every day. Furthermore, the authors did not characterize the properties of the BG before and after fermentation. However, there is evidence that fermentation by LAB can compromise BG solubility and extract viscosity (Moriartey, Temelli, and Vasanthan 2010). As evaluated in the previous sections, this is likely to compromise the physiological benefits as well.

The implementation of BG to noncereal liquid matrices was also investigated, despite receiving much less research attention. The addition of 3% OBG to chocolate flavored milk was reported to improve the texture, mouthfeel and viscosity of the product (Chatterjee and Patel 2016). The fortified milk can be claimed as source of fiber but further investigations regarding the fate and functionality of BG during upstream processing were omitted. Therefore, it remains unclear if health–beneficial properties can be expected from the milk drink. The fortification of fruit juices with BG resulted in both, positive and negative hedonic ratings of consumers (Andersen et al. 2017). The authors concluded that supplementation of fruit juices with BG as nutraceutical ingredient is, from a hedonic point of view, difficult. It further needs to be considered that hydroxyl radicals and organic acids, particularly in beverage formulations, induce oxidative depolymerization of the BG molecule (Aman, Rimsten, and Andersson 2004; Kivelä et al. 2009; Makela et al. 2017). As a result, the content of ascorbic acid in food preparations needs to be maintained as low as possible to avoid compromising of the added BG. It was further reported, that due to the depolymerization during storage, the viscosity of a BG fortified drink decreased in direct correlation to the molar mass (Kivelä et al. 2009). Since many of the health–beneficial properties are linked to the viscosity (as discussed above) this acid induced depolymerization

would induce a substantial deterioration of the nutraceutical properties. One point, which should be investigated more intensely is the apparently lower susceptibility of ß-(1,4)-glycosidic bonds for depolymerization, in particular by ascorbic acid (Makela et al. 2017). Hence, BG with low molar ratio is expected to show a higher resistance against oxidative depolymerization.

Regarding solid food matrices, addition of BG is primarily investigated for cereal-based products. To study the potential for food applications, the impact of roasting (140–200 °C, 20 min) of oat and barley flakes on BG was investigated (Schlormann et al. 2019; Schlormann, Zetzmann, et al. 2020). Both studies reported no changes in BG content but a significantly reduced extract viscosity after the treatment. Furthermore, roasting temperatures up to 160 °C even improved the sensory properties of the cereal flakes. However, the fortification of bakery products with physiologically active amounts of BG encounters some technological difficulties. These include most prominently the gel forming, water holding and high viscosity of BG preparations (Harasym, Suchecka, and Gromadzka-Ostrowska 2015). In order to overcome these, the effect of various pretreatments on the technological properties of BG fortified bread (>0.75 g/serving) was investigated (Kurek et al. 2018). It was found that the best pretreatments are drying, freezing and freezing with subsequent boiling before addition to the bread dough. The resulting breads showed the best technological performance in terms of crumb firmness, springiness and color, while also containing highest BG levels in the final product. However, the author did not investigate the impact on the physiological traits of the added BG. As discussed before, factors such as depolymerization or intermolecular aggregation can heavily impact the physiological performance of BG (Zhao et al. 2020). The production of a high BG bread by Jayachandran et al. (2018) found an increased loaf volume and reduced glycemic index. It was further shown, that the reduced rate of starch digestion, due to the encapsulation in a high viscosity BG gel in the intestine, is the reason behind the lower glycemic index of the bread. To this end, development of a low-starch, high-fiber functional bread, with an increased BG/starch ratio was reported to improve long term metabolic control (Tessari and Lante 2017). The authors further concluded, that it may potentially be used in the dietary treatment of type 2 diabetes. Investigations on the importance of BG molecular weight on dough and bread quality revealed that higher molecular weight leads to better bread quality, in particular when used in combination with a flour, exhibiting poor bread making quality (Skendi, Papageorgiou, and Biliaderis 2009; Skendi et al. 2010). The addition of OBG to gluten-free bread, substantially enhanced the rheological dough and bread qualities and nutritional value (Hager et al. 2011). However, the authors also concluded that the adaptability for wheat breads is limited, due to the activity of endogenous β-glucanase. This is further supported by Moriartey, Temelli, and Vasanthan (2010), who found a reduced nutraceutical activity, due to the lower solubility and viscosity. However, it also should be considered that

during food storage, a substantial degradation of BG can occur. It was shown in bread, manufactured with 5.5% OBG (based on dry matter), that after 3 days of storage at ambient temperatures the viscosity of the bread slurry started to decrease rapidly. This was attributed to depolymerization events induced by enzymatic activity (Gamel, Badali, and Tosh 2013). To prevent the depolymerization, freezing at −18 °C was found efficient to preserve the physicochemical and nutraceutical properties of BG in bread (Gamel, Badali, and Tosh 2013). However, repeated freeze–thaw cycles result in the decreased solubility and viscosity (Lan-Pidhainy et al. 2007). Based on this information, the shelf-life of the health-endorsing properties should find more consideration in future research.

The replacement of 30% semolina flour with high BG barley flour for the production of pasta was found possible (De Paula et al. 2017). The authors further stated, that their product meets the requirements for the BG-related health claims. Despite the detrimental effect of extruding and drying on the physicochemical properties of the BG, cooking enhanced the viscosity enough to compensate these effects. Similarly, the replacement of semolina with BG rich barley flour for the production of couscous was found to be successful. The resulting couscous showed no noteworthy quality deterioration and was found to be eligible for a health claim (Messia et al. 2019). However, both studies evaluated the BG addition only in a dose dependent manner, omitting parameters, such as molar mass from the observation.

In addition to the health-endorsing properties, good sensory characteristics of BG fortified processed foods are essential to achieve consumer acceptance. To this end, the hedonic ratings of BG fortified fruit drinks revealed no differences in overall liking and taste compared to the control drink. However, odor, aroma, texture and aftertaste were compromised by the addition of 10 g/L BG (Andersen et al. 2017). Likewise, the fortification of yellow alkaline noodles with OBG resulted in compromised sensory quality (Choo and Aziz 2010). Although no differences in flavor and elasticity were evident, firmness, surface smoothness and overall acceptability were reduced compared to the control.

In contrast, no impact on sensory quality was found for sponge cake, fortified with up to 4% BG (Yu et al. 2007). Even improved ratings for taste and overall appearance were found for a cereal bar enriched with 5.2% BBG (Vitaglione et al. 2010). The investigation of BBG as fat replacer for yoghurt reported a good textural and sensory quality low-fat products after addition of 0.5% BBG (Brennan and Tudorica 2008). The authors concluded, that BBG has good potential as fat replacer, but did not investigate the sensory impact at levels high enough to warrant a health claim.

From the literature available, it becomes evident that studies on the incorporation of OBG or BBG in food products are almost exclusively limited to beverages and baking products. Moreover, often the concentrations applied are not high enough to induce health-endorsing properties and the fate of BG during processing and food storage is often not investigated. The fate of BG during food processing and storage, in particular due to acids and enzymatic activity

needs to be investigated more intensely. This will be of major importance to produce food products which can deliver maximum health benefits to the consumer. In addition, expanding the field of applications beyond cereal-based products should be explored more. Thereby, a number of additional challenges will become evident. These include a bigger impact on textural and sensory properties of the final products, as well as more complex interactions between BG and the surrounding food matrix.

Conclusions

The health–beneficial properties of cereal BG have been extensively studied and acknowledged by a number of health authorities in form of health claims. Since BG naturally occurs in cereal bran, which is often removed as a milling by-fraction, it provides a great opportunity for foods with added health value. However, this opportunity is just rarely utilized. As discussed in this article, health claims are legally issued in a dose-dependent manner. As a consequence, most intervention studies provide very detailed information only on the dose of BG. But based on the scientific evidence this approach is insufficient to predict the health value of BG-rich foods. Instead, parameters, such as molar mass, solubility, extract viscosity and food matrix are equally important to monitor and consider for maximum health benefits. More high-quality investigations, including comprehensive characterization of the administered BG are required to obtain a better understanding of the interactions between physical and health-endorsing properties. This will allow to identify the key parameters and according thresholds for BG-rich food products to exhibit substantial health benefits. On the other hand, this provides the possibility to optimize and possibly simplify the industrial handling of BG and BG-rich foods.

The extraction, food processing and storage subject the BG molecule to a number of stress factors, which change the essential characteristics to varying degrees. Therefore, future studies need to pay close attention to the fate of BG during upstream processing. Based on this information, the processing conditions applied will need reevaluation to ensure maximum functionality. This also requires the possibility to obtain reliable results, which can be compared across different studies. Hence, the development of accurate analytical methods needs to receive more attention also. To this end, extraction and analysis of BG needs to be adjusted to closely mimic the conditions in the human gastric system. Only then, accurate evaluation of key parameters, such as gastric and intestine viscosity is possible. Otherwise, changes in the molecule due to the food processing and extraction procedure prevent the gain of a clear understanding regarding the relationship between structure and physicochemical and health endorsing properties.

Alongside the well-studied reduction of glycemic response and lowering of blood cholesterol levels, there is increasing evidence on additional health benefits due to a high-BG diet. These include weight control through increased satiety, anticancer activity as well as pre- and pro-

biotic effects on the intestine microbiota. To date there is only very limited literature on such properties available. But further exploration could contribute to make cereal BG a more popular functional ingredient, in particular if new key characteristics can be identified for these effects. For instance, the anticancer activity appears to be promoted by lower molar mass (Choromanska et al. 2015), while glycemic control and cholesterol reduction are favored by high molar mass.

In order to provide the health benefits of BG to a broad range of consumers, the most critical aspects for buying and consuming food products must be considered also. This includes a high textural and sensory quality of the product. Furthermore, it was shown, that the advertisement of a product with certain health benefits increases the likelihood of consumption (Loebnitz and Grunert 2018). Only if consumers accept and consume the products with maximum health benefits, this research can be seen as a success.

To this end, future research also needs to focus on the acceptability and consumer awareness for cereal BG as nutraceutical food ingredient. Applying BG as functional ingredient to a broader variety of food products in combination with the appropriate advertising of the health-endorsing effects can make a valuable contribution. Furthermore, attributes, such as color and overall appearance of the final products require high attention, in order to produce functional foods with high consumer acceptance.

Finally, expanding the field of applications beyond bread and cereal based drinks will be necessary to fully utilize the benefits of cereal BG. Very limited research has been conducted to expand the product variety, which can profit from BG as nutraceutical ingredient. In order to accelerate this expansion, the development of effective extraction methods and better understanding of the key characteristics responsible for the health-endorsing effects is required. Ultimately, these steps will help to fully utilize the potential of BG to produce nutraceutical food products with high sensory quality.

Disclosure statement

The authors declare no conflict of interest.

Abbreviations

ASE	accelerated solvent extraction
BBG	barley beta-glucan
BG	beta-glucan
DP	degree polymerization
EFSA	European Food Safety Authority
FDA	U.S. Food and Drug Administration
HDL	high density lipoprotein
HPLC	high performance liquid chromatography
LAB	lactic acid bacteria
LDL	low density lipoprotein
MRI	magnetic resonance imaging
OBG	oat beta-glucan
SCFA	short chain fatty acids

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