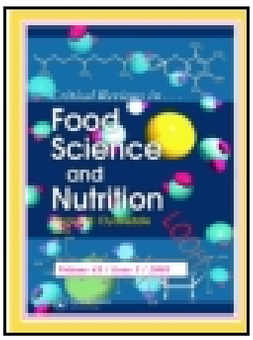

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REVIEW

A comprehensive review on cereal β-glucan: extraction, characterization, causes of degradation, and food application

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ABSTRACT

β-glucan derived from cereal sources are high in soluble dietary fiber and can be used as thickeners, texture enhancers, stabilizers, and fat substitutes in foods. Due to its pronounced viscosity, β-glucan has physiological activity in the body, such as decreasing the glycemic index of foods and reducing the incidence of cardiovascular disease in people. This review focuses on the characteristics of cereal β-glucans, extraction methods, and causes of degradation, while presenting the most relevant and recent applications in foods. Today, there is an abundant amount of information regarding extraction and characterization of β-glucans. However, studies on the degradation and application of fiber are more recent and warrant review. The incorporation of β-glucan has worked well in high carbohydrate foods (e.g., pasta and snacks), but there are still challenges with its inclusion in protein-rich foods (e.g., dairy and meat products). After a comprehensive search and an objective point of view of these aspects, the primary challenges with the incorporation of β-glucan in foods are the inclusion of sufficient amounts of dietary fiber to have a significant nutritional contribution, the combination with other ingredients and other components of the food (evaluated synergistically or antagonistically), and the new incorporation of β-glucan in foods without their degradation during processing.

KEYWORDS

Cereal compounds; dietary fiber; fiber incorporation; fiber ingredients; soluble fiber

Introduction

It has been suggested that the consumption of dietary fiber improves intestinal health and helps in the prevention and treatment of chronic diseases by lowering blood cholesterol (Wang et al. 2014; Whitehead et al. 2014) and by maintenance of glucose homeostasis in people that are pre-diabetic or in patients with type II diabetes (Liatis et al. 2009; El Khoury et al. 2012). Therefore, incorporation of dietary fiber may result in foods that are healthier, lower-calorie, cholesterol-lowering, and fat-free (Elleuch et al. 2011).

The recommendations for total dietary fiber intake are 21 to 25 g/day for women and 30 to 38 g/day for men (Li and Uppal 2010). Moreover, around 20 to 30% of daily total dietary fiber intake should come from soluble dietary fiber (Elleuch et al. 2011). This means that between 4 to 9 g (using the lower range) of the total dietary fiber consumed each day should be soluble dietary fiber. However, the daily intake of total dietary fiber in the world remains considerably lower than the recommended levels (Dong et al. 2018; Lie et al. 2018; Du, Zhu, and Xu 2014; Zhang and Wang 2013; Levy et al. 2012). This has led to many research initiatives by food scientists to find ways to incorporate dietary fiber into commonly consumed foods. Soluble dietary fiber from cereals sources, such as β (1-3)(1-4)-glucans from oats and barley, present useful application in terms of both health and food functionality (Zhu, Du, and Xu 2016; Comin, Temelli, and Saldaña 2012). The consumption recommendations of β-glucan are 3 g/day (0.75 g/serving) to have an effect on health (FDA, 1997), or 4 g/30 g of available carbohydrates (EFSA 2011). From a health perspective, the beneficial effects of β-glucan are associated with their ability to form viscous solutions by retaining water in the digestive tract, namely the large intestine. This in turn, improves digestive health by increasing stool volume, and improves homeostasis of blood glucose levels based on the impacts on hyperglycemia (Gamel et al. 2014; Burkus and Temelli 2005). A recent study reported that consumption of cereal β-glucan was related to decreased body weight and body mass index, but no effects were observed on waist circumference or energy intake/maintenance (Rahmani et al. 2019). At the same time, the application of β-glucan ingredients in food products has the potential to improve textural characteristics since β-glucan can act as a thickening agent, emulsion stabilizer, and fat substitute (Piñero et al. 2008; Álvarez and Barbut 2013). These attributes have encouraged food manufacturers and researchers to investigate the incorporation of β-glucan enrichment in various types of foods.

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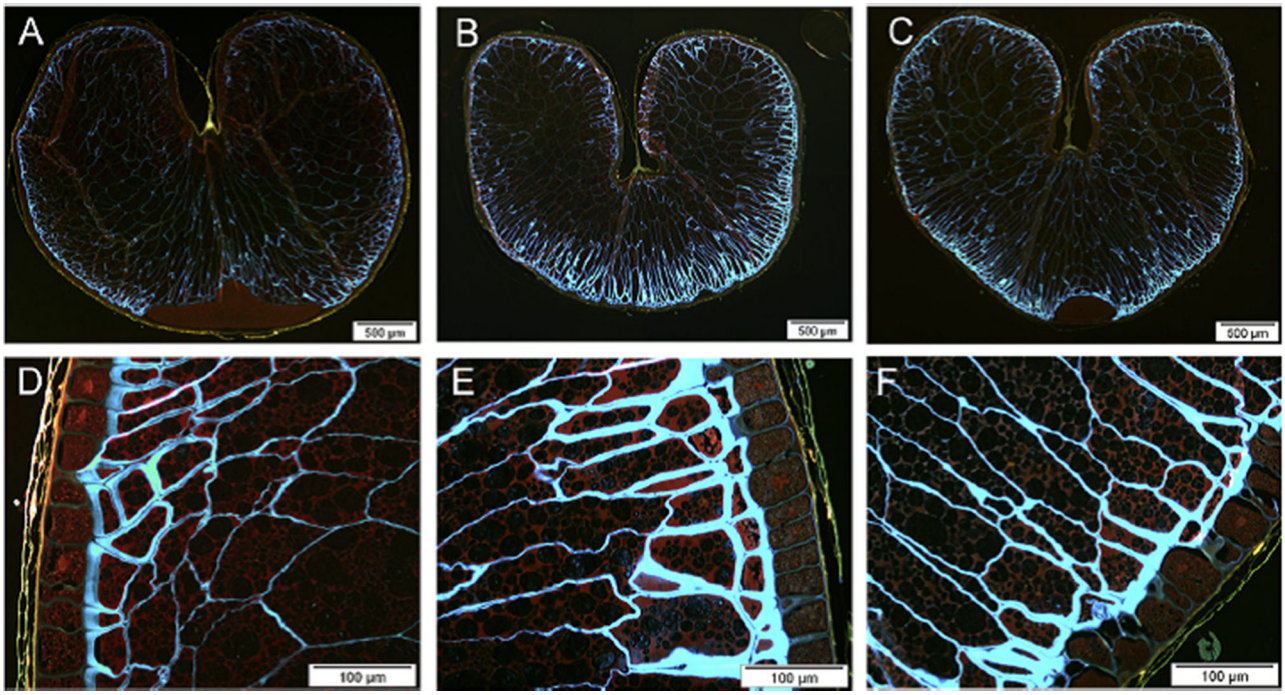

Figure 1. Location of β-glucan in seed kernel oat. A–C; cross sections of whole seeds. D–F; A 10X higher magnification of the same sections. A and D; SW Belinda. B and E; SW Betania. C and F; SW Kerstin.
Source: Sikora et al. 2013.

However, there are several limitations when β-glucan ingredients are applied in foods, such as the maximum quantity that can be incorporated, the characteristics attributed to the final product, and the possible degradation of the fiber by properties and reactions of the food (pH, minerals, or other compounds) or during food processing/preparation. Therefore, this article aims to discuss the most relevant aspects of cereal β-glucan in recent years, addressing the extraction methodologies, the main molecular and physicochemical characteristics, the causes of degradation, and the diverse applications in foods.

Sources and chemical structure of β-glucan

Cereal β-glucan are defined as fibrous structures that form mixed linkage glucans with a combination of 1-3 β-glycosidic and 1-4 β-glycosidic linkages. β-glucan with these structures are mostly found in the aleurone, the subaleurone layer, and the cell walls of the endosperm of certain cereals; such as oats, barley, wheat, and rice. The grain's structure can be further observed and defined with fluorescence microscopy (Sikora et al. 2013) (Figure 1). In addition to cereal β-glucan, non-cereal β-glucan are also fibrous structures that are commonly found in yeasts, mushrooms, bacteria, and algae. These structures are different in several ways, including the glycosidic linkages which are a combination of 1-3 β-glycosidic and 1-6 β-glycosidic linkages (Zhu, Du, and Xu 2016). These differences in structure (glycosidic linkages) affect chemical and molecular characteristics in food processing and functional characteristics in digestive health. Specifically, the differences in glycosidic linkage structure alter solubility during processing and digestion. According to Ahmad and Kaleem (2018), other minor sources of β-glucan exist; such as the ones found in beans, lentils (*Lens culinaris*), millet (*Panicum miliaceum*), corn/maize (*Zea mays*), and canary seeds (*Tropaeolum peregrinum*).

Structurally, β-glucan (1-3)(1-4) is a linear homopolymer of D-glucopyranose, which contains two to three consecutive β-(1-4) linkages separated by a β-(1-3) linkage with a degree of polymerization between 5 to 28 (Figure 2). β-(1-3) bounds make the molecule more soluble, and the "β" configuration is not digestible by enzymes in the human gastrointestinal tract, allowing for the classification as soluble dietary fiber (Burkus and Temelli 2005). Cereal β-glucan share the same molecular structure regardless of source but exhibit differences in some of their characteristics; such as the presence and amount of long cellulose fragments, the ratios of β (1-4) and β (1-3) linkages, molecular size, and molar ratio (ratio of cellotriosyl/cellotetraosyl units) (Table 1) (Izydorczyk and Dexter 2008; Benito-Román et al. 2013).

There are differences in the β-glucan content among cereals, with a greater amount found in barley sources, followed by oat sources, and in a lesser amount in rice and wheat sources. Commercially, β-glucan concentrates which have undergone an extraction process contain fiber composition greater than 50%. However, most concentrates contain high amounts of starch and proteins bound to the molecule for which enzymatic treatments are suggested to help remove the impurities of these extracts (Limberger-Bayer et al. 2014; Kivelä et al. 2012). Additionally, purified β-glucan isolates may contain between 70% and 90% β-glucans (Ghotra, Vasanthan, and Temelli 2008; Jonker et al. 2010; Limberger-Bayer et al. 2014; Zhu, Du, and Xu 2016). However, these isolates are used in greater capacity for research purposes than for food applications, due to the

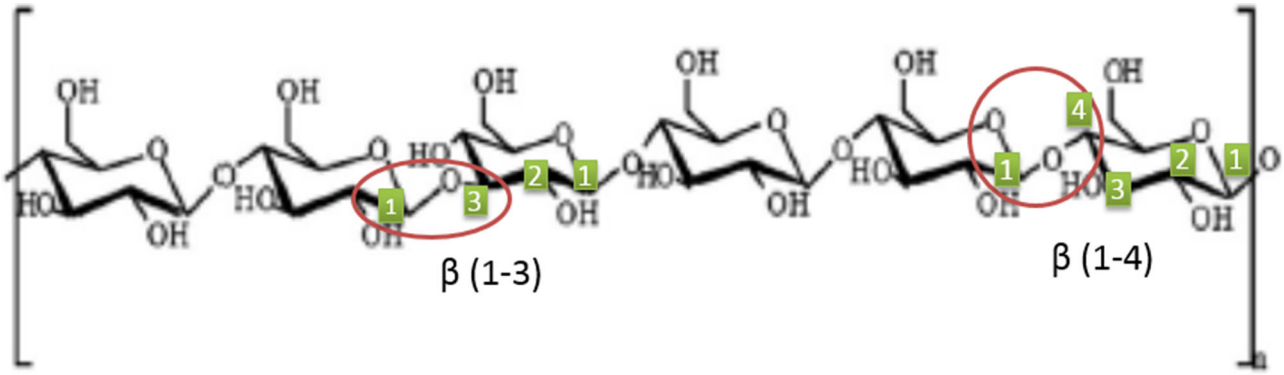

Figure 2. Chemical structure of β-glucan from cereals.
Source: Adapted from Zhu; Du; Xu, (2016)

Table 1. Common sources and characteristics of cereal β-glucan.

Source	Content	Molar ratio (DP3/DP4)	Molar mass (kDa)	References
Barley	3.5–11.3%	1.8–3.5	31–2700	Ryu et al. (2012); Izydorczyk and Dexter (2008); Benito-Román et al. (2013).
Oat	2.2–7.8%	1.5–2.1	65–3100	Izydorczyk and Dexter (2008); Lazaridou and Biliaderis (2007); Colleoni-Sirghie et al. (2003
β-glucan (Barley) concentrates	40–70%	–	>117	Izydorczyk and Dexter (2008); Benito-Román et al. (2013)
Purified β-glucan	71.1–78.9% and 99%	–	103–617	Shelat et al. (2011)

high costs of production and purification (Zhu, Du, and Xu 2016). For this reason, methods used for commercially available β-glucan ingredients in food application normally follow simple extraction techniques (dry or wet) and further isolation of purified β-glucan is not conducted. To this end, the development of various extraction technologies for obtaining β-glucan from cereals remain of interest, for example using subcritical-water extraction (Yoo, Ko, and Chung 2020) or supercritical fluids (Comin, Temelli, and Saldaña 2012) for extraction are of particular interest.

Main physicochemical characteristics of cereal β-glucan

Molar ratio of β-glucan

The molar ratio is considered as the ratio between cellotriosyl/cellotetraosyl units (DP3/DP4) after depolymerization of the β-glucan molecule. The molar ratio is a unique feature of each cereal (fingerprint of the cereal's β-glucan structure), and ranges among source [e.g. for wheat (3.0-4.5), barley (1.8-3.5), rye (1.9-3.0), and oat (1.5-2.3)] (Lazaridou and Biliaderis 2007). According to Ryu et al. (2012), segments with β-(1-4) bonds are considered semi-flexible (with greater intermolecular connection) causing stronger bonds between the glucan chains and providing more resistance against flow and high viscosity, while the β-(1-3) segments increase the twists in the chains. The cellotetraosyl units and the longer segments of β-(1-4) bonds would be a significant contributor to increasing the viscosity and gel formation of cereal β-glucan.

There is a relationship between the degree of polymerization (DP) of β-glucans and their molar mass. Therefore, the greater the length of the chains, the greater that the molar mass is expected to be. In this sense, if the molar ratio is a relationship between DP3/DP4, a lower molar ratio is expected to lead to greater DP4, and due to the characteristics of DP4 fractions, the polymer molar mass will be greater, creating an inverse relationship between the molar ratio and molar mass.

Molar mass of β-glucan

Previous studies indicated that the molar mass of β-glucan is related to their viscosity and functional properties in the food (Liu, Wang, et al. 2015; Gamel, Badali, and Tosh 2013; Shelat et al. 2011) as well as the physiological properties in the intestine when consumed (Rieder, Ballance, and Knutsen 2015).

Molar mass of cereal β-glucan is highly variable. According to the European Food Safety Authority (EFSA), the molar mass of barley β-glucan can range from 50 to 2000 kDa (EFSA 2011). These differences are attributed mainly to environmental factors, but may also be influenced by extraction, purification, depolymerization events, and the analytical methodologies used to calculate the molar mass (including the type of detector and the standards used) (Lazaridou and Biliaderis 2007). According to Regand et al. (2011), factors that affect the molar mass of the homopolymer include the physical state of β-glucan in plant material, betaglucanase activity, processing conditions, and storage conditions.

Recently, barley-sourced and oat-sourced β-glucan have been extracted on an industrial scale, resulting in molecular masses around 200 to 300 kDa (Mikkelsen et al. 2013). The molar mass of β-glucan has a significant influence on health effects. In this sense, Whitehead et al. (2014), indicated that β-glucan with a molar mass greater than 210 kDa, had better properties and contributed to the improvement of lipid profile, cholesterol lowering, and obesity control in dry food matrices (e.g. morning cereals). The authors recommended the consumption of oats or products containing oats with at least 3 grams of β-glucans/day with a molar mass greater than 100 kDa.

On the other hand, the molar mass of this polysaccharide could be an essential factor in the microbiota growing in the colon when evaluated as a prebiotic. According to Hamaker and Tuncil (2014), β-glucan hydrolysates less than 172 kDa showed an increase in *Bacteriodes-Prevotella* growth after 24 hours using an in vitro study. The variability in this characteristic and its relationship with health effects and rheological characteristics becomes important to make a physical-chemical and molecular characterization of the β-glucan extracted before its use or application in foods.

Solubility of β-glucan

The solubility of β-glucan represents the maximum amount of the compound that can be diluted in water to form homogeneous solutions of the polymer, under controlled conditions of temperature and pressure (Benito-Román, Alonso, and Lucas 2011). Although β-glucan are classified as soluble fibers, the molecular irregularity of β-glucan is reflected in their water solubility properties (El Khoury et al. 2012; Izydorczyk and Dexter 2008; Mira, Graf, and Cândido 2009). According to Elleuch et al. (2011), the presence of COOH or SO_2 increased the solubility of the polysaccharide. The chemical conformation of the molecule allows large interactions and associations between its chains and water molecules; however, a high degree of polymerization could decrease the solubility (El Khoury et al. 2012).

The solubility and subsequent extraction of β-glucan into water decrease with time, temperature, pH, and other physical extraction conditions. The solubility of oat-sourced β-glucan is generally higher than barley-sourced β-glucan because the solubility decreases with the increase of the molar ratio (Lazaridou and Biliaderis 2007; Izydorczyk and Dexter 2008). Additionally, the coexistence of several biopolymers in the cell wall, their spatial organization and the interactions between the cell wall components, will likely affect the mechanical resistance and the permeability, and therefore compromise the solubility of the compounds (Izydorczyk and Dexter 2008).

Several authors have evaluated the best extraction conditions of barley β-glucan and indicated that maximum solubility is reached around 55 °C, but under these conditions partial solubilization of the starch is favored and consequently the contamination of the fibers take place (Burkus and Temelli 2005; Benito-Román, Alonso, and Lucas 2011; Limberger et al. 2011; Limberger-Bayer et al. 2014).

Viscosity of β-glucan

There is a direct relationship between the viscosity increase and the molar mass of this compound reflected in the characteristics of pseudo-elasticity and viscoelastic properties (Lazaridou and Biliaderis 2007). According to Wang et al. (2016), β-glucan samples with low molar mass and high solubility exhibited low viscosity.

At low concentrations, β-glucan solutions behave as a Newtonian solution; however, in concentrations greater than 1%, the molecules form a viscous and pseudoplastic complex, which is characteristic of β-glucan (Burkus and Temelli 2000). The viscosity also decreases slightly with temperature, showing the pseudoplastic behavior in solutions of barley β-glucan at 1% (w/v) (Limberger-Bayer et al. 2014). According to Zhang et al. (2018), β-glucan solutions showed typical random colloid behavior where the solution had a second order dependence on shear rate with a Newtonian plateau at low shear rates and a shear thinning region at higher shear rates. β-glucan patterns with low (10 cP), medium (28 cP), and high (100 cP) viscosity and with a molar mass established among 179 and 500 kDa, and purity among 95-97% have been used in research at a concentration of 1% (Shelat et al. 2011). Generally, dynamic rheology tests of β-glucan solutions and products containing β-glucan are performed in fresh preparations of variable concentrations (0.25% to 3%), but the concentration does depend on the objectives of the study. Solutions are heated before analysis at 80–85 °C for 1 or 2 hours to achieve complete dilution of the material in water and then evaluated (Gamel et al. 2014; Limberger-Bayer et al. 2014; Faure, Knüsel, et al. 2013; Gamel, Badali, and Tosh 2013).

The rheological behavior of β-glucan solutions is generally evaluated by the Ostwald de Waale model (Power law). From this model, a pseudoplastic behavior of high viscosity β-glucan gums has already been established. According to Burkus and Temelli 2005, these types of samples have a high coefficient of consistency (K) and low (<1) flow behavior index (n). The viscosity of β-glucan solutions can also be measured by in vitro digestion. In this perspective, Pentikäinen et al. (2014) estimated the in vitro viscosity of different types of breakfast foods containing β-glucan. The results showed that the viscosity under intestinal conditions is regulated by the amount of β-glucans incorporated, regardless of the form of the foods (liquid or solid). In a recent study, Makela, Brinck, and Sontag-Strohmused (2020) used an in vitro gastro intestinal (GI) simulation to model the state of β-glucan from various oat products. The authors indicated that viscosity had very high levels of variation within product categories and the functionality of β-glucan depended greatly on product type. This variation could likely be explained by differences in ingredients and processes. According to Wang et al. (2016), variety and processing conditions significantly affect the concentration, viscosity, molar mass, and solubility of β-glucan. The importance of the viscosity of the β-glucan is related to the physiological properties in the intestine and its beneficial effects on health (Regand et al. 2011; Wolever et al. 2010).

Table 2. Comparison between dry extraction conditions of β-glucan using milling.

	Extraction conditions				
Vegetal source	Sample size (g)	Method characteristic	Coarse/fine fraction	Purification	References
Barley	100	The material was sieved with a circular, stainless steel, certified test (ASTM series). Mesh sizes ranging from 2.36mm to 0.85 mm.	60% Coarse 40% Fine	No	Messia et al. (2019).
Oats	Not provided.	Soluble OβG was extracted from hull-less oats with a bulk density over 0.3 g/mL and 95% particles through 80-mesh sieve.	Not provided.	No	Wang, Ye, et al. (2017).
Oat bran regular and concentrate	Not provided.	Prior to electrostatic separation, the particle size of oat bran was reduced down to 30–60 μm either by an ultra-fine milling equipment Turborotor G-55 (ambient conditions) with a rotor speed of 1800 rpm, or by a fine impact mill 100 UPZ with a 0.3 mm grid at −100 °C (cryogenic conditions) with a rotor speed of 18,000 rpm.	The first coarse bran fraction was separated by air classification, was milled and air classified again to yield an oat bran fraction highly enriched in β-glucan.	After milling, Jet-milling and air classification was used.	Sibakov et al. (2014).
Sorghum cultivars	Not provided.	The grains were manually harvested from the plants, cleaned of impurities, milled into fine flours using a hammer mill, sieved to pass 0.5 mm mesh screen, and stored in polyethylene bags at 4 °C.	Not provided.	No	Hamad et al. (2019).
Hulled grain of four barley cultivars, three non-waxy (Gotic, Scarlett and Braemar) and one waxy (USA)		Grains were dehulled and pin-milled. After that, the whole meal was micronized and air-classified into coarse and fine fractions.	Coarse fraction (CF) (40%) (particle size range of 120–477) and fine fraction (FF) (60%) particle size 45–120 μm).	No	Gómez-Caravaca et al. (2015).

Extraction methods of β-glucan from cereals

The operating conditions for the extraction of β-glucan are influenced by the type of solvent, temperature, pH, extraction time, and agitation. However, the particle size also significantly affects the extraction processes, indicating that the phenomena of transfer of mass could restrict this type of extraction (Benito-Román, Alonso, and Lucas 2011). Removal of the lipid content of the plant material may also improve β-glucan extraction from cereals (Sibakov et al. 2014).

The dry β-glucan extraction processes involve steps with milling and sieving to separate and concentrate the compound (Table 2). This type of extraction includes the sequential removal of the shell, pericarp, aleurone, subaleurone, and embryo layers by abrasive cleaning until enriched fractions of the molecule can be obtained. This requires extensive separation procedures and the yield of the product is generally low (less than 20%), (Sibakov et al. 2014; Benito-Román et al. 2013). In order to increase the concentration of β-glucan in extracts produced by dry methods, Sibakov et al. (2014) evaluated the effect of ultrafine grinding and electrostatic separation on enriched fractions of oat recovered, obtaining 56.2% of β-glucan in the final product.

Extraction using wet methods involve the inactivation of the endogenous enzymes and extraction with water or alkaline solutions (Figure 3). The removal of contaminants (proteins and starch) is accomplished using hydrolytic enzymes or by selective adsorption. The precipitation of β-glucan is accomplished using alcohol (99%) and finally the β-glucan extraction process is completed with drying (by freeze-drying or spray drying) (Izydorczyk and Dexter 2008; Liu 2014). Temperature, pH, extraction time, and particle size should be controlled when using wet methods for β-glucan extraction (Table 3). The yield could be high (>50%) and the final treatment of the β-glucan extracts obtained should depend on subsequent uses (purification, drying, freezing, freeze-drying, etc.). However, wet extractions are limited by the high viscosity of the aqueous extracts even at low concentrations of β-glucan. This leads to high volumes of liquid and high costs related to the drying of the concentrates. Beyond this, low pH and endogenous enzymes may reduce the molar mass of β-glucan when exposed to moisture conditions (Sibakov et al. 2014). In this end, Gangopadhyay et al. (2015) reported that at pH 8, the endogenous beta-glucanase is inactivated, molar mass is high, and consequently viscosity was increased. On the other hand, a pH of 4 can lead to acid hydrolysis of the glycosidic bonds decreasing the viscosity.

After β-glucan extraction, purification processes to remove starch and proteins is not always performed. These contaminants in the extract can prevent adequate characterization and create significant difficulty with application in foods. The main purification technique for β-glucan is the

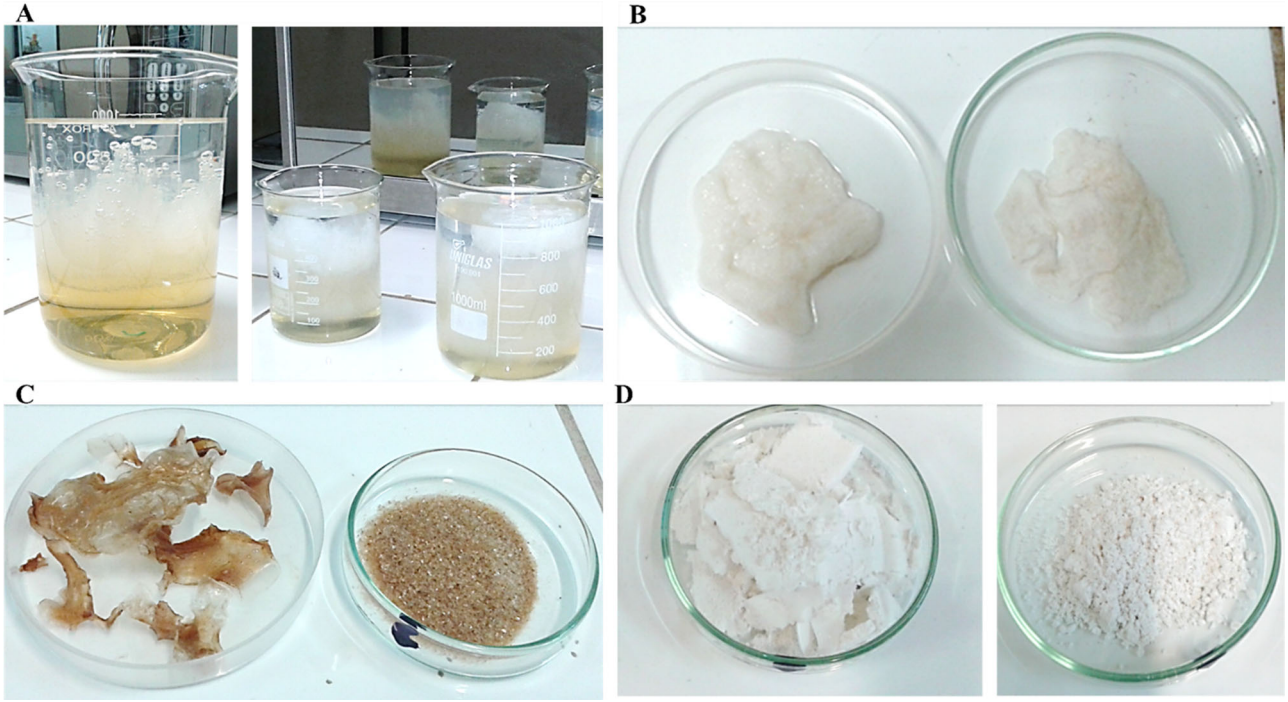

Figure 3. Barley β-glucan extracted using a wet method (using water as solvent) and then purification with enzymatic processes.
A) Precipitation of soluble fiber (β-glucan) made with alcohol (95%) during 16 hours at 4°C. B): β-glucan precipitated before drying process. C): β-glucan dried at room temperature (20°C) for 24 hours. D): β-glucan after enzymatic purification and freeze-drying.

enzymatic treatment with α-amylase and a protease (Liu 2014). To reduce contaminants, it is recommended the evaluation of several enzymatic combinations be used during the extraction of β-glucan (Limberger et al. 2011).

Recently, the extraction process by modern separation techniques like high pressure and supercritical fluid have been evaluated. In this sense, Benito-Roman et al. (2013) obtained β-glucan of different cereal types using pressurized hot water (20 bar) as a solvent in a fixed bed extractor. The authors achieved yields of 97% of purified β-glucan (with an approximate molar mass of 500 kDa) using 4 grams of water at 155 °C/min for 105 minutes of operation, revealing the viability of this methodology for the extraction of soluble fiber. The extraction of β-glucan using supercritical fluids also allowed for the obtainment of β-glucan gels with little or no damage associated with conventional drying techniques (by oven or freeze-drying) (Comin, Temelli, and Saldaña 2012). The aerogels obtained had densities lower than those obtained with dry air with a more consistent structure than freeze-drying. The authors indicated that β-glucan aerogels have great potential as vehicles for medicinal or pharmaceutical products because of their biodegradability, biocompatibility, and edible characteristics. In a recent study, when β-glucan was extracted using subcritical-water extraction method under high temperature and pressure conditions the yield of β-glucan was optimized, further indicating that this methodology could be a feasible alternative for extracting β-glucan in a single-step process (Yoo, Ko, and Chung 2020).

β-glucan degradation

The activity of endogenous beta-glucanase is primarily responsible for the degradation of β-glucan. In flours, this degradation is a challenge identified during food processing. Particularly at the time of mixing during the production of bread, fermentation, and waterproofing of the dough causes a substantial decrease in the β-glucan content (Rieder, Ballance, and Knutsen 2015). Thus, extraction conditions and food processing techniques can cause the degradation of β-glucan, resulting in a decrease in their molar mass and inherent activity (Gamel, Badali, and Tosh 2013; Benito-Román, Alonso, and Lucas 2011; EFSA 2011; Tosh et al. 2010).

On the other hand, β-glucan can be degraded by the oxidation process. Previously, the degradation of β-glucans by presence of reactive oxygen molecules that cause polysaccharide oxidation were investigated (Faure, Werder, et al. 2013). The authors evaluated in a non-enzymatic Fenton reaction the presence of iron in β-glucan solutions that caused the formation of hydroxyl radicals (OH-) and reported that iron (Fe^{2+}), even when in small amounts, was able to promote the formation of OH radicals, and therefore, polysaccharide degradation. This degradation process was increased with the addition of ascorbic acid.

In the same sense, Faure et al. (2014) modulated β-glucan degradation induced by OH radicals and compared it with heat-induced degradation. The authors monitored OH formation, viscosity, and molar mass changes on the polymer and reported that heat treatment (85 °C) induced the hydrolysis of the polymer and consequently decreases its molecular weight and viscosity. However, this degradation temperature caused a slow hydrolysis, which did not affect the monomer structure (glucose). On the other hand, with iron (Fe2 +) and hydrogen peroxide (H_2O_2) presence at 85 °C, large amounts of OH was induced, causing rapid and extensive degradation of β-glucan and simultaneously

Table 3. Comparison between wet extraction conditions of β-glucan using water as solvent.

	Extraction conditions						
Vegetal source	Sample size (g)	pH	Temp (°C)	time (hour)	Final treatment	Purification	References
Barley iris spring	10	6.6	55.7	3	–	α-amylase and papain	Gangopadhyay et al. (2015).
Barley H13 e D24	25	8.0	55.0	1–5	Dried at 105 °C		Benito-Román; Alonso and Lucas, (2011)
Barley BRS 195	50	7.6	45.5	0.5	Dried at 25 °C/24 h	No purification.	Limberger et al. (2011); Limberger-Bayer et al. (2014).
Oat	10	–	–	1	Frozen −80 °C	α-amylase, pancreatin	Colleoni-Sirghie et al. (2003).
Barley (Gwangan and Chal variety) e oat (Ohl variety)	1000	10	45.0	0.5	Freeze-drying	Precipitation with ammonium sulfate and alcohol.	Ryu et al. (2012).
Barley	–	>7	50.0	–	Dried at 40 °C		Ghotra, Vasanthan, and Temelli (2008).
Flour and barley	100–120	–	50.0	2	Dried at 40 °C	α - amylase tthermostable	Papageorgiou et al. (2005).

generating new functional groups (lactones, carboxylic acid, aldehydes, and ketones).

Kivelä et al. (2012) investigated the effects of temperature, high pressure homogenization, and the presence of ascorbic acid on β-glucan dilutions. The authors indicated that at temperatures above 95 °C, β-glucan undergo cleavage which decreased their molar mass. Thermal degradation was drastic at 120 °C/30 minutes and was even greater in unpurified extracts.

Previous research has indicated that not only extraction methods, but also thermal processing, contact with endogenous enzymes, and presence of minerals and other compounds in foods can affect β-glucan characteristics causing its degradation and decreasing their functional activity. Contrary, the use of phytic acid proved to have a retarding effect on the oxidative degradation of the β-glucan and a considerable delay in viscosity loss was observed when a phytate chelation of iron occurred, considerably improving the oxidative stability of β-glucan (Wang, Ye, et al. 2017).

β-glucan applications in food matrices

The technological properties of β-glucan as texture enhancers (Burkus and Temelli 2000; Brennan and Cleary 2005) have sparked significant interest for their application in food matrices. In a recent study, Zhang et al. (2018) reported that based on the rheological evaluation of hull-less barley β-glucan, this soluble fiber can be incorporated into beverages and other liquid products as a thickener and as source of dietary fiber. In spite of this interest, β-glucan incorporation is limited by its high viscosity and handling difficulties in the industry. During β-glucan incorporation, it is important to consider the characteristics that the fiber confers to the final products when applied at large concentrations. According to Izydorczyk and Dexter (2008), the incorporation of barley components into foods greatly increases water absorption, inevitably influencing the viscoelastic properties of food products.

In recent years, β-glucans have been applied in many different food matrices (Table 4). β-glucan has potential to be used as a thickener agent (Zhu, Du, and Xu 2016), a fat substitute (Piñero et al. 2008), an emulsifier, and a stabilizer in the formation of foams and emulsions (Liu, Singh, et al. 2015; Burkus and Temelli 2000). This polysaccharide also showed potential as a prebiotic in products with high levels of folate (Kariluoto et al. 2014) and could also be a promising source of soluble fiber in meat emulsions when mixed with other hydrocolloids (Vasquez Mejia et al. 2018).

β-glucan extraction techniques will depend on the objectives that are to be achieved in the ingredient and in the final product. To this end, when focusing on products with considerable amounts of carbohydrates such as pasta, flour, and breads – it is possible to use dry extraction methods where obtained extracts are less concentrated and function adequately in the presence of other molecules such as proteins and starch. On the other hand, when focusing on products with low amounts of carbohydrates, such as dairy and meat products, it is proposed to work with more concentrated β-glucan products (wet extraction methods) in which low inclusion levels of the ingredient can be used in the formulation of the food products. The low inclusion levels in these food products is mainly recommended in an effort to avoid negative effects on taste and texture due to the high viscosity of β-glucan inclusion. However, it is possible that food applications have been made from various sources of β-glucan (more or less purified) and the affect on the final product is evaluated to still be of adequate quality.

The β-glucan content of foods varies depending on the source used (commercial or laboratory extraction). The amount used in a food application really depends on the characteristics of the food matrix (e.g. noodles maximum of 10%, soups maximum of 2%, meat emulsions from 0.3 to 3%, milk and dairy products maximum of 2.5%, and bread from 5.5% to 20%). While these ranges or maximums values do provide some insight, there is still no consensus on the maximum and minimum amount of β-glucan that can be

Table 4. Applications of cereal β-glucan in foods.

Food	Brand/concentration	Amount used	Application method	Technological function	Main results	References
Couscous enriched in barley β-glucans	Coarse fraction of barley flour (14.4% βG)	Mixtures of semolina and enriched barley flour (70/30 and 80/20).	Mixtures of semolina and enriched barley flour were moistened with water (about 40%) in a dish and stirred by hand to obtain couscous.	Enriched couscous with barley β-glucans.	The incorporation of β-glucan-enriched barley flours in couscous production did not cause significant changes in the characteristics or properties of the final product, which had high β-glucans content (4.09 and 2.79% for mixtures 70/30 and 80/20, respectively)	Messia et al. 2019.
Meat emulsions system	Commercial βG (Barliv®) (79%)	1.5 to 4%	Mixed with hydrocolloids and added in different concentrations during processing.	Textural enhancer and source of soluble fiber.	The optimized emulsion had a homogeneous structure and normal thermal behavior. The manufacture of products with high amounts of βG was possible. However, the hardness of the optimized emulsion was greater than expected.	Vasquez Mejia et al. (2018).
Yogurt	Glucagel (76%)	0.40%	Initially solubilized at 80 °C, cooled to 40 °C and then added.	Increased viscosity and evaluation of bioavailability of peptides in vitro.	Yogurts with β-glucan showed high viscosity, rapid proteolysis, and a higher proportion of free amino acids.	Rinaldi et al. (2015).
Oats and whole wheat bread	OatWell 22©	20% of total flour used.	Dry blend with wheat flour and other ingredients.	Evaluation of fermentation effect under the molecular weight and viscosity of β-glucan.	A longer fermentation time showed significant impacts on molecular mass, and viscosity, but not on the solubility of β-glucan.	Gamel et al. (2014).
Prebiotic sausages	Oat β-glucan (promoat)	1–3% mixed with resistant starch until reaching a maximum concentration of 6% in the final product.	Completely blended with the other ingredients within the formulation.	Formulation optimization increase cooking yields and decrease weight loss	The interaction of the β-glucan with the resistant starch can improve the cooking yield properties and overall acceptability.	Amini Sarteshnizi et al. (2015).
Skimmed fresh milk	Produced in pilot plant (80%)	1.20%	Dilutions in water at 90 °C before applying to milk.	Fat substitute.	β-glucan caused phase separation at concentrations less than 0.2%. That amount would not be enough to be nutritionally significant in food products.	Sharafbafi et al. (2014).
Fermented milk	OATLY, (70% after purification)	2% purified β-glucan, 1.4% in the final product.	Initially solubilized at 80 °C, cooled to 40 °C and added in the milk solution to the yogurt.	Increase of fiber in the final product. Health and prebiotic claims.	The inclusion of this polysaccharide in milk reduces the processes of protein aggregation and acidification due to phase separation (weaker gels at the end of fermentation).	Lazaridou et al. (2014).
Bread and oat bran porridge, frozen and freeze-dried	OatWell (22%).	5.5 % of bread composition.	Direct application in product formulation. Pre-mixed for 2 minutes.	To evaluate the effect of freezing (−80°C) and lyophilization, under the physicochemical characteristics of β-glucan in oat bran bread and porridge.	The viscosity of β-glucan extracts from bread and porridge decreased significantly after freezing at -80 °C and freeze-drying. Freezing and freeze-drying did not drastically affect the molar mass or solubility of β-glucan in any of the products.	Gamel, Badali, and Tosh (2013).
Extruded snacks	Barley β-G (74%) and β-G fungi (71 %)	5 and 10%	Substitution of the wheat flour within the formulation.	Evaluation of textural properties of extruded snacks.	The products with β-glucan had better textural properties and decreased glycemic index.	Brennan et al. (2013).
Meat emulsion	Viscofiber©	Solutions of 10%				

			Diluted and applied in concentrations of 0.15% - 0.3% and 0.6% of the total emulsion.	Fat substitutes and stabilizers of meaty emulsions.	The adequate addition of mixtures of Inulin gel (3% and 6%) and β-glucan (0.3% and 0.6%) may compensate for some changes by fat reduction, and maintain main textual characteristics of the product.	Álvarez and Barbut (2013).
Bovine milk	Glucagel©	2.5% maximum.	Dilution in water under heating and stirring and addition to the colloidal dispersions of casein at 85 °C.	Stabilizer of colloidal dispersions of casein micelles.	Dairy systems added with β-glucan separate from a certain range of β-glucan concentrations.	Repin, Scanlon, and Gary Fulcher (2012).
Chicken breast emulsion	Viscofiber© (46%)	0.30%	Meat was minced and mixed with additives using pestle and mortar for 5 minutes.	Salt replacer in meat processed at high pressures.	The addition of β-glucan with reduction of NaCl and in the absence of sodium tripolyphosphate produces gels with properties similar to the addition of 2.5% NaCl.	Omana, Plastow, and Betti (2011).
Meatballs	Nutrim10© (10%)	2.69 g in 10.76 ml water (13. 45%).	Mixture in formulation.	Fat replacer.	Improved texture as well as retention of moisture and fat, there was no significant difference in reduction of the diameter after cooking.	Piñero et al. (2008).
Asian noodle	Nutrim5© (5%)	10% of the formulation	Mixing with the formulation flours.	Increase cooking yield, bonding and extensibility of the dough.	The soluble fiber of oats contributed to the final quality of the product and improves the functionality of the rice flour.	Inglett et al. (2005).

used in a food matrix, nor the procedures of application of β-glucans in each food group or category. While, only few studies have focused on the evaluation of the soluble fiber in mixtures with other ingredients to determine optimal levels or synergistic or antagonistic action.

The use of β-glucan in foods can have adverse effects on the final product quality in several ways, most can be described by the characteristics of fiber (Lazaridou et al. 2014; Brennan and Cleary 2005). This polymer may not always act consistently (as expected) due to impurities such as proteins and starches in the ingredient (Burkus and Temelli 2000). Furthermore, some researchers indicate that it is not possible to add high fiber content for some foods as the product characteristics are strikingly different (Sharafbafi et al. 2014).

Recommendations for consumption of oat and barley β-glucan (3 grams/day; FDA, 1997) have been established, and it has been determined that β-glucan does not generate toxicity in the body (Tiwari and Cummins 2012; Jonker et al. 2010). Notwithstanding, the possibilities of application for β-glucan in some foods are still limited, and the quantities used may not be sufficient to contribute significantly to the enrichment of food products (Sharafbafi et al. 2014).

On the other hand, few sources of β-glucan have concentrations above 50%, which makes it difficult to effectively increase the amount of fiber in the final product. In order to be used in amounts greater than 1%, it is necessary to use high amounts of the lowly concentrated β-glucan ingredient and consequently change the characteristics of the conventional product drastically.

Additionally, with β-glucan incorporation, like other functional ingredients, there should be significant consideration on the interaction of the macromolecule with the food components and the possible changes that the molecule will undergo during conventional processing and storage. For example, Burkus and Temelli (2000) indicated that the presence of other ingredients (such as sucrose between 20 and 50% or salt between 1 and 10%) might increase the viscosity of these polymers. Even so, information about β-glucan interactions with other ingredients is still scarce. Recently, the interactions of the homopolymer with other barley components in aqueous solutions were studied and it was demonstrated that there were no proteins covalently bound to the β-glucan, but a direct relation between proteins and β-glucan could be established suggesting that electrostatic interactions occur during aggregation (Zielke, Lu, and Nilsson 2019). However, more studies are needed about the interactions that occur when β-glucan ingredients are added to other foods.

Food applications evaluated in this review indicated and described the actual β-glucan amount added in the formulation or during the food preparation, yet the amount of soluble fiber (β-glucans) that would be available in the final product was not reported or fully described. This creates obvious challenges in functionality from a food processing standpoint and unclear benefits from a nutritional standpoint. Measurements of β-glucan content or soluble fiber content are imperative for labeling the food product as a

significant source of fiber and could give an idea about the effects of processing in the molecule integrity after interactions and processing. In the last two years, β-glucan research has focused on its evaluation as an encapsulation agent for other ingredients such as fish oil (Kurek et al. 2018) and probiotics (Gani et al. 2018). It is expected that dietary fiber and β-glucan will drive the nutraceutical industry in the 21st century, where food processors are persuaded by consumers to use more natural ingredients (rather than synthetic ingredients) when formulating food products (Ahmad and Khalid 2018). In this sense, the potential for β-glucan to help consumers increase dietary fiber consumption and improve health, further justifies that research focusing on the incorporation of β-glucan in food should continue.

Conclusions

The procedures for extracting and characterizing cereal β-glucan have been extensively studied and optimized for oats and barley. However, during application, the molecule can be degraded mainly by oxidation reactions, thermal cleavages, or the interaction with other compounds present in the food. Beyond this, the processing/extraction conditions significantly affect the concentration, viscosity, molar mass, and solubility of β-glucan. Thus, the properties of the β-glucan should be evaluated to understand the behavior of the fiber after its extraction, during its application in food, when determining optimal mixtures with other fibers or ingredients (synergism or antagonism), and to provide a more thorough understanding of interactions with other compounds.

The main challenge with incorporating soluble fiber (β-glucan) in foods are the use of great enough concentrations (significant amounts) that will allow for healthy (enriched/fortified product) label claims and intended health effects. Evaluation of β-glucan content in the final product can help to prove the extent of fiber degradation during processing (if and when it occurs).

Abbreviations list

βG	β-glucan
FDA	Food and Drug Administration
EFSA	European Food Safety Authority
DP3	Degree polymerization 3
DP4	Degree polymerization 4
COOH	Carboxyl group
SO_2	Sulfur dioxide
cP	centipoises (1 cP = 1 mPa·s)
KDa	kiloDaltons

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