Advances in the Valorization of Lignocellulosic Materials by Biotechnology: An Overview

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In view of the worldwide economic and environmental issues associated with the extensive use of petro-chemicals, there has been increasing research interest during the past decade in the value of residual biomass. Because of its renewable nature and abundant availability, residual biomass has attracted considerable attention as an alternate feedstock and potential energy source. To expand the range of natural bio-resources, significant progress related to the lignocellulose bio-technology has been achieved, and researchers have been re-directing their interests to biomass-based fuels, ligninolytic enzymes, chemicals, and biocompatible materials, which can be obtained from a variety of lignocellulosic waste materials. This review article focuses on the potential applications of lignocellulosic materials in biotechnology, including the production of bio-fuels, enzymes, chemicals, the pulp and paper, animal feed, and composites.

Keywords: Lignicellulosic Material; Green Chemistry; Applications; Lignocellulose Biotechnology

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INTRODUCTION

Lignocellulosic materials may be described as one of the most promising natural, abundant, and renewable feedstock available for the enhancement and maintenance of industrial societies and critical to the development of a sustainable global economy (Kumar *et al*. 2009). Large amounts of lignocellulosic materials are generated through agricultural practices mainly from timber operations, pulp and paper manufacture, and many agro-based processes (Pérez *et al.* 2002). Today, lignocellulosic materials have gained a special importance for product development because of their renewable nature (Asgher *et al.* 2013). Their physical and chemical characteristics give them great potential for biotechnical applications (Malherbe and Cloete 2002). Regrettably, many lignocellulosic materials are still often disposed of by burning, a practice that is not restricted to developing countries alone, but can be considered a global problem. However, the huge amounts of lignocellulosic biomass that are available on the planet can potentially be converted into a variety of different value-added products (Hu *et al*. 2008; Lucia 2008; Isroi *et al.* 2011) (Fig. 1), including bio-fuels, cheap energy sources for microbial fermentation and their enzyme production, chemicals, pulp and paper production, improved animal feedstuffs, and polymer composites for materials science.

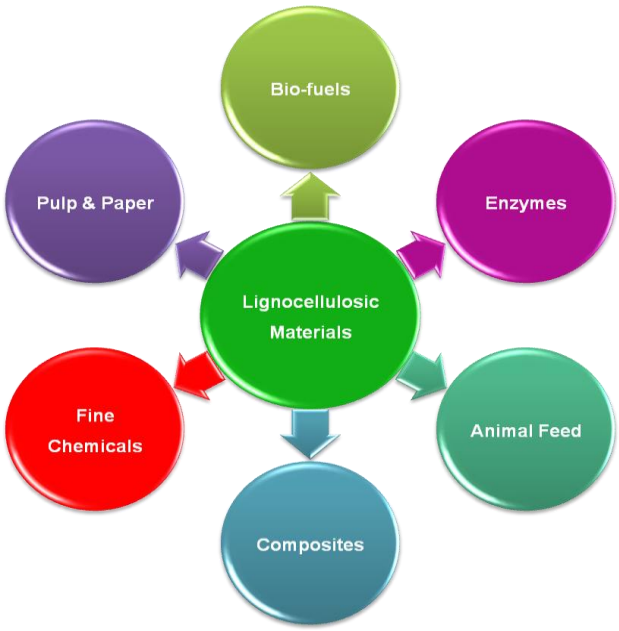

Fig. 1. Options for bio-conversion of biomass into value-added bio-products

Composition of Lignocellulosic Materials

The major structural components of woody plants, as well as grasses and agricultural residues, are lignin, hemicellulose, and cellulose. Most agricultural lignocellulosic biomass is comprised of 10% to 25% lignin, 20% to 30% hemicellulose, and 40% to 50% cellulose (Pérez *et al.* 2002; Kumar *et al*. 2009).

Lignin can be regarded as a complex polymer comprised of variously linked aromatic alcohols (coniferyl alcohol, sinapyl alcohol, and *p*-coumaryl alcohol) (Fig. 2), and is further linked to both hemicelluloses and cellulose, forming a physical seal around the latter two components (Pérez *et al.* 2002; Sánchez 2009; Calvo-Flores and Dobado 2010; Jiang *et al*. 2010).

Hemicellulose macromolecules are often repeat polymers of pentoses, hexoses, and a number of sugar acids. Depending on the source, the hemicelluloses are highly branched with a lower degree of polymerization than cellulose, and they vary in the structural composition due to the genetic variability among different sources. However, most of the lignocellulosic materials have similar properties even though they may differ in the chemical composition and the matrix morphology.

Cellulose is a homogenous linear polymer of D-glucopyranose sugar units (Sánchez 2009; Kumar *et al.* 2009; Bertero *et al.* 2012), that are linked in a β configuration (Fig. 2). The average cellulose chain has a degree of polymerization of about 9,000 to 10,000 units. About 65 percent or more of the cellulose is highly oriented, crystalline, and not accessible to water or other solvents. The cellulose is further protected from degradation because of its close association to a sheath of matrix polymers that include lignin and hemicelluloses. Table 1 shows the typical chemical compositions of all of these three components in various lignocellulosic materials that vary in their composition due to the genetic variability among different sources (Malherbe and Cloete 2002; McKendry 2002; John *et al.* 2006; Prassad *et al.* 2007; Kumar *et al.* 2009; Sánchez, 2009; Bertero *et al.* 2012).

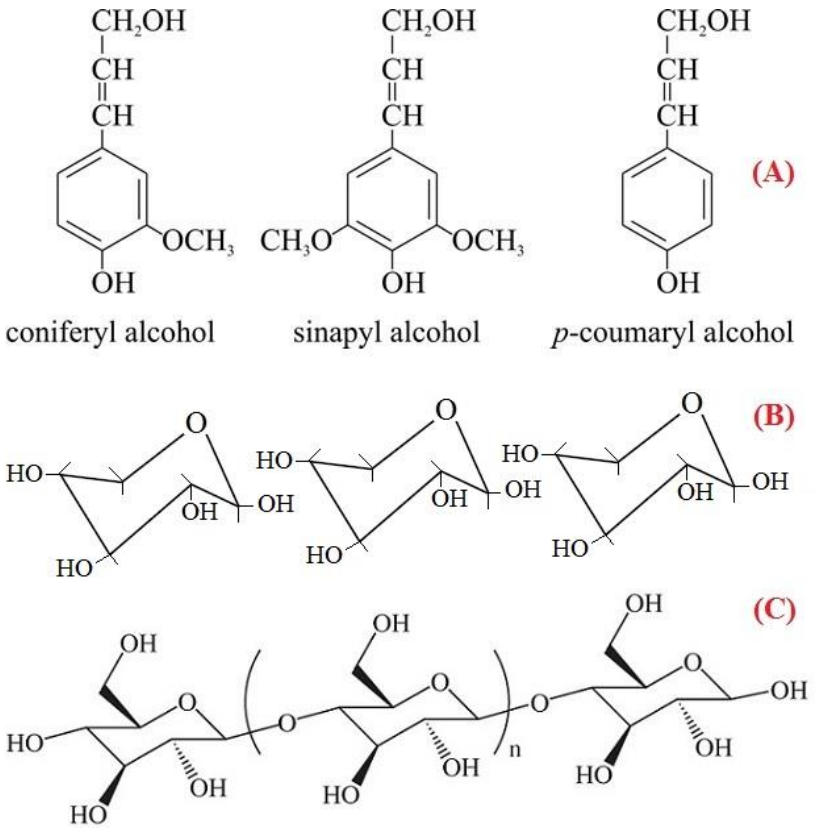

Fig. 2. Chemical structure of lignocellulosic material; (A) Building blocks/units of Lignin; (B) Xylose unit of hemicellulose; and (C) Cellulose

Table 1. Percent Composition of Lignocellulose Components in Various Lignocellulosic Materials

Lignocellulosic material	Lignin (%)	Hemicellulose (%)	Cellulose (%)	Reference
Sugar cane bagasse	20	25	42	Kim & Day, 2011
Sweet sorghum	21	27	45	Kim & Day, 2011
Hardwood	18–25	24–40	40–55	Malherbe & Cloete, 2002
Softwood	25–35	25–35	45-50	Malherbe & Cloete, 2002
Corn cobs	15	35	45	Prassad *et al.* 2007
Corn stover	19	26	38	Zhu *et al.* 2005
Rice Straw	18	24	32.1	Prassad *et al.* 2007
Nut shells	30–40	25-30	25-30	Abbasi & Abbasi, 2010
Newspaper	18-30	25-40	40-55	Howard *et al.* 2003
Grasses	10-30	25-50	25-40	Malherbe & Cloete, 2002
Wheat straw	16-21	26-32	29-35	McKendry, 2002
Banana waste	14	14.8	13.2	John *et al.* 2006
Bagasse	23.33	16.52	54.87	Guimarães *et al.* 2009
Sponge gourd fibers	15.46	17.44	66.59	Guimarães *et al.* 2009

Potential Applications of Lignocellulosic Materials

From a biotechnological point of view, a wide variety of lignocellulosic resources are available for conversion into value-added bio-products. During the last several years, considerable improvement in processes related to lignocellulose biotechnology has been achieved. In addition to the growing concerns for traditional applications (bio-fuels, enzymes, chemicals, pulp and paper, animal feedstuff, composites, *etc.*), novel markets for lignocellulosics have been identified in recent years. The most ambitious of these has been the conversion of lignocellulose to alternative energy carriers, *e.g*. fuel ethanol (Shuit *et al.* 2009; Sakamoto *et al*. 2012; Asgher *et al.* 2013; Shahsavarani *et al*. 2013). The pulp and paper industry has discovered that lignocellulose biotechnology can improve process efficiency, yielding savings in money and energy. Defeating the lignin barriers, which prevent commercial exploitation of lignocellulose, will be the key to its successful application in biotechnological endeavors. As indicated in the descriptions that follow, some of this research has focused on potential applications in the industrial sector of the modern era of bio-technology. This article focuses on an area that has not been comprehensively reviewed – potential applications of lignocellulosic materials in bio-technology, mainly including the production of bio-fuels, enzymes, chemicals, the pulp and paper, animal feedstuff, and composites.

Bio-fuel

Increasing costs of fossil fuels and their greenhouse gas effects are creating an urgent need to explore alternative cheaper and environment friendly bio-fuel resources as a strategy for reducing global warming. Air pollution, global warming, and the future of oil production are among the major causes of public and private interest in developing ethanol as an additive alternative or substitute for fossil fuel oil. Currently, bio-ethanol is produced on an industrial scale from sucrose and starch-based grains (Reijnders and Huijbregts 2007; Asgher *et al.* 2013). However, to avoid direct competition between fuel ethanol and food production, the feedstocks for bio-ethanol production ideally should be derived from inedible parts of food crops (Mathews 2007; Goldemberg *et al.* 2008; Andrade de Sá *et al.* 2011; Gnansounou 2011).

One potential approach for the low-cost fermentative production of ethanol is to utilize agro-industrial residual materials. The carbohydrates present in such biomass must be first converted into simple sugars (especially glucose), which then can be fermented into ethanol, a potential fuel for transportation (Lin and Tanaka 2006; Alonso *et al*. 2008; Balat and Balat 2009). The leading nations in the production of bio-ethanol are Brazil and the USA (Aalam *et al.* 2007). Asian countries altogether account for about 14% of the world's bio-ethanol production. Research has shown that ethanol can be produced using raw materials from sugar cane bagasse, maize cobs, coconut husks (copra), groundnut, other nut shells, sawdust, cereal straw corn stover, rice straw, and rice husks (Chandra *et al*. 2007; Yang and Wyman 2008, Shuit *et al.* 2009; Sukumaran *et al*. 2009; Sakamoto *et al*. 2012; Asgher *et al.* 2013; Shahsavarani *et al*. 2013). Such transformation of biological resources, including energy-rich crops or forestry residuals requires pre-treatment of the feedstock to allow more rapid enzymatic conversion into sugar, *i.e.* saccharification (Cardona and Sánchez 2007). Fermenting organisms then convert the sugar into ethanol. Pre-treatment of these lignocellulosic biomass-based materials release sugars and, most importantly, glucose for the fermentation into ethanol.

Many different pre-treatment methods have been reported, including biological,

chemical, physical, thermal, and enzymatic approaches (Chandra *et al*. 2007; Yang and Wyman 2008, Yang *et al*. 2011; Asgher *et al.* 2013; Hamzeh *et al.* 2013; Rohowsky *et al*. 2013). Bio-delignification is useful in the pre-treatment, and it replaces or supplements the chemical-based pre-treatments, which include mechanical treatment with acid, alkali, and steam explosion. Recent advances in the characterization of ligninolytic enzymes involving the degradation of lignin have given new impetus to the research in this area, which has now become amenable to biotechnological exploitation (Asgher *et al.* 2012a,b,c; Pal *et al.* 2013). Bio-conversions of lignocellulosic materials to useful products normally require multi-step processes that include pre-treatment, enzymatic hydrolysis, and fermentation (Fig. 3).

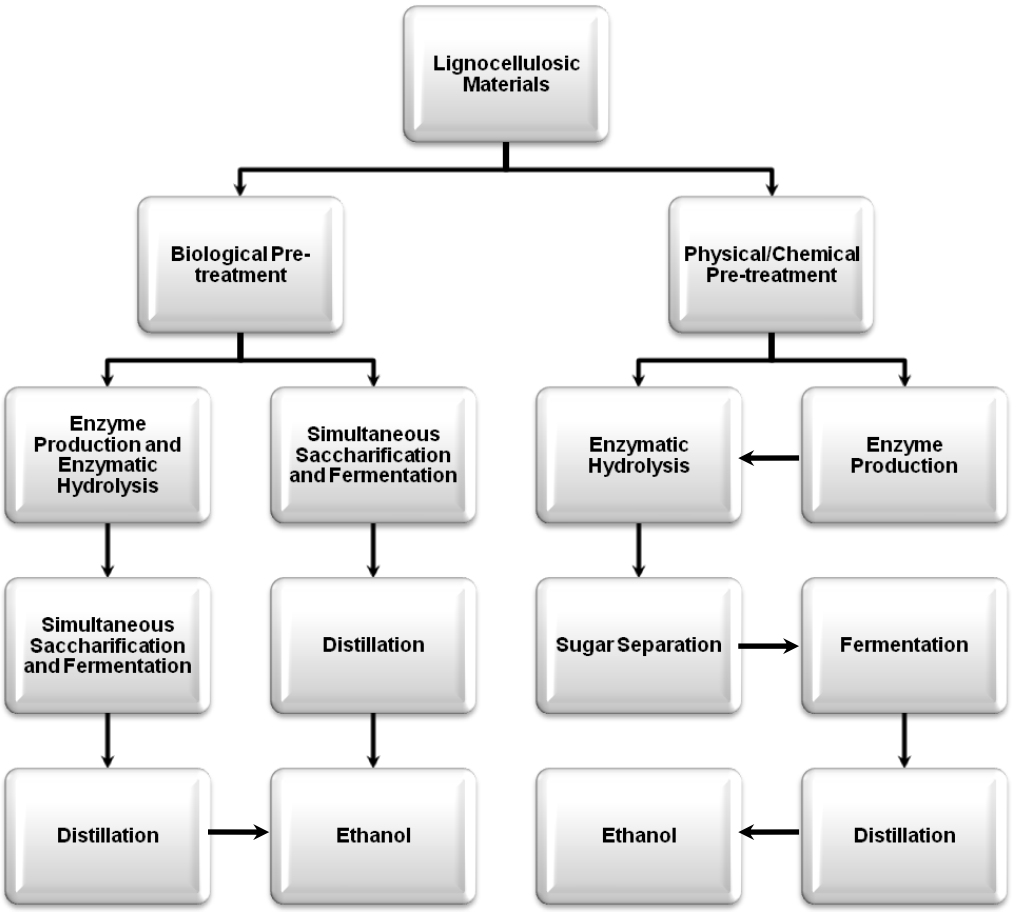

Fig. 3. Generalized schematic representation of lignocellulosic materials bio-conversion into ethanol

Production of Enzymes

Enzyme production is a growing field of biotechnology and has become a central part of the modern biotechnology industry. One of the most appropriate approaches to produce low cost and efficient enzymes for biotechnological application purposes is to utilize the potential of lignocellulosic waste materials. Some such mixtures may contain significant concentrations of soluble carbohydrates and inducers of enzyme synthesis so as to allow efficient production of ligninolytic enzymes (Reddy *et al*. 2003, Moldes *et al.* 2004; Elisashvili *et al.* 2006; Iqbal *et al.* 2011a,b; Asgher and Iqbal 2011; Asgher *et al*.

2012c). To date, the production of various ligninolytic enzymes including lignin peroxidase (LiP), manganese peroxidase (MnP), versatile peroxidase (VP), laccases, and other lignocellulytic enzymes, mainly cellulases, have been widely studied in submerged and solid culture processes in the laboratory, ranging from shake flask to a large scale (Xia and Len 1999; Moldes *et al*. 2004; Elisashvili *et al.* 2006). Due to the lower capital investment and operating costs of solid state fermentation (SSF), that approach has been reported as an attractive alternative process to produce fungal microbial enzymes using different agro-industrial based lignocellulosic materials (Jecu 2000; Couto and Sanromán 2005; Couto and Sanromán 2006; Levin *et al*. 2008; Oberoi *et al.* 2010; Iqbal *et al*. 2011a,b).

A wide spectrum of lignocellulosic materials has gained special attention from both the academic and industrial researchers because of their potential as inexpensive carbon and energy sources for the production of ligninolytic and lignocellulolytic enzymes. A miscellaneous spectrum of lignocellulolytic or lignin-degrading micro-organisms, mainly white rot fungi (Baldrian and Gabriel, 2003; Ander and Eriksson 2006; Asgher *et al*. 2008; Sánchez, 2009; Alvira *et al.* 2010; Asgher *et al.* 2012a,b,c; Asgher and Iqbal 2013; Iqbal and Asgher 2013), have been isolated and identified in recent years, and this list still continues to grow rapidly. The white-rot fungi belonging to the basidiomycetes are the most efficient and extensive lignin degraders (Asgher *et al*. 2008; Irshad *et al*. 2012), with *P. chrysosporium* being regarded as the model culture and best-studied lignin-degrading fungus, producing copious amounts of a unique set of lignocellulytic enzymes. Enzymes denoted by LiP, E.C. 1.11.1.14, MnP, E.C. 1.11.1.13, and laccase E.C. 1.10.3.2 are the major types secreted by white-rot fungi during the degradation of lignin in the lignocellulosic substrates (Bandounas *et al*. 2011; Asgher *et al.* 2011; Asgher *et al.* 2012a). *Phanerochaete chrysosporium* has drawn considerable attention as an appropriate host for the production of lignin-degrading enzymes or for direct application in the lignocellulose bioconversion processes (Bosco *et al*. 1999; Ruggeri and Sassi 2003). Ligninolytic enzymes, cellulases, and hemicellulases are important industrial enzymes having numerous applications and the biotechnological potential for various industries including chemicals, fuel, food, brewery and wine, animal feed, textile and laundry, pulp and paper, and agriculture (Bhat 2000; Jecu 2000; Beauchemin *et al*. 2003; Couto and Sanromán 2005; Couto and Sanromán 2006; Eun *et al.* 2006; Papinutti and Forchiassin 2007; Papinutti and Lechner 2008; Levin *et al.* 2008; Oberoi *et al*. 2010; Stoilova *et al.* 2010; Asgher *et al*. 2011; Asgher and Iqbal 2011; Iqbal *et al.* 2011a; Yoon *et al.* 2012; Asgher and Iqbal 2013; Iqbal and Asgher 2013; Irshad *et al*. 2013). A range of different lignocellulosic materials that have successfully been adopted for the production of different enzymes having industrial importance are summarized in Table 2.

Chemicals Production

Lignocellulosic materials are renewable resources that can be directly or indirectly used for the production of many useful biological and chemical products (Ghosh and Singh 1993; Moldes *et al.* 2007; Sarrouh *et al.* 2009; Chandel *et al.* 2011; Kamat *et al*. 2012; Misra *et al*. 2013). Production of such chemicals could significantly improve the economics of a bio-refinery. The introduction of a bio-refinery approach to produce bio-chemicals from renewable raw materials is one potential opportunity to cover the increased demand for fine chemicals and consequently reduce the fossil

dependence of the petro-chemicals. The goal of the bio-refinery approach is the generation of energy and chemicals from different biomass feedstocks, through the combination of different treatment technologies (Fitz-Patrick *et al.* 2010). In the last several years, some studies have revealed the potential of lignocelluloses for bio-refinery purposes (Cherubini 2010). A simple lignocellulose bio-refinery scheme involves a single or multi-step pre-treatment (physical, chemical, or biological) of biomass to initially separate fractions of different lignocellulosic biomass components (cellulose, hemi-cellulose, and lignin). Figure 4 displays a simple integrated lignocellulose bio-refinery scheme for the production of various value-added bio-chemical products. In this context, extensive research has been undertaken for the bio-conversion of lignocellulosic materials, and hydrolysate-derived carbohydrates, into several value-added products and renewable bio-chemicals (Chandel and Singh 2011).

A range of products such as glucose (mainly from cellulose and hemicellulose), xylose, mannose, galactose, and acetic acid (from hemicellulose), and phenolic compounds (from lignin) are produced during the hydrolysis process. Many authors have investigated the polymeric fractionation of the hemicellulose portion of agricultural residues such as corn stover, rice straw, sugarcane bagasse, eucalyptus, spent grain, and corncob to obtain a variety of marketable and renewable bio-chemicals, including xylitol, phenols, guaiacols, catechols, vanillin, vanillic acid, syringaldehyde, benzene, biphenyls, and cyclohexane from lignocellulosic biomass (Canilha *et al*. 2004; Carvalho *et al.* 2005; Deng *et al.* 2006; Moldes *et al.* 2007; Kumar *et al.* 2008; West 2009; Gandini, 2011; Ji *et al.* 2012; Reichert *et al.* 2012; Varanasi *et al.* 2013).

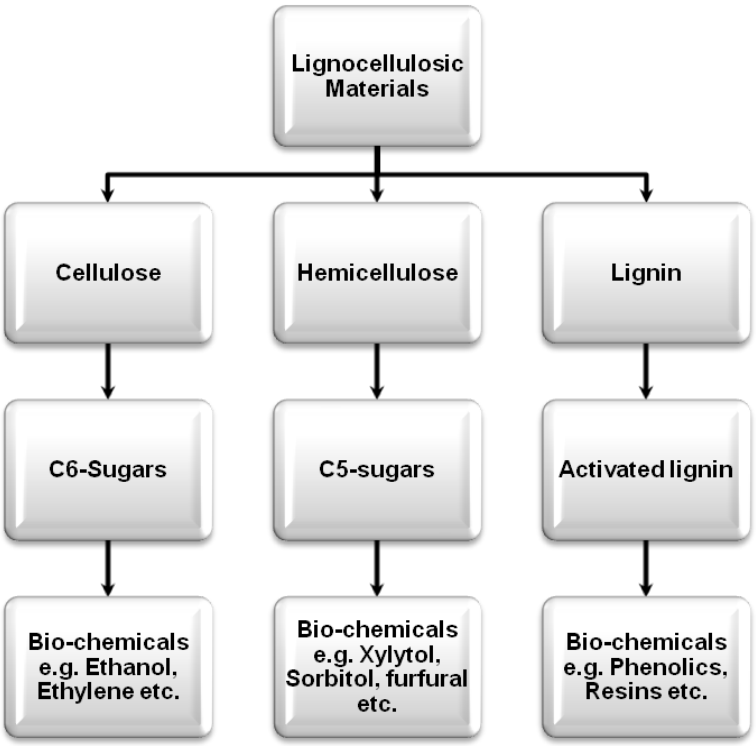

Fig. 4. Generalized scheme of integrated lignocellulose bio-refinery for the production of various value-added bio-chemical products

Table 2. List of Various Lignocellulosic Materials Used for the Production of Different Microbial Enzymes

Lignocellulosic material	Pre-treatment Type	Microbial Culture	Enzymes Produced	Reference
Sugar cane bagasse	Biological/ Chemical	*P. chrysosporium*; *T. versicolor; Trichoderma viride; P. Sanguineus; Trichoderma viride*	MnP, LiP, Laccase, Cellulases, xylanase	El-Nasser *et al.* 1997; El-Gammal *et al.* 1998; Kansoh *et al*. 1999; Irshad *et al.* 2012a,b; Yoon *et al.* 2012; Irshad *et al*. 2013
Orange peel waste	Chemical	*Trichoderma viride*	Endoglucanase, exoglucanase, β-glucosidase	Irshad *et al*. 2012a; Irshad *et al.* 2013
Corn cobs	Biological	*Trametes versicolor; P. chrysosporium*; *Aspergillus niger*	MnP, LiP, Laccase, Protease, Xylanase	El-Nasser *et al*. 1997; Ahmed *et al.* 2011; Iqbal *et al*. 2011a; Asgher and Iqbal 2011; Asgher *et al*. 2012a,b
Corn stover	Biological/ Chemical	*P. chrysosporium*; *T. versicolor; Penicillium decumbens*	MnP, LiP, Laccase, Cellulase, Xylanase	El-Nasser *et al.* 1997; Yang *et al*. 2001; Asgher *et al*. 2011
Rice Straw	Biological/ Chemical	*P. chrysosporium*; *T. versicolor; Trichoderma reesei*	MnP, LiP, Laccase, Cellulase	Eun et al. 2006; Iqbal *et al.* 2011a; Asgher *et al.* 2011
Peanut shells	Biological	*G. leucidum; P. chrysosporium*	Laccase, Xylanase	El-Nasser *et al.* 1997; Irshad *et al.* 2012b
Newspaper	Chemical	*Trichoderma viride*	Endoglucanase, Exoglucanase, β-glucosidase	Irshad *et al*. 2013
Wheat straw	Biological/ Chemical	*P. chrysosporium*; *T. versicolor; T. viride*; *F. trogii; L. edodes; P. dryinus; P. tuberregium*	MnP, LiP, Laccase, Cellulases, Xylanase	El-Nasser *et al.* 1997; Kachlishvili *et al.* 2006; Elisashvili *et al.* 2008; Iqbal *et al.* 2011a; Asgher *et al*. 2011; Irshad *et al.* 2013
Banana stalk	Biological	*S. commune*; *P. chrysosporium*; *T. versicolor; P. ostreatus*	MnP, LiP, Laccase, Xylanase, Endoglucanase	Reddy *et al.* 2003; Irshad *et al.* 2011; Iqbal *et al.* 2011a; Asgher *et al.* 2011; Asgher *et al*. 2012c
Rice bran	Biological	*Aspergillus niger*	Protease	Ahmed *et al*. 2011
Wheat bran	Biological	*Aspergillus niger; Morchella sculenta; F. sclerodermeus; Trametes versicolor*	Protease, Endoglucanase, β-glucosidase, Laccase, MnP	Papinutti and Forchiassin 2007; Papinutti and Lechner 2008; Stoilova *et al.* 2010; Ahmed *et al*. 2011
Apple pomace	Chemical	*Trichoderma viride*	Cellulases	Irshad *et al.* 2013
Oil palm empty fruit bunch fiber	Chemical	*Thermobifida fusca; Aspergillus terreus*	CMCase, FPase, β-glucosidase	Shahriarinour *et al.* 2011; Harun *et al.* 2013
Beech tree leaves	Biological	*F. trogii; L. edodes; Pleurotus dryinus; P. tuberregium*	Laccase, CMCase, FPase, MnP, Xylanase	Kachlishvili *et al.* 2006; Elisashvili *et al.* 2008
Eucalyptus residue	Biological	*Lentinula edodes*	Xylanase, Cellulase, MnP, Laccase	Silva *et al*. 2005

Xylitol has been identified as one of the most valuable chemicals derived from agro-residual lignocellulosic biomass (Kumar *et al.* 2008). Because of its proven marketable applications in food and pharmacological industries, it is an attractive candidate for its low-cost production using lignocellulosic materials (Misra *et al.* 2013). The hemicellulosic fraction of waste materials, such as sugar industry wastes (sugar cane bagasse), provides an important source of xylose that can be converted to xylitol by microbial fermentation (Sarrouh *et al*. 2009; Chandel *et al.* 2011). In this regard, several researchers have explored an alternative route, wherein the selection of naturally occurring xylose-fermenting microorganisms *i.e.*, bacteria, yeasts, and fungi capable of producing xylitol from agro-industrial lignocellulosic residues is emerging as a promising approach (Ji *et al*. 2012; Kamat *et al.* 2012; Misra *et al.* 2013).

The major bottleneck against comprehensive applications of lignocellulosic biomass as raw material to obtain bio-chemicals is the lack of technology for the efficient conversion of biomass into various value-added bio-chemicals. However, there are certain other drawbacks and limitations in using different pre-treatments methods. These include high costs of alkaline/acids catalyst and the need for recovery, high costs of corrosive resistant equipment, partial degradation of hemicellulosic components during the process, and the generation of inhibitory/toxic compounds. The limiting factor is simply that low cost processing technologies to efficiently convert a large fraction of the lignocellulosic biomass into bio-chemicals do not yet exist. In this regard, extensive research is needed in order to develop a comprehensive understanding of the fundamental chemistry, science, and engineering underpinning the transformation of lignocellulosic materials into value-added products.

Pulp and Paper Industry

Paper is a ubiquitous product used for many applications in our daily lives (Manda *et al.* 2012). The pulp and paper industry processes huge quantities of lignocellulosic materials. In addition to direct harvesting of wood, straw, and bamboo, *etc.*, the industry also uses residual materials from other manufacturing processes (wood chips from sawmills, bagasse from sugarcane processing, *etc.*), or fibers recovered from recycled paper or paperboard (Gupta 2007). With an increasing demand for paper, and with improvements in pulp processing technology (Singh *et al*. 2012), pulp and paper can be made from different lignocellulosic materials, and three major processing steps are involved, *i.e.* (i) pulping, (ii) bleaching, and finally (iii) paper production (Habibi *et al.* 2008; Singh *et al*. 2010). There are three main types of pulping, *i.e.* (i) mechanical pulping, (ii) chemical pulping, and lastly (iii) chemi-mechanical pulping (combination pulping). The mechanical pulping mainly involves the grinding of raw material (usually a lignocellulosic material) to separate the fibres without significant dissolution of lignin (Havimo and Hari 2010). Chemical pulping typically involves use of alkaline chemicals at high temperatures to remove much of the lignin and to separate the fibres. In comparison to mechanical pulping, the chemical pulping process uses less energy and produces a lower fibre yield, typically ranging from 50 to 60% (Messner *et al.* 1998; Bajpai 1999; Bajpai *et al*. 2003) with a superior paper quality. On the other hand, it produces concentrated liquid effluents, some components of which are toxic, mutagenic, persistent, bio-accumulating, and cause numerous harmful disturbances in biological systems (Bajpai 1999). A large amount of energy and water is required for the entire processes of the pulp and paper industry (Pokhrel and Viraraghavan 2004). Because of

the high chemical consumption, chemical pulping also poses some serious effects to the environmental ecosystem. As an alternative to the existing chemical-based pre-treatment technologies, which are usually hazardous to health, expensive, commercially and environmentally unattractive, biological pre-treatment or bio-pulping offers an alternative cost-effective, low chemical demanding, and eco-friendly approach to overcome some of the challenges inherent in the manufacture of pulp and paper. Recent reports show that a biological-based approach has potential for improving both the economics and the environmental impact of the pulp generation. Bio-pulping can be defined as the biological pre-treatment using white rot fungus to metabolize the lignin in wood, freeing up the fibers so that they can be used for paper production (Rademacher 2004; Habibi *et al.* 2008; Tuncer *et al*. 2009; Singh *et al*. 2010; Fu *et al.* 2012) (Fig. 5). Bio-pulping by the introduction of certain lignocellulytic enzymes at different stages of pulp manufacturing prior to bio-bleaching allows substantial savings of electrical power and it decreases pollutants (Singh *et al.* 2010; Singh *et al.* 2012; Saritha and Arora 2012).

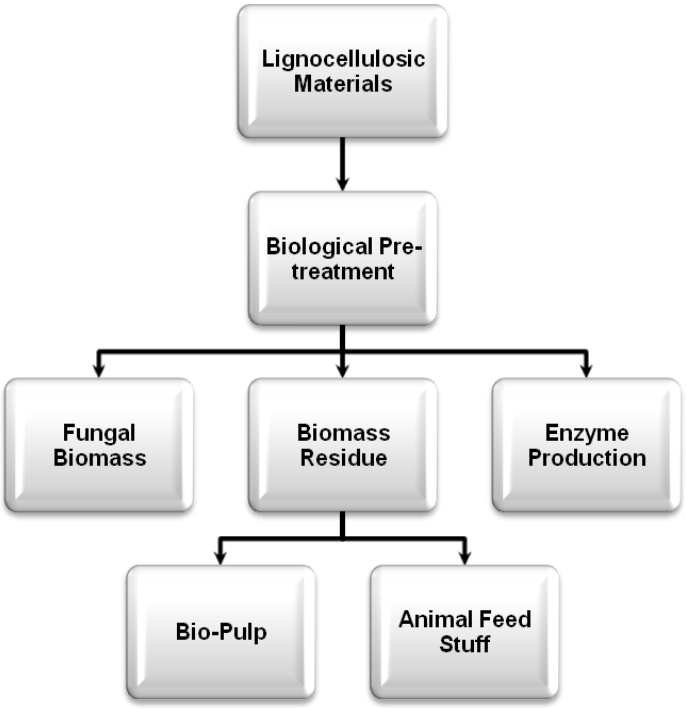

Fig. 5. Scheme of integrated bio-processing of lignocellulosic materials for the production of bio-pulp and animal feedstuff

Animal Feed Production

Cellulose is the most important carbon and energy source in a ruminant's diet. The concept of preferential delignification of lignocellulose materials by white-rot fungi has been applied to increase the nutritional value (Chen and Dixon 2007; Chen *et al.* 2010). The white-rot fungi degrade lignin and improve the *in-vivo* dry matter digestibility of lignocellulosic materials (Cohen *et al*. 2002; Phan and Sabaratnam 2012; Saritha and Arora 2012). This increased digestibility provides organic carbon that can be fermented to organic acids in an anaerobic environment, such as the rumen. Most of the lignocellulosic agricultural residues are enriched in microbial protein, enzymes, and bio-factors that can be used as animal feedstuff directly or after partial treatments (Isikhuemhen *et al*.

1996; Nigam, and Singh 1996; Huettermann *et al.* 2000) (Fig. 5). A more promising avenue is the supplementation of animal rations with feed enzymes produced by solid-state fermentation using many other cellulosic-based materials (Pluske and Lindemann 2000). For instance, in the integrated bio-processing of sweet sorghum, the extracted partially digested and enzyme enriched pulp is a valuable feed ingredient in animal feed rations (Tengerdy *et al.* 1996). According to the investigations of Adamović *et al.* (1998), the most notable change of composition in spent straw substrate is the reduction of hemicelluloses by 17%, cellulose by 15%, lignin by 4%, and gossypol by 60% (Zhu *et al.* 2012). Recent studies have proved that some polysaccharides, vitamins, and trace elements such as Fe, Ca, Zn, and Mg, are valuable components and play an important role for animals in the digestibility of feedstuffs (Medina *et al*. 2009; Paredes *et al.* 2009; Zhu *et al*. 2012).

Composites Production

In recent years, a great deal of research effort has been directed towards the use of lignocellulosic waste residual materials in the place of synthetic materials to prepare various composites with different functionalities of interest. For this reason, the development of bio-based composites has been a subject of interest in materials science from both ecological and environmental perspectives (Bajpai *et al*. 2013). Among the possible alternatives, the development of composites using lignocellulosic materials as reinforcing fillers for thermo-plastic polymers is currently receiving increasing attention. There are various methods of manufacturing lignocellulosic material based thermo-plastic polymer composites, depending on the processing technique. This guarantees a continuous fiber supply at all times around the year, and it provides a significant material cost saving to the plastics industry. Synthetic fibers, such as glass and carbon fibers, are brittle and are often broken into smaller fragments (Hancox 2001), while lignocellulosic fibers are flexible and will not fracture when they are processed over sharp curvatures. This permits a high volume fraction filling during processing, which results in high mechanical properties as compared to the problems associated with abrasive synthetic fibers, especially when using glasses and ceramics. All of these features enable the fibers to maintain the desired aspect ratio for good performance of the prepared composites (Shaw 2002; Tserki *et al.* 2005). Moreover, lignocellulosic-based fibers offer a high ability for surface modification, an eco-friendly approach, a non-toxic nature, easy handling, and they present no health problems characteristic of most synthetic fibers, which cause skin irritations and respiratory disease (Hattotuwa *et al*. 2002; Yang *et al.* 2004). Many authors (Bledzki and Gassan, 1999; Jayaraman, 2003; Lee *et al.* 2004; Kim *et al.* 2004; Yang *et al.* 2004) have carried out studies on the mechanical properties of natural fiber-filled thermo-plastics. Similarly, the dispersion characteristics of yellow poplar wood fibers in cellulose acetate butyrate/ yellow poplar wood fiber composites have been studied by Onyeagoro (2012). Medium-density fiber board has become one of the most popular wood-based composite materials due to its numerous advantages and favorable machining properties. Many successful attempts have been reported to produce medium-density fiber board or other composite panels using various lignocellulosic materials (Li *et al.* 2013). Globally, wheat and rice are the most important food grains, ranking second and third in terms of total cereal production (Halvarsson *et al.* 2008), and seem to be the most promising agriculture residues for manufacturing different composites.

CONCLUDED REMARKS AND FUTURE OUTLOOK

1. The energy and environmental crises that the world is experiencing are forcing people to re-evaluate the efficient utilization of or to find alternative uses for natural, renewable resources, using clean technologies.
2. Lignocellulosic biomass holds considerable potential for renewable fuels such as the production of bio-ethanol to meet the current energy demand of the modern world.
3. Lignocellulosic materials offer significant opportunities to developing countries in the area of lignocellulose biotechnology to utilize the readily available residual plant biomass to produce numerous value-added products.
4. In the current scenario, future trends are being directed toward lignocellulose biotechnology for improved processes and products.
5. To overcome the current energy problems, it is envisaged that lignocellulosic materials in addition to green chemistry will be a main focus of future research.

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