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Review

The path forward for lignocellulose biorefineries: Bottlenecks, solutions, and perspective on commercialization

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ABSTRACT

Lignocellulose biorefinery encompasses process engineering and biotechnology tools for the processing of lignocellulosic biomass for the manufacturing of bio-based products (such as biofuels, bio-chemicals, biomaterials). While, lignocellulose biorefinery offers clear value proposition, success at industrial level has not been vibrant for the commercial production of renewable chemicals and fuels. This is because of high capital and operating expenditures, irregularities in biomass supply chain, technical process immaturity, and scale up challenges. As a result, commercial production of biochemicals and biofuels with right economics is still lagging behind. To hit the market place, efforts are underway by bulk and specialty chemicals producing companies like DSM (Succinic acid, Cellulosic ethanol), Dow-DuPont (1,3-Propanediol, 1,4-Butanediol), Clariant-Global bioenergies-INEOS (bio-isobutene), Braskem (Ethylene, polypropylene), Raizen, Gran-bio and POET-DSM (Cellulosic ethanol), Amyris (Farnesene), and several other potential players. This paper entails the concept of lignocellulose biorefinery, technical challenges for industrialization of renewable fuels and bulk chemicals and future directions.

1. Introduction

One of the major bottlenecks of chemistry as well as biology, fueled by the urgent requirement of climate alteration diminution, is to develop sustainable approaches/ methodologies towards the transformation of lignocellulosic biomass into biofuels/bioenergy and range of value-added products i.e. biodegradable plastics, biochemicals, advanced biofuels etc. (Sheldon, 2014; Isikgor and Becer, 2015). Biorefining of lignocellulosic biomass into these products employing lignocellulose biorefinery platform is not only primarily linked to pollution prevention but also offer sustainable development involving the three pillars of sustainability: people, planet and profit, i.e., social, environmental and economic elements. Lignocellulose biorefinery can be considered as an analogue of petroleum refinery and has the potential to fulfillment the renewable fuels, chemicals and material demand in near future. Sustainable development stresses on the requirement of the renewable chemicals/fuels/energy/materials together with societal development (Brundtland, 1987). Twentieth century has witnessed the establishment and development of the petroleum industries as most important sources of energy, chemicals as well as various substances. However, it appears that the twenty-first century will present the gradual flourishing of lignocellulose biorefineries, thriving on biomass as a renewable base material (Cherubini et al., 2009; FitzPatrick et al., 2010). Under the biorefinery regime, all the major components of biomass i.e. lignin, hemicellulose, cellulose and trace components are the promising shareholders efficiently contributing in the overall development of global bioeconomy (Chandel et al., 2010; Rinaldi et al., 2016; Schutyser et al., 2018). Biorefineries have the potential to play a catalytical role for the holistic and sustainable development of society. Industrial biotechnology has an impeccable role in the overall success of biorefineries (Erickson et al., 2012; Pandey et al., 2015).

The definition of biorefinery is almost same whether it is given by National Renewable Energy Laboratory (NREL), Colorado, USA or International Energy Agency (IEA), Bioenergy- France (Fernando et al., 2006). Biorefinery refers to the “the sustainable processing of biomass into a spectrum of marketable products and energy”. The term biorefinery encompasses a network of facilities that integrate different technologies (processes and equipment) either to separate the constituents of biomass or to use as intact for bio-based products (chemicals, materials, energy, fiber) (Kamm and Kamm, 2004; FitzPatrick et al., 2010; Sanford et al., 2016). Globally, bio-based chemicals

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Table 1
Potential bio-based products/chemicals selected by US Department of Energy (USDOE) from lignocellulose biorefinery platform.

Potential bio-based products/ chemicals selected by USDOE in 2004	Top platform chemicals based on green chemistry by USDOE in 2010
• 1, 4 Succinic, fumaric and malic acids • 2, 5 Furan dicarboxylic acid • 3-Hydroxy propionic acid • Aspartic acid • Glutaric acid • Glutamic acid • Itaconic acid • Levulinic acid • 3-Hydroxybutyrolactone • Glycerol • Sorbitol	• Ethanol • Furans (furfural, 5-hydroxymethylfurfural, 2, 5-FDCA) • Glycerol and its derivativos (propanediol, glycerol carbonate, epichlorohydrin) • Hydrocarbons (isoprenes…) • Lactic acid • Succinic acid/Aldehyde/3-hydroxy propionic acid • Levulinic acid • Sorbitol • Xylitol

U.S. Department of Energy (2011).

(excluding biofuels) amount is estimated to be 50 billion kilos per year with the growth of 3–4% per year (de Jong et al., 2012). Remarkably, in 2013, the only United States produced $126 billion direct sales of biobased products (Sanford et al., 2016). The key constituents of biomass can be divided into five types namely starch, cellulose, hemicellulose, lignin and oils and each component is a shareholder in the overall success of lignocellulose biorefinery (Bhowmick et al., 2018). More than 200 value-added chemicals can be produced from the refining of lignocellulosic biomass (Isikgor and Becer, 2015). Table 1 presents the potential bio-based products from lignocellulose biorefinery as identified by US Department of Energy (USDOE, Washington). The most common routes harnessing biomass into biofuels/bioenergy and bioproducts are shown in Fig. 1. The upper portion of the figure depicts a variety of promising raw feedstocks, whereas the lower portion reveals progressive sequence of substances, which may be formed from C_6 or C_5 sugar core backbones by chemical catalysis or microbially mediated fermentation. However, consequent transformation of these components by chemical catalysis resulted into other group of chemicals.

This review presents the potential of lignocellulosic biorefineries for biofuels and biochemicals production under the current scenario. Details pertaining the major bottlenecks and their solutions in the commercialization of lignocellulose biorefinery are also discussed in this review.

2. Lignocellulosic biomass: Potential source for 2G sugars production in LBRs

Lignocellulose biorefinery use lignocellulosic biomass (agro-residues, forestry waste, energy crops, municipal solid waste etc.) as a base. In lignocellulose biorefinery, carbohydrate fraction of biomass is broken into sugars so called cellulosic sugars or second-generation (2G) sugars in addition to the valorization of lignin. Nature generates the huge quantity of one hundred seventy billion metric tons of biomass annually via photosynthesis, 75% of which belonging to the category of carbohydrates (Somerville et al., 2010). Remarkably, merely 3 to 4% of these substances are exploited by humans in the form of food as well as non-food materials/purposes (Bhowmick et al., 2018). There is an increasing attention to develop economical methods using lignocellulosic biomass as the feedstock in industrial biotechnology processes including biorefinery. The key constituents of lignocellulosic biomass involve cellulose in a range of 35–50%, hemicelluloses from 20 to 35%, 5–30% lignin and other extracted substances (1–10%) (Menon and Rao, 2012).

2.1. Pretreatment of lignocellulosic biomasses: Gateway to access the sugars in biomass

Pretreatment of lignocellulosic biomass leads to efficient generation of second generation (2G) sugars which are backbone of biorefinery and are natural intermediates in the biological as well as chemical

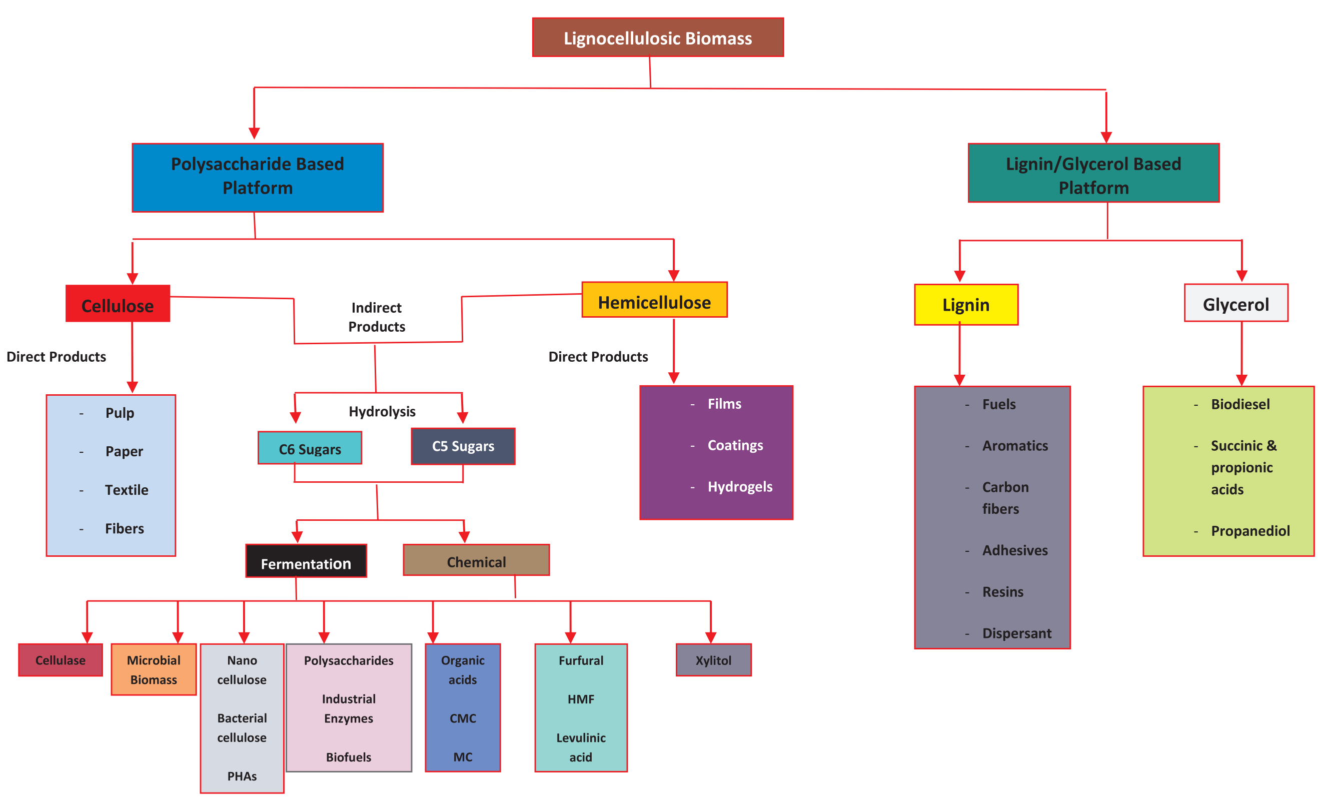

Fig. 1. Commercial bioproducts from lignocellulosic biomass in lignocellulose biorefinery platform.

transformation (Sindhu et al., 2016; Jönsson and Martín, 2016). However, accessibility to 2G sugars is hampered because of natural recalcitrance of plant cell walls. Pretreatment of lignocellulosic biomass results in cellulose substrate redistribution substances either as an enhanced cellulose surface area and/or the solubilized lignin (Banerjee et al., 2010). Thus, the major characteristics of an efficient pretreatment technique involve the break-down of the lignocellulosic complex which in-turn reduces the crystallinity of cellulose with the preservation of hemicellulose sugars and minimized production of inhibitory compounds.

The degradation products of pretreated lignocellulosic biomass may subsequently have inhibitory effect on hydrolysis and fermentation steps of 2G ethanol production. Beside this, reduction of energy and extraneous chemicals inputs, producing lignin as a high value commodity, reducing the formation of toxic and hazardous wastes and minimum waste discharge are also important factors in the desired pretreatment method (Banerjee et al., 2010).

Various physical, physicochemical as well as biological processes have been introduced for the pretreatment of lignocellulosic materials, which increase lignocellulose accessibility/ digestibility in very different manners. The key obstacle hampering the economic 2G sugars production at large-scale as building block from the lignocellulosic biomasses is the nonexistence of cost-effective pretreatment method. Based upon the current literature survey, the conventional pretreatment techniques are price intensive because of excessive usage of chemicals and energy (Banerjee et al., 2010). The fundamental knowledge of each phase in the process with respect to consequent commercial feasibility as well as operation is needed towards marketable triumph in converting biomasses into sugars as building block for the production of fuels and other value-added chemicals (Amin et al., 2017).

2.2. Enzymatic hydrolysis

Pretreatment of these lignocellulosic biomasses are essential so as to not only liberate the cellulosic as well as hemicellulosic polymeric chains but also towards the modification of pores of these substances for enhance enzymatic hydrolysis into fermentable sugars. Amongst hydrolytic strategies of cellulosic feedstocks/ biomasses, non-enzymatic hydrolysis is usually found to be more complex and non-specific with lower production of sugars including significant involvement in environmental pollution. Nevertheless, so far enzymatic saccharification exploiting cellulases are the most effective, viable, convenient as well as eco-friendly approach for biomass hydrolysis, where reasonable production of sugars from cellulosic feedstocks reaching more than 90% under optimized hydrolytic environments. Furthermore, usually the cellulosic feedstocks hydrolysis mediated through cellulases resulting in reasonable generation of sugars in small duration with no generation of fermentation inhibitors (Table 2). In addition, less corrosion issues as well as lower utility consumption together with lower toxicity of the hydrolyzates are the other benefits associated with this approach (Taherzadeh and Karimi, 2007; Chandel et al., 2012). During enzymatic lignocellulosic biomass hydrolysis, various kinds of hydrolytic enzymes are required in order to break the different kinds of linkages present in biomass (Somerville et al., 2010). For instance, cellulosic enzymes represent complex enzyme systems (new thermophilic enzymes, expansins and other ancillary enzymes). These enzyme cocktails are made up of three main constituents namely endoglucanase [endo-1,4-β-D-glucanase (EC 3.2.1.4)], exoglucanase [1,4-β-D-glucancellobiohydrolase (EC 3.2.1.91)] as well as synergy of cellobiase/ β-glucosidase (EC 3.2.1.21) (Harris et al., 2014).

Significant advancement has been observed in cellulosic enzyme biotechnology owing to technological improvements and innovations in structural biology, bioprocess engineering, system biology, biochemistry and molecular biology (Sukumaran et al., 2005). Cellulase enzymes are largely produced from fungal species like *Aspergillus/Trichoderma* sp. under submerged growth conditions (Chandel et al.,

Table 2
Enzymatic hydrolysis of selected lignocellulosic biomass in lignocellulose biorefinery.

Biomass	Type of pretreatment	Conditions	Sugars recovery/Fraction Composition	Bioproduct	Reference
Rice husks	Pretreatment with Sodium hydroxide	Enzyme loading of Celluclast 1.5 L (1.0%) and Novozyme 188 (0.25%), Substrate loading of 2.5% (w/v), 72 h.	87% Sugar yield	Maximum cell dry weight of 4.9 g L^{-1} and 40 wt% of poly-hydroxy alkanoates	Heng et al. (2017)
Corn stover	DMR (deacetylation and mechanical refining), 1900 L paddle mixer, dilute (0.1 M) sodium hydroxide	–	230 g L^{-1} of monomeric sugars	10.7% v/v ethanol	Chen et al. (2016)
Poplar wood chips	Neutral sulphonation post-treatment	Cellic CTec 3 (Novozymes), 20 mg protein/g; solids loading of 10%	More than 80% of sugars recovery	–	Chandra et al. (2016)
Sugarcane bagasse	Autohydrolysis, 180 °C for 20 min	5 FPU/g enzyme (Cellic CTec2 + HTec2 (Novozymes).	84.4% of sugar recovery	–	Batalha et al (2015)
Wheat straw	Organosolv with diethylene glycol at 160 °C for 40 min	Substrate loading of 13%, enzyme load (Cellic CTec2) of 9 mg g^{-1} substrate	89% of cellulose conversion	67% ethanol yield	Salapa et al. (2017)
Corn stover	NaOH pretreatment, Anthroquinone (0.125% w/w dry corn stover), 120 °C, 55 mg/g NaOH	20% total solids loading, 20 mg protein/g pretreated corn stover, CellicCtec 3	glucose (> 90%) and xylose (> 70%) yields	> 85% cellulose conversion	Kuhn et al. (2016)
Corn stover	Extractive ammonia (EA) for 30 min at 120 °C	Low enzyme loading (7.5 mg protein per g glucan) and high solids loading (8% glucan, w/v)	Ammonia-soluble fraction contained 44 wt % of the biomass lignin	18.2 kg ethanol per 100 kg untreated corn stover	Souza et al. (2016)
Corn stover	Hydrothermal pretreatment of 200 °C, 0.75% H_2SO_4	–	Recovery of almost 100% of the total xylose from the oligomers	–	Zhang et al. (2017)
Sugarcane bagasse	Alkaline pre-treatment with anthraquinone	Reactions at 130 °C, 1.5% NaOH, 30 min and 170 °C 1.5% NaOH, 30 min respectively	67.4% and 28.5% of cellulose preservation; 293 kg of glucose from 1 ton of raw sugarcane bagasse	–	Nascimento et al. (2016)
Eucalyptus urograndis chips and sugarcane bagasse	Steam explosion autohydrolysis at 195 °C for 7.5 min for sugarcane bagasse and 210 °C for 5 min for *Eucalyptus* chips	Enzymatic hydrolysis at high total solids (20 wt%) and relatively low enzyme (13.3 FPU/g TS of Cellic CTec3 from Novozymes).	125 g/L and around 94 g/L of glucose in 72 h, from steam-treated *E. urograndis* and sugarcane bagasse, respectively.	Ethanol yields of above 25 g/l and productivities of 2.3 g/l/h from *Eucalyptus* and 2.2 g/l/h from bagasse	Chiarello et al. (2016)

2012). To date, the foremost impact of cellulosic enzymes in a biorefinery is the price of cellulases that requires to be cost-effective so as to make the biofuels venture fruitful globally (Losordo et al., 2016). In spite of substantial research carried out in the past on cellulosic enzymes, there are still remaining several issues/concerns that require serious attention in order to come up with novel/ innovative/ improved solutions.

3. Fermentation and products recovery

Within the biorefinery concept, fermentation is a process that assisted by or involves microorganisms, where a value-added product or product of economic value is achieved. Microbial fermentation transforms sugars generated from lignocellulosic biomass to biofuels such as ethanol, butanol, acetone, iso-butanol, lipids, etc., or other value added biochemicals like organic acids exploiting fungus, yeast or bacteria. The hydrolyzed biomass fermentation towards bioethanol and value-added products/chemicals can be done through different process configurations such as SHF (Separate Hydrolysis and Fermentation), SSF (Simultaneous Saccharification and Fermentation), SSCF (Simultaneous Saccharification and Co-fermentation and CBP (Consolidated Bio-Processing (CBP) (Morales-Martínez et al., 2017). SHF depicts the benefit of optimizing saccharification as well as fermentation in separated process. SSF can generate high ethanol productivities with the considerable time savings as both hydrolysis and fermentation happen simultaneously. SSCF is an analogous to SSF, involving the fermentation of C_6 and C_5 sugars simultaneously, therefore, lead to high biofuel yield. CBP includes the production of cellulases, hydrolysis of pretreated biomass and fermentation of released sugars (C_5 and C_6) to ethanol, or other valuable products, in a single reactor thus reducing the process complexity. Amongst these four processes, SSF is the most advantageous one as it needs low initial cost and can provide high product yield and productivity. To obtain the high amount of bioproduct in the fermentation process, it is necessary to use the microorganism which can metabolize all lignocellulosic sugars into the desired product (s). One of the most commonly used industrial microorganisms, *S. cerevisiae* fail to utilize xylose but can ferment D-xylulose, isomer of xylose. By employing modern genetic engineering methods, gene encoding bacteria (xylose isomerase) or fungi (xylose reductase) that has the ability to utilize xylose and arabinose to produce D-xylulose can be incorporated into *S. cerevisiae* to enhance fermentation of pentose into ethanol (Wertz and Bedue, 2013).

The different approaches exploited towards the actual recovery of value-added products/ chemicals from fermentation or any other industrial process are termed as downstream processing. The price of downstream processing is often not only more than 50% of the overall production price, but also there is loss of value-added products/ chemicals at each step of downstream processing (Valdivia et al., 2016). Thus, the downstream processing should be effective, include few steps as far as possible (in order to minimize value-added products/ chemicals loss) and be economical. The separation of particles, disintegration of cells (if product is intracellular), extraction, concentration, purification and drying are the different steps in downstream processing. The development of the optimum product recovery process may need considerable effort and the final engineering of this process is often having a large impact on price, equipment size and waste (Valdivia et al., 2016). For example, a range of value-added products from bio-based processes are specifically recovered by distillation, which involves separation of more volatile value-added products from less volatile value-added products by evaporation and consequent condensation. Fractionation according to boiling points depends on the boiling point differences of product and other volatile constituents of the reaction mixture. Distillation process can produce a maximum of 95% pure ethanol. Nevertheless, distillation process is not only energy demanding, but also needs high steam amount. *In situ* ethanol removal from the fermentation broth has been reported to be beneficial for enhancing volumetric productivity of ethanol with decreasing process prices owing to decreased ethanol inhibition of the fermenting strains. *In situ* ethanol separation occurs as a result of reaction-separation integration (Sanchez and Cardona 2008). Process intensification through conglomeration of unit operations is a crucial factor for the techno-economic feasibility of biorefinery making value-added products at large scale (Liguori and Faraco, 2016).

4. Potential bioproducts of high commercial significance from lignocellulosic biomass

Among different biomass sources, lignocellulosic and algal biomass are considered as predominant ones due to their abundant supply and no conflicts with the food chain. The economy of the industrial process mainly enhanced through the complete utilization of the biomass (substrate). The product enhancement is one of the approaches to place any process in competitive market price. To achieve this goal, various approaches are utilizing to get the emerging product through the waste to wealth approach (O'Hara, 2003; Clark, 2017). Lignocellulosic biomass is proven substrate for different commercial value products such as fuels/energy and biochemicals (Isikgor and Becer, 2015). The overall applications of lignocellulosic materials towards commercial products include through the direct consumption or conversion towards secondary value-added products. The bioproducts from lignocellulosic biomass has further classified based on the basic constitute as polysaccharides based and lignin-based platforms (Fig. 1). Polysaccharides (cellulose and hemicelluloses) constitute up to 45–80% of the lignocellulosic biomass (Azadi et al., 2013). These polysaccharides can be utilized primarily and secondarily (through conversion) for production of different commercial commodities.

4.1. Primary products from polysaccharide platform

The direct products of cellulose include pulp, paper, textile, nano- and bacterial-celluloses. As being present in nano-size, nano-cellulose has high hydrophilicity and reactiveness than the usual cellulose. The specific properties of nanocellulose are mainly attributed to larger surface areas and sole characteristics of being present in nano-size (Dufresne, 2008). Bacterial cellulose produced from lignocellulosic biomass has unique features such as high purity, crystallinity, degree of polymerization, water binding capacity, tensile strength and bio-compatibility than the plant cellulose (Huang et al., 2014; Cavka et al., 2013). Currently, commercial PHA production is being met through fermentations using the first-generation sugars. However, cellulosic sugars if available at affordable price, could be an option to produce PHA's at industrial scale. PHAs are considered as the probable replacement of synthetic plastics (Pan et al., 2012). Pure cellulose from the lignocellulosic biomass also serves as a substrate for the production of microbial cellulases, which have high commercial value in various industries (Salamanca-Cardona et al., 2014). Hemicellulose serves as a direct substrate for production of different types of films, coating and hydrogels. The films and coatings of hemicelluloses are mainly used in food industry for packing and coating purposes. The hydrogels prepared from hemicellulose and other polymers have medical and pharmaceutical applications (Hansen and Plackett, 2008).

4.2. Secondary products from polysaccharide platform

Various secondary products can be produced from cellulose and hemicelluloses through chemical modification approaches. The main secondary products from cellulose and hemicelluloses (polysaccharide platform) are C6 and C5 sugars so called 2G sugars. These sugars are the predominant substrates for the production of renewable and sustainable biofuels namely, bioethanol, biobutanol, biodiesel, biohydrogen and biomethane. The lignocellulosic sugars can be further fermented to a mixture of acetone, butanol and ethanol through ABE pathway by

Clostridium acetobutilicum or to ethanol by *Saccharomyces cerevisiae, Scheffersomyces stipitis, Scheffersomyces shehatae* and *Zymomonas mobilis*. Biomethane production from lignocellulosic biomass mainly relies on the performance of anaerobic mixed cultures (hydrolyzing, acidogens, acetogens and methanogens) (Wyman et al., 2018; Sawatdeenarunat et al., 2018). Biodiesel can also be produced from lignocellulosic materials, where cellulosic sugars serve as a prominent feedstock for single cell oil production by oleaginous microbes. The extracted oils will further go through a transesterification process to produce biodiesel (Zeng et al., 2013; Yousuf, 2012).

Various cellulose derivatives can be produced from cellulose through chemical means either by esterification or by etherification. The major products with higher yields through chemical route include cellulose acetate, carboxymethyl cellulose, methyl cellulose and hydroxyethyl cellulose (Majewicz and Podlas, 2000). The toxicity issues of chemical-based lignocellulosic sugars hindered them for human consumption and hence diverting towards the production of different secondary products (Rødsrud et al., 2012). The lignocellulosic sugars also serve as a substrate for production of various secondary products through the fermentation process. The commercial products under this route include various organic acids, polysaccharides, feed and nutritional materials (Rødsrud et al., 2012).

The hydrolysates from lignocellulosic biomass play a role in the production of different microbial biomasses, which have subsequent applications as animal feed Ferreira et al., 2013; Guo et al., 2018). Moreover, the lignocellulosic hydrolysate serves as a low-cost feedstock for production of polysaccharides such as chitosan, xanthan, bacterial and nano-celluloses. The cationic biopolymer, chitosan has antimicrobial, metal-binding and gel- and film-forming characteristic features. The chemical route of lignocellulolytic sugars leads to produce different industrial important chemicals such as levulinic acid, xylitol, furfural and hydroxymethyl furfural (Chandel and Silveira, 2017).

Fermentation of lignocellulosic materials by co-cultures of *Yarrowia lipolytica* SWJ-1b and Immobilized *Trichoderma reesei* Mycelium results in citric acid production (Liu et al., 2014). Apart from citric acid, lactic acid is another industrial organic acid, produced through fermentation using a lignocellulosic material as substrate. Lactic acid is also serving as a precursor for polylactic acid, a promising substitute for synthetic plastics. Lignocellulosic materials such as corn stover and wood are also utilized as substrates for production of succinic acid through fermentation (Zheng et al., 2010). Production of propionic acid through fermentation using lignocellulosic sugars by *Propionibacterium* is one of the approaches to fix the atmospheric carbon dioxide. The production is usually done by genetically engineered microorganism via anaerobic fed-batch fermentations using a CO_2-fixing anaerobic pathway (Song and Lee, 2006). Xylitol is a sugar alcohol, produced through utilization of C5 sugar, xylose as a substrate through fermentation route (Su et al., 2013). Lignocellulosic sugars serve as a precursor for the production of furfural, 5-hydroxymethylfurfural and levulinic acid through dehydration reaction under acidic conditions in the presence of higher temperatures (Chandel and Silveira, 2017).

4.3. Lignin/ glycerol platform based commercial products

Lignin is the effective high-volume end product of lignocellulosic-based industry. The complex structure of lignin makes challenging to use for production of commercial products. Based on the properties of lignin, it is possible to produce different industrial commodities like fuels, aromatics, carbon fibers, adhesives, resins and dispersant either directly or indirectly (Azadi et al., 2013). The end product of lignin from pulp and paper industries falls under sulfite, kraft and soda lignin forms with a high heating value (26 MJ/kg) (Azadi et al., 2013;).

Glycerol is another by-product of biodiesel production through microbial single cell oils. Glycerol serves as a precursor for succinic and propionic acids production. It can also be utilized to produce ethanol through engineered *E. coli* (Garlapati et al., 2016; Dharmadi et al., 2006). The raw glycerol can also serve as a precursor for the production of propylene glycol by catalytic upgrading. Glycerols also serve as a protectant against high osmotic pressures (Dasari et al., 2005). 1,3 propanediol and butanediol are another fermented product from glycerol by different bacterial strains, which include *Klebsiella oxytoca*, *Klebsiella pneumoniae*, *Citrobacter freundii, Enterobacter agglomerans* and *C. butyricum* (Lin et al., 2005; Syu, 2001).

5. Commencement and establishment of lignocellulosic material based biochemical plants

The recent reviews of Putro et al., 2016, Sanford et al., 2016 depicted that pretreated lignocellulosic biomass could result into the formation of several value-added products. The biofuels (like biogas, syngas, biohydrogen, bio-oil and bioethanol etc.) and other commercially viable chemicals (such as furfural and 5-hydroxymethylfurfural, sugar alcohols like sorbitol and xylitol, glycerol, lactic acid and succinic acid) may be developed from pretreated lignocellulose feedstock either through carbohydrate source or from lignin. The last decade has seen a substantial push for biofuel production owing to reduce the dependency of fossil fuel and check the deposition of greenhouse gasses into atmosphere. With a critical requirement of carbon dioxide emissions as well as bearing in mind the diminishing fossil fuel resources, the governments of different countries have diverted considerable funds towards bio-based fuel ventures with announcement of incentives to vendors, which generate biofuels. Table 3 summarizes the production facilities for 2G ethanol and various value-added chemicals produced from various lignocellulosic biomass sources at commercial scale. The transformation of cellulosic material into fermentable sugars might speed up the establishment of commercial biochemical plants. The exploitation of biomass originated fermentable carbon towards the formation of biosurfactants, biomaterials as well as biofuels is being commercialized by some industries/companies (Marti et al., 2015). Abengoa S.A., DuPont, Beta-Renewables SA., and Poet-DSM Advanced Biofuels, LLC, have established the transformation of cellulose into 2G sugars for their eventual conversion into bioethanol and biochemicals on large-scale. DuPont has established a fully combined facility at a scale of 250,000 gallons bioethanol per year at Vonore, Tennessee plant. This pilot scale process has the capability to transform of a range of biomasses into bioethanol. The data generated at this plant, can be useful to construct as well as operate a full-scale plant, which have a generating potential of 30 million gallons of bioethanol/year at Nevada, Iowa, using corn stover (corn residues, including cobs, leaves and stalks) collected within a 30-mile radius. The industry has initiated for licensing this methodology to third parties to generate value-added products including biofuels (Sanford et al., 2016). However, under the current scenario, when gasoline prices are low and high price of cellulosic ethanol production, Dupont is not running the plant.

Similar to biofuels, microbial polyhydroxyalkanoates (PHAs) have received considerable interest for research as well as commercial

Table 3
Commercial scale facility established for some biochemicals and cellulosic ethanol production (Based on Sanford et al., 2016).

Product	Major Producer
Cellulosic ethanol	Raizen Combustíveis S.A, Brazil Granbio-Alagoas, Brazil, Poet-DSM Inc., Iowa, USA
Succinic acid	Bioamber, Québec, Canada
2, 5 Furan dicarboxylic acid	Avantium Inc., Amsterdam The Netherlands
3-Hydroxy propionic acid	Cargill Inc., MN, USA
Aspartic acid	Flexible solutions International Ltd., B. C., Canada
Glucaric acid	Rivertop Renewables, Missoula, MT, USA
Glutamic acid	Meihua Holding Co Ltd. Hebei Province, China
Itaconic acid	Qingdao Kehai Biochemistry Co Ltd. Huangdao, China
Levulinic acid	Biofine Inc, 300, Waltham, MA, USA

ventures because of their environment-friendly, biodegradable as well as renewable nature, with material properties analogous to non-biodegradable traditional plastics (Dietrich et al., 2017). PHAs are moving towards the path of commercialization after decades of investigation. Production of polyhydroxybutyrate including other PHAs are presently carried out by many companies such as Biomer, Germany; Biomatera and PolyFerm, Canada; Bio-On, Italy; DSM & Tianzhu, Tianjin GreenBio Materials and Tianan Biopolymer, China; DaniMer/Meredian, USA and Kaneka, Japan; (Dietrich et al., 2017). Irrespective of the several benefits of PHA bioplastics, the PHAs commercialization still is showing a slow progress. One of the reasons is the price of the substrate towards the PHAs production through fermentation. Furthermore, the successful and feasible microbial production of an PHAs using lignocellulosic sugars/ hydrolysates warrant the optimal combination of technological innovations associated with economic viability and integrated scale-up for commercial production and marketing.

6. Perspective on business and commercialization of lignocellulose biorefineries

Lignocellulose biorefinery, constitutes a sustainable business ecosystem, presenting a clear value proposition from the same site, where the connected units exchange raw material/intermediate products, steam/energy/water, utilities/machineries (boiler, chiller, air compressor etc). Sugarcane biorefinery is best example consisting of sugar unit, ethanol production unit and then sending bagasse/straw to interconnected 2G ethanol producing facility allowing using surplus steam, water at the same site. In this way, 2G ethanol or biochemicals producing biorefinery can be maximally benefitted from the annexed sugar and 1G ethanol making ethanol units developing an economically competitive integrated biorefinery ecosystem (Junqueira et al., 2016; Chandel and Silveira, 2017). Clauser et al. (2016) simulated a process for the xylose recovery employing the unit operations in a small sized biorefinery and found that production of medium density fiberboard from cellulignin (a product from acid hydrolysis of sugarcane bagasse) and process optimization for xylose recovery by autohydrolysis, fermentation and crystallization will aid the revenues recovery in sugar mills and reduce the capital costs. Rajendran and Murthy, 2017 comprehensively studied the various pathways impacting economic viability and environmental assessment of banagrass and energy cane in lignocellulose biorefineries. They found that production of ethyl acetate from 2G sugars from banagrass is highly economically competitive with a payback period of 11.2 year and return of investment of 8.93%. On the other hand, electricity production from both the feedstock was most unprofitable (-29.6% return of investment).

In Europe, Bazancourt-Pomacle biorefinery encompasses sugar factory and dehydration plant, starch and glucose producing plant, ethanol producing plant, carbon dioxide collection facility and some industrial R&D centers. Bazancourt-Pomacle biorefinery offers a business ecosystem, which is based on the concept of the territorial integrated biorefinery presenting a business niche between local biodiversity and optimized use of bioresources in order to develop new bioproducts and their potential market (Schieb et al., 2015). Mohan et al., 2016 comprehensively reviewed the various bioprocessing models directly addressing the circular economy and proposed a closed loop approach in order to assess the holistic potential of biomass resources.

More recently, Dou et al. (2017) proposed a business model encompassing of integration of the plantation and the lignocellulose biorefinery. A generalized business model on LBR has been depicted in Fig. 2. Various feedstocks were evaluated using product tonnage/unit land used/year. This economic model facilitates a linkage between farmers and users to maximize the overall production efficiency for a win-win situation of each shareholder in poplar biomass biorefinery.

At global scale, renewable biochemicals (excluding biofuels) volume is around 50 billion kilos per year which is continuously growing with the CAGR (compound annual growth rate) of 3–4% (de Jong et al., 2012). In 2015, the global biorenewable chemical market was 6.8 billion US$, with a CAGR of 22.8% from 2010 to 2015. By 2021, the global biorenewable chemical market is expected to be 12.2 billion US$ (www.rnrmarketresearch.com). USA recorded 126 billion-dollar direct sales of biochemicals in 2013. Table 4 presents the information on interesting biochemicals (selected by NREL-2009, CO, USA) the manufacturing company and production capacity of biochemicals (excluding biofuels). For cellulosic ethanol production, several industries in the world have set up pilot, demonstration and production facility using sugarcane bagasse, sugarcane straw or corn stover.

Beside ethanol (1G or 2G) and other value-added products listed in Table 3, several other promising bio-chemicals have emerged out in recent years which will have the high demand in future. Plant cell wall chemistry-based products such as ethylene (Braskem Inc., Brazil), isobutanol (Gevo Inc Colorado, USA), farnesene (Amyris Inc, Brazil), epichlorohydrin (PTT, Map Ta Phut, Thailand), p-xylene (Virent, Madison, WI, USA), acrylic acid and adipic acid (ADM and BASF, Germany), 5-HMF (AVA Biochem, Germany) and others could play a pivotal role in bioeconomy. Some of these chemicals are considered as base or platform chemicals, intermediate chemicals for developing further various household chemical commodities.

7. Biorefinery complexity profile (BCP) and technology readiness levels (TRL)

Biorefinery has several multidisciplinary and complex processing steps. The complexity of biorefinery can be measured with different features involved into the process (IEA, 2014). The complexity of a biorefinery depends on the different influential features of a biorefinery. More number of features leads to more complexity of biorefinery. The status of technology and number of features are the principle elements of Biorefinery Complexity Profile [BCP]. If the complexity is very low then technology is closer to attempt at commercial scale. The complexity decreases the closer a technology is to a commercial application. These features eventually are taken into consideration to calculate “Technology Readiness Level” [TRL]. TRL is measured from 1 to 10 scale. If the TRL is close to 9 or 10 that means that technology is ready for commercial level. TRL is basic parameter or assumption to analyze the Biorefinery Complexity Index [BCI]. The complexity of biorefinery is connected with the number of features and TRL of each feature. BCI and BCP are the numeric indication for the comparison of different biorefinery concept and their potential. BCP includes number of features such as feedstocks, platforms, processes & products, and overall “TRL”. The higher the BCI, higher the complexity profile of biorefinery. BCP of a biorefinery gives an indication on the technological and economic risks. Jong and Jungmeier (2015) reported the BCP of 8 and 29 of oil biorefinery and lignocellulose biorefinery, respectively.

Technology scouting is a method of technology forecasting in industrial corporate sector. TRL can be taken into consideration to analyze the real scenarios of technologies of biochemical/biofuels production. The National Aeronautics and Space Administration [NASA] firstly introduced TRL, to characterize the technologies on a scale score from 1 to 9, the higher scored technology being those that are able to be employed at a commercial scale (Chandel and Silveira, 2017). Table 4 shows the TRL of some biochemicals that can be produced from lignocellulose fractionation in biorefinery.

8. Bottlenecks and possible solutions for the commercialization of biorefineries

Major drivers for the deployment of biorefineries are (i) sustainable and renewable energy supply (ii) inclusive economic growth in turn saving foreign exchange reserves and less dependency on imported crude petroleum (iii) establishment of carbon neutral and circular economy (iv) low carbon footprint and green environment (Oh et al.,

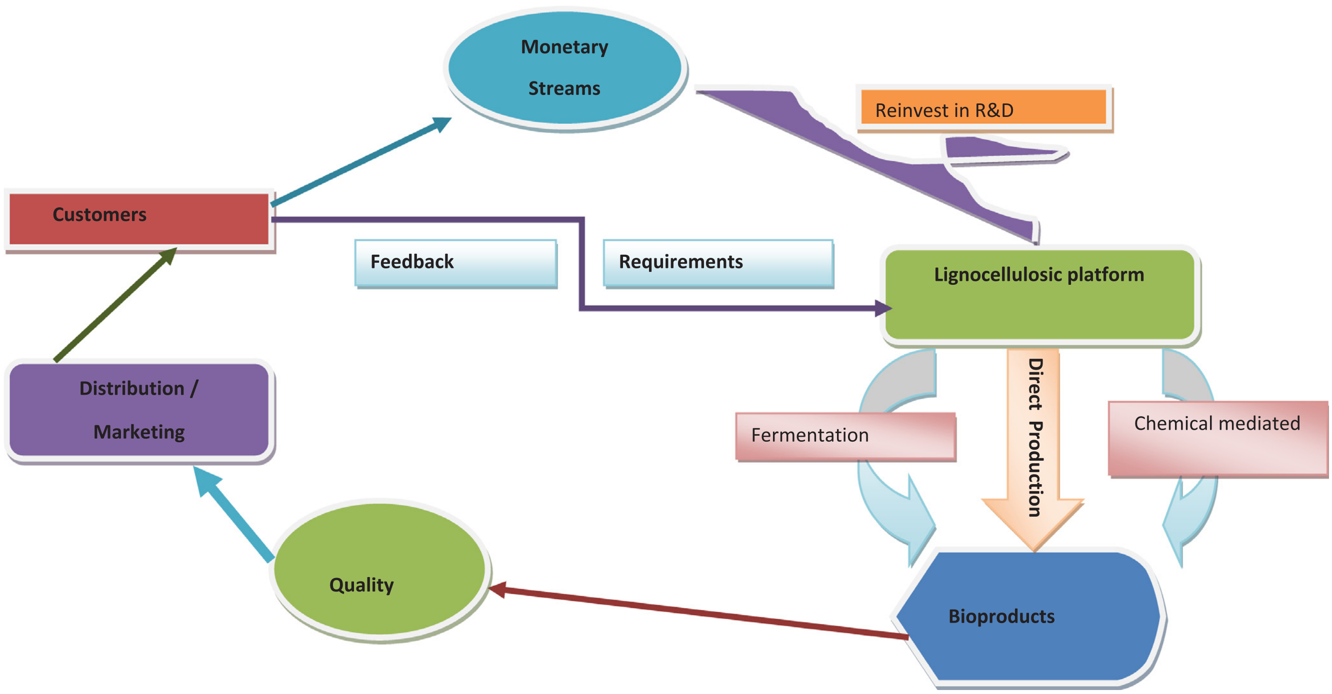

Fig. 2. Generalized business model for commercial products from lignocellulosic biomass.

Table 4
Technology Readiness Level [TRL] of some biochemicals made from biomass (Chandel and Silveira, 2017).

Compound	TRL	Market size	Market price	Theoretical market value	Manufacturers
		Kilo tone year^{-1}	USD t^{-1}	Million USD year^{-1}	
Acetic acid	8–9	1357	617	837.3	Jubilant Life Science Ltd., India, Songyuan Ji'an Biochemical, China
Lactic acid	8–9	472	1450	684.4	Chongqing Bofei Biochemical Products, China; Corbion Ltd, USA, Henan Jindan, HiSun, Wuhan, China
Levulinic acid	6–7	3	6500	19.5	Segetis Inc, MN, USA; Zibo Shuangyu Chemicals Ltd, China
Acrylic Acid	5	0.3	2688	0.8	ADM Company, IL, USA; BASF Inc, Germany
5-HMF	5	0.02	2655	0.1	AVA Biochem Ltd, Germany

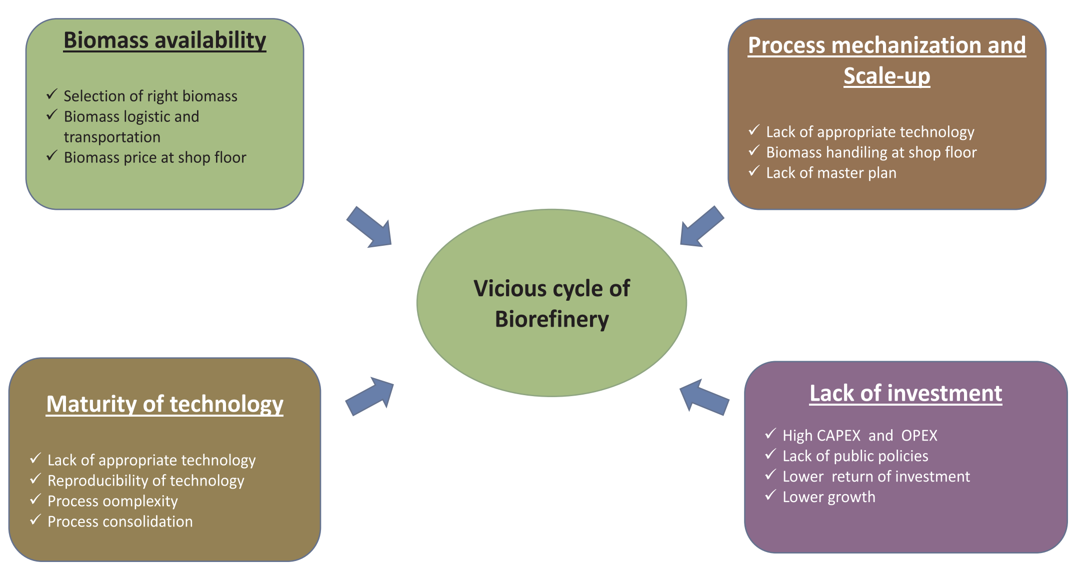

Fig. 3. Major challenges associated with lignocellulose biorefinery deployment.

2018; Valdivia et al., 2016). However, there are numerous challenges are associated with successful deployment of biorefinery operations as summarized in Fig. 3.

8.1. Biomass availability

Round the year availability of lignocellulosic biomass at competitive price is the primary concern for biorefineries to continue running the operations. Lignocellulose biorefinery may not thrive upon a single feedstock so the facility should be flexible using multiple feedstock based on the availability in the year. Countries like Brazil and USA may depend on sugarcane residues (bagasse and straw) and corn stover, respectively. Other biomass sources such as corn stover, forestry waste, energy crops, and other agro-residues can also be utilized on the basis of availability. As new biofuel policy in Brazil so called Renova Bio, is promoting to use corn for ethanol production so corn stover seems a promising feedstock for 2G ethanol production. In USA, beside corn stover, other lignocellulosic feedstock such as miscanthus, switchgrass, poplar etc. are promising feedstock for the biorefineries (Somerville et al., 2010). Approximately, 30% replacement of current petroleum consumption is possible by 2030, if all these biomass sources harnessed judiciously (Perlack and Stokes, 2011). Being the second and third largest producer of sugarcane and sizeable production of other major agricultural crops, India and China will have to explore multiple or mixed feedstock for the biofuels or biochemicals production in biorefineries (Chandel and Singh, 2011). India produced approximately 200 Mt agro-residues in 2015, which could be substantially used in biorefineries. However, a sizeable proportion of this biomass is being burnt in open fields causing dangerous air pollution. Sugarcane, corn, beet, sorghum and their lignocellulosic residues are principle fermentable sugars source in first generation and lignocellulose biorefineries, respectively. In lignocellulose biorefinery, cost of the feedstock has more than 50% share in cellulosic ethanol production (Junqueira et al., 2016). Therefore, accurate analysis of biomass availability and their costs has paramount importance in lignocellulose biorefineries.

8.2. Supply chain and transportation

Biomass supply chain in nutshell has following key steps in biorefinery: collection-storage-preprocessing-transportation-postprocessing (Sharma et al., 2013). Long-term and round the year supply of biomass to biorefineries is a critical issue. In both-localized and centralized biorefineries, an agreement between biomass (agro-residues, wood biomass, energy crops etc.) suppliers and processing units via agricultural associations required to be in place (Richard, 2010; Valdivia et al., 2016). Lignocellulose feedstock management and transportation from agricultural farm to factory are two most important cost contribution factors in the overall economics of biorefineries. According to Humbird et al. 2011, current logistics and transportation infrastructure, feedstock production cost, biomass processing and supply shares for 40–60% of the cost of biofuel production at large scale. Marvin et al., 2012 studied critical factors such as facility location, capacity and technology selection for biomass to biofuel supply chains and suggested that Renewable Fuel Standard mandates for 2015 could be met in midwestern U.S.

The primary aim of biomass logistics and transportation of bulk amount of biomass of low or high energy density is to minimize the overall transportation cost and energy/exergy input. Second-generation ethanol or biochemicals production cannot be cost competitive without massive development in biomass feedstock supply logistics, storage and transportation. Transportation cost will be high if biorefinery stays far from the biomass producing sites (Balan, 2014). These are the neglected issues which have not been taken into account with much attention while studying the operational feasibility of biorefinery. Biomass collection followed by storage and supply system logistics are the parameters which differ from one unit to another biorefinery unit. Most of the sugarcane bagasse is utilized in boiler in sugar processing units to generate heat and power. Remaining bagasse and leaves can be used in biorefineries for biofuels and biochemicals production. Processing, storage and transportation of agro-residues and energy crops have challenges to transport from harvest sites to the biorefinery sites (Miao et al., 2013). Agro-residues and grassy crops have lower bulk density (50–100 kg dry matter m^{-3}) than corn (721 kg dry matter m^{-3}), which cause major impediment in efficient feedstock supply. Miao et al., 2013 conceptualized that systems approach encompassing validated models is necessary to systemize the biomass supply chain in complete biorefinery chain. Biomass supply chains should meet the overall goal of biorefinery i.e. meeting the economic and environmental aspects eventually empowering farmers, entrepreneurs and locals (Richards, 2010).

8.3. Process mechanization and automation

Process automation and mechanization are prerequisites for the success of biorefineries. All procedural steps in biorefineries i.e. biomass handling during the pretreatment, enzyme hydrolysis, filtration, fermentation and recovery of bioproducts need to fully automated and mechanized in order to obtain the desired product yield and productivities. The important criteria in the success of petroleum refineries are the process automation, input and output flexibilities, processing capabilities and product generation. Similarly, biorefineries must have merited matching these parameters in order to get desired success at full scale operations (Fernando et al., 2006). First generation (1G) ethanol from sugarcane juice or corn grains is well established. In last one or two decades, cellulosic ethanol plants have been built in many countries. However, their full-scale operations have not attained the desired success so far due to the lack of process maturity, process automation, and mechanical hurdles for the biomass processing at large scale.

Lignocellulose biorefineries have inherently multiprocessing flow of heterogeneous material starting from first step biomass screening for pretreatment reaction to product recovery, which needs process automation and fully mechanization to get higher productivities (Parisutham et al., 2017). Furthermore, as Farzad et al. (2017) observed that sugarcane biorefineries annexed with existing sugar mills is essential to utilize full potential of sugarcane residues into cellulosic ethanol and biomass derived specialty bulk chemicals along with first generation products (1G ethanol, sugars, other byproducts), so the process automation and mechanization of overall biorefinery is utmost important (Chandel et al., 2014). Smooth transfer of lignocellulosic biomass from one step to another and pretreated slurry for filtration and then transfer to enzymatic hydrolysis and eventually movement of 2G sugar streams to fermentation with 1G stream sugars or molasses is vital to run the biorefinery under continuous fully automated operations. Biorefineries with multiproduct need process automation and fully mechanized operations enabling profitability, energy integration and product diversification. Multiproduct lignocellulose biorefineries harnessing each component of lignocellulose allows diversification of revenues which in turn reduces the risk of investment (Haro et al., 2014).

8.4. Scale up challenges

Like petroleum refinery, biorefinery is certainly a large amount of biomass processing phenomenon having scale up challenges. For the scale up of biorefinery operations, efficient processing of both cell and steel factories (manufacturing and product recovery/purification facilities with regulatory concerns) is prerequisite. The effective management of both cell and steel factories with regulatory concerns will enable product and process innovations in biorefinery (Sanford et al., 2016). Because of the magnitude and several interfaces in processing, experimental data from research laboratories or pilot scale operations may not necessarily have reproducibility at several tones biomass processing commercial biorefinery units. Development of accurate processing flow sheets, process modeling and simulation focusing on cost sensitivity analysis, life cycle assessment, forecasting and identifying risk factors play a vital role in scale up of biorefineries (Junqueira et al., 2016). To meet up the increasing demand of biobased products (3–4% growth rate per year), scale up of biorefineries is essential. However, scale up of biorefineries from laboratory or pilot scale operations is always challenging. Dammer et al., 2013 have deeply studied the current and projected global production of biochemicals and biopolymers up to 2020. Later, Choi et al., 2015 appraised the commercialization and technological status of top building block chemicals and their derivatives. Taking into consideration these studies, identification of bottlenecks and methods to overcome the challenges dealing with scale up, a good deal of effort is required. Success of biomass processing scale-up is primarily depends on the correct amalgamation of biomass feedstock with process design. For example, for sugarcane bagasse, steam explosion pretreatment has shown better results in terms of C5 sugar recovery in liquid and C6 sugars recovery in fiber. Ammonia hydroxide pretreatment has been found more successful for corn stover. Nature of biomass, biomass composition, pretreatment conditions and other factors have profound effect in scale up operations. For the scaling-up of biorefineries, factors like process integration, selection of products, clear-cut master plan, risk factors analysis, cost sensitivity analysis, safety & regulatory norms and reproducible economic modelling play pivotal role (Sanford et al., 2016). Water usage, minimized production of wastes with zero waste discharge policy and fullest utilization of equipment/manpower are critical factors in biorefinery scale-up.

8.5. Technical maturity

Peer experience from lignocellulose biorefineries has shown that technical immaturity has the main drawback in successful implementation of lignocellulosic biomass processing plants globally. Despite from numerous research efforts at laboratories, mature process deployable at commercial scale with competitive economic indicators is still not available. There is still a large gap exists between research laboratories and commercial scale operation as the parameters established at laboratories often fails when deployed at commercial scale. There is huge scope of technological improvements in each biomass processing step (pretreatment, enzyme hydrolysis, fermentation and product recovery) to be deployed at full commercial scale operations. Biomass handling at biorefinery site right from storage and transportation to the site, screening to remove dust/fine particulate and even stones and during pretreatment is a challenging task.

Pretreatment is the first step where biomass fractionation starts. Biomass from sugarcane processing mills normally has 50% moisture. In ideal conditions and to make process economic there should no preprocessing (soaking with dilute acid or alkali) which is now commonly performed to remove the sand from biomass to minimize the corrosion in pretreatment reactors and biomass transfer lines. Another challenge in pretreatment is high-pressure feeding of biomass into pretreatment reactors and then slurries for filtration or vessels for enzymatic hydrolysis. Because of the heterogenous nature of biomass slurries, pumping with high total solids concentration and desired flow rates is difficult for the smooth processing at large scale operations (Elliott et al., 2015). Pretreatment is the main step in lignocellulose biorefineries, which has maximum technical immaturity. Steam explosion with or without acid catalyst is a preferred pretreatment process of Beta renewables, Raizen, Granbio and the Sao Manoel demonstration plant of CTC-Piracicaba, Brazil. High C5 sugars recovery in liquid stream and C6 retainment in fiber has been observed along with inhibitors primarily acetic acid, formic acid and lignin derived phenolics. Continuous biomass feeding, holding of desired steam pressure for the certain time period in pretreatment vessel and control on steam loss are critical parameters during steam explosion. Commercial players in lignocellulose biorefineries such as Abengoa, Poet-DSM and Du-Pont have single-stage dilute acid, two-stage dilute acid and ammonia hydroxide-based pretreatment process respectively. Each technology has its advantages and disadvantages. As all these pretreatments require high steam and dilute acid or alkali, which is a serious economic and environmental concern.

Enzymatic hydrolysis is an inevitable step to solubilize the carbohydrate fraction present in pretreated biomass into fermentable sugars. The pretreated slurry (with or without filtration) is then send to another tank and cellulase enzyme solution are being added. In order to obtain high sugar titers from pretreated biomass, an effective cellulolytic enzyme cocktail is required to catalyze the reaction with > 20% total solids biomass loading, which is a big mechanical concern. Commercial enzyme companies such as Novozymes has developed most successful enzyme cocktail-Cellic CTec 3 and Cellic HTec 3. Other companies such as VTT, DSM, Du-Pont also have cellulases but as far as our knowledge they are not commercially supplying to other industries. In the long haul, it is necessary to have competencies among cellulase suppliers to avoid dependency on one commercial supplier. Enzymatic hydrolysis of pretreated biomass yields to fermentable sugar monomers which are readily fermented to product or other microbial product. Enzymatic hydrolysis and fermentation can also be done simultaneously and the released sugars are being utilized by microorganisms in the process so called simultaneous saccharification and fermentation or co-fermentation (SSF or SSCF). Microorganism which can utilize both sugars (pentose and hexose) will be more of practical viable to get desired fermentation yield of the product. This is difficult to find native microorganism which can thrive upon pentose and hexose sugars and give the high yield and productivity. Several genetic engineering companies such as Genomatica, Global yeast, Taurus, Xylome are into this business of developing desired biocatalyst which could be directly applied in lignocellulose biorefineries.

Product recovery or downstream processing in lignocellulose biorefineries is the area which has not been explored much and thus needs a great deal of efforts. After the fermentation of sugars, the product is recovered by distillation or centrifugation, purification and concentration, crystallization. The lignin cake is separated and sends to boilers for energy generation. Lignin cake may add the significant value in overall lignocellulose biorefineries. However, lignin cake has high energy density which is an excellent source of steam and electricity generation but it has shown several specialized applications which needs the priority research as lignin is generated in huge amount in lignocellulose biorefineries (Ragauskas et al., 2014).

8.6. Economic aspects and lack of investment

Based on the current scenario of lignocellulose biorefineries, investors don't find it attractive for return of the investment. There are several reasons for this trend for example high capital and operational expenditure (CAPEX and OPEX), dwindling price of gasoline, process uncertainty, low growth and products yield (Chandel et al., 2010).

Availability of biomass for lignocellulose biorefineries and cost is very important factor for the overall interest of investors in investing in biorefineries. Biomass costs also vary on seasonal availability, region and area. A variety of biomass feedstocks (such as agro-residues, energy crops, forestry waste and others) are basic shareholder in lignocellulose biorefinery. Cost of biomass feedstock cost to lignocellulose biorefinery includes the procuring cost from landowner, loss during storage, storage and transportation cost to biorefinery (Thorsell et al., 2004).

Processing wise, pretreatment is the primarily capital intensive representing from 30% to 50% of the total equipment cost, operational cost in pretreatment constitutes up to 20–25% of the total operational costs. In general, enzyme cost contributes up to 30% of total processing cost, which is significantly high as compared with 1G sugar which is only 3%. Both pretreatment and enzyme hydrolysis step are necessary

Fig. 4. SWOT (Strength, weakness, opportunities and threats) analysis of lignocellulose biorefinery.

for economic 2G sugars production and are considered "core" of the biorefineries. Fermentation is a central step in lignocellulose biorefineries which depends on the type of biocatalyst is being used and for which product formation. Hydrolysis and fermentation can be merged in order to develop integrated process which can substantially save the OPEX in lignocellulose biorefinery. Product recovery or downstream processing is specifically depending on the manufacturing product. In case of 1G or 2G ethanol, distillation represents between 15% and 20% of total equipment costs. The recovered lignin cake from lignocellulose biorefineries can be burnt in boilers with the value of the generated energy is \$5–10 US/ton. Lignin should be valorized to increase the return of investment in lignocellulose biorefinery.

Flow of investment should be ramp up for success of lignocellulose biorefinery as the products are renewable, green and sustainable. Partnerships at every front and level are crucial for the successful deployment of lignocellulose biorefineries near future. Partnerships in any form (joint collaboration, turn-key, technology licensing or sub-licensing, supply chain, production, service and utilities, marketing etc), continuous collaborations between technologists and final clients are pivotal for the desired success of biorefineries.

9. SWOT analysis of lignocellulose biorefinery

SWOT analysis of biorefinery assesses four important parameters i.e. internal factors such as strengths and weaknesses and external factors such as opportunities and threats from a business and strategic point of view. The results of the SWOT analysis of biorefinery are shown in Fig. 4.

Lignocellulose biorefinery has several internal strengths and weaknesses. Geopolitical factors such as climate change, de-carbonizing the fossil economy and uncertainty in availability of fossil sources have led the way to look out the search for potential alternatives while higher capital and operational investments and lacking of technical process maturity are serious weak points (Chandel and Silveira, 2017). Biorefineries have offered several promising opportunities in terms of reduction of greenhouse gasses (GHG) emissions and several major research outcome and positive interest of key chemical players in investing the biorefinery projects (IEA, 2014). However, recent failures of cellulosic production projects have shown substantial threats. In next 5 years from now on i.e. year 2023, cellulosic ethanol production plants could be maintained with the current situation. However, to give a headwind to 2G ethanol drive, more public/private investments is necessary to surpass from the ongoing early stage to next level mature technology feasible at industrial operations (Valdivia et al., 2016). However, more recently, there have been several mixed news came from cellulosic ethanol plants worldwide. For example, British Petroleum's and Abengoa have decided to come out from cellulosic ethanol business and later in early of 2018, Beta Renewable has declared to close their 2G ethanol plant in Crescentino, Italy. Recently, Dow-DuPont also has announced to close their 2G ethanol plant in Nevada, Iowa state. While, POET-DSM has recently developed a new pretreatment process and prepared for licensing the technology to interested key partners or clients. Similarly, Praj Industries from India announced to start a demonstration level 2G ethanol productions from a variety of biomass feedstock. Therefore, this is time to rethink rationally for the researchers to address the real challenges at industrial level and the same time how farmers can be benefitted by supplying feedstock to industries (Dale, 2018). Further, the author advocated for the development of low price bio-commodity rather than high value bioproducts and the higher value bioproducts should be self-sustained purely based on their own merit and not with the support from ethanol production plants.

Counting on the strong points, lignocellulose biorefineries would generate employment opportunities and income in rural areas along with cutting in GHG emissions. However, to foster the commercialization of lignocellulose biorefineries, governmental support is crucial in terms of correcting tax regime, deregulation of price of feedstock and early on subsidies (Chandel et al., 2010).

10. Conclusions

Lignocellulose biorefinery has the potential to turn out to be sustainable platform towards the bulk production of value-added products/chemicals like biofuels, PHA, bioplastics, organic acids etc. at competitive price to the end user. However, in the current scenario, full-fledged production of these renewable products at commercial scale is often difficult in conjunction with high production cost. Economic and hassle-free production of renewable 2G sugars is the cornerstone in the success of lignocellulose biorefineries. The concept "Sugar is the new oil" recognizes the potential the cost-effective transformation of recalcitrant lignocellulosic material into sugars, which is the backbone of lignocellulose biorefinery. This will be a paradigm shift in the realization of sustainable supply of bulk chemicals, materials and biofuels from lignocellulose biorefineries to the societal needs and development.

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