CHAPTER 11

β-Glucan as a Food Ingredient

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1 Introduction

There is a direct relationship between epidemiology and food ingredients having their origin from plants. A growing trend of utilizing novel plant food ingredients as a prophylactic measure against several ailments is evident from the documented literature. Extraction, characterization, and utilization of these food constituents are directly associated with better human health. Among these vital food constituents, β-glucan holds a high position in plant-based and microbial sources that possess functional properties for industrial products as well as having several health implications. Chemically, it is a nonstarch polysaccharide belonging to the carbohydrates family and is composed of long chains of glucose units either in a branched or in an unbranched fashion. The binding force for these long-chain molecules are glycosidic linkages among β-D-glucopyranose molecules. Glycosidic linkages among glucose molecules may vary according to the source of β-glucan. For instance, β-glucan from cereal sources may have β-(1→3) and β-(1→4) linkages, thus forming a wormlike β-D-glucopyranose structure. In these cereal sources, β-(1→3) predominantly exists as cellotriosyl and cellotetraosyl units that constitute approximately 90% of the whole molecular structure (Ahmad and Anjum 2010; Wood et al., 1994). Most of the chemical properties such as gel formation can be best explained on 1→3 and 1→4 linkages and are under the control of specific genes (Schreiber et al., 2014; Wilson et al., 2015).

The dietary fiber nature, health benefits, and numerous sources of β-glucan are documented in the literature. The usage of β-glucan against certain diseases may also vary according to different sources. Baker's yeast is an important source of β-glucan that is associated with lowering of cholesterol and boosting of the immune system. These health-related benefits have a leading role for the development of dietary supplements from baker's yeast. Mushrooms are another source from which β-glucan can be extracted and may be used for the development of similar dietary supplements. The health-related properties in these sources are attributed to the presence of β-(1→3) (1→6) linkages and are different from cereal source linkages that consist of β-(1→3) (1→4) linkages (Ahmad and Ahmed 2011;

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Ahmad et al., 2012a). In these sources, glycosidic linkages in the form of β-(1→3) dominate and may connect approximately 1500 glucose units, whereas the number for β-(1→6) linkages is comparatively low and may connect about 150 glucose molecules. With reference to β-glucan from the cell wall of baker's yeast, the 85% share of 1→3 linkages have more influence on characteristics and health implications as compared to 1→6 linkages that have a share of about 15% in the cell walls of these biological sources (Klis et al., 2002). The dietary fiber nature of β-glucan is responsible for reduction in blood low-density lipoprotein (LDL) cholesterol, which is confirmed by animal model studies (Anderson, 1995), as well as in clinical studies that β-glucan can impart health effects similar to those of other dietary fibers (Glore et al., 1994). β-Glucan from cereal source with 1→3 and 1→4 linkages provides relief in coronary heart disease. This kind of β-glucan dietary fiber, along with psyllium fiber and soy protein, is authorized by the US Food and Drug Administration (FDA) for patients with coronary heart disease. Regular consumption of barley or oat β-glucan is highly effective in reducing total serum and LDL cholesterol. Especially, barley β-glucan is highly effective in reducing postprandial glucose levels and modifying endocrine response related to digestion and absorption of sugars and glucose (Jenkins et al., 2002).

β-Glucan is well known for its water holding, stabilizing, and texturing properties. Use of β-glucan in selective products as a fat replacer provides a way to develop products for weight watchers and diabetic patients. This will not only increase the range of food products for specialty use but also provide some health benefits to the general population. Regular consumption of β-glucan-containing foods also showed positive effects in coronary heart disease, diabetes, and hypercholesteremic conditions (Ahmad et al., 2009a; Yokoyama et al., 1997). The major health benefits are attributed to high viscosity introduced by β-glucan in the small intestine, and sometimes this intake is associated with appetite suppression. The viscous behavior of β-glucan in vivo and in vitro is highly associated with its molecular weight and chain length. In general, long-chain high-molecular-weight β-glucan has a tendency to form viscous gels due to the complex arrangement of the chains from mixed linkages (Vaikousi et al., 2004). Solubility and water holding capacity are other important factors in addition to molecular weight that may affect the viscosity and flow behavior of β-glucan. β-Glucan from barley has a capacity to form highly viscous gels of pseudoplastic nature. This pseudoplastic nature of barley β-glucan offers great resistance to digestion in the small intestine of human beings and other monogastric animals. High-viscosity pseudoplastic gels also aid in reduction of serum cholesterol, regulation of insulin secretion, and glucose absorption (Jenkins et al., 2002).

Based on documented health benefits of β-glucan from various sources, there is a growing trend of utilization of β-glucan in value-added nutraceutical food products and supplements. Most of the interest in developing new products originates owing to positive impacts on metabolic parameters', tendency to combat chronic diseases like diabetes, cardiovascular conditions, and cancer. Currently, functional and nutraceutical foods that address these chronic problems are limited in number, but the number of sufferers from these problems is increasing day by day. This is the driving force behind the ever growing market of β-glucan-containing products. The development of β-glucan-containing functional foods will be of paramount importance in the present era for diabetic, cardiovascular, and cancer patients (Ahmad et al., 2012b; American Diabetes Association, 1999; Ho et al., 2016).

Apart from nutritional benefits of β-glucan that have implications for health, this valuable ingredient is also popular in the food industry owing to several industrial important properties. Some of these properties include provision of thickness to products, emulsification properties, water holding capacity, texturizing power, stabilizing properties, and gelation (Ahmad and Anjum, 2010). All of these properties along with several others define the suitability of β-glucan for incorporation into bread, soups, cookies, sauces, noodles, beverages, and other food products (Ahmad et al., 2008; Burkus and Temelli, 2000). Although β-glucan from various sources may be incorporated to develop these products, cereal β-glucan is the preferred and easily available source for application in food products. Among cereals, barley and oat β-glucan is more explored for this purpose as it imparts a better mouth feel and texture to previously mentioned food products with the provision of ample amounts of dietary fiber. β-Glucan from these two sources may be used to replace conventionally used stabilizers and thickeners such as gum arabic, carrageenan, modified starches, alginates, modified celluloses, pectin, xanthan gum, and guar gum. Based on the aforementioned arguments, β-glucan as a food ingredient has a greater potential to be used in numerous products that may extend from cereal-based products to meat-based products. It is equally good for beverages, pasta, noodles, sausages, yogurts, cakes, breads, soups, confectionary products, and many more (Ahmad and Ahmed, 2011; Skouroliakou et al., 2016; Temelli et al., 2004).

2 β-Glucan From Different Sources

With the progress in research, scientists have discovered new sources of β-glucan. Conventionally, cereal is perhaps the oldest source from which β-glucan has been extracted, or these sources in unpurified form have been used for the development of food products. Apart from conventional cereal sources, β-glucan is now extracted from yeast, algae, molds, mushrooms, bacteria, and marine animals. These sources along with their β-glucan content are briefly presented in Table 11.1. A brief account of these sources with respect to β-glucan is explained in following sections.

2.1 β-Glucan From Cereal Sources

Barley, oats, rye, and rice are the common cereals that have been under research focus for the extraction of β-glucan. However, barley and oats are considered richer in terms of β-glucan, having β-glucan content of 4%–7%. Hull-less varieties of barley are recognized as

Table 11.1: Sources of β-glucan and its content.

Sources	β-Glucan Content (%)
Beans	2.4–3.5
Canary seeds	1.1–2.3
Corn/maize	0.1–1.3
Flax	0.3–0.7
Lentils	0.4–1.1
Millet	0.5–1.0
Peas	0.3–0.7
Rice	0.4–0.9
Rye	0.7–2.4
Spelt	0.6–1.1
Spring wheat	0.4–1.4
Winter wheat	3.7–11
Hull-less barley	5–10
Barley	5–10
Oat	3–7
Barley mutant (HiAmi x Cheri) x Cheri	7–12

Source: Ahmad, A., Munir, B., Muhammad, A., Shaukat, B., Muhammad, A., Tahira, T., 2012b. Perspective of β-glucan as functional ingredient for food industry. J. Nutr. Food Sci. 2(2), 133–139.

having more β-glucan content than normal barley and may range up to 10%–13% β-glucan. In general, β-glucan is concentrated in bran and endosperm cell walls of oats and barley. Within the same cereal source β-glucan content may vary from cultivar to cultivar and also be influenced by environmental factors. In barley, waxy cultivars contain more amylose and β-glucan. Strong interaction between cultivars and environmental factors suggests that suitable cultivars should be selected for a specific region to have higher β-glucan content than the respective cereals source. Cereal β-glucan is characterized as having 1→3 and 1→4 glycosidic linkages and is often referred to as mixed linkages β-glucan (Fig. 11.1). Although β-glucan from oats and barley appeared similar in chemical nature, they differ slightly in their functional properties. The oat bran and endosperm part of the kernel is also a rich source of β-glucan, and its concentration during extraction can be further increased at the purification step that focuses on removal of starches. The nature of oat β-glucan is inclined toward soluble dietary fibers that resist digestion in the small intestine and extend a feeling of satiety.

The US FDA (1997) approved the claim that oat β-glucan is effective in reducing the cholesterol level of plasma and lowering the risk of heart disease. A similar move was adopted by the UK Joint Health Claims Initiative (JHCI) to recognize oat β-glucan for cholesterol-lowering health benefits. These agencies recommended a dose of 3 g oat β-glucan on a daily basis to reduce LDL cholesterol and total cholesterol (Ahmad et al., 2009a, 2012b). Rye is another cereal source from which β-glucan can be extracted but at lower levels. β-Glucan from this source is difficult to extract at this time, and more research is required to develop feasible extraction techniques for the extraction of β-glucan from rye. Alkali

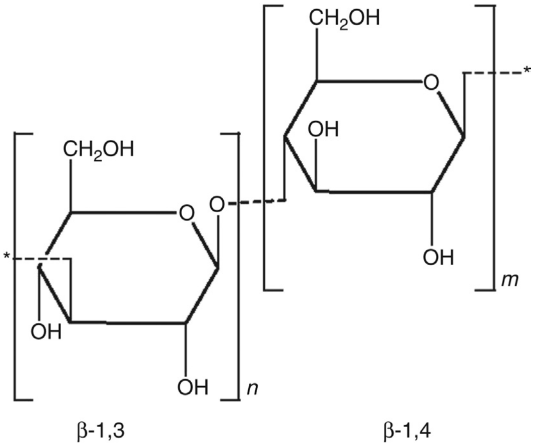

Figure 11.1: Chemical Structure for Cereal β-Glucan.
*, Sequence of glucose molecules continues with corresponding glycosidic linkages in the polysaccharide chain.

extraction techniques will have better prospects to extract β-glucan from this source (Tosh et al., 2004). A similar situation exists for wheat, which contains lesser amounts of β-glucan, and extraction is still a problem from this source (Hollmann and Lindhauer, 2005). Inglett et al. (2004) developed a technique for extraction of β-glucan from rice, and commercialized the product with the name of Ricetrim.

2.2 β-*Glucan From Mushrooms*

In Asian countries, mushrooms and mushroom-derived materials have been used for centuries for health purposes. These mushrooms are good sources of dietary fibers, β-glucan, antioxidants, and many other bioactive compounds and are exploited for the manufacturing of commercial products. β-Glucan extracted from cereal and mushroom sources has demonstrated health implications and is composed of basic β-D-glucan units that are arranged differently in cereals (1→3 and 1→4) and in mushrooms (1→3 and 1→6) (Zhang et al., 2013). In mushrooms, a higher amount of β-glucan is concentrated either in mycelia or in fruiting bodies. Mushroom sclerotia of *Pleurotus tuberregium* is a great source of β-glucan (Zhang et al., 2004). The edible mushroom *Termitomyces eurhizus* is another important source of β-glucan that can be extracted using the hot alkaline method (Banik et al., 2015). Some other researchers used a hot water extraction method instead of alkaline media to extract β-glucan from the fruiting bodies of edible mushrooms, *Pleurotus eryngii* and *Pleurotus ostreatoroseus* (Carbonero et al., 2006). β-Glucan was extracted from *Penicillium chrysogenum* mycelia by Wang et al. (2007). β-Glucan extracted from these fruiting bodies is effective to enhance the immune system and is used to stimulate the tumor necrosis factor. Some studies showed its potential against infection through activating infection-fighting cytokines. Mushroom β-glucan with some other bioactives of mushrooms provide major protection against DNA damage to lymphocytes. The 1→3 glycosidic linkages in mushroom β-glucan are supposed to activate the macrophages to kill the disease-causing cells of pathogens through induction of nitric oxide synthase, tumor necrosis factor, and macrophage inhibitor proteins. Many more researches are available indicating the effectiveness of mushroom β-glucan and other allied bioactives against radiation, infection, and tumors. However, more research is required to understand the mechanism of how the mushroom β-glucan acts to produce these beneficial effects. Nevertheless, it appears to have very different actions and activities from oat- and barley-derived β-glucan and dietary fiber (Ahmad et al., 2012b; Devi et al., 2015).

2.3 β-Glucan From Yeast Cells

Like cereals and mushrooms, the yeast cell wall is also a great source of the β-glucan polysaccharides. Several scientists have extracted β-glucan from the cell walls of yeasts such as *Saccharomyces cerevisiae*, *Kloeckera apiculata*, *Meyerozyma guilliermondii*, *Debaryomyces hansenii*, *Laminaria digitata*, *Zygosaccharomyces bailii*, *Pichia membranaefaciens*, *Kluyveromyces marxianus*, *Brettanomyces bruxellensis*, *Schizosaccharomyces pombe*, and *Candida milleri*. These may be grown on various carbon sources, including sucrose, glucose, and fructose. Extracted β-glucan from these sources is composed of repeating units of β-D-glucose that are arranged together via 1→3 linear linkages, whereas branching originates as 1→6 linkages (Fig. 11.2). Side branching in yeast β-glucan is an important factor that determine its biological activity. Length of branched chain and frequency at which this branch originates influence the implications for biological activity. A higher degree of branching is considered better to achieve greater biological activity from the extracted β-glucan from these sources (Ahmad and Anjum, 2010; Carpenter et al., 2013; Nguyen et al., 1998; Solís-Pacheco et al., 2013; Sweeney et al., 2012).

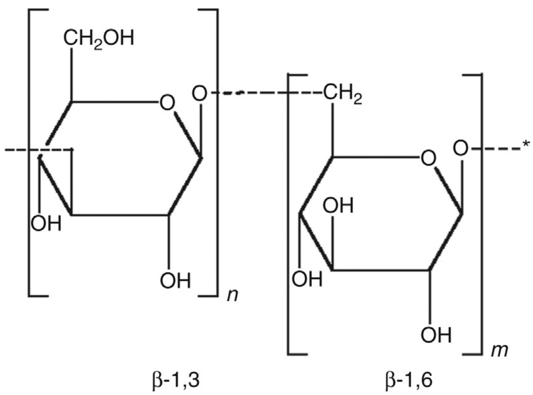

Figure 11.2: Chemical Structure for Yeast β-Glucan.
*, Sequence of glucose molecules continues with corresponding glycosidic linkages in the polysaccharide chain.

2.4 β-Glucan From Bacterial Sources

It is possible to extract β-glucan from the bacterial cell wall. Bacterial cell walls offer diversified types of β-glucan that may vary from species to species. Chemistry of extracted β-glucan may range from linear to branched β-glucan. In linear fashion, bacterial β-glucan may exist as repeating glucose units linked together by β (1→3) linkages, but in branched form it consists of glucose units having (1→3,1→6) glycosidic linkages. A cyclic form also exists with branching at 1→2 position to get a chemical structure of (1→3,1→2)-β-glucans. The production capacity of β-glucan is evident in most of the prokaryotic and eukaryotic organisms. The biological activity and physiochemical properties of different variants of bacterial β-glucan may vary. The linear β-glucan that is often documented with the name of curdlan has good gelling and rheological properties in addition to excellent biological activity. A variety of bacterial microorganisms may be employed in a fermentation process to produce linear curdlan. Members belonging to *Agrobacterium*, *Bacillus*, and *Pseudomonas* are renowned for the production of curdlan. In recent times, a *Pseudomonas* species named *Pseudomonas* sp. QL212 from soil samples appeared as a potential source of low-molecular-weight curdlan. The low-molecular-weight property of curdlan is highly associated with increased solubility (Yang et al., 2016). Another species recently discovered from a Saudi Arabian soil sample is *Paenibacillus* sp. NBR-10; it is capable of producing reasonable amounts of curdlan as exopolysaccharide. Sophisticated machine analysis revealed the chemical nature of this curdlan product as having β-glucose units linked together with 1→3 glycosidic linkages (El-Sayed et al., 2016). Some of the bacterial members of the *Agrobacterium* genus possess high capacity to produce curdlan in the form of homopolysaccharide with a glycosidic linkage of (1→3)-β-glucans. This type of curdlan is devoid of branching, and *Agrobacterium* includes perhaps the most used bacteria for the scientific studies of curdlan. Among various strains from this group, *Agrobacterium* sp. ATCC 31749 has the highest potential to produce curdlan (Wu et al., 2016).

2.5 Other Sources of β-Glucan

Some other plant sources that contain minor amounts of β-glucan are millet (*Panicum miliaceum*), beans, corn/maize (*Zea mays*), flax, canary seed (*Tropaeolum peregrinum*), lentil (*Lens culinaris*), peas, spelt (*Triticum spelta*), spring wheat, and winter wheat (Ahmad et al., 2012b; Demirbas, 2005).

3 Structure and Composition of β-Glucan

Chemically, β-glucan is a nonstarch homopolysaccharide associated with cereal grains, but these are widespread in nature. Great diversity exists in structure and molecular weight of β-glucan based on its source. Today advancements in research make it possible to distinguish linear and branched structures, α- and β-anomers, as well as mixed α,β-glucans with various glycoside bond positions and molecular masses. To enhance purity, substances like proteins, starches, lipids, minerals, and other polysaccharides need to be removed during extraction and purification steps. A great number of spectroscopic, chemical, and infrared machine analysis methods are available for identifying the nature and structure of β-glucan. Among these, Fourier-transform infrared (FTIR) spectroscopy and nuclear magnetic resonance (NMR) spectroscopy are powerful tools for elucidation of structural features of β-glucans. Vibrational spectroscopy is most effective to determine structure based on anomeric carbon of glucans and can be used for purity control as well. Size-exclusion chromatography along with multiple angular laser light scattering detectors is a useful tool for estimation of molecular weight for extracted β-glucan (Ahmad et al., 2012a; Synytsya and Novak, 2014). For fungal β-glucan analysis, organic elemental analysis may provide valuable information about composition. Extraction of nitrogenous compounds along with fungal β-glucan can be linked with proteins, amines, and chitosans. These contents along with sugars, uronic acids, and nitrogenous substances can be determined through chemical analysis and give an idea about the purity of extracted β-glucan. Use of sophisticated techniques provides valuable information about homogeneity, molecular weight distribution, and branching and may include techniques like gel permeation, size-exclusion chromatography, angular laser light scattering, and viscometry. A detailed sugar profile can be carried out using the gas chromatographic technique. These samples have to undergo strong acidic conditions for conversion into respective alditol acetate, and they require elevated temperature. FTIR and NMR spectroscopy again provide reliable data on the structure of yeast and fungal β-glucans (Borchani et al., 2016; Vetvicka and Novak, 2013).

In cereals, β-glucan resides within the cell wall of the endosperm and bran part of the kernel. Barley endosperm contains about 75% of grain β-glucan along with arabinoxylan and minor proteins. Good sources of β-glucan include oat and barley, but there is little variation in the β-glucan content of these two cereals (i.e., oat contains 3%–7% whereas barley contain 3%–11% β-glucan) (Skendi et al., 2003). Burkus and Temelli (2000) reported β-glucan content of oat and barley in the range of 4%–7%. These results are also supported by the findings of Wood (2002), but several cultivars of oat may contain 6%–7% and some cultivars of barley contain β-glucan up to 12%. The presence of arabinoxylan and minor proteins along with β-glucan within the cell wall influence the extraction method. For each extraction method these are extracted and purification is required to have a higher percentage recovery. During extraction from cereal source, (1→3) (1→4) β-glucan is the major product, whereas arabinoxylans and cellulose along with small quantities of vitamins, lipids, proteins, minerals, phenolic compounds, and antioxidants are impurities (Panfili et al., 2003). Sometimes other components having nutritional importance are attached with fibers that are capable of immunopotentiating, whereas others have antioxidant activities. Several minerals in hull-less barley and β-glucan content of the hull-less barley correlate with each other. Out of these, Ca, Zn, Fe, Cu, Mn, and Se not only are related to β-glucan content but also have an impact to reduce blood sugar. Similar function is achieved through β-glucan, so these minerals are complementary to each other, reinforcing their effect if they exist in combination (Yan et al., 2016). Presence of β-glucan in cereal grain is directly controlled by genetic and environmental factors. The nature of polysaccharides in barley, oats, wheat, and rye is variable. For wheat and rye these polysaccharides are in the form of pentosans, whereas barley and oats are rich in β-glucan polysaccharides. In wheat, arabinoxylan is in the range of 4%–8%, whereas barley contains 4%–10%. Wheat has β-glucan content of 0.5%–1.0%, whereas in the case of barley it is 3%–11%. All tissues in barley seedlings except the root cap have been reported to contain β-glucan. However, β-glucan content in barley increases during elongation and decreases at the maturation stage. β-Glucan is found in the lowest quantity in the meristematic tissue as compared to other tissues (Ahmad and Anjum, 2010; Gibeaut et al., 2005; Yalcın et al., 2007).

Several factors are responsible for variation in β-glucan content of cereal grains grown under different environmental conditions. The most important are agronomic factors, irrigation, type of cultivar, and nitrogen fertilizers. Cultivars of barley that are grown in Canada and the USA contain the highest β-glucan content; similarly, oat cultivars grown in the United States also have greater content of β-glucan. Oat cultivars grown in Sweden contain the lowest content of β-glucan (Genc et al., 2001). The effect of environmental and genetic factors on the β-glucan content of barley that is grown in Australia, Canada, and China was studied by Zhang et al. (2002). The β-glucan contents of cultivars grown in China are in the range of 2.98%–8.62%. The Tibet region was unique for cultivation of barley with the highest amounts of β-glucan. Temperature also influenced the presence of β-glucan content irrespective of location: Barley cultivars grown during the winter in China showed the same amounts of β-glucan content as the cultivars grown in Canada and Australia. Similarly, environmental factors and availability of water at maturation stage also significantly influence the β-glucan content in cereal grains. A moisture stress just before harvest usually increases β-glucan levels in grain (Ahmad and Anjum, 2010).

4 Defining Dietary Fiber and Recognition of β-Glucan as Dietary Fiber

One comprehensive definition of dietary fiber proposed by Trowell (1972) is based on resistance to enzymes digesting the plant cell wall. On the basis of this definition and several other definitions of dietary fiber that originated later on, β-glucan fulfills the requirements of these definitions and can therefore be classified as dietary fiber. As research progresses, the definition of dietary fiber is undergoing dynamic revision. In another definition of dietary fiber, Stear (1990) proposed a definition declaring polysaccharides, oligosaccharides, lignin, and associated plant substances to be dietary fibers. During the past two decades there have been global debates on defining dietary fiber. Codex (1998) presented a more comprehensive definition of dietary fiber that includes edible parts of plant origin or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine. A few years later, DeVries presented another definition of dietary fiber that relates dietary fiber as plant material that is digested by the microflora of the gut and is not hydrolyzed by the enzymes secreted by the human digestive system. Components of plants that come under this definition include polysaccharides that are not starches such as hemicellulose, cellulose, pectins, and gums along with resistant starches. Vegetables, wheat, and other cereals are good sources of dietary fiber (DeVries, 2001). At the same time, the Codex Alimentarius Commission (CAC) set up a special committee to revise the definition of dietary fiber; this Codex Committee on Nutrition and Foods for Special Dietary Uses (CCNFSDU) reviewed the definition of dietary fiber and included both edible animal and plant material for defining dietary fiber. However, the majority of the latest research and reports have shown that dietary fiber is obtained from plant sources. It was recommended by this committee that the definition of dietary fiber require an amendment to the current definition (WHO, 2001). A new definition proposed by the National Academy of Sciences shares the idea of functional fiber and claims that the total fiber is the sum of dietary fiber and functional fiber. Tungland and Meyer (2002) defined dietary fiber as a complex of nondigestible carbohydrates and lignin that are intrinsic and intact in plants, and functional fiber comprises nondigestible carbohydrates that have beneficial physiological effects in the human body. One year later, the World Health Organization (WHO, 2003) also supported the idea of intrinsic and added fiber in food. In 2006, CAC again modified the definition of dietary fiber and included the idea of degree of polymerization (DP). According to this definition, carbohydrates with at least DP value of 3 that are indigestible and unabsorbable in the human small intestine may be included in the definition of dietary fiber (CAC, 2006). Some modification was made to this definition with inclusion of a footnote that empowers national authorities to either consider it as dietary fiber or not (CAC, 2009; Phillips and Cui, 2011). Later on, researchers again finalized another definition that relates 10 or more monosaccharide units in the polysaccharide structure and that should not be broken down by the endogenous enzymes in the small intestine of humans (CAC, 2008, 2015). β-Glucan fulfilled all the requirements of all of these definitions presented in different eras. Therefore, β-glucan has been recognized as a dietary fiber in all of these eras.

There are valid incidents that show the activity of β-glucan as dietary fiber. The same health benefits can be achieved through consumption of β-glucan as from other dietary fibers. These may include health benefits for diabetic patients due to change in glycemic index (Schulze et al., 2004), increased frequency of bowel movements (Sanjoaquin et al., 2004) and relief of constipation, and physiological benefits related to depression of cholesterol levels and the risk of colon cancer (Ahmad et al., 2009a; Anderson, 1991). To achieve all of these health-related benefits, WHO recommends consumption of about 25 g dietary fiber on a daily basis, whereas the FDA recommends 3 g of β-glucan per day. These amounts of dietary fiber or β-glucan can be achieved by consumption of fruits, vegetables, oats, barley, and beans (FDA, 2004; WHO, 2003).

Processing in industrial conditions or fermentation in the large intestine has an effect on dietary fiber as well as β-glucan. No matter what is the source of β-glucan or dietary fiber, it undergoes changes during processing as well as by microbial flora in the large intestine. The actual dietary fiber contents may decrease through conversion into short-chain fatty acids in the large intestine. Some of the products produced as a result of this fermentation process are butyrates, lactates, propinonates, and acetates. The processing condition such as fermentation may affect the dietary fiber contents of the cereals. Under these changes insoluble dietary fiber undergoes more changes than does soluble dietary fiber from barley and oats. Fewer changes appeared in the case of oats as compared to other cereals. The soluble fiber and soluble β-glucan fraction from barley experiences major changes in viscosity and molecular weight during the fermentation process in large intestine. But oat dietary fiber, including β-glucan, showed fewer changes in viscosities after the fermentation process and there appeared less change in molecular weight (Dodevska et al., 2013; Lambo et al., 2005). Production of short-chain fatty acid in the large intestine by the ingestion of β-glucan and dietary fiber ensures maintenance of a balance for probiotic and prebiotic strains that have a favorable physiological response in the human body as well as help to maintain gut health. Consumption of β-glucan causes slow absorption of nutrients and glucose so important for diabetic patients. The viscosity changes result in delayed gastric emptying and change in mixing behavior of the intestinal content, thus modifying the body's metabolism. Ingestion of β-glucan influences the gut transit rate; this may help provide relief to constipation patients. The capacity of β-glucan in binding excess bile acids helps to interact several mutagens and carcinogens for their removal from the body. The details for anticancer activity of β-glucan are reported by Cheung et al. (2002), who observed that β-glucan synergizes antitumor activity in xenograft tumor models by the production of monoclonal antibodies (mAb). Molecular size of β-glucan, as described earlier, also influenced these activities as an anticarcinogenic agent.

5 β-Glucan Extraction and Purification

The chemistry of sources from which β-glucan can be extracted varies to a high degree; thus the extraction and purification process may have variation. Many more techniques have been described in the scientific literature for the extraction and purification of β-glucan from numerous sources. One of the most used techniques for the extraction of β-glucan is based on hot water extraction. The basis for this extraction technique is dependent on the solubilization of β-glucan in extraction media increasing with a rise in temperature up to a certain limit. Several scientists used this technique for the extraction of β-glucan. In an attempt, Morgan and Ofman (1998) employed the hot water extraction process with inclusion of a modification of freeze–thaw cycles. A greater recovery of β-glucan along with a high level of purity can be achieved using this method. Several other researchers used this technique by combining

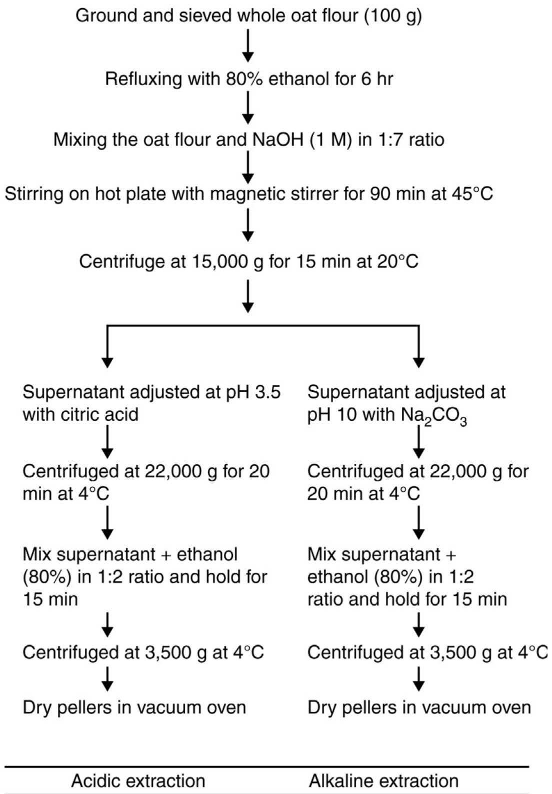

Figure 11.3: Extraction of β-Glucan From Oat.

From Ahmad, A., Anjum, F.M., 2010. Perspective of β-glucan: Extraction and Utilization. VDM Publishers, Germany.

alkaline or acidic extraction from cereal sources mainly from oats (Fig. 11.3). This technique with the application of high temperature as the sole treatment or in combination of acid or alkali resulted in higher recoveries of β-glucan. Overall extraction condition and sources under these techniques showed variation of about 45%–81% recovery (Ahmad and Anjum, 2010; Burkus and Temelli, 2000). In a similar method of extraction based on temperature, Knuckles et al. (1997) used consecutive hot water extraction applied in a series employing variable temperatures in the presence of alkali NaOH that was used at a later stage of extraction. The authors claimed a high yield of β-glucan in the form of gum material.

Another most used technique for the extraction of β-glucan is an enzymatic process. A preparation of several enzymes is used to remove impurities that will improve purity and extraction within the extraction media, while impurities are separated using a centrifugation process in a series of steps. For that purpose a large number of enzymes that may include endo-β-(1→3)(1→4) glucanase, feruloyl esterase, endo-xylanases, xyloacetylesterase, and arabinofuranosidase may be used. Some indigenous enzymes need to be deactivated during the extraction process, as they can reduce the quantity and quality of extracted β-glucan.

One of the indigenous enzymes is glucanase, which causes hydrolysis of β-glucan and increases during germination of the cereal source. Luckily, this enzyme can be deactivated at elevated temperature. Kanauchi and Bamforth (2001) described a method of β-glucan extraction using enzymes from outer sources. This method is based on solubilizing the β-glucan from cell wall from their source. Some other enzymes that may increase recovery of β-glucan from the source are lichenase, xylanase, and esterases. Sometimes these enzymes are used as the sole treatment, but in other cases these may be used along with acid, alkali, or heat treatment to improve the solubilization of β-glucan. Skendi et al. (2003) made use of a heat-stable enzyme, termamyl, along with hot water treatment for the extraction of β-glucan from separate varieties of oats, and reported higher yields of β-glucan by this method. In a similar method Johansson et al. (2005) employed the same enzyme (termamyl) along with hot water treatment. This treatment effectively solubilized the β-glucan molecules for easy separation from the milled grains of oats. In addition to these treatments, the authors also used isopropanol and petroleum ether as defatting media that resulted in higher yield. During this extraction method, soluble and insoluble substances can be separated from each other using high-speed centrifuges. Most of the protein impurities can become insoluble at their isoelectric point or by use of protein-degrading enzymes and are removed during the centrifugation process. After removal of impurities, solubilized β-glucan was precipitated by either ethanol and calcium sulfate. Another enzymatic extraction technique for the extraction of β-glucan involved boiling and refluxing of grounded oat powder with ethanol. After defatting, all of the material was suspended in water and heat treated to further inactivate the indigenous enzymes. In this medium while it was maintained at hot temperature, α-amylase (termamyl) preparation that is stable at high temperature was added to degrade starch impurities. For removal of protein impurities the enzyme pancreatin was used. Finally, β-glucan was precipitated by slow addition of ethanol until the concentration reached 50% in the extraction media. High-speed centrifugation at low temperature was carried out to recover β-glucan (Dongowski et al., 2005). In a similar attempt, Papageorgiou et al. (2005) recovered β-glucan from barley and oats by adopting an enzymatic process. The slurries of barley and oat flours were made by maintaining temperature of 50°C followed by removal of insoluble material through centrifugation. Material was heated with heat-stable amylase for starch removal followed by centrifugation. Further purification was carried out by addition of sodium azide during the cooling process. A slightly acidic condition was developed at this stage, and the mixture was kept overnight at 25°C. After centrifugation, the pH of the mixture was adjusted to neutral and it was again centrifuged. The water dialysis process was carried out for 3 days on the supernatant. Finally, ethanol was used to precipitate the β-glucan. Apart of barley and oat, β-glucan extraction can be carried out from other cereals using these extraction methods. Homogeneous rye flour having fine and uniform particle size can be used for extraction of β-glucan. For this purpose the prepared raw material is defatted using ethanol through continuous refluxing. For removal of starch impurities, thermostable α-amylase can be used followed by the centrifugation technique (Tosh et al., 2004).

β-Glucan extraction from noncereal sources may vary slightly as the compositions of these sources are variable in nature. This condition prevails in the case of yeast, molds, and mushrooms from which β-glucan can be extracted. This kind of β-glucan has different chemical composition, and alkaline treatment favors this type of extraction. For the extraction of β-glucan, the cell mass needs to be treated with a high concentration of alkali (1 M KOH) at low temperature for a long period of time with continuous agitation. This is followed by an exhaustive centrifugation process to separate supernatant and residue. The residue material still contains β-glucan, so it needs to be resuspended twice in the alkaline media for complete separation of β-glucan under the same conditions of temperature. All of the alkali extracts may be precipitated using ammonium sulfate by keeping the material overnight at a temperature of 4°C or lower followed by use of centrifugation at high speed under low temperature to recover β-glucan. This method is highly effective to recover higher amounts of β-glucan with elevated levels of purification from the mushroom cell wall (Nguyen et al., 1998). For extraction of β-glucan from mycelium of *P. chrysogenum*, the mycelium was first freeze-dried and then ground into powder form. In this freeze-dried powder form the material was treated with alkaline solution for the extraction of β-glucan. In this form NaOH is a more effective alkali for the extraction of β-glucan. A concentration of 1 M NaOH at 40°C is quite sufficient to achieve maximum recovery. Freeze-dried powder of mycelia initially treated with the said concentration of alkali can extract β-glucan but with protein impurities that need to be separated by the sevage method that works at low pH. After removal of protein, the pH of the media is again adjusted toward neutral for separation of β-glucan. Further purification may be achieved through dialysis against distilled water (Wang et al., 2007).

6 β-Glucan Characterization and Gelation

Growing trends of functional and nutraceutical foods all over the world have major implications for people's health. The idea is based on development of food products with health-promoting active food ingredients that provide some physiological benefits beyond basic nutrition. The nutritional scientists are striving hard to develop cereal-based, fruit-based, and milk-based nutraceutical products. Among these and several others, the cereal-based nutraceutical products are perhaps at the top of the list. The reason for acceptance of cereal-based nutraceutical products lies in the presence of diversified macro- and micronutrients and the use of cereals as staple food, making it ideal for nutrient fortification programs. Dietary fiber and β-glucan fortification and enrichment from cereal sources is a novel approach that most nutritionists and food technologists are adopting. These foods are helpful in the reduction of bowel transit time, reduction of risk of colorectal cancer, prevention of constipation, and promotion of the growth of beneficial gut microflora (Ahmad and Anjum, 2010).

β-Glucan and other dietary fibers have a diversified nature of physiochemical properties that may be exploited in the food industry. These properties may include solubility, water holding capacities, foam stability, foaming capacities, and their rheological characteristics. All of these characteristics vary significantly in different types of dietary fibers and β-glucan from variable sources. Sometimes water holding capacity in these fibers represents hydrophobic/hydrophilic balance, change in chemical structure, and particle size of the fibers. For instance, β-glucan and guar gum have a capacity to form viscous solutions in the gut, some other fibers may form gel-like structures in the gut, and still other dietary fibers may have good water absorption power (Tungland and Meyer, 2002). In human gut conditions, almost all the dietary fibers retain high amounts of water and act as hydrocolloids, and sometimes dietary fiber rich in insoluble types of dietary fibers may provide bulk to the stool. These water-insoluble fibers, such as cellulose, have comparatively low water retention power as compared to soluble dietary fiber of the type of pectin and guar gum. The water retention power is also important from the point of view of gut microflora growth and existence. There is a direct relationship between water holding capacity and penetration of microorganisms in undigested food to ferment in the large intestine. It is a common phenomenon that β-glucan and dietary fibers having the capacity to retain more water are quickly fermented by gut microflora (Ahmad and Anjum, 2010; McIntyre et al., 1991). The barley- and oat-enriched products having more β-glucan content favor the growth and functioning of microflora in the large intestine that consume β-glucan and other dietary fibers during fermentation. Such barley and oat may be added in the cereal products as such or in the form of β-glucan. This addition of β-glucan will result in more water retention, improved dough development, viscosity, dough stability, mixing tolerance index, and other rheological parameters. The bread products produced by this technique still have high sensory acceptability even up to 15% of barley flakes addition. This type of fortified bread can be used as a prophylactic product against several diseases related to gut health (Ahmad et al., 2008; Ahmad and Anjum, 2010; Kawka et al., 1999).

A water holding capacity of 4–5 g H_2O/g sample is considered sufficient to benefit gut health or industrial processes. Most of the dietary fibers have water-holding capacity in this range. Barley and oats due to higher β-glucan content have slightly higher water holding capacity. This is attributed to the nonionic nature of β-glucan from barley and oats that not only facilitates retention of more water but also provides higher viscosity and weak gel formation characteristics. Furthermore, the addition of β-glucan from these sources also augments the emulsion-forming and stabilizing properties. In solution form, β-glucan depicts a low flow behavior index and a high consistency index in the power law model to support an increase in viscosities (Ahmad and Anjum, 2010; Drzikova et al., 2005; Kontogiorgos et al., 2004).

Gelling behavior for barley β-glucan is unique as it depicts reversible behavior for gels. Temperature rise is required to form stable gels, but temperature above 63°C causes destabilization of these gels. At these temperatures gels start to melt. Sometimes if β-glucan is used at a low level (0.5%) for gelation purposes, the cooling process causes softness of gels (Burkus and Temelli, 2000). During this process, gelation time can be reduced if β-glucan of higher molecular mass is used (Lazaridou et al., 2003). The dependence of gelling on molecular weight explains why β-glucan from different sources has variable time for gelation. Among cereal sources, the gelling ability follows the following order of gelation: wheat > barley > oat. Gelation is a complex phenomenon, and researchers have presented various views about gelling of β-glucan. Fincher and Stone (1986) were of the view that β-glucan gelation initiates with aggregation of β-glucan chains to form a network structure, whereas Böhm and Kulicke (1999) believed that 1→3 linkages in the form of cellotriose units of β-glucan are responsible for the gelation phenomenon. Strong linkages in these units along with some junction points provide the basis for β-glucan gelation. Some researchers have explained the mechanism of gelation on the basis of the ratio of trisaccharides to tetrasaccharides. A higher ratio that depicts more cellotriosyl units favors the formation of β-glucan gels (Lazaridou et al., 2003; Vaikousi et al., 2004).

7 Rheology of β-Glucan

Most industrial processes consider viscosity and rheology as vital parameters. These parameters are influenced by the presence of β-glucan and hydrocolloids. There are numerous applications of viscosity at the industrial level. Sometimes processors need higher viscosities, and sometimes lower viscosity in the product is required. For instance, too much high viscosity in some products has a negative sensory impact. This is especially important in beers and some other beverage products in which stabilizers, β-glucan, or hydrocolloids are added. Similarly, high viscosity in the feed industry is considered a negative practice and is considered an antinutritional factor (Lyly et al., 2003; Wang et al., 1992). In contrast to these examples, higher viscosity may be suitable for some industrial products. In these situations, β-glucan will have great applications as a thickening agent (Wood, 1984). In addition to industrial processes, an increase in viscosity due to β-glucan in the human body is related to vital benefits that reduce sugar absorption in diabetic patients or bring about lowering of cholesterol. When lower viscosity is required in the product, processors often prefer to use either a low concentration of β-glucan or low-molecular-weight β-glucan as ingredients. In these products, this will enhance sensory properties but physiological benefits that are associated with ingestion of β-glucan will be lowered. Therefore, while developing nutraceutical foods enriched with higher amounts of β-glucan, a satisfactory balance among nutraceutical properties, physiological health benefits, and sensory properties should be kept in mind (Brennan and Cleary, 2005).

Concerning the viscosity of β-glucan solution, factors like pH, temperature, source, and extraction conditions are important. The β-glucan solution can be kept in unchanged form over a wide pH range (2–10), but stability decreases with a rise in temperature over a specific limit. Normally a slight rise in temperature is required to achieve an increase in viscosity, but when the temperature rises above 75°C viscosity tends to decline. The molecular weight of β-glucan is also a deciding factor for the viscosity of β-glucan-containing solutions (Ahmad et al., 2009b; Dongowski et al., 2005; Papageorgiou et al., 2005). Concentration of β-glucan is highly correlated with higher viscosities in an aqueous solution. This is equally true for industrial conditions as well as the intestinal tract of the human body. Variation in sources of extraction of β-glucan affects the molecular mass of β-glucan and thus the viscosity behavior of a solution to which this β-glucan is added as an ingredient. As the research carried out on muffins, thus holds true for muffins and require more research to confirm this phenomenon for other bakery products. The only thing affected during storage of β-glucan product is its solubility at freezing temperatures (Beer et al., 1997).

Extraction conditions also affect the final viscosity of the β-glucan. Extraction of oat β-glucan at very high pH will cause changes in β-glucan that may lower its viscosity property. The interaction between high pH and medium temperature is highly unfavorable for the viscous property of β-glucan. This is attributed to the sensitive nature of 1→3 linkages at higher pH levels or medium temperatures.

The endogenous enzymes are responsible for the changes in viscosity. There are at least two endogenous glucan hydrolase enzymes that cause degradation of β-glucans that ultimately modify the viscosity property of β-glucan. Sometimes these enzymes initiate depolymerization reactions, resulting in low viscosities (Ahmad and Anjum, 2010; Burkus and Temelli, 2000). Other factors that may affect the viscous nature in solution form are concentration of β-glucan content, salt concentration, sugars, and their interactions. These factors were studied by Vaikousi and Biliaderis (2005) with reference to changes in viscosity. During this study, viscosity was measured at different shear rates using response surface methodology. The researchers developed a positive linear model for β-glucan content and sugars. Salt did not significantly affect the viscosity property in solution form at a shear rate of 125 per second. However, the inclusion of β-glucan in solution form showed a significant negative quadratic effect for all three responses. Interaction between β-glucan and sucrose was negative and significant. A similar trend was observed for the interaction of salt and β-glucan at shear rates of 10 and 50 per second; significant interaction was observed only between β-glucan concentration and sucrose contents.

In biological studies, several changes in dietary fiber are evident. Dietary fiber may undergo changes as it travels into the stomach and intestine. During this passage under gut conditions some of the insoluble dietary fiber and β-glucan may transform into soluble form. This transformation causes changes in viscosity and water absorption capacity in the gut. These changes in rheological properties are also important for the purpose of attaining a specific physiological response by ingestion of dietary fiber and β-glucan (Wood, 2002).

8 Utilization of β-Glucan in Food Products

Physiochemical properties of β-glucans show great potential to use this valuable ingredient for preparation of various foods (e.g., ice creams, sauces, and salad dressings) (Wood, 1986). The major use of β-glucan in food relates to its stabilizing and hydrocolloid nature that makes it an alternative to guar gum, xanthan gum, locust bean gum, and gum arabic. In this form its best application could be for frozen ready-to-eat foods (Dawkins and Nnanna, 1995; Wood, 1986). Lyly et al. (2004) incorporated β-glucan into frozen ready-to-eat foods. As a thickening agent for beverages, sauces, ice creams, and salad dressings, β-glucan has applicable properties (Temelli et al., 2004; Wood, 1986). There is evidence that β-glucan from barley and mushroom sources has great potential to enrich snack products that have exhibited better physical and textural characteristics as compared to a control recipe. Such β-glucan-containing products may increase the possibility of controlling glycemic responses to a suitable condition (Brennan et al., 2013; Tosh, 2013). Similar potential of β-glucan was demonstrated while studying the effect of resistant starch, β-glucan, and simple starch on sausages using a response surface methodology technique. All of these treatments influenced most of the physical and sensory parameters. β-Glucan in combination with resistant starch produced a softer texture in sausages that is required for great consumer acceptance. The addition of these dietary fiber sources also positively influenced the color and other sensory parameters. Optimum formulation with the addition of 1.328% is possible in addition to incorporating resistant starch and simple starch (Amini Sarteshnizi et al., 2015).

Owing to greater health benefits and the potential of using it as a vital ingredient in the food industry, the US FDA supported the usage of β-glucan as a functional ingredient in food items and endorsed a dose of 3 grams daily to provide health benefits (FDA, 1997). There is a strong relationship between consumption of β-glucan and other dietary fibers and the lowering of heart-related problems and incidence of diabetes. Their usage in staple foods offers a great advantage to achieve these health parameters. Administration of β-glucan in the body stimulates increased macrophage activity and enhances phagocytosis and secretory activities of macrophages. A cascade of reactions started by macrophage regulatory factors can be anticipated to occur and to eventuate in conversion of the glucan-treated host to an arsenal of defense (Fig. 11.4). Bread is a common staple food used in breakfasts in most countries. The use of β-glucan and other dietary fibers in bread will be an applicable strategy to activate phagocytosis activity and related reactions that may improve immune responses within the body. Other beneficial applications of β-glucan involve reduction of coronary heart problems and diabetes, and control of LDL cholesterol. This usage in food products will also impart better viscoelastic properties in bread dough and other bakery products (Ahmad et al., 2008; Byun et al., 2016; Jalil et al., 2015).

Another industrial advantage of using β-glucan is its nature to act as a carbohydrate-based fat replacer, thus lowering the amount of fat in the product in order to develop products

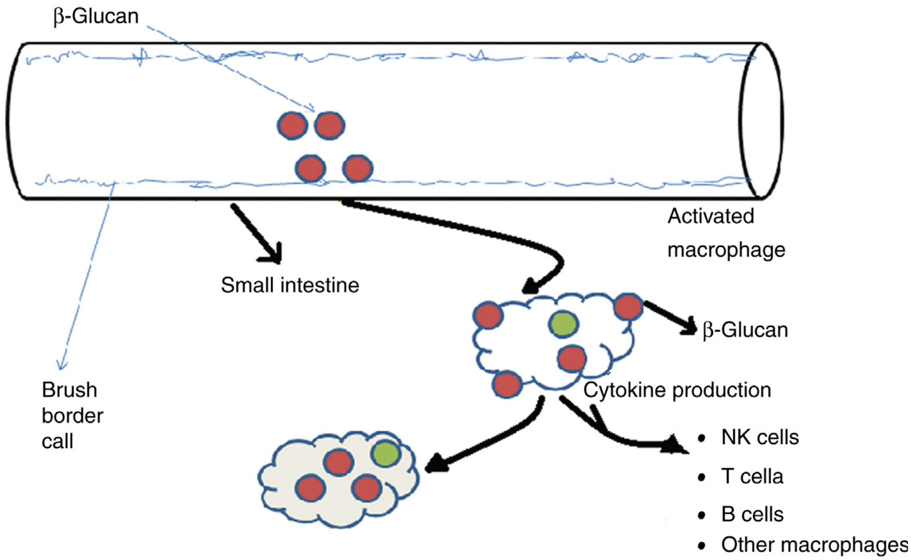

Figure 11.4: β-Glucan Activation of Macrophages.

for weight watchers and diabetic patients. The β-glucan from spent brewer's yeast may be extracted and can be used to develop a low-fat mayonnaise product. The replacement of fat in this case is dependent on the texture-modifying properties of β-glucan. Several levels of β-glucan have a tendency to exhibit acceptable quality parameters when added to a mayonnaise product. However, selective organoleptic properties related to color and appearance may have undesirable effects on the quality of mayonnaise (da Silva Araújo et al., 2014). Apart from spent yeast β-glucan, there is evidence that cereal β-glucan also imparts similar fat replacer properties. This was explored for the development of a low-fat cheese product. Cereal β-glucan resulted in improved texture in the final product (Lazaridou et al., 2014). The effectiveness of β-glucan as a fat replacer in meat products was explored by Álvarez and Barbut (2013), who found the suitability of β-glucan in color, emulsion stability, microstructure, and other textural characteristics in cooked meat batters. Without the use of β-glucan or other dietary fiber source, reduction in fat content adversely affects the cooking loss and causes a reduction in emulsion stability. This reduction in fat content also adversely influences the lightness properties, hard texture, and fracturing properties of cooked meat emulsions. This therefore necessitates that some dietary fiber ingredients be added in the system to lessen the effect of fat reduction. For that purpose, use of β-glucan, inulin, or their mixtures can provide a solution as fat replacer in this system. Published micrographs in this case have highly supported the idea of the addition of β-glucan alone or in mixtures of inulin plus β-glucan. This will have a positive effect on most textural properties and also reduce the losses during cooking. Another β-glucan preparation was made using oat as raw material. Later on, this product was commercialized with the name of Nutrim. This product has several uses, including usage as fat replacer since its properties make it possible to partially replace saturated fats. In another research attempt, the extracted β-glucan preparation with the name of Nutrim-5 was developed from oat flour and bran using thermo-shearing processing. This again has excellent fat replacer and hydrocolloid properties. Its usage in rice flour noodles gives excellent results when incorporated at a level of 10%. The binding and rheological properties of this preparation are ideal in these products (Inglett et al., 2003, 2005). The hydrocolloid nature of this product is also important for use in Thai foods as a fat replacer. This addition enables the researchers to reduce saturated fats from the product. This strategy may lead the way to incorporation in cakes, cookies, pumpkin pudding, dips, custard, and sauté. A similar product with the name of Oatrim is again extracted from oat as raw material and is rich in β-glucan contents in addition to amylodextrins. This product is also meant for replacing fats with the soluble fiber nature of β-glucan. Several potential food products in which this ingredient may be used are muffins, meats, cakes, salad dressings, frozen desserts, sauces, gravies, soups, mayonnaise, margarine, breakfast cereals, and candy products (Inglett and Warner, 1992; Inglett et al., 2004).

Large numbers of dairy products are consumed in every part on the globe. The addition of β-glucan in these products will ensure provision of nutraceutically based products to the population. It is a unique concept to develop new products with bioactive compounds. To implement this idea, a study was planned to investigate the interaction and mechanism for acid-set milk products containing caseinates. The details about microstructure and mechanical behavior were used to explain the results on texture of fermented dairy products. In the case of β-glucan-fortified cheese, desirable product development is possible with the use of oat β-glucan at levels of 0.7% and 1.4% (w/w). This product was compared with two controls; one was with full fat and the other was without β-glucan. Samples containing β-glucan in low-fat cheese milk showed a significant increase in organic acids during the cheese ripening stage (Kontogiorgos et al., 2006; Lazaridou et al., 2014; Volikakis et al., 2004). Food applications are not the only area in which β-glucan from different sources can be used. There are some instances where β-glucan was used for pharmaceutical products, showing its effectiveness as biological material. This is based on its natural applications against antiinflammatory activity and antitumor activity (Ishibashi et al., 2004; Li et al., 2004).

8.1 β-Glucan and Bakery Products

For developing bakery products having nutraceutical value, the importance of dietary fiber and β-glucan is evident from the literature. In these preparations they are used as stabilizers, thickening agents, and foaming agents and to promote water retention. With these properties, products may be marketed as nutraceutical products. Normal breads prepared with ordinary wheat flour contain less than 2.5% of dietary fiber, which is insufficient to provide the daily requirement of dietary fiber if this product is used as a staple food. If citizens of Western nations who are deficient in dietary fiber consumption use β-glucan-containing flour for bread preparation in their daily diets, it will improve their dietary fiber status on a daily basis (Ahmad et al., 2009a; Dziezak, 1987). In a research study, Brennan and Cleary (2007) explored the way we can increase the nutritional status of bread using dietary fiber. They suggested the use of barley β-glucan to improve the dietary fiber content of bread. The addition of β-glucan in these breads at a level of 2.5%–5% also reduced the release of reducing sugars while conducting an in vitro experiment. This happened in the bread with less conversion of starch into reducing sugars and resulted higher value of starch in the product. Overall, these mechanisms resulted in reduction of hyperglycemia and hyperinsulinemia, with reference to the control of diabetes (Ahmad et al., 2009a,b; Hajifaraji et al., 2012). A strong correlation exists between glycemic index and content of β-glucan in bread. Incorporation of oat flour into wheat flour that can increase β-glucan content by a value of 2.5% β-glucan is highly beneficial, as it ensures the daily consumption of β-glucan recommended by the FDA, provided that the person consumes at least two slices of this bread (Flander et al., 2007). Addition of β-glucan into bread sometimes causes a reduction in loaf volume with a firm crumb structure. This reduction in loaf volume is attributed to dilution of gluten content that reduces its property to hold gases during the fermentation process. Binding of more water in the dough also causes less availability of water to gluten. This underdeveloped gluten network is not capable of retaining gases in the cells to gain in volume and texture. Trogh et al. (2004) incorporated cereal β-glucan in wheat flour and raised the soluble dietary fiber with chemical structure of (1→3)(1→4)-β-D-glucan and arabinoxylan (AX) of dough. To solve the problem of substandard loaf volume, scientists directed their research toward the use of β-glucan in unpurified form instead of purified form. For this purpose, they used the whole barley flour, which is a good source of β-glucan. In this experiment, β-glucan in refined form was not added to the wheat flour. This resulted in production of bread with good sensory properties, and such breads have an acceptable volume. During this process, enzymatic degradation of β-glucan in the raw blend of wheat and barley flour was restricted by using coarse flour that offered less surface area for enzymatic action (Ahmad et al., 2008; Cavallero et al., 2002; Flander et al., 2007; Trogh et al., 2004).

A recent study evaluated the potential use of barley flour for the production of sour dough. The production of sourdough is often characterized by use of microorganisms capable of running a fermentation process, and physically it seems difficult to produce sourdough of improved quality, as microorganisms in sourdough can hydrolyze β-glucan during fermentation (Sullivan et al., 2013). The effect of β-glucan incorporation in rice-based dough that offered a gluten-free product was evaluated. As expected, the rheological properties with reference to water holding capacity were influenced significantly. A negative correlation was evident between loaf-specific volume with dough elastic modulus (G') and the viscosity (η_0). Loaf volume was positively correlated with the loss tangent. After hydration to a maximum point, the rheological behavior and bread quality was affected by the levels of incorporated barley β-glucan. In contrast, the use of oat β-glucan at various levels influenced these parameters to a lesser extent. These trends elucidate that β-glucan from barley consists of a low-molecular-weight substance that can generate a gel network if it is added in higher amounts. On the other hand, oat β-glucan with higher molecular weight shows more viscous behavior even at low concentration of β-glucan. Quantification of β-glucan in bread indicated that enzymes like β-glucanase significantly hydrolyze the β-glucan molecule, thus cutting their molecular weight. This necessitates that enzymatic activity must be controlled during this process in gluten-free doughs to reap the full benefit of β-glucan as a nutraceutical component and to achieve certain health benefits (Ahmad et al., 2008; Ronda et al., 2015).

8.2 β-Glucan and Meat Products

Meat and its derivatives are considered functional foods, but still there is a possibility to add more functional ingredients into them. This idea of supplementation of meat with dietary fiber, β-glucan, and some other nutraceutical ingredients for the purpose of achieving health benefits beyond basic nutrients will open up new avenues for the meat industry. Despite using conventional meat products, meat processors should explore innovative prospects for the meat industry. This may include controlling the composition of raw and processed materials via reformulation of a product recipe through inclusion of β-glucan, dietary fiber, antioxidants, probiotics, and some other nutraceutical ingredients (Siró et al., 2008). When mushroom extract was added into meat products, it provided protection against bacteria and oxidation reactions. This was actually attributed to the presence of β-glucan and other dietary fibers along with several natural antioxidants. This addition of mushroom extract also resulted in stabilization of meat color in the final products. Storage duration may be doubled or even tripled by this technique (Aida et al., 2009). Dietary β-glucan also has an impact on the quality of broiler breast meat following ingestion of β-glucan by chickens. A quantity of 60 ppm β-glucan in the feed of broiler chickens not only guarantees improvement in survival rate and feed conversion rate, but it also provides immunity against disease. Thus, consumption of β-glucan at this level in broilers shows the same effect as the quantity of antibiotics Zn-bacitracin at the level of 55 ppm. The outcomes of this study showed the potential of β-glucan (60 ppm) as an alternative to antibiotics in extending the survival rate of broilers (Moon et al., 2016). In an attempt to investigate the effects of β-glucan and inulin as dietary fiber sources for low-fat beef burgers, researchers observed more moisture holding capacity, increase in cooking yield, reduction in lightness, and satisfactory textural parameters of burger patties. Optimization results indicated that the combination of inulin (3.1 g per 100 g), β-glucan (2.2 g per 100 g), and bread crumbs (2.7 g per 100 g) may provide better textural characteristics and cooking properties without altering organoleptic characteristics of the burger (Afshari et al., 2015). The properties of β-glucan as a fat replacer is applicable in meatball products. The molecular weight of β-glucan in this case is an important determinant to declare the overall quality of the low-fat meatballs. Intact β-glucan or hydrolyzed β-glucan from oats may influence the quality of the product to which it is added as a nutraceutical ingredient. Both the hydrolyzed form and the unhydrolyzed form of β-glucan exhibit shearthinning behavior in these products, and hydrolyzed β-glucan due to low molecular weight also showed a decrease in the apparent viscosity. Scanning electron microscopy indicated improvement in smooth surface by the addition of hydrolyzed β-glucan (Liu et al., 2015). Some other functions of β-glucan and several other forms of dietary fibers in processed meat include: as binding agent, as filler agent, as extender ingredient, and as fat replacer, as well as to add a synergistic effect with nutrients, to control pH, to improve emulsion stability, to improve water holding capacity, and to expand its sensory parameters (Talukder, 2015).

8.3 β-Glucan and Dairy Products

Fermented dairy products have a great potential to develop effective delivery systems for β-glucans from various sources. Addition of β-glucans into milk or milk products or into dairy-based derived protein gels during the process of fermentation that produce acids and oxidative products of monosaccharides results in production of glucono-δ-lactone. This substance may modify textural, physiochemical, chemical, and sensory properties of milk products due to phase separation between these polysaccharides and milk proteins, thus altering the gelation process through retardation of interaction between proteins and carbohydrates. Higher temperatures during fermentation also favor acidification in these products, yielding a shorter gelation time. Probiotic strains, if included during the fermentation process, resulted in an increase in gelation rate (Lazaridou et al., 2014). Exopolysaccharides from *Lactobacillus kefiranofaciens* are rich in dietary fiber, including β-glucan, and also possess similar capacities to apply in dairy products (Ahmed et al., 2013a,b). Another exopolysaccharide-producing strain is *Lactobacillus mucosae* DPC 6426, which has a great potential to be used as an adjunct culture for the manufacturing of low-fat yogurt. These exopolysaccharides hold space in the pores of the gel network as confirmed by confocal laser scanning microscopy (London et al., 2015). Addition of glucagel, a commercial product derived from barley that is rich in β-glucan dietary fiber, influences the phase separation phenomenon in skimmed milk. In the presence of β-glucan dietary fiber, casein micelle showed depleted flocculation that is the driving force behind controlling phase separation. Volume fraction of casein molecules and the concentration of glucagel also control the rate at which phase separation may occur in dairy-based systems. Low-molecular-weight β-glucan was effective to limit the range of attraction between protein micelles and to produce a stable phase in the presence of casein micelles. These phase diagrams will be useful to dairy product manufacturers striving to improve the nutrient profiles of their products while avoiding product quality impairment (Repin et al., 2012; Sharafbafi et al., 2014).

8.4 β-Glucan and Pasta Products

In the modern era, consumers are demanding more products having health implications. These health benefits may be added in commonly consumed foods like pasta products. When β-glucan from an unusual source, *Amaranthus mantegazzianus*, was added in wheat flour, it improved the pasta characteristics and influenced positively the dietary fiber content and the glycemic index, along with an improvement in carbohydrate and protein digestibility. Beneficial effects can be achieved if this source is added at the 30% level (Martinez et al., 2016). The incorporation of barley β-glucan into pasta has documented health benefits such as lowering of the glycemic index. Beyond its physiological benefits, it also requires suitable changes in processing methods as well to cause improvement in color, flavor, taste, and texture (Izydorczyk and Dexter, 2008). Barley β-glucan, when incorporated into wheat flour, imparts increased strength to dough, causes required changes in viscoelastic properties of the dough, and makes the dough have high resistance during mixing (Izydorczyk et al., 2001). Similarly, soluble β-glucan from barley has a capacity to reduce the resistance of dough against extension. Stickiness properties of starches are also influenced by the presence of β-glucan in these products. This addition also causes lowering of the viscosity of gel and elevation in gelatinization temperature (Brennan and Cleary, 2007). Pasta products produced with addition of β-glucan and enriched with wheat semolina showed a great potential for substitution at a level of 50%. This may result in a slightly darker color pasta product but have better quality cooking (Marconi et al., 2000). To produce yellow alkaline and white salted noodles using conventional processes with addition of barley flour as a source of β-glucan results in an increase in water absorption in the pasta dough. This reduces the quantity of available water in the system and thus suppresses the gluten development and gas holding capacity that are considered positive traits for pasta production (Gill et al., 2002). The recipe for white salted noodles contains about 40% hull-less flour of barley, which was sufficient to satisfy the β-glucan level recommended by the FDA (2004). However, the effect is dependent on the physicochemical properties of β-glucans (Brennan and Cleary, 2007). Addition of β-glucan in pasta products produces dough that has high set thermoirreversible properties and is regarded as a β-glucan-enriched functional product (Laroche and Michaud, 2007). The β-glucan-enriched functional pastas produced by 50% of standard wheat durum semolina with barley flour that is enriched in β-glucan showed better quality with regard to firmness, bulkiness, and stickiness than pasta products produced by durum wheat (Marconi et al., 2000).

Conclusions

β-Glucan is a nonstarch polysaccharide having documented health benefits and industrial applications. It can be extracted from various sources, including cereals, bacteria, molds, and fungi. The chemical nature of extracted β-glucan from these sources differs slightly. This variation in chemistry defines its industrial uses and health benefits. Apart from source, the properties of β-glucan also depend on extraction techniques. Although several extraction techniques have been developed for extraction of β-glucan, there is yet more need to devise new extraction and purification techniques that can be materialized to increase the recovery of β-glucan from various sources. Documented health benefits make β-glucan a potential candidate for food product development having nutraceutical status. In the past decade, research was focused on investigating the use of β-glucan in bakery products, dairy products, meat products, and beverage products. There is still room to explore more areas for product development with reference to industrially important properties in these products.

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