Valorization of lignocellulosic biomass in production of β-glucans

Peyman Abdeshahian[1*], Jesús Jiménez Ascencio[1] , Rafael R. Philippini[1], Silvio Silvério da Silva[1]

[1] Department of Biotechnology, Engineering School of Lorena , University of São Paulo, Brazil

*Corresponding author:

Peyman Abdeshahian

Department of Biotechnology, Engineering School of Lorena , University of São Paulo, Brazil

Email: peyman_137@yahoo.com

Abstract

β-glucans are carbohydrate polymers in which several D-glucose monomers are linked by B-glycosidic bonds. β-glucans show different molecular structures with tremendous medical activities including anti-cancer, anti inflammatory, and immune-modulating properties. An increasing interest has been shown by the researchers to produce β-glucans from lignocellulosic biomass as an abundant source for production of value –added products and chemicals. The utilization of lignocellulosic biomass for β-glucan production makes the production processes economically viable and environmentally friendly. This article aims to overview the utilization of lignocellulosic biomass for the synthesis of β-glucan.

Keywords: β-glucan production; Lignocellulosic biomass; Valorization, Biopolymer

1. Introduction

Glucans $(C_6H_{12}O_5)_n$ are known as a type of polysaccharides of D-glucose monomers which are linked through glycosidic bonds. Glucans are categorized as **α**-glucans and β-glucans in accordance with the chemically glycosidic bounds including α- glycosidic and β-glycosidic linkage, respectively. Furthermore, some types of glucans are composed of mixed αand β glycosidic bonds [1, 2].

β-Glucans are composed of D-glucose monomers which are linked through β-glycosidic bonds [3].

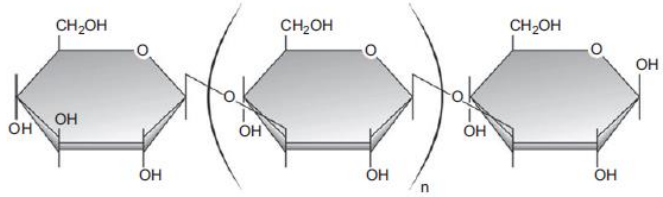
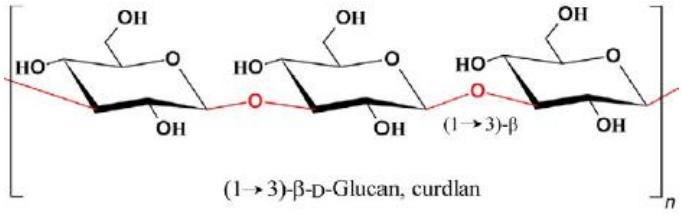


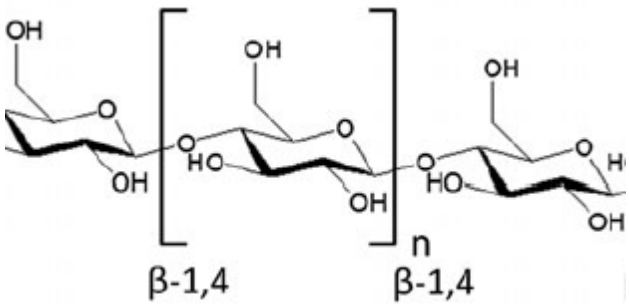
Figure 1. Structure of B-glucan [4]

Various types of β-glucan may be found based on the glycosidic linkage position. The molecular studies of β-glucans have revealed that glucose unites can be linked by β-(1→3), β-(1→4) and β-(1→6) bond in the polymeric structure of the β-glucans [5].

A

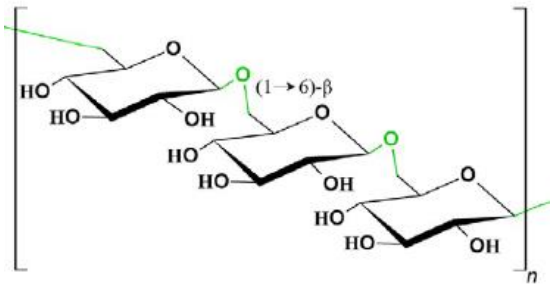


B



(1→4)-β-glucan

C



(1→6)-β glucan

Figure 2. Molecular structure of: (A) (1→3)-β ghlucan, (B) (1→4)-β glucan and (C) (1→6)-β glucan [6, 7]

In this regard, the mixed β-glucosidic linkage can be detected in the β-glucans including β-(1→3), β-(1→4) linkage and β-(1→3), β-(1→6) linkage [7-10].

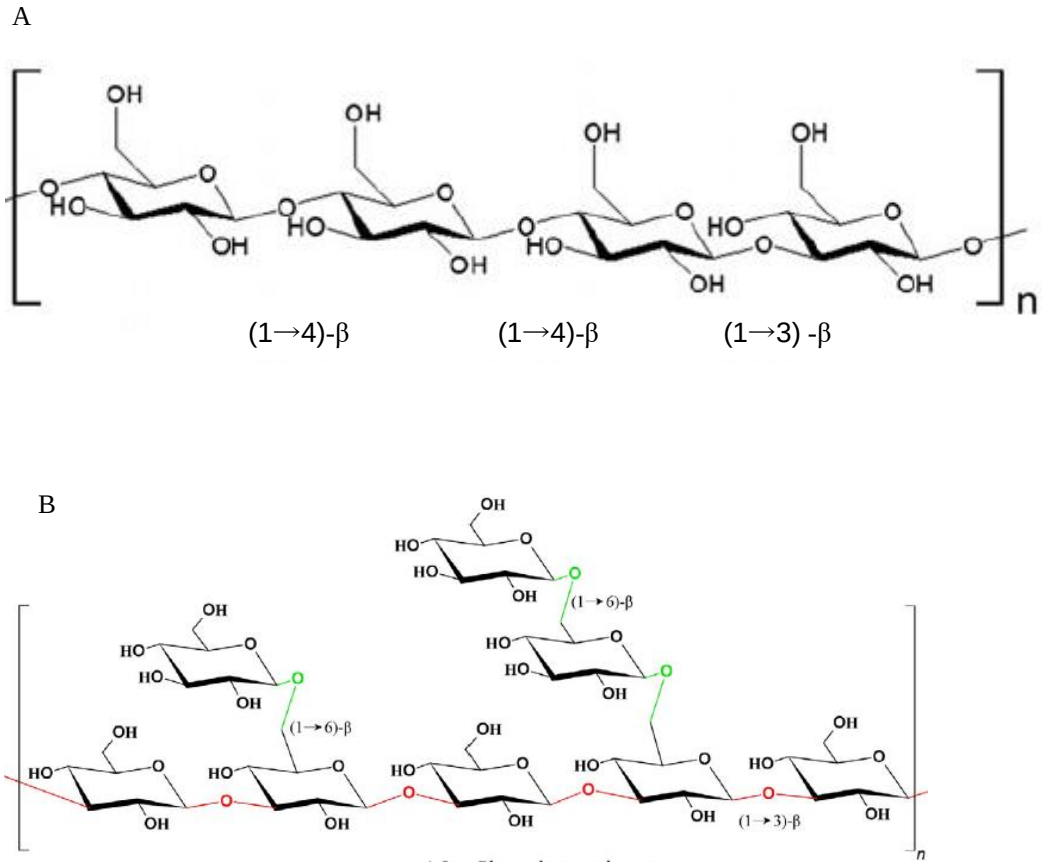


Figure 3. Molecular structure of (1→3), (1→4)-β glucan (A) and (1→3)-β, (1→6)-β glucan (B) [6, 7].

B-glucans have been derived from different biological sources. B-Glucan is found in the cell wall of many organisms including microbes, agricultural grains and seaweed which have been used for extraction of B-glucan [11-13]. Main agricultural grains used for β-glucan extraction are oat, barley, maize , rice , wheat and rye [12, 14]. On the other hand, β-Glucan has been obtained from various microbial sources such as fungi, algae and bacteria [15]. Among the microbial β-Glucan producers, bacteria and fungi (including filamentous fungi, mushroom and yeast) have received more interest for utilization in β-glucan extraction [16]. Table 1 present different B-glucan producing microorganisms.

Table 1. Various microorganisms used for production of β-glucan

Microorganism	Type of β-glucan	Reference
Botryosphaeria rhodina	(1→3), (1→6)-B glucan	[3]
***Agaricus brazei* MURRILL**	(1→6)-B glucan	[17]
Pleurotaceae citrinopileatus	(1→3)-B glucan	[18]
Aureobasidium pullulans	(1→3), (1→6)-B glucan	[12]
Paenibacillus polymyxa JB115	(1→3), (1→6)-B glucan	[19]
Bacillus sp. SNC 107	(1→3)-B-glucan	[20]
Alcaligenes faecalis	(1→3)-B-glucan	[20]
Agrobacterium sp. ATCC 31750	(1→3)-B-glucan	[21]
Lasiodiplodia theobromae	(1→6)-B glucan	[22]
Botryosphaeria rhodina	(1→3),(1→6)-B glucan	[3]
Candida utilis	(1→3),(1→6)-B glucan	[24]
Panebacillus polymyxa	(1→3),(1→6)-B glucan	[25]
Bradyrhizobium japonicum	(1→3),(1→6)-B glucan	[26]
Pleurotus eryngii	(1→3)-B glucan	[2]
Saccharomyces cerevisiae	(1→3),(1→6)-B glucan	[27]
Botryosphaeria sp.	(1→3),(1→6)-B glucan	[28]
Botryosphaeria rhodina	(1→3),(1→6)-B glucan	[29]
Euglena gracilis	(1→3)-B glucan	[30]
Sparassis crispa	(1→3),(1→6)-B glucan	[31]
Aspergillus flavus	(1→3)-B glucan	[32]
Paecilomyces variotii	(1→6)-B glucan	[31]
Pleurotus ostreatus	(1→3),(1→4)-B glucan	[33]
Eisenia bicyclis laminarin	(1→3),(1→4)-B glucan	[33]
Claviceps purpurea	(1→3),(1→4)-B glucan	[33]
Sclerotinia sclerotiorum	(1→3),(1→4)-B glucan	[33]
Poria cocos	(1→3)-B glucan	[33]
Vitis vinifera	(1→3)-B glucan	[33]
Larix laricina	(1→3)-B glucan	[33]

The physicochemical properties of β-glucans vary depending on their structural features, i.e., their linkage type, degree of branching, degree of polymerization,conformation (triple helix, single helix, or random coil), and molecular weig [11].

β-glucans have found different applications. In this view, β-glucans have notable applications in medicine. β-glucan is known as biological response modifiers (BRMs). In this context, β-glucan acts through pattern recognition receptors (PRRs) which are on the surface of pathogenic microorganisms and release different kinds of immune responses. Subsequently, cell-mediated immunity is activated and increases phagocytosis activity. On the other hand, inflammatory responses trigger anti cancer agents and anti microbial substances [12, 22, 25]. Furthermore, β-glucans prevent the absorption of lipids or the reabsorption of bile acids and their metabolites which lead to reduction of cholesterol level [27].

The further studies have revealed that the supplementation of fish, shrimp and animal feed by β-glucans results in the improvement of natural immunity which increases its application in aquaculture and livestock [19]. In addition to medical and pharmaceutical products, β-glucan is applied in food industry as fat replacers, oil-binder, dietary fibers, emulsifiers, food thickener with gelling property [13, 33]. β-glucan has also found a specific application in wound healing and cosmetic [1, 9, 24].

β-glucans derived from different sources have different molecular weights with varied biological activities [14]. Although yeast , fungi and agricultural crops have mostly been used for extraction of B-glucan, the production of β-glucan cannot currently meet the wide demand owing to its high costs of production [12]. The major costs used for β-glucan production are the supply of raw materials.

Lignocellulolsic substances are the most plentiful biomass formed during photosynthesis and constitute more than 60% of plant biomass. The yearly lignocellulose production has been approximated to be 1×10^{10} MT around world [34, 35]. Lignocellulose is composed of lignin, cellulose and hemicellulose and is the most important structural constituent of woody and non-woody plants on the earth. Lignocellulosic biomass may be derived from the forestry and agricultural sectors, paper and pulp industries, timber industries and varied agro-industrial sectors [36, 37]. In this context, a huge quantity of lignocellulosic substances is

considered as waste and is generally burned to be disposed [37]. Cellulose fraction of lignocellulosic biomass is the most frequently skeletal composition, constituting about 50% of the cell wall structure of plants. Cellulose is a linear polymer containing D-glucose subunits linked by β-1,4 glycosidic bonds which constitute the dimeric cellobiose.

In addition to hemicellulose and lignin, cellulose is recognized as the main fraction of agricultural residues and municipal waste [38]. Cellulose is regarded as one of the most basic sources of carbon on the planet so that its annual production by both plants and marine algae is accounted for 0.85×10^{11} tonnes [39].

Considering the huge amount of yearly generation of cellulosic waste, the lignocellulosic biomass is considered as the highly available low-cost carbon source for utilization in the synthesis of glucose –based biopolymers. In this view, B-glucan production from lignocellulose could be economically viable and environmentally friendly where the industrial scale of production is targeted. However, the use of lignocelluloses as the feedstock for biochemical process of B-glucan production has been neglected in previous research studies. There is scarce information available regarding the biological conversion of lignocellulose to B-glucan based biopolymers. Hence, it is imperative to study the potential uses of lignocellulosic feedstocks for laboratory production of B-glucan with development of biological processes in commercial scale. Although production of B-glucan has been extensively taken into account by many researchers, there is a scientific lack of information regarding the potential application of lignocellulose as a renewable carbon source for synthesis of β-glucan. To the best of authors' knowledge , no work has been published to discuss the possible utilization of lignocelluloses in the production of B-glucans by microorganisms.

In this review article, an overview of the current B-glucan –derived sources is presented with processes used for B-glucan production. Finally, the feasibility of b-glucan production from lignocellulosic substances is discussed.

2. βglucan production sources

2.1. Agricultural crops

Cereal grains are considered one of the main sources of the B-glucan production. A number of cereal grains have been utilized to extract β-glucan. Production of β-glucan from cereal grains has difficult procedures so that it increases the B-glucan production costs. For extraction of B-glucan firstly, B-glucan is solubilized in hot water and in alkaline solutions. Next step is the separation of the dissolved proteins by isoelectric precipitation, and precipitation of the B-glucan by ammonium sulfate, 2-propanol, or ethanol [14]. Among cereals, barley and oat are rich sources for this type of dietary fiber where the major part of this dietary fiber resides within the endosperm, and the other may be concentrated within the aleurone layer.

Barley represents a known B-glucan production which on average contains about 5% beta-glucan. The B-glucan content of barley is composed of β(1→3), B (1→4) glucan as structural polysaccharides [6, 38]. Barley β-glucan has a high molecular weight (≤1000 kDa) which causes a high viscosity in food products [8].

Barely can grow on the land during winter in areas with the mild winter, which can be used as a winter cover crop for protecting soil. Barley captures nitrogen (N) of the soil with improving sodium (Na) and potassium (K) cycling. On the other hand, barley grains have a low amount of starch with a high content of fibers which provides a potential source of β-glucan [38 , 39]. Most of the barley harvested is used for livestock feed, while a low amount of barley is consumed in human food [40].

Different methods have been used for the extraction and recovery of B-glucan from barley. In a study, the techniques of accelerated solvent extraction (ASE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and reflux extraction were utilized for the extraction of B-glucan from bran of hull-less barley. It was found that ASE gave a large extent in a short time, compared to other methods used [41]. Liu et al. (2009) used dry fractionation methods for enhancement of B-glucan in dehulled and hulless barleys. They found that combination of pearling method with milling and sieving was effective to obtain maximum shifting B-glucan content **[40].** The ratio of the β(1→4) to β(1→3) linkage in barley bran β-D-glucan and in lichenan is appropriately 3:1 and 2:1[6].

Oat is a potential alternative cereal grain B-glucan. The major soluble component of oat fiber is composed of B-glucan. Oat contains a quite high quantity of B-glucan so that its B-glucan content accounts for between 25 and 66 g/kg. Molecular structure of B-glucan is composed of β(1→3), B (1→4) glucan. The structure and characteristics of oat B-glucan differ between species and cultivars of oats, and are also influenced by the conditions adopted for growing, keeping and processing of oat grain. On the other hand, the amount of B-glucan of oat is affected by the environmental factors and in a higher extent of genetics [8, 42, 43]. For extraction of oat B-glucan, Morgan (2006) studied the process of B-glucan production from oat grains. The process entails different sequential steps including the preparation of flour from oat grins and subsequent mixing of flour with water to obtain a slurry of an aqueous solution of B-glucan and a solid residue. It is followed by the separation process of aqueous solution from the solid residues using evaporation of slurry or ultrafiltration method or combined both methods to produce B-glucan as gel or solid [44]. Beer et al (1996) used oat bran for production of B-glucan. In this method, oat bran was mixed with aqueous sodium carbonate at pH 10 and a temperature of 40^{o}C. The oats gums rich in B-glucan were then separated and collected by dialysis, ultrafiltration or alcoholic precipitation methods [45].

Skendi et al. (2003) extracted B-glucan form milled seeds of oat obtained from Greek varieties in which purification was performed by adjusting pH of B-glucan aqueous to the value of 4.5 [46]. Wheat is of a lower importance source for production of B-glucan. Wheat contains b-glucan content ranging from 2 and 12 g kg^{-1} dry base. Other grain cereals which are composed of β-glucan include rice, millet, and maize, however, in lower levels [47, 48].

2. 2. Microorganisms

B-glucan is one the main molecules in the cell wall of microorganisms. In this regard, different kinds of β-glucan are produced in microorganisms which are used as either saccharides for providing cell energy or for strength of cell wall structure. On the other hand, some microorganisms secrete β-glucan molecules into extracellular medium [12, 13, 16].

2.2.1 Fungal β-glucan

Fungal cells are embedded in a polysaccharide complex, including mainly B-glucans and chitin, which provide the strenghtening and rigidifying framework for the cell wall. Hence, B-glucans confer the structural integrity of the fungal cell wall [4, 49]. Fungi – originated B-Glucans are mainly composed of D-glucose units with (1→3) glucosid linkage. However, mixed linkages (1→3;1→6) are basically found in the cell wall of fungi. On the other hand, some B-Glucans are also secreted exocellularly [22]. In this regard, lasiodiplodan, scleroglucan and botryospheran are known as B-glucans which are produced by fungal cells and secreted extracellularly [16 , 50]. Lasiodiplodan is a (1→6)-B-glucan that is produced by the fungus Lasiodiplodia sp. from glucose in a microbial culture medium [22]. Scleroglucan represents an extracellular polysaccharide which is produced by the filamentous fungus *Sclerotium sp. Scleroglucan is composed of* (1→3), (1→6)-B-glucan [51, 52]. Botryosphaeran is designated as an extracelluklare B-glucan produced by ascomyceteous fungus Botryosphaeria sp containing (1→3), (1→6)-B-D-glycosidic linkage [53].

It has been found that mushrooms can contain a high amount of B-glucans ranging from 30 to 40% of their weight (w/w) with a (1→3), (1→6)-B-D-glycosidic bond. In this context, *Sparassis crispa* is an edible mushroom species which has a high quantity of B-glucan accounting for 43.6% of the dry weight of the fungus with β-1,3-linked glucose residues [2, 5, 31]. Biochemical studies of the fruit body of the edible mushroom *Lentinus edodes have reveled that a* B-glucan polysaccharide, namely lentinan can be found at the cell walls of the mycelium. It has been found that lentinan contains a chemical composition of (1→3), B-D-glycosidic linkage backbone with a (1→6)-B-D-glycosidic bond branch [54]. The fruiting body of mushrooms are mostly utilized for the isolation and extraction of B-glucan. In this regard, Bhanja et al. (2014) extracted B-glucan from fruiting body of the mushroom *Ramaria botrytis using sodium hydroxide* . The extracted B-glucan contained nonlinear B-(1 /3)-D-glucan branched at O-6 [55]. A B-glucan polysaccharide was extracted from the fruiting body of the mushroom *Agaricus blazei* Murill where the fungus was mixed with distilled water at a ratio of 1:10 (w/v) and extracted three times with hot water (100 ^{o}C) for 3 h [56]. Other mushrooms containing B-glucan are *Grifola frondosa, Agaricus blazei* and *Phellinus baummi* [57]. On the other hand mycelium of fungi has been used for the extraction of the B-glucans. In this context, a B-glucan polysaccharide from the mycelium of fungus

Schizophyllum commune was extracted by cultivation of fungus in a liquid culture in which a synthetic adsorbent was supplemented [58].

2.2.2 Yeast B-glucan

There is an increasing biotechnological and industrial trend in the synthesis of B-glucans derived from yeast. B-D-glucan occurs as a natural structural constituent of the yeast cell walls. Its presence represents mechanical rigidity and consequently makes the structural integrity of the cell wall of yeasts to sustain under environmental stressing factors [24].

B-glucans form 50–55 % of cell wall of yeast. The b-glucans of yeast cell walls are mainly as 1→3B-D-glucan accounting for 85 % of B-glucans, whele 15 % B-glucans are found as (1→6)-B-D glucan [13]. A number of yeasts have been applied for the production of B-glucan such as *Saccharomyces cerevisiae*, *Candida utili and* winery spent yeast [13, 24 , 35]. In order to produce B-glucan from yeasts, the cell wall needs to be prepared for extraction of B-glucan. For this purpose, the yeast cell wall is subjected to a lysis or disruption process to flow out cytoplasmic content of yeast cells. The yeast cell lysis or disruption of yeast cells can be attained by physical methods (sonication, homogenization), chemical methods (alkali, acid) and enzymatic methods such as using glucanases [13].

2.2.3. Bacteria B-glucan

Similar to fungi, bacteria can produce extracellular **B-glucan.** Curdlan is a water-insoluble linear unbranched exopolysaccharide which is produced by the *Agrobacterium* sp., *Alcaligenes faecalis* and *Bacillus* sp. SNC 107. Chemical studies show that curdlan is comprised of (1→3)-B-glucan. It was noted that soil-isolated bacterial strain *Paenibacillus polymyxa* JB115 which was isolated from soil could produce B-glucan containing (1→3), (1→6)-B-D-glycosidic bond [20, 50, 59]. Stack et . (2010) studied on the production of B-glucan by bacterial strain *Lactobacillus paracasei* NFBC 338. They detected extracellular B-glucan production from this strain using membrane-associated glycosyltransferase enzyme [60]. The study fulfilled by Crognale et al. (2007) revealed that B-glucan was produced by Botryosphaeria rhodina DABAC-P82 in which concurrently glucan-hydrolytic enzymes and their reaction place, rheology of cultivation medium and oxygen transfer was studied. It was

noted that highest B-glucan concentration attained in the bioreactor was related to the nitrogen and dissolved oxygen quantities [61].

3. Lignocellulose as potential carbon source for B-glucan production

Lignocellulose is a potential carbon source for the synthesis of B-glucan by microorganisms such as fungi and bacteria. Cellulose is a basic fraction of lignocellulosic substances which could be utilized by B-glucan producing microorganisms. Cellulose content is composed of long chains of β-D-glucopyranose residues which are linked by 1-4 glucosidic bonds [62] .

Hence, microorganisms are able to utilize glucose for production of B-glucan polymer.
Cellulose fraction of lignocellulose is bounded by hemicellulose and lignin fractions. In order to microorganisms utilize cellulose constituent for B-glucan synthesis, cellulose fraction must be converted to glucose units. However, cellulose degradation is hindered by the recalcitrant structure of lignocellulose in which there are robust linkages between cellulose and other fractions, namely hemicelluloses and lignin. Consequently, for the efficient utilization of cellulosic biomass in B-glucan production, hemicellulose and lignin must be removed to access cellulose fraction.

Cellulose is then saccharified by enzyme hydrolysis to liberate glucose monomers. This entails the use of pretreatment methods. Since lignocellulose has a recalcitrant structure and complex nature, pretreatment is a prerequisite step to remove or disrupt hemicellulose and lignin constituents from cellulose fraction for further penetration of enzymes to active site of cellulose where enzymatic saccharfication is adopted. In addition to disaggregation of cellulose from lignocellose matrix, pretreatment reduce the degree of cellulose cristallinity, which in turn enhances enzymatic hydrolysis and glucose liberation. A number of pretreatment methods have been developed to split lignocellulose constituent including physical pretretment, chemical pretretment and biological pretretment. Physical pretreatment referes to the methods used for the decrease of the ligniocellulose particles by grinding, milling, hacking, rolling, mechanical interactions, as well as for changing chemical structure through microwave radiation, sonication, spray drying, gamma radiation, liquid hot water, steam explosion and pyrolysis. Chemical prtretment involves the application of chemicals for dissociation of lignocellulose . Various chemical approaches have been utilized for this purpose such as dilute acid degradation, alkaline delignification and ozone pretreatment.

Biological pretreatment has been known as the application of microorganisms such as brown, white and soft rot fungi for dissociation of lignin and hemicelluloses fraction from the lignocellulosic biomass **[**63].

Although pretreatment methods are used to fractionate lignocellulose structure for efficient enzyme hydrolysis of cellulose, they bring about the formation of inhibitory compounds which are derived from lignocellulose during prtetreatment. These inhibitory substances such as aliphatic carboxylic acids (acetic acid, formic acid, levulinic acid) and the furan aldehydes (furfural and hydroxymethylfurfural) hinder enzymatic hydrolysis and microbial cell growth [64]. Hence, inhibitory compounds need to be subjected to a detoxification step using detoxifying substance such as resin and activated charcoal [65]. Lignocellulosic feedstocks serve a potential source for the production of B-glucan by microorganisms in a biorefinary system since it is composed of 75% carbohydrate polymer [66].

Various lignocellulosic biomass can provide crud cellulose as a base substrate for microorganisms to synthesize B-glucan. In this context, lignocelluloses obtained from agriculture and forestry, including agro-industrial residues, forest-industrial residues and energy crops such as sugarcane bagasse, rice straw, wheat straw, switch grass, corn stover, barley straw, rice hull, hard wood, soft wood, are low cost cellulosic substances [67, 68] which can be taken into account of a viable source for cost effective B-glucan production. On the other hand, lignocellulosic raw materials such as municipal solid waste, pulp milles, residues from biorefineries waste, and anima manures [67, 69] can contribute to the future economically viable production of B-glucan. Table 2 presents different lignocellulosic feedstocks as a potential substrate for B-glucan production [70-72].

Among microorganisms fungi (molds and yeasts) and and bacteria are most suitable microorganisms for B-glucan synthesis using lignocellulosic biomass since their cells are capable of utilize glucose for producing a high quantity of B-glucan in the fermentation processes either as cell wall β-glucan or extracellular polymers [22, 24, 50, 73].

Generally, in β-glucan fermentation from lignocellulose, the cellulose fraction of holocellulose (whole cellulose, hemicellulose and lignin) must be dissociated from hemicellulose and lignin fractions by means of pretreatment approaches. Cellulose pulp obtained is further hydrolyzed by cellulolytic enzymes to liberate glucose monomers as a

base carbon source for production of β-glucan by microorganisms. Glucose-rich hydrolysate is then transferred to fermentation medium for microbial growth and β-glucan synthesis. Although to date no work has been reported to exploit lignocellulosic feedstocks for β-glucan production, it is noteworthy that the utilization of lignocellulose from raw materials and agro-industrial waste for biochemical production is economically viable and environmentally friendly because of their high availability and low cost [74, 75]. In this context, the research studies performed by the authors (data still not published) revealed that the utilization of agricultural residues containing a cellulosic content are a promising lignocellulosic substrate for the synthesis of β-glucan by the fugal strains which produce extracellular polysaacharide in fermentation media.

Same studies showed that the alkaline pretreatment of agricultural residues tested following dilute acid pretreatment under high pressure and temperature of steam in an autoclave could split lignocellulose structure to provide a high enough cellulose component for enzymatic saccharification by cellulase. The biochemical analysis of the hydrolysate content obtained from enzymatic hydrolysis of the cellulose fraction revealed that a high quantity of glucose monomer was triggered [76] which was used as a structural block for β-glucan production by microorganisms.

4. Conclusion

β-glucan is the biopolymer of glucose molecules linked by glycosidic bonds. β-glucan is obtained from different sources such as microorganisms and agricultural cereals. β-glucan has found various application in medicine, food industry and cosmetic. The major costs used for β-glucan production are the supply of raw materials. Lignocellulose is composed of cellulose, hemicellulose and lignin. Lignocellulosic biomass is a sustainable source of carbon-based substance which is produced in huge amount in environment. In this regard, lignocellulosic feedstocks can be considered as economically viable raw materials for production of β-glucan by microorganisms. Hence, lignocellulosic compounds are promising raw substances which can make β-glucan production more cost effective and environmentally friendly.

Acknowledgement

This work was supported by the São Paulo Research Foundation – FAPESP (Processo Fapesp No. 2018/14095-7) in São Paulo, Brazil

Table 2 Different lignocellulose containing materials with the respective quantity of cellulose, hemicellulose and lignin content [70-72]

Lignocellulosic materials	**Cellulose (%)**	**Hemicellulose (%)**	**Lignin (%)**
Hardwood stems	40-55	24–40	18–25
Softwood stems	45-50	25–35	25–35
Nut shells	25-30	25–30	30-40
Corn cobs	45	35	15
Rice straw	32.1	24	18
Waste paper from chemical pulps	60-70	10–20	5-10
Switch grass	45	31.4	12
Sugar cane bagasse	19–24	27–32	19-24
Wheat straw	29-35	26–32	16-21
Barley straw	31-34	24–29	14-15
Oat straw	31-37	27–38	16-19
Rye straw	33-35	27–30	16-19
Bamboo	26-43	15–26	21-31
Coffee pulp	35	46.3	18.8
Banana waste	13.2	14.8	14
Corn stalks	61.2	19.3	6.9
Sugar beet waste	26.3	18.5	2.5
Soya stalks	34.5	24.8	19.8
Sunflower stalks	42.1	29.7	13.4

References

1. Sun Hee Kang, Hye Ryun Kim, Jae Ho Kim, Byung Hak Ahn, Tae Wan Kim & Jang-Eun Kim: Identification of Wild Yeast Strains and Analysis of Their β-Glucan and Glutathione Levels for Use in *Makgeolli* Brewing. *Makgeolli* Brewing, Mycobiology, 42:4, 361-367 (2014). DOI: 10.5941/ MYCO.2014.42.4.361

2. Sharon Avni, Nirit Ezove, Hilla Hanani, Itamar Yadid, Michal Karpovsky , Hilla Hayby , Ofer Gover , Yitzhak Hadar , Betty Schwartz and Ofer Danay. Int. J. Mol. Sci. 18, 1564 (2017) doi:10.3390/ijms18071564.

3. S. Crognale, F. Federici & M. Petruccioli: *β*-Glucan production by *Botryosphaeria rhodina* on undiluted olive-mill Wastewaters. *Biotechnology Letters* 25: 2013–2015 (2003)

4. Malcolm A. Finkelman.: *Pneumocystis jirovecii* infection: Cell wall (1→3)-β-Dglucan biology and diagnostic utility. Critical Reviews in Microbiology, 36:4, 271-281 (2010). DOI: 10.3109/1040841X.2010.484001

5. Michael Driscoll, Richard Hansen, Chuanlin Ding, Daniel E. Cramer & Jun Yan: Therapeutic potential of various β-glucan sources in conjunction with anti-tumor monoclonal antibody in cancer therapy, Cancer Biology & Therapy, 8:3, 218-225 (2009)

DOI: 10.4161/cbt.8.3.7337

6. Misumi Kataoka & Kazuhiko Ishikawa.: Complete saccharification of β-glucan using hyperthermophilic endocellulase and β-glucosidase from *Pyrococcus furiosus*, Bioscience, Biotechnology and Biochemistry, 78:9, 1537-1541(2014) DOI: 10.1080/09168451.2014.923300

7. M.A. Alves da Cunha, S.L. Albornoz, V.A. Queiroz Santos, W.N. Sa´nchez, A.M. Barbosa-Dekker and R.F.H. Dekker.: Structure and Biological Functions of D-Glucans and Their Applications. In: Atta-ur-Rahman (eds.) Studies in Natural Products Chemistry, pp. 309-336. Elsevier B.V. (2017).

8. Thomas A. Wilson, Robert J. Nicolosi, Bryan Delaney, Kim Chadwell, Vikas Moolchandani, Timothy Kotyla, Sridevi Ponduru, Guo-Hua Zheng, Richard Hess, Nathan Knutson, Leslie Curry, Lore Kolberg, Melanie Goulson, and Karen Ostergre.: Reduced and High Molecular Weight Barley β-Glucans Decrease Plasma Total and Non-HDL-Cholesterol in Hypercholesterolemic Syrian Golden Hamsters. J Nutr. 134 (10):2617-22 (2004)

9. Zhaomin Zheng, Qilin Huang, Xiaogang Luo, Yidong Xiao, Wenfei Cai, Huiyu Ma: Effects and mechanisms of ultrasound- and alkali-assisted enzymolysis on production of water-soluble yeast β-glucan. Bioresource Technology 273 , 394–403 (2019)

10. Peter J. Wood.: Oat and Rye β-Glucan: Properties and Function. Cereal Chem. 87, 315–330 (2010)

11. Tada R, Yoshikawa M, Kuge T, Tanioka A, Ishibashi K, Adachi Y, Tsubaki K, Ohno N.: Granulocyte macrophage colony-stimulating factor is required for cytokine induction by a highly 6-branched 1,3-β-D-glucan from Aureobasidium pullulans in mouse-derived splenocytes. Immunopharmacol Immunotoxicol. 33, 302-308 (2010). doi: 10.3109/08923973.2010.503707

12. Naoyuki Moriya, Yukiko Moriya, Hideo Nomura, Kisato Kusano, Yukoh Asada, Hirofumi Uchiyama, Enoch Y. Park, and Mitsuyasu Okabe.: Improved *β*-glucan Yield Using an Aureobasidium pullulans M-2 Mutant Strain in a 200-L Pilot Scale Fermentor Targeting Industrial Mass Production. Biotechnology and Bioprocess Engineering .18, 1083-1089 (2013)

13. Vassileios Varelas, Panagiotis Tataridis, Maria Liouni, Elias T. Nerantzis.; Valorization of Winery Spent Yeast Waste Biomass as a New Source for the Production of b-Glucan. Waste Biomass Valor . 7:807–817 (2016)

14. Fengmei Zhu, Bin Du , Baojun Xu.: A critical review on production and industrial applications of betaglucans. Food Hydrocolloids. 52, 275-288 (2016)

15. Vassileios Varelas,Maria Liouni, Antony C. Calokerinos and Elias T. Nerantzis.: An evaluation study of different methods for the production of β-D-glucan from yeast biomass. Drug Test. Analysis. 8, 46–55 (2015) DOI 10.1002/dta.1833

16. Subhadip Mahapatra and Debdulal Banerjee. Fungal Exopolysaccharide: Production, Composition and Applications. *Microbiology Insights* . 6, 1–16 (2013)

17. Takimoto, H., D.Wakita, K. Kawaguchi, and Y. Kumazawa.: Potentiation of cytotoxic activity in naïve and tumor-bearing mice by oral administration of hot-water extracts from Agaricus brazei fruiting bodies. Biol. Pharm. Bull. 27: 404-406 (2004)

18. Zhang, J., G. Wang, H. Li, C. Zhuang, T. Mizuno, H. Ito, C. Suzuki, H. Okamoto, and J. Li.: Antitumor polysaccharides from a Chinese mushroom, "Yuhuangmo," the fruiting body of Pleurotus citrinopileatus. Biosci. Biotechnol. Biochem. 58: 1195-1201 (1994)

19. Hee-Kyoung Jung, Joo-Heon Hong, Seung-Chun Park, Byung-Kwon Park, Doo-Hyun Nam, Sang-Dal Kim.: Production and Physicochemical Characterization of β-Glucan Produced by
Paenibacillus polymyxa JB115. Biotechnology and Bioprocess Engineering.12, 713-719 (2007)

20. Sathyanarayana N. Gummadi, Kislay Kumar.: Production of extracellular water insoluble β-1,3-glucan (curdlan) from*Bacillus* sp. SNC07. Biotechnology and Bioprocess Engineering. 10, 546–551 (2005)

21. Gayathiri T Kalyanasundaram, Mukesh Doble and Sathyanarayana N Gummadi. Production and downstream processing of (1-3)-β-D-glucan from mutant strain of Agrobacterium sp. ATCC 31750. AMB Express 2:31,1-10 (2012)

22. Ma´rio A. Alves da Cunha , Janaı´na A. Turmina , Raphael C. Ivanov , Roney R. Barroso , Patrı´cia T. Marques , Eveline A. I. Fonseca , Zuleica B. Fortes , Robert F. H. Dekker , Neelam Khaper , Aneli M. Barbosa .: Lasiodiplodan, an exocellular (1-6)-b-D-

glucan from Lasiodiplodia theobromae MMPI: production on glucose, fermentation kinetics, rheology and anti-proliferative activity. J Ind Microbiol Biotechnol, 39:1179–1188 (2012)

23. Corradi da Silva ML, Fukuda EK, Vasconcelos AFD, Dekker RFH, Matias AC, Monteiro NK, Cardoso MS, Barbosa AM, Silveira JLM, Sassaki GL, Carbonero ER.: Structural characterization of the cell wall D-glucans from the mycelium of Botryosphaeria rhodina MAMB-05. Carbohydr Res. 343,793– 798 (2008). doi:10.1016/j.carres.2007.12.021

24. Anna Bzducha-Wróbel, Katarzyna Pobiega, Stanisław Błażejak, Marek Kieliszek.: The scale-up cultivation of Candida utilis in waste potato juice water with glycerol affects biomass and β(1,3)/(1,6)-glucan characteristic and yield. Applied Microbiology and Biotechnology. 102, 9131–9145 (2018)

25. Hee-Kyoung Jung , Seung-Chun Park, Byung-Kwon Park , Joo-Heon Hong. : Physiological activities of a *b*-glucan produced by Panebacillus polymyxa. Biotechnol Lett .30, 1545–1551 (2008)

26. Nair AV, Gummadi SN, Doble M.; **Characterization and biological activities of cyclic (1 → 3, 1 → 6)-β-glucans from Bradyrhizobium japonicum.** Biotechnol Lett. 38, 1519-25 (2016). doi: 10.1007/s10529-016-2122-3

27. Ji-Young Hong, Sung-Ho Son, Sang-Pil Hong, Sung-Hun Yi, Sun Hee Kang, Na-Kyoung Lee, Hyun-Dong Paik.: Production of β-glucan, glutathione, and glutathione derivatives by probiotic *Saccharomyces cerevisiae* isolated from cucumber *jangajji.* LWT - Food Science and Technology 100, 114–118 (2019)

28. Aneli M Barbosa, Rosângela M Steluti, Robert F. H Dekker, Marilsa S Cardoso, M. L Corradi da Silva.: Structural characterization of Botryosphaeran: a (1→3;1→6)-β-d-glucan produced by the ascomyceteous fungus, Botryosphaeria sp. Carbohydrate Research, Volume 338, 1691-1698 (2003)

29. L. Selbmann, S. Crognale and M. Petruccioli.: Beta-glucan production by Botryosphaeria rhodina in different bench-top bioreactors. Journal of Applied Microbiology. 96, 1074–1081 (2004)

30. Bozidar Šantek, Michael Felski, Karl Friehs , Martin Lotz .: Production of paramylon, a b-1,3-glucan, by heterotrophic cultivation of Euglena gracilis on potato liquor. Eng. Life Sci. 10,165–170 (2010)

31. Rhim Ryoo, Hong-Duck Sou, Kang-Hyeon Ka & Hyun Park.: Elicitorinduced β-glucan contents in fruit body of cauliflower mushroom (*Sparassislatifolia*), Forest Science and Technology. 14:3, 119-125 (2018) . DOI: 10.1080/21580103.2018.147 5307

32. V. Belewa, H. Baijnath, C. Frost and B.M. Soma.: Tulbaghia violacea Harv. plant extract affects cell wall synthesis in Aspergillus flavus. Journal of Applied Microbiology 122, 921--931 (2017)

33. Vesna ZECHNER-KRPAN, Vlatka PETRAVIĆ-TOMINAC, Ines PANJKOTA-KRBAVČIĆ, Slobodan GRBA, Katarina BERKOVIĆ.: Potential Application of Yeast β-Glucans in Food Industry. Potential Application of Yeast β-Glucans in Food Industry. Agric. conspec. sci. 74, 277- 282 (2009)

34. Hui Li., Nag-Jong Kim., Min Jiang., Jong Won Kang., Ho Nam Chang.:Simultaneous saccharification and fermentation of lignocellulosic residues pretreated with phosphoric acid–acetone for bioethanol production. Bioresource Technology. 100, 3245–3251 (2010)

35. R.P. Tengerdy., G. Szakacs.: Bioconversion of lignocellulose in solid substrate fermentation. Biochemical Engineering Journal. 13, 169–179 (2003)

36. Daniela Alonso Bocchini Martins., Heloiza Ferreira Alves do Prado., Rodrigo Simões Ribeiro Leite., Henrique Ferreira., Márcia Maria de Souza Moretti., Roberto da Silva., Eleni Gomes.: Agroindustrial Wastes as Substrates for Microbial Enzymes Production and Source

of Sugar for Bioethanol Production. In: Mr. Sunil Kumar (Ed.); Integrated Waste Management - Volume II . pp: 319-360. InTech; Europe & China (2011)

37. R.L. Howard., E. Abotsi., E.L. Jansen van Rensburg., S. Howard.: Lignocellulose biotechnology: issues of bioconversion and enzyme production. African Journal of Biotechnology. 2 , 602-619 (2003)

38. Gongshe Hu , Sabrina Trupia , Sherry R. Ellberg.: A Promising Low Beta-Glucan Barley Mutation of m351 for Better Bioethanol Production Use. Bioenerg. Res. 8, 1158–1164 (2015)

39. Andy Clark.: Barley. Managing Cover Crops Profitably, 3rd Edition; *Handbook Series Book 9;* Published by the Sustainable Agriculture Research and Education
(SARE) program, with funding from the National Institute of Food and Agriculture, U.S. Department of Agriculture (2012)

40. KESHUN LIU, FREDERIC T. BARROWS, AND DON OBERT.; Dry Fractionation Methods to produce Barley Meals Varying in Protein, Beta-Glucan, and Starch Contents. JOURNAL OF FOOD SCIENCE. 74, c4877- c489 (2009)

41. Du, B., Zhu, F. M., & Xu, B. J.:B-Glucan extraction from bran of hull-less barley by accelerated solvent extraction combined with response surface methodology. Journal of Cereal Science. 59, 95-100 (2014)

42. C. J. LEE, R. D. HORSLEY, F. A. MANTHEY, and P. B. SCHWARZ.: Comparisons of b-Glucan Content of Barley and Oat. Cereal Chem. 74, 571–575 (1997)

43. Qi Wang, and Peter R. Ellis.: Oat b-glucan: physico-chemical characteristics in relation to its
blood-glucose and cholesterol-lowering properties. British Journal of Nutrition . 112, S4–S13 (2014)

44. Morgan, K. R.: Process for extraction of b-glucan from cereals and products
obtained therefrom. US patent 7138519 B2 (2006)

45. Beer, M. U., Arrigoni, E., & Amado, R.: Extraction of oat gum from oat bran: effects of process on yield, molecular weight distribution, viscosity and (1/3)(1/4)-b-D-glucan content of the gum. Cereal Chemistry. 73, 58-62 (1996)

46. Skendi, A., Biliaderis, C. G., Lazaridou, A., & Izydorczyk, M. S.: Structure and rheological properties of water soluble b-glucans from oat cultivars of Avena sativa and Avena byzantina. Journal of Cereal Science. 38, 15-31 (2003)

47. Asif Ahmad, Nauman Khalid.: Dietary Fibers in Modern Food Production: A Special Perspective With β-Glucans. in Alexandru Mihai Grumezescu, Alina Maria Holban (eds.) Biopolymers for Food Design, pp: 125-156 , Elsevier. (2018)

48. Pritchard JR1, Lawrence GJ, Larroque O, Li Z, Laidlaw HK, Morell MK, Rahman S.: A survey of β-glucan and arabinoxylan content in wheat. J Sci Food Agric. 9,1298-303 (2011)

49. *Jan S. Tkacz.:* Gluean Biosynthesis in Fungi and its Inhibition. In: J. A. Sutcliffe et al. (eds.), *Emerging Targets in Antibacterial and Antifungal Chemotherapy* In: Routledge, Chapman & Hall, Inc. (1992)

50. Ying Liang, Li Zhu, Minjie Gao, Jianrong Wu & Xiaobei Zhan.: Effective production of biologically active water-soluble B-1,3-glucan by a coupled system of *Agrobacterium* sp. and *Trichodermaharzianum*, Preparative Biochemistry and Biotechnology, 48:5, 446-456 (2018) DOI:10.1080/10826068.2018.1452259

51. Namita Jindal, Jasvirinder Singh Khattar .: Microbial Polysaccharides in Food Industry. In: Alexandru Mihai Grumezescu, Alina Maria Holban (eds.) Biopolymers for Food Design, pages 95-123 (2018)

52. J.K. Park, T. Khan.: Other microbial polysaccharides: pullulan, scleroglucan, elsinan, levan, alternant, dextran, in G.O. Phillips, **P.A. Williams (eds.)** Handbook of Hydrocolloids (Second Edition), Pages 592-614 Elsevier (2009)

53. Barbosa AM, Steluti RM, Dekker RF, Cardoso MS, Corradi da Silva ML.: Structural characterization of Botryosphaeran: a (1-->3;1-->6)-beta-D-glucan produced by the ascomyceteous fungus, Botryosphaeria sp. Carbohydr Res. 29;338, 1691-8 (2003)

54. Chin-Han Shu.: Fungal Fermentation for Medicinal Products. In: Shang-Tian Yang (eds.) Bioprocessing for Value-Added Products from Renewable Resources, pp: 447-463 Elsevier (2007)

55. Bhanja, S. K., Rout, D., Patra, P., Sen, I. K., Nandan, C. K., & Islam, S. S. Water insoluble glucans from the edible fungus Ramaria botrytis. Bioactive Carbohydrate and Dietary Fibre. 3, 52-58 (2014)

56. Kim, Y. W., Kim, K. H., Choi, H. J., & Lee, D. S.: Anti-diabetic activity of bglucans and their enzymatically hydrolyzed oligosaccharides from Agaricus blazei. Biotechnology Letters. 27, 483-487 (2005)

57. Sandeep Rahar, Gaurav Swami, Navneet Nagpal, Manisha A. Nagpal, and Gagan Shah Singh.: Preparation, characterization, and biological properties of β-glucans. J Adv Pharm Technol Res. 2, 94–103 (2011)

58. Kim, M. S., Park, Y. D., & Lee, S. R.: Method of using beta-glucan from Schizophyllum commune. US patent 0023681 A1 (2009)

59. Hee-Kyoung Jung, Joo-Heon Hong, Seung-Chun Park, Byung-Kwon Park, Doo-Hyun Nam, Sang-Dal Kim.: Production and physicochemical characterization of β-glucan produced by *Paenibacillus polymyxa* JB115. 12, 713-719 (2007)

60. Stack, H. M., Kearney, N., Stanton, C., Fitzgerald, G. F., & Ross, R. P.: Association of beta-glucan endogenous production with increased stress tolerance of intestinal Lactobacilli. Applied and Environmental Microbiology. 76, 500-507 (2010)

61. Crognale, S., Bruno, M., Fidaleo, M., Moresi, M., & Petruccioli, M.: Production of b-glucan and related glucan-hydrolases by Botryosphaeria rhodina. Journal of Applied Microbiology. 102, 860-871 (2007)

62. M. Petre., G. Zarnea., P. Adrian., E. Gheorghiu.: Biodegradation and bioconversion of cellulose wastes using bacterial and fungal cells immobilized in radiopolymerized hydrogels. Resources, Conservation and Recycling 27: 309–332 (1999)

63. *Raveendran Sindhu , Parames waran Binod, Ashok Pandey*.: (Biological pretreatment of lignocellulosic biomass – An overview. Bioresource Technology. 199, 76-82 (2016)

64. Leif J. Jönsson, Carlos Martín.: Pretreatment of lignocellulose: Formation of inhibitory by-products and strategies for minimizing their effects. Bioresource Technology 199, 103–112 (2016)

65. Shukor, H., Al-Shorgani, N.K.N., Abdeshahian, P**.,** Hamid, A.A., Anuar, N., Rahman, N.A., Kalil, M.S., Production of butanol by *Clostridium saccharoperbutylacetonicum* N1-4 from palm kernel cake in acetone-butanol-ethanol fermentation using an empirical model. *Bioresource Technology*. 170: 565-573 (2014)

66. B. Olver , J. S. Van Dyk, N. Beukes , B. I. Pletschke.: Synergy between EngE, XynA and ManA from Clostridium cellulovorans on corn stalk, grass and
pineapple pulp substrates. 3 Biotech . 1, 187–192 (2011)

67. Mohammad J. Taherzadeh 1,* and Keikhosro Karimi.: Pretreatment of Lignocellulosic Wastes to Improve Ethanol and
Biogas Production: A Review. *Int. J. Mol. Sci*, *9*, 1621-1651(2008) DOI: 10.3390/ijms9091621

68. Parveen Kumar, Diane M. Barrett, Michael J. Delwiche, and Pieter Stroeve.: Methods for Pretreatment of Lignocellulosic Biomass for Efficient Hydrolysis and
Biofuel Production. *Ind. Eng. Chem. Res. 48,* 3713–3729 (2009)

69. Leif J Jönsson, Björn Alriksson and Nils-Olof Nilvebran.: Bioconversion of lignocellulose: inhibitors
and detoxification. Biotechnology for Biofuels. 6:16, 1-10 (2013)

70. Carmen Sánchez.: Lignocellulosic residues: Biodegradation and bioconversion by fungi. Biotechnology Advances. 27, 185–194 (2009)

71. Pardeep Kumar Sadh., Surekha Duhan., Joginder Singh Duhan.: Agro-industrial wastes and their utilization using solid state fermentation: a review. Bioresource Bioprocess. Vol: 5:1, 1-15 (2018)

72. J.S. Van Dyk, B.I. Pletschke.: A review of lignocellulose bioconversion using enzymatic hydrolysis and synergistic
cooperation between enzymes—Factors affecting enzymes, conversion and synergy. Biotechnology Advances. 30, 1458–1480 (2012)

73. Byung-Kwan Kang , Hee-Jong Yang , Nack-Shick Choi , Keug-Hyun Ahn , Chan-Sun Park , Byung-Dae Yoon , Min-Soo Kim.: Production of pure *b*-glucan by Aureobasidium pullulans after pullulan synthetase gene disruption. Biotechnol Lett. 32, 137–142 (2010)

74. Karolina Kucharska , Piotr Rybarczyk , Iwona Hołowacz , Rafał Łukajtis , Marta Glinka and Marian Kami´ nski. Pretreatment of Lignocellulosic Materials as
Substrates for Fermentation Processes. Molecules. 23, 2937; 1-32. (2018) . doi:10.3390/molecules23112937

75. Mustafa Balat.: Production of bioethanol from lignocellulosic materials via the biochemical pathway: A review. Energy Conversion and Management. 52, 858-875 (2011)

76. Kamila Buzała, Piotr Przybysz, Justyna Rosicka-Kaczmarek, Halina Kalinowska.: Production of glucose-rich enzymatic hydrolysates from cellu