Clean Energy Production Technologies

Series Editors: Neha Srivastava · P. K. Mishra

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Ashutosh Kumar Rai *Editors*

Agricultural Biomass Nanocatalysts for Green Energy Applications

Springer

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The consumption of fossil fuels has been continuously increasing around the globe and simultaneously becoming the primary cause of global warming as well as environmental pollution. Due to limited life span of fossil fuels and limited alternate energy options, energy crises is important concern faced by the world. Amidst these complex environmental and economic scenarios, renewable energy alternates such as biodiesel, hydrogen, wind, solar and bioenergy sources, which can produce energy with zero carbon residue are emerging as excellent clean energy source. For maximizing the efficiency and productivity of clean fuels via green & renewable methods, it’s crucial to understand the configuration, sustainability and techno-economic feasibility of these promising energy alternates. The book series presents a comprehensive coverage combining the domains of exploring clean sources of energy and ensuring its production in an economical as well as ecologically feasible fashion. Series involves renowned experts and academicians as volume-editors and authors, from all the regions of the world. Series brings forth latest research, approaches and perspectives on clean energy production from both developed and developing parts of world under one umbrella. It is curated and developed by authoritative institutions and experts to serves global readership on this theme.

Manish Srivastava • Ashutosh Kumar Rai
Editors

Agricultural Biomass Nanocatalysts for Green Energy Applications

Springer

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ISSN 2662-6861 ISSN 2662-687X (electronic)
Clean Energy Production Technologies
ISBN 978-981-97-1622-7 ISBN 978-981-97-1623-4 (eBook)
https://doi.org/10.1007/978-981-97-1623-4

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Preface

The present book, entitled *Agricultural Biomass Nanocatalysts for Green Energy*, provides a facile and sustainable fabrication process for nanomaterials used as catalysts in green energy production applications. The existence of different types of nanocatalysts and their contributions to the field of green energy has been explored in this book. The impact of nanomaterials as a promising catalyst for boosting bioenergy production processes has been well established, though the cost-intensive synthesis methods and their adverse environment impacts have created barriers in the form of severe pollution in sustainable surroundings. In contrast, the fabrication of these nanocatalysts from waste biomass offers a green, sustainable, ecofriendly, and pollution-free pathway that is completely cost-effective. The book comprises ten promising chapters focusing on nanocatalyst fabrication and applications in the area of energy. Chapters 1–3 delve into the compositional analysis of lignocellulosic biomass and their availability for sustainable valorization while Chaps. 4–6 discuss details about the bioenergy area, covering lignocellulosic waste like paddy straw, nanomaterial synthesis, and characterization for a better understanding of readers. Next, Chaps. 7 and 8 explore nanomaterials type and synthesis along with their sustainable application in the bioenergy sector. Similarly, Chaps. 9 and 10 explore the feasibility and improvement in nanomaterial synthesis and their application in the bioenergy field. The book aims to deliver promising insights into the sustainable fabrication of nanomaterials-based catalysts for green energy production and applications.

The Editors have no conflicts of interest to declare that are relevant to the content of this book.

Gorakhpur, Uttar Pradesh, India — Manish Srivastava
Dammam, Saudi Arabia — Ashutosh Kumar Rai

Contents

Editors and Contributors

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Ashutosh Kumar Rai has been working as an Assistant Professor of Biochemistry at the College of Medicine, Imam Abdulrahman Bin Faisal University, Saudi Arabia, since 2017. Dr. Rai completed his PhD (2012) in Applied Biochemistry from the School of Biotechnology, Banaras Hindu University, India, in the area of microbial biotechnology and molecular biology. Dr. Rai has 17 years of teaching and research experience with more than 50 SCI publications.

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Chapter 1
Lignocellulosic-Derived Carbohydrates: A Splendid Biomolecule for Human Health and the Environment

Latika Bhatia, Dilip Kumar Sahu, Shruti Singh, and Bikash Kumar

Abstract In recent times, resources based on fossil fuels have been considered the basis for the generation of energy. Currently, there has been a paradigm shift in this conventional practice, and the investigation of more sustainable, cost-effective, and eco-friendly feedstocks is being pursued for the generation of fuels and prebiotics. Lignocellulosic biomasses (LCBs) are a sustainable and alternate renewable resource that has been recognized as a substitute to curtail the dependency of this sector on fuels derived from fossil resources and to remove their imprints on the environment. Lignocellulosic biomasses are not only abundant but also renewable resources. The concept of biorefineries has set a stage for numerous biomasses, principally lignocellulosic biomasses, to be investigated for the production of fuels and prebiotics. The production of biofuels in a biorefinery can substantially curtail the emission of greenhouse gases (GHG) and are sustainable and eco-friendly. The industrial production of biofuels has taken novel dimensions, and approaches are reorganized for their production. Their production helps in uplifting the renewable economy under a sustainability regime. This chapter provides a deep insight into various aspects of oligosaccharides and biofuel, along with the strategies employed in the production of various oligosaccharides and biofuels.

Keywords Prebiotics · Xylo oligosaccharides · Biofuels · Ethanol · Oligomers · Monosaccharides

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M. Srivastava, A. K. Rai (eds.), *Agricultural Biomass Nanocatalysts for Green Energy Applications*, Clean Energy Production Technologies,
https://doi.org/10.1007/978-981-97-1623-4_1

1.1 Introduction

The biotechnology industry is unique and dynamic, as it is constituted of firms specialized in microbial biotechnology. This industry plays an important role in the execution of technologies, applications, and products involved in diverse industries like pharmaceuticals, agriculture, and chemicals (Srivastava et al. 2021). These aspects are responsible for the keen interest of various research groups in the biotechnology industry. Microbial biotechnology has a broad horizon of impact that not only includes human healthcare but also involves diverse applications such as industrial, animal health, and environment (Alonso et al. 2010).

There are significant impacts of fossil fuels on the growth of society and development. However, these energy resources are nonrenewable and nonsustainable. Moreover, there are significant issues generated due to their usage. Chief among them is climate alteration and the emission of greenhouse gases, namely, carbon dioxide. So, it is the need of the hour that if we want to continue the sustenance of the economy and environment along with the growth and development at the same pace, then we need to switch ourselves to resources that are not only renewable but also sustainable too (Sudhakar and Premalatha 2015). Along with the environmental concerns, human health is equally important and that is why the synergistic approach is now being adopted to explore the resources that can be equally beneficial to human health as well as the environment. The application of prebiotics or other nutraceuticals from bio-based resources can greatly impact human health. Similarly, the increased utilization of biofuel can resolve many environmental issues that are generated because of the use of fossil fuels. These two facts and concerns have acted as an impelling cause for immense inspiration for lignocellulosic biomass research (Bhalamurugan et al. 2018).

Valorization of lignocellulosic biomass (LCB) has been a source of keen interest for various researchers globally. These biomasses are excellent sources of various forms of carbohydrates, namely, polysaccharides (e.g., cellulose, starch), oligosaccharides (e.g., xylooligosaccharides), disaccharides (e.g., sucrose, maltose), and many monosaccharides (e.g., glucose, galactose, mannose, xylose, fructose, etc.). These carbohydrates support various metabolic pathways in microorganisms, thereby supporting the physiological production of metabolites that are of significance as a fuel (biofuel) or support human health (Hassan et al. 2015; Kumar and Verma 2020).

Biofuels have grabbed the attention of the governments of various countries and have been the driving force for the implementation of various policies nationally and globally. Blending biofuels with conventional fuels is one such approach or policy implemented by various nations including India (Esposito and Antonietti 2015). The reasons behind the use of biofuels are many. It curtails not only the reliance on conventional fuels but also the release of greenhouse gases (Nanda et al. 2015). It is considered a neat fuel that improves energy self-reliance, reinforces the progression of domestic agriculture, and reduces the prices involved in importing fuels. Biofuels are not only renewable but also sustainable, and hence their use ensures the sustainability of the transport sector. Biofuel is the fuel of choice for many industries such as marine transport, aviation, and heavy freight, as biofuel is low-carbon in comparison to fossil fuel (Bhatia et al. 2020).

The most important and prevalent organic matter on this planet is lignocellulosic biomass (LCB). These LCBs have significant applications when they are converted into numerous forms of biochemicals, biomaterials, food/feed, and fuels. There is a copious availability of LCBs in the form of crop residues, grasses, and forestry materials. There are various forms of LCBs, such as agro-residues, forest residues, fruits, vegetables, seeds, grasses, and energy crops. Around the year, there is copious generation (millions of tons) of agro and forest waste from farming and forest and due to various practices of agroindustries. Numerous waste sources such as municipal solid waste (MSW), agrowastes (corn stover, peels, sugarcane bagasse, and rice husk), and industrial waste (pulp and paper mills) (Fig. 1.1) are the significant alternate sources of biomass along with natural resources. Inappropriate disposal of these wastes is responsible for serious environmental issues like pollution. On the other hand, if utilized logically, these biowastes are a cheap and excellent source of various biofuels, biochemicals, food, and various enzymes (Bhatia et al. 2019b).

As mentioned earlier, sustainability is now considered an important base for socioeconomic development. Taking this fact into consideration, present-day biorefineries put all their effort into the exploration and valorization of all the components of LCB. This will ensure the 360-degree progression of mankind both environmentally and socioeconomically. The sustainability matrix is composed of environment, economics, and employment, and LCB has the potential to directly influence these key parameters, as they are the pivotal source of biofuels or biochemicals (Chandel et al. 2018; Kumar and Verma 2021).

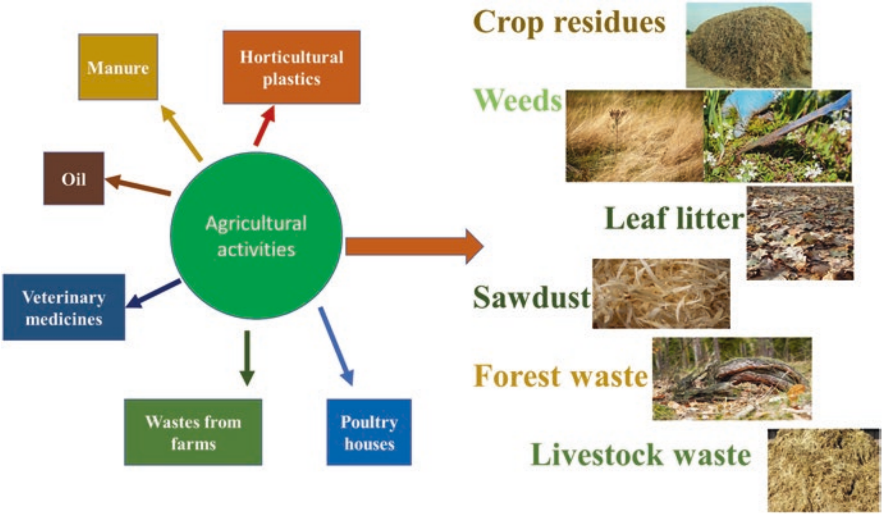

Fig. 1.1 Numerous agrowastes produced as an outcome of several agriculture-related activities

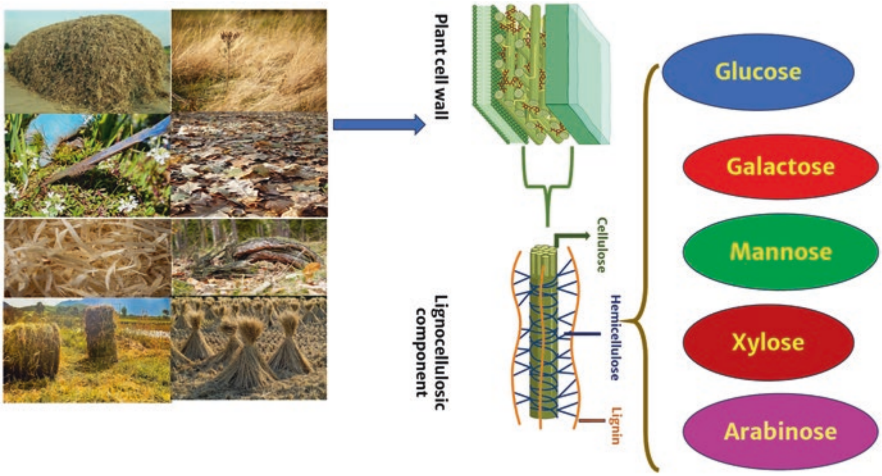

Fig. 1.2 Lignocellulosic-derived carbohydrates

1.2 Important Constituting Component of Lignocellulosic Biomass

The three chief constituents of LCB are cellulose, hemicelluloses, and lignin (Fig. 1.2). The lignocellulosic biorefineries are supported by these constituents. Moreover, these constituents play a substantial role in the complete progression of the full bioeconomy. The composition of these three primary constituents varies greatly depending on numerous factors such as biomass type, climate/weather, soil conditions, cultivation methods, and genetic origin (Bhatia et al. 2012; Bhardwaj et al. 2020a).

1.2.1 Cellulose

Cellulose is defined as a linear homopolysaccharide composed of anhydrous glucopyranose molecules that are linked by β-1, 4-glycosidic bonds. About 15–10,000 units of glucose combine to form an anhydrous-glucose chain. These chains when tightly packed together with the help of hydrogen bonds constitute a native crystalline cellulose that is insoluble in nature. In cellulose polymer, the hydrogen bond helps in associating the elementary microfibrils. When microfibrils are combined, they result in bundles or microfibrils. The accession of enzymes to this crystalline form of cellulose is difficult, thereby limiting the efficiency of enzymatic hydrolysis. Cellulose is resistant to chemical or biological treatments because of its inherent complexity and robust cross-linkages. Moreover, cellulose, hemicellulose, pectin, and lignin are closely associated with each other, developing a very intricate assembly (Bhardwaj et al. 2020b). The approachability of any lignohemicellulolytic catalytic agents such as laccases, hemicellulase, and cellulase gets impaired due to this intricate structure of LCB, thereby affecting the delignification of lignin and hemicellulose/cellulose conversion to their constituent monomeric forms (Kumar et al. 2020). The production of novel bioproducts as a result of biomass bioconversion is a thrust research area in biotechnology (Bhardwaj et al. 2017, 2021; Bhatia et al. 2018).

On the other hand, the hemicellulose structure is nonlinear in which sugars are associated with each other not only by hydrogen bonds but also with weak van der Waals force. Lastly, lignin covers the hemicellulose structure.

1.2.2 Hemicellulose

Hemicellulose is a branched polymer consisting of heterogeneous chemical constituents collectively called xylans, such as pentoses (arabinose, xylose), hexoses (glucose, mannose, rhamnose, galactose), uronic acids (glucouronic and galacturonic), and acetyl groups that are arranged in a nonlinear branched manner (Fig. 1.2). In plant cells, hemicellulose makes up 25–35%, and due to its amorphous nature, it can be broken down to fermentable sugars in the presence of hemicellulases such as xylanases (Bhardwaj et al. 2021).

The percentage composition of xylose varies significantly in a variety of plants, e.g., in annual plants, xylose constitutes ~25 to 30% of the overall amount of hemicellulose, whereas in hardwoods and softwood, it is 15–30% and 7–10%, respectively. When hydrolyzed by enzymes or acids, xylan produces xylooligosaccharides (XOS) (Bhardwaj et al. 2019). Although xylose is the chief component of hemicellulose, methylated or acetylated sugars are also important constituents. Zero- or near-zero waste is produced when hemicellulose is converted into its monomer and oligosaccharides (Deng et al. 2023).

Upon hydrolysis, hemicellulose yields xylotetrose, xylotriose, xylobiose, and substituted oligomers of two to four xylosyl residues. When 2–10 xylose units combine with each other to form a chain, this oligosaccharide is known as xylooligosaccharides (XOS) (Fig. 1.4). XOS are considered nondigestible food ingredients. Similarly, another class of oligosaccharides are arabinooligosaccharides (AOS) constituting 1,3 and 1,5 α L-arabinofuranosyl residues. Naturally, arabinose exists in the plant's cell wall and its constituents are arabinans, arabinogalactans, or arabino xylans (Placier et al. 2009). Mannan is a chief component of hemicelluloses. Linear mannan, galactomannan, glucomannan, or glucogalactomannan are various forms of mannans. Numerous mannan-catalytic enzymes have the potential to depolymerize mannan into its oligosaccharides. For instance, short-chain manno-oligomers are produced when β-(1,4)-linkages are broken down by β-1,4-D-mannanases (BIO 2016).

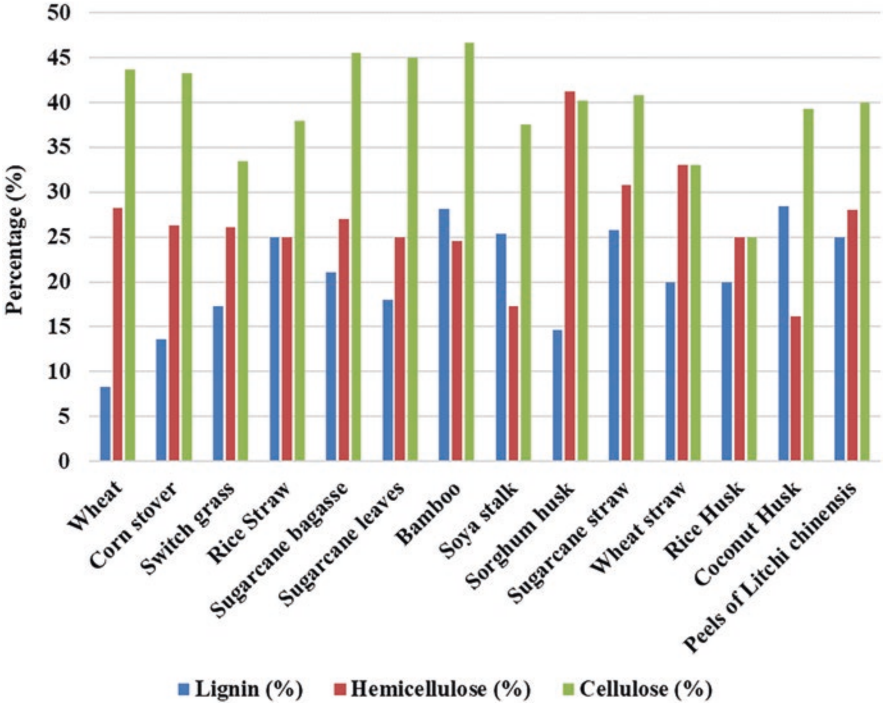

Fig. 1.3 Composition of the cell wall with different lignocellulosic materials (Bhatia and Johri 2015a, b, 2016, 2017, 2018) (Data used for preperation of Fig. 1.3, has been used with permission from Bhatia et al. 2019b)

1.2.3 Lignin

The role of lignin is to provide the plants with mechanical strength because lignin acts as a "glue," binding together all the constituents of the cell wall. Lignin also provides the necessary protection to the carbohydrate part of the cell wall from the enzymatic action of enzymes such as cellulases whose penetration toward cellulose is obstructed (Kumar et al. 2018). The chief phenolic components of lignin are guaiacyl, hydroxyphenyl, and syringyl units (Chandel et al. 2017). Figure 1.3 depicts the major constituents of various lignocellulosic biomass of the cell wall.

1.3 Lignocellulosic Biomass: A Potential Source of Oligosaccharides

Lignocellulosic biomass has been investigated for the production of oligosaccharides, which are known for their health benefits in humans. Many researchers have explored a variety of LCBs for the production of oligosaccharides. As mentioned above, the percentage of cellulose, hemicellulose, and lignin varies among diverse LCBs; hence, their potential to produce oligosaccharides also varies and chiefly depends upon the composition of hemicellulose. Many substrates are particularly rich in hemicellulose. Chief among them are stalks of pigeon pea, corn, corn cob, sugarcane bagasse, and husks of green coconut. These agroresidues have been biovalorized for the production of xylooligosaccharides (XOS), thereby also solving the problem of biomass management (Taniguchi 2004) (Fig. 1.4). Heteroxylan is the chief constituent of hemicellulose, which is made up of acetyl esters and arabinosyl residues consisting of an average of 39 acetyl esters with ferulic and coumaric acid esters and 9 glucuronic acid and 14 arabinosyl residues (Moure et al. 2006). XOS are small chains of xylose (2–20 units) joined by β-1,4-xylosidic bonds (Fig. 1.4). Corn stover pretreated with dilute ammonia was explored by Jonathan et al. (2015) for the identification of oligosaccharides obtained from it. These researchers observed that residues xylosyl and glucosyl are the chief carbohydrates in this pretreated corn stover without any hydroxycinnamic acid ester or acetylated oligosaccharide. Also, several glycosidic linkages appear in arabinan.

Sorghum (*Sorghum bicolor* L.) is a known cereal crop that has a wide availability globally and is chiefly employed for forage, fiber, and sugar production. Its stem is reported to have excellent levels of soluble sugars. Another cost-effective feedstock for the production of fermentable sugars is soybean straw. Coconut husk has a substantial quantity of hemicellulose and is counted as an appropriate source for producing xylooligosaccharides (Quiñones et al. 2015). Vegetables and fruits are known to be important sources of pectin-derived acidic oligosaccharides (pAOS). Soluble sugars and pectin are the chief constituents of wastes of orange fruit. The

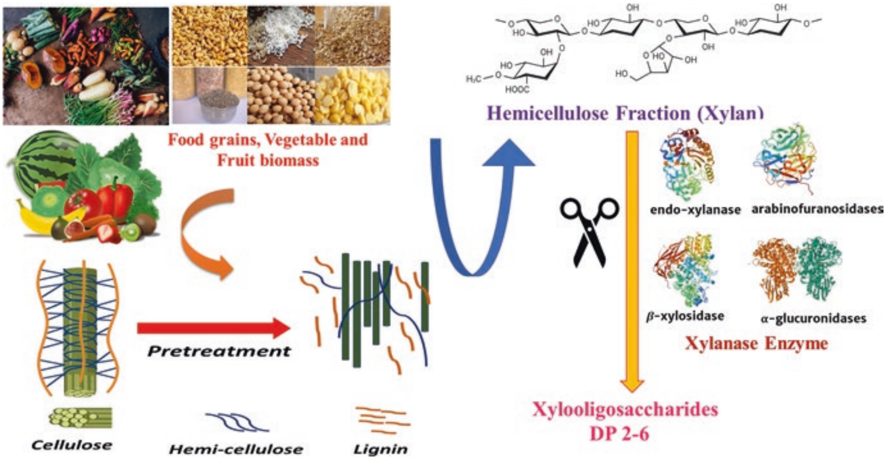

Fig. 1.4 Schematic representation of steps involved in the production of oligosaccharides from different fruits, vegetables, cereals, agroresidues, etc. (Kaenying et al. 2023; Leggio et al. 2001; Nurizzo et al. 2002; Siguier et al. 2014)

concentration of soluble sugars and starch in the orange fruit wastes was 16.9 and 3.75% wt, respectively. This 3.75% wt concentration of starch was composed of pectins (42.5% wt), cellulose (9.21% wt), hemicelluloses (10.5% wt), and lignin (0.84% wt) (Rivas et al. 2008; Torrado et al. 2011). The hemicellulose and pectin of orange fruit waste are composed of xylo-oligosaccharides and fructo-oligosaccharides, which makes this waste a suitable source for producing prebiotics materials (Jain et al. 2015). Similarly, banana peels are also considered a rich source of oligomeric carbohydrates and useful as nutraceuticals and pharmaceutical products (Pereira et al. 2021). Other promising sources of oligosaccharides are straw and sugarcane bagasse, as a substantial amount of hemicellulose is found in them (Bhatia et al. 2019b). Forest waste also produces a substantial quantity of oligosaccharides (Karnaouri et al. 2019). The main oligosaccharides prevalent in pinewood hemicelluloses are arabino-4-*O*-methylglucurono-D-xylans and *O*-acetyl-galactoglucomannan (Coulier et al. 2013). Dotsenko et al. (2017) found that ryegrass and wheat straws have linear and branched xylooligosaccharides and arabinoxylooligosaccharides (AXOS).

1.4 Health Benefits of Oligosaccharides

XOS has prebiotic properties and the prominent sources of XOS are honey, vegetables, fruits, milk, and bamboo shoots (Cruz-Guerrero et al. 2022). There are several ways to generate XOS. Chief among them is the chemical, enzymatic, chemoenzymatic hydrolysis of xylan from numerous sources such as rice hulls, wheat straws, barley hulls, corn cobs, and others (Otieno and Ahring 2012). The structure and properties of XOS extracted differ in their structure and properties that are chiefly governed by the degree of polymerization (Dp), type of the existing linkages, and methods employed for their extraction. XOS are excellent novel prebiotics that immensely support human health in many ways. It enhances calcium absorption to intensify its biological activity and the cytotoxic activity of leukemia (Chen et al. 2009, 2021; Chen et al. 2009). Xylooligosaccharides have the notable advantage of being unique prebiotics with antioxidant properties, and they depict several advantages like cytotoxic activity on leukemia and an increase in the absorption of calcium to intensify their biological action (Chen et al. 2021). XOS improves bowel function and minimizes the possibility of site-specific action on type II diabetes mellitus and colon cancer (Sheu et al. 2008; Nabarlatz et al. 2007).

XOS are immunomodulators, immunostimulators, and anti-inflammatory agents. It also shows mitogenic activity and can potentially prevent cancer by inhibiting carcinogenesis (Chen et al. 2021). XOS also exhibits a cytotoxic effect. It was noticed that β-1, 3 XOS generated from green algae such as *Caulerpa lentillifera* exhibits anti-MCF-7 human breast carcinoma cell's cytotoxic properties. Hence, β-1, 3-XOS has the ability to halt breast cancer proliferation (Maeda et al. 2012). XOS's phenolic substituent exhibits antioxidant effect. Acidic xylooligomers comprising uronic acids are well known for their antiallergic and antioxidant properties

(Jain et al. 2015; Valls et al. 2018; Freitas et al. 2019). They have effects on the production of IgE antibodies (Shimoda et al. 2011).

XOS is beneficial in type 2 diabetes mellitus as it has a substantial influence on lessening blood sugar lipids. Acidic XOS obtained from Birchwood xylan exhibits antimicrobial activity against many bacteria such as *Bacillus cereus*, *Helicobacter pylori*, and *Staphylococcus aureus* (Christakopoulos et al. 2003). Xu et al. (2009) described that xylooligosaccharides can be used as an important ingredient for the preparation of fish (*Carassius auratus gibelio*) feed. XOS is becoming important in the current scenario and is used in many food items like yogurt, milk powder, soft drinks, soy milk, jellies, cocoa drinks, and honey products. These additions help in the preparation of healthy foods for children and the elderly (Qing et al. 2013). The production of XOS has to be cost-effective to implement its use in daily meals. This is feasible only by using cheap substrates and efficient processes (Albayrak and Yang 2002).

1.5 Lignocellulosic Biomass: A Potential Source of Biofuel

The world in the current scenario of the fuel crisis and environmental safety issues is focusing on the development of strategies to explore sustainable, renewable, cost-effective, and eco-friendly fuels. Many countries are rich in the production of particular grains, crops, or vegetables, and hence the surplus amount is left after its export and domestic use. These countries have excellent technologies to utilize this surplus production of grain/crop for biofuel production, particularly bioethanol (Popp et al. 2016). For instance, Brazil is leading in the generation of bioethanol from sugarcane. The USA and China produce ethanol from wheat and potato, respectively. This type of biofuel is known as the first-generation biofuel, as it directly involves the grain, vegetable, crop, etc (Boro et al. 2022).

Beets, cassava, sugarcane, and starch obtained from wheat/corn are rich in sugars. These sugars when fermented, produce ethanol. The production of biofuel by this method becomes a part of food safety issues, as hunger is also a matter of global concern. Utilizing carbohydrates from crops and vegetables for biofuel production is not possible for many nations, as they have a huge population of people to feed (Naik et al. 2010). To avoid food controversies, nations are now focusing on utilizing agrowaste, forest waste, municipal waste, and other household waste that are rich in lignin (Sahoo et al. 2023). As mentioned earlier, lignocellulosic biomass is chiefly composed of cellulose, hemicellulose, and lignin. Upon degradation, cellulose releases glucose. Glucose is a hexose and a principal sugar of cellulose. Glucose along with galactose and mannose constitutes hexose sugars present in hemicellulose. Pentose sugars are also found in hemicellulose, namely, arabinose and xylose. When lignocellulosic material is pretreated (Fig. 1.5) either physiochemically, chemically, or enzymatically, the complex arrangement between lignin, hemicellulose, and cellulose is damaged, thus helping in the hydrolysis of LCB, releasing constituent monosugars such as hexose and pentose sugars which can be further

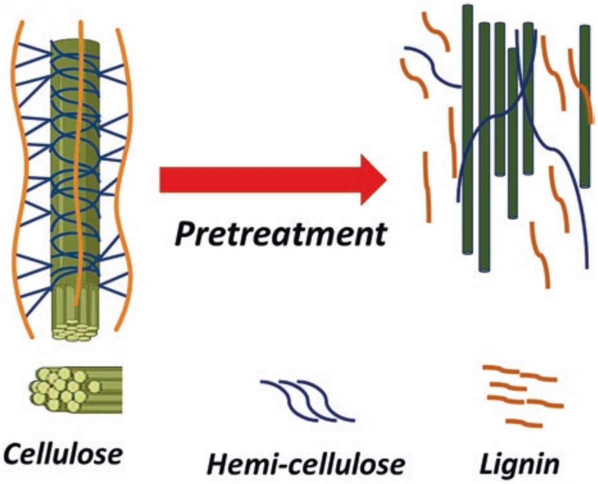

Fig. 1.5 Pretreatment effect on lignocellulosic biomass

fermented by yeast or other ethanologenic microbes. These natural sources of sugars are now being explored by researchers for biofuel production (Zhao et al. 2020; Kumar et al. 2020).

The agroresidues are copiously produced around the globe both in terms of quantity and quality. Varieties of sugars are found in these agroresidues that act as a base material for the production of many biofuels. These biofuels are known as second-generation biofuels as they are generated from agro or forest residues. The production of second-generation biofuels has been reported from many residues such as peels of banana, *Ananas comosus*, *Citrus sinensis* var. mosambi, and *Litchi chinensis* (Bhatia and Johri 2015a, 2015b, 2016, 2017). Agroresidues like sugarcane bagasse, corn stover, rice husk, and rice straw are other sources that are rich in carbohydrates and are employed for producing bioethanol. Producing biofuels from these lignocellulosic biomasses is an approach that is cheap, environment-friendly, renewable, and sustainable (Ginni et al. 2021).

Fermentable sugars can be efficiently generated out of the lignocellulosic material by involving efficient strains of microbes or their enzyme systems, which can withstand stress conditions and can efficiently transform both varieties of sugars, i.e., hexoses and pentoses (Silveira et al. 2018). *Pichia stipitis* is a known producer of bioethanol and has the potential to ferment pentose sugars (Agbogbo and Coward-Kelly 2008). This organism can potentially utilize the pentose sugars generated out of a variety of lignocellulosic materials, as depicted in Table 1.1. Along with *Pichia stipitis,* there are many other pentose fermenting organisms like *Pachysolen tannophilus* and *Candida shehatae* that are promising for industrial applications (Sanchez et al. 1999).

Saccharomyces cerevisiae is the most popular organism, known from ancient times for its capacity to generate ethanol. It is capable of metabolizing both glucose

Table 1.1 Potential of *Pichia stipitis* strains to produce ethanol from various substrates

Substrates	Parameters	Strain of *Pichia stipitis* used	Ethanol production	Reference
Prosopis juliflora	Hemicellulosic hydrolysates (18.24 g sugar/L broth)	*Pichia stipitis* 3498	7.13 g/L ethanol	Gupta et al. (2009)
L. camara	pH = 5 Temperature = 30 °C Time = 36 h	*P. stipitis* 3498	0.33 g alcohol/gram lignocellulose employed	Pasha et al. (2007)
Water hyacinth	Use of acid hydrolysate of hemicellulose that is detoxified and is rich in pentose sugars pH = 6.0 Temperature = 30 °C	*P. stipitis* NCIM-3497	0.425 g ethanol per gram of lignocellulose	Pothiraj et al. (2014)

and sucrose. It is also normally identified as safe (GRAS). The only limitation associated with this organism is its incapability to metabolize pentose sugars. However, this incapability is not a disadvantage in the era of genetic engineering, where it is feasible to engineer *Saccharomyces* with the genes involved in the metabolism of pentose sugar (Bhatia and Johri 2014). *Zymomonas mobilis* is also a known potential producer of ethanol on a commercial scale due to many of its physiological merits (Geng et al. 2020). Various strains of *Kluyveromyces marxianus* have the potential to grow at high temperatures and ferment a cocktail of sugars such as xylose, glucose, galactose, and mannose to produce ethanol (Fonseca et al. 2008).

Extremophiles, mostly thermophiles, and their enzyme systems have earned attention for their use as biocatalyst analytical tools on a broad scale (Fernando et al. 2006). The use of biofuels intensifies the self-sustaining energy, curtails the costs of import, and restores the advancement of domestic agriculture.

1.6 Impact of Lignocellulosic-Derived Biofuels on the Environment

Biofuels are getting popular because there are many merits associated with these fuels. These fuels are considered clean as they are low in carbon content and lower vehicle emissions. Consumption of oil and liberation of carbon dioxides will be reduced if we switch to biofuels (Bhatia 2019). There are many industries such as aviation, marine transport, and heavy freight that have started using biofuels. An efficient combustion property of ethanol as a biofuel is due to its energy content. Moreover, when ethanol is used as a fuel, engines can operate at a higher compression ratio. Octane ratings of ethanol are excellent. It is easier to mix ethanol (10%) with petrol rather than a complete replacement of conventional fuel with bioethanol.

Table 1.2 Difference between ethanol and gasoline as a fuel (Chandel et al. 2017; Bhatia et al. 2018)

Characteristics	Ethanol	Gasoline	Significance
Inflammability in air	1.3–7.6% v/v	3.5–19% v/v	The frequency and severity of vehicle fires are less for ethanol
Reid vapor pressure	16 kPa	71 kPa	Evaporative emission of ethanol is lower
Range of heating values	21.2 and 23.4 MJ/L	30.1 and 34.9 MJ/L	Ethanol has a lower energy density
Need to add methyl tertiary butyl ether (MTBE)	Absent	Present	No contamination of groundwater in case of ethanol

Vehicle companies are designing their new vehicles in such a way that would allow blending at a mid-level of 20–40% along with enhancing their efficiency (Bhatia and Johri 2014). Ethanol is far a better fuel when compared to gasoline, and there are many reasons for that (Table 1.2).

Another eco-friendly biofuel is hydrogen. It is known for its high density, which creates fewer pollutants in combustion (Hallenbeck and Ghosh 2009). Hydrogen helps in the detoxification of various pollutants prevalent in water (Nath and Das 2004). Lignocellulosic biomass, crops, aquatic plants, algae, and agroresidues can produce hydrogen (Bhatia et al. 2023; Beer et al. 2009). There are three methods to generate biohydrogen: (1) microbial electrolysis cells (MEC), (2) fermentation, and (3) photosynthesis. In the fermentation process, the protons are employed for accepting electrons (Bhatia et al. 2023; Chatterjee et al. 2015). The best part of the fermentation process is that it supports the use of complex organic substrates, thereby serving as an alternative approach to decomposing lignocellulosic biomass (Balat and Kirtay 2010).

Butanol is another fuel of choice for transportation. It is used as a blend with gasoline for transportation. Its transportation can be managed in the prevailing gasoline pipeline. When compared with ethanol, the energy content of butanol is higher, and its corrosivity, volatility, and hygroscopicity are less (Hakkim et al. 2020). ABE fermentation is conventionally used for biobutanol production, in which carbohydrates are digested by *Clostridium* strains under anaerobic conditions. The product formed is a blend of acetone, butanol and ethanol (hence known as the ABE process) (Khamaiseh et al. 2014). Sources of carbohydrates such as sugarcane, sugar beet, and cereal crops are considered first-generation feedstocks, and feedstocks such as lignocellulosic materials, corn fiber, barley straw, corn stover, wheat straw, switchgrass, degermed corn, sago, domestic organic waste, extruded corn, cassava, liquefied corn starch, and defibrated-sweet-potato-slurry (DSPS) are considered second-generation feedstocks (Kumar and Gayen 2011).

Biomethane is a biofuel and is also known as a green gas and synthetic natural gas. It is synthesized through the hydrolysis of organic material under anaerobiosis (Niesner et al. 2013). All sorts of biomass comprising cellulose, hemicellulose carbohydrates, proteins, and fats are suitable feedstock for producing biomethane (Hendriks and Zeeman 2009).

1.7 Conclusion

Lignocellulosic biomasses are the reservoir of sugars, both quantitatively and qualitatively. The composition of these sugars varies among different biomasses and depends on many other factors. However, the pretreatment of lignocellulosic biomasses is a must to release these sugars and for further utilization. Pretreatment can lead to the formation of small chains of sugars of prebiotic importance or can produce monosaccharides that can be metabolized by various microorganisms to produce biofuels. Both prebiotics and biofuels are of industrial significance and support mankind in some way or the other. Prebiotics are good for human health, as they not only support many human physiologies but also have curing properties. Countries can address the issues of malnutrition besides prospering their agroeconomy. Functional foods can be developed by the combinatorial formulation of oligosaccharides, which will ensure holistic health by combating issues of diabetes, cancer, etc.

It can also be concluded that lignocellulosic biomasses are the sources of biofuels too. Biofuels are renewable, sustainable green fuels of the future, as the time demands to switch to these eco-friendly fuels. Metabolism of various organisms utilizes the sugars released from the pretreatment of lignocellulosic biomass, thereby converting them into biofuels. Production of biofuels is a sustainable approach toward a cost-effective, eco-friendly bioeconomy. Hence, time demands the development and elaboration of the perception of integrated biorefinery, which is a sustainable biorefinery-generating bio-energies and high-value-added bioproducts. It can be concluded that many biofuel industries reached the modulation point of innovation, where industries based on renewable resources have wholly accompanied petrochemical industries, and bio-based methods will certainly have a place in driving the economy.

Declaration of Competing Interest The authors declare that they have no competing interest to declare.

Funding and Acknowledgments BK is thankful to the DST-SERB NPDF (PDF/2022/001781) scheme for his post-doctoral research.

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