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Agave bagasse biorefinery: Processing and perspectives

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Abstract

Agave bagasse is the main solid waste generated by the tequila industry in Mexico, which is an environmental concern due to its considerable volume of production (377 000 Ton in 2016). Agave bagasse is a lignocellulosic biomass that has been considered as a potential feedstock for different industrial uses in the framework of a lignocellulosic biorefinery. The lignocellulosic biomass is a complex structure constituted by cellulose, hemicellulose and lignin. Therefore, for complete waste revalorization, different processing steps would be required. In this work, the scientific advances towards the agave bagasse biorefinery composed by three sequential stages: pretreatment, treatment, and biofuels production are reviewed. Moreover, the byproducts generated during the process could also be recovered and used for the synthesis of value-added products. This integrative approach of agave bagasse in the conceptualized biorefinery generates positive impacts in environment as well as in local and regional economies.

Keywords: *Biorefinery, agave bagasse, lignocellulosic biomass, byproducts, biofuels.*

1. INTRODUCTION

The blue agave (*Agave tequilana* var. Weber) is a perennial arid plant, cultivated and harvested in Mexico to produce distilled alcoholic beverages, such as tequila, since the 17th century (Murillo-Alvarado et al., 2014; Valenzuela, 2011). The agave plant requires from 8 to 12 years to maturate while it accumulates fructans in the stem (commonly called "pinecones"). In the production of tequila, the pinecones are cooked into stone or brick ovens to hydrolyze the fructans to fermentable monosaccharides. Afterwards, the cooked pinecones are grinded and pressed to extract the syrup that will be used in the downstream steps of tequila production. As by-product of the syrup extraction, a fibrous residue called agave bagasse (AB) is generated (Barrera et al., 2016). According to Cedeño-Cruz & Alvarez-Jacobs, (1991), the bagasse waste is equivalent to 40% (dry weight) of the initial mass of processed pinecones. Considering the 2016 agave consumption, reported by the Tequila Regulatory Council, the generation of bagasse for that year was equivalent to 377 000 ton (CRT 2016).

The AB is composed by three main fractions, cellulose (31-43 % w/w), hemicellulose (11-22 % w/w) and lignin (11-20 % w/w) (Arreola-Vargas et al., 2015; Corona-González et al., 2016; Iñiguez-Covarrubias et al., 2001; Perez-Pimienta et al., 2016; Saucedo-Luna, Castro-Montoya, Martinez-Pacheco, Sosa-Aguirre, & Campos-Garcia, 2011), embedded in a heterogeneous matrix. Other compounds can also be present in lower concentrations, e.g. calcium oxalate. The cellulose fraction is a glucose polysaccharide that can form two types of microfibers, amorphous and crystalline, in different ratios (Kestur et al., 2013; Montiel et al., 2016; Perez-Pimienta et al., 2013). The hemicellulose is a heterogeneous group of polysaccharides constituted by hexoses (mannose, galactose and glucose) and pentoses (xylose and arabinose) (Xuebing & Zhang, 2012). Finally, the lignin is an amorphous heteropolymer constituted by phenyl propane monomers (p-coumaryl, coniferyl and sinapyl alcohol).

To avoid environmental problems related to its improper disposal, for instance, leachates, odor generation, and atmospheric pollution, the AB has been used in different applications such as compost, fertilizer, ruminant feed, etc. (Crespo et al., 2013; Velazquez-Jimenez et al., 2013). Another interesting alternative is its incorporation into a biorefinery scheme with the aim to produce biofuels and value-added by-products.

According with the biofuel biorefinery objectives, AB with high proportion of amorphous cellulose and high content of hemicellulose is desirable since these fractions can be readily hydrolysed to soluble carbohydrates that can be used in downstream biological processes, i.e. biofuels production. However, the lignin fraction has been identified as the major barrier to such applications; thus, lignin must be removed (Hendriks and Zeeman 2009). Lignin could be separated and recovered to produce chemicals and value added products, achieving an integral revalorization of the lignocellulosic material (Cherubini 2010; Jong and Jungmeier 2015).

In this work, the scientific advances towards the AB biorefinery composed by three sequential stages: I) pretreatment, II) treatment, III) biofuels production (ethanol fermentation, dark fermentation or anaerobic digestion) are reviewed. Moreover, the technological alternatives to revalorize the byproducts generated during this three-stage biorefinery process are discussed. The AB biorefinery concept embraces various steps and byproducts as shown in Fig. 1.

2. THE AGAVE BAGASSE BIOREFINERY

A biorefinery can be a process, a plant, a facility or a cluster of facilities that integrates upstream, midstream and downstream processing of biomass into a range of valuable products (Jong and Jungmeier 2015). Different processes such as mechanical pretreatments (extraction, fractionation, separation) or chemical pretreatments (acid and alkaline hydrolysis, delignification) and thermochemical (steam explosion), and enzymatic and microbial conversions (enzymatic saccharification, fermentation, and anaerobic digestion) can be included (Sannigrahi et al. 2010; Jong and Jungmeier 2015). It is worth to mention that a well-developed biorefinery system must be economically driven based on innovative and cost-effective use of biomass to produce both biobased products and bioenergy. In addition, it should contribute to the reduction of greenhouse gas emissions and minimize the generation of waste materials (Jong and Jungmeier 2015).

The agave bagasse biorefinery includes the transformation of bagasse organic matter to biofuels along with the recovery of value-added by-products (i.e. lignin derivatives, volatile fatty acids, residual fibers). This review includes the three main steps shown in Fig. 1; the first stage consists in the conditioning and pretreatment of the raw material with the objective to remove lignin and prepare it for the polysaccharide hydrolysis. In the second stage, hydrolysis or saccharification, the solubilization of the cellulose and

hemicellulose with acid or enzymatic treatments take place. The objective of this step is the production of a liquid fraction rich in fermentable sugars called hydrolysate. In the last step, the hydrolysate can be used in three main biological processes to produce biofuels: hydrogen by dark fermentation (Contreras-Dávila et al., 2017), methane by anaerobic digestion (Arreola-Vargas et al., 2016) and ethanol by alcoholic fermentation (Caspeta et al. 2014). The generated residues (i.e. lignin, residual fibers, and VFA) throughout the bagasse processing, can be used in different industrial applications that will be reviewed in following sections.

3. CONDITIONING AND PRETREATMENTS

3.1 Agave bagasse conditioning

Previous to the use of AB for biofuels production, the AB fibers must be rinsed with water to remove soluble compounds formed during the cooking process of pinecones (Perez-Pimienta et al. 2015; Corona-González et al. 2016). Thereafter, the AB fibers must be partially reduced in size (0.5-15 mm) to enhance the pretreatment efficiency (Perez-Pimienta et al. 2013; Arreola-Vargas et al. 2015b; Corona-González et al. 2016; Montiel et al. 2016; Velázquez-Valadez et al. 2016). The particle size of lignocellulosic biomass is considered as an important factor that impacts the process efficiency (the smaller the size particle the better process efficiency); however, it is important to note that grinding of the material to small sizes is an energy-intensive process that increases the cost of the process (Li et al. 2015). Therefore, a full economical evaluation of the pros and constrains of size reduction should be carried out.

3.2 Delignification pretreatment

The lignocellulosic biomass is a highly recalcitrant material, i.e. biomass is hardly biodegradable by microorganisms and/or enzymes mainly due to the presence of lignin; thus, a pretreatment for its removal will be generally required (Zhu et al. 2008; Perez-Pimienta et al. 2013; Li et al. 2016). In the delignification pretreatment, the biomass is swelled and the lignin structure gets disrupted and solubilized (Zhu et al. 2008). As a result, the hemicellulose and the cellulose microfibrils become more accessible to enzymes or microorganisms in subsequent stages (Saini et al. 2016).

A universal pretreatment is difficult to envision given the diverse nature of lignocellulosic residues. In this regard, different delignification pretreatments have been suggested during the last years (Table 1). These can be classified into biological, chemical and physico-chemical pretreatments (Alvira et al. 2010).

In the case of AB, mainly physical, chemical, and physico-chemical pretreatments have been applied, including autohydrolysis, thermo-mechanic-chemical process, ammonia fiber expansion (AFEX^{TM}), ionic liquids, ozonolysis, and acid hydrolysis (Perez-Pimienta et al. 2013, 2016; Ávila-Lara et al. 2015; Barrera et al. 2016; Montiel et al. 2016; Rios-González et al. 2017). In these pretreatments, hemicellulose is depolymerized and solubilized, while a small fraction of the lignin is dissolved (Saucedo-Luna et al. 2011; Perez-Pimienta et al. 2016). However, in the AB biorefinery, the aim is to apply a selective pretreatment to remove lignin with minimal effects in the hemicellulose fraction. In this sense, organosolv, alkaline and oxidative-alkaline pretreatments have advantages that have already been evaluated in AB.

The organosolv pretreatment consists in the extraction of lignin with organic solvents including methanol, ethanol, ethylene glycol, glycerol, etc. (Taherzadeh and Karimi 2008; Zhao et al. 2009). Pérez-Pimienta et al. (2017) used organosolv to remove lignin for ethanol production using 25 g bagasse with 500 mL of solution (74.5% water, 25% ethanol and 0.5% H_2SO_4). The experiment was carried out into a high-pressure chemical reactor (160 ° C and 138 psi) for 10 min. In this work, delignification yields of 45% with a loss of xylan of 86% were reported (Pérez-Pimienta et al. 2017). The organosolv pretreatment has the advantage of allowing solvent recovery to be re-used, which makes it a cost-effective process (Carvajal et al. 2016); however, the delignification yields are generally low (Pérez-Pimienta et al. 2017).

Alkaline pretreatment has also been used for the delignification of bagasse of *Agave atrovirens*, another species of the genus *Agave* (Hernández-Salas et al. 2009). In this hydrolytic pretreatment, the authors used an alkali solution of NaOH (2% w/v) at 121 °C by autoclaving at 1.1 kg/cm^2 for 4 h, although the delignification yields were not reported. With rice straw, other authors reported delignification yields of 28.4% using an alkali solution of NaOH (6% w/v) (He et al. 2008). Moreover, He et al. (2008) argued that, in such pretreatment, the ester bonds between lignin and carbohydrate complexes are broken, releasing cellulose and hemicellulose to further utilization.

The alkaline-oxidative pretreatment is another process that has been used to treat AB (Velázquez-Valadez et al. 2016). This pretreatment consisted of two sequential steps. The first one was an alkaline pretreatment employing a 6% (w/v) NaOH solution in a ratio of 1:5 with respect to the bagasse solids. This mixture was autoclaved at 120° C and 2 atm for 1 h. Subsequently, an oxidative pretreatment was performed by adding 6% (w/v) H_2O_2 to the aforementioned mixture, maintaining the initial solid-liquid ratio, at 30 °C for 24 h. In this pretreatment, the H_2O_2 decomposes into more active radicals such as hydroperoxyl (•OOH), hydroxyl (•OH) and superoxide (O_2-•) (Sun et al. 2002; Wilkinson et al. 2014). These radicals disrupt the ether and ester bonds between the subunits of lignin and hemicellulose, which causes the lignin solubilization. The delignification yield with this method was 82.6%, while only 3.8% of the structural carbohydrates were released (Velázquez-Valadez et al. 2016). Important constrains of this process is the use of high amounts of reagents and energy, which make it a relatively expensive process. In this regard, Su et al. (2015) improved the oxidative process by using only 2% (w/v) H_2O_2 at 50 °C and pH 11.5, for 1.5 h. Under such conditions, these researchers reported a lignin removal efficiency of 74% from corncob. This study makes evident that the oxidative pretreatment can be optimized to use less reagents, while keeping good delignification yields. In addition, it is worth to note that the waste generated in this process is considered environmentally friendly (e.g. use of less hazardous reagents). Therefore, the alkaline-oxidative pretreatment seems to be an excellent option to implement in a biorefinery of AB from the efficiency point of view, although further studies are needed to optimize this process.

3.3 Lignin revalorization

The solubilized lignin obtained in the pretreatment of AB can be concentrated to obtain lignin powder. Its properties will depend on the origin and the type of the pretreatment process. For instance, as result of oxidative pretreatment, lignin can be fragmented into monophenolic compounds (Ouyang et al. 2014). The lignin precipitation from the aqueous phase can be done by concentrating it (previously diluted with ethanol to remove impurities) and adjusting its pH to 1.5 (Su et al. 2015). Lignin possesses structural features that can make it a promising starting material that enables its further revalorization into value-added products (Stewart 2008).

According with the results reviewed previously, in the oxidative pretreatment, up to 112 kg of lignin/ton bagasse can be obtained. However, despite the enormous research efforts, the feasibility of the conversion of lignin to value-added products has yet to be established (Zhou et al. 2016). In fact, vanillin is currently the only molecular phenolic compound manufactured at industrial scale from softwood lignin (Fache et al. 2016). Nevertheless, the formation of vanillin and other compounds is strictly linked to the available percentage of its precursor in the lignin structure (Silva et al. 2009). Lignin from softwoods (gymnosperms) is predominantly based on structural units derived from the coniferyl alcohol (guaiacyl units), which are the precursors for vanillin. However, in herbaceous (angiosperm) plants, such as Agave, lignin is constituted not only by guaiacyl units, but also by sinapyl alcohol (syringyl units) and p-coumaryl alcohol (4-hydroxyphenyl units) (Zhou et al. 2016). Therefore, applications of herbaceous lignins for vanillin production may be limited.

Kalliola et al. (2015) reported that oxidized lignin have a potential as a renewable plasticizer in cement-containing products, such as concrete, because it has the ability to endure under alkaline conditions, and it does not introduce air in concrete. Oxidized lignins may provide a sustainable and techno-economically feasible option for future plasticizer technology. Lignin recovered from the oxidative pretreatment of AB could be used in this developing application.

4. TREATMENTS

The treatment of agave bagasse to obtain fermentable sugars is an essential step in the biorefinery since it can substantially increase the biological availability of the substrate and reduces the processing time. In this regard, saccharification of AB with chemical (acid hydrolysis) and biological (enzymatic hydrolysis) treatment has been evaluated.

4.1 Acid hydrolysis

The acid hydrolysis consists in the conversion of lignocellulosic biomass into monosaccharides and oligosaccharides; however, the saccharification efficiency depends on the severity of the hydrolysis conditions (temperature, reaction time and acid concentration). In general, there are two types of acid hydrolysis, diluted and concentrated, being the first one the most implemented due to its highly efficient hemicellulose depolymerization (mainly xylan) and low cost (Jiang et al. 2016). However, at high

temperatures and pressures, the carbohydrates can be degraded into furfural and hydroxymethylfurfural (HMF) (Mussatto and Roberto 2004); which may affect the microbial metabolism in the fermentation step (Saha 2004). Thus, this aspect has to be carefully considered in a biorefinery scheme.

Using AB, acid hydrolysis treatment has been tested and optimized by Saucedo Luna et al. (2010) in two sequential batch stages. In the first stage, the optimal conditions were 151°C, 2% of sulphuric acid for 10 min of reaction. In second stage, the optimal experimental conditions were 175 °C, 2% of sulphuric acid and 30 min of reaction. The total fermentable sugars yield from the overall process was 326 g/kg dry matter, which represented 48.5% of the theoretical value. In recent years, the acid hydrolysate of AB has been used for hydrogen and methane production. In these cases, HCl has been used instead of H_2SO_4 to avoid the sulphate-reduction processes (Arreola-Vargas et al. 2015b). Arreola-Vargas et al. (2015) reported a total sugar concentration of 27.9 g/L and HMF concentration up to 1,2 g/L using 2.7% of HCl at 123.6 °C for 1.3 h of reaction.

4.2 Enzymatic hydrolysis

Enzymatic hydrolysis of lignocellulosic substrates requires several enzyme types working in synergy, such as cellobiohydrolases (exo-glucanases), endo-glucanases, β-glucosidases, endo-xylanases, etc. In contrast to other treatment processes, the enzymatic process has the main advantage of high specificity; consequently, it does not produce by-products. Nevertheless, nowadays it is not economically viable because of the high enzymatic cost, slow time of reaction, and high quantities of enzyme required. Nonetheless, some studies have explored different solutions to cope these constraints (Montiel et al. 2016).

The enzymatic hydrolysis of AB has been used after pre-treatment as well as without pre-treatment. Table 2 shows some results of enzymatic hydrolysis of agave bagasse after pre-treatment reported form the literature. Regarding to enzymatic hydrolysis without any pre-treatment, Contreras-Davila et al. (2017) reported hydrolysis using an enzymatic preparation (Celluclast 1.5 L) at pH 4.5, 100 rpm and 45°C for 10 h obtaining about 12.5 g total sugars/L. Arreola-Vargas et al. (2016) studied the enzymatic hydrolysis using Celluclast 1.5 L at pH 4.5 and 45 °C for 10 h, and 8.9 g total sugar/L, 328.7 mg phenols/L were obtained. In accordance with literature, the enzymatic hydrolysis has a promising potential towards the revalorization of AB residues, though optimization of enzymatic cocktails has to be further studied.

4.3 Fibre uses

The residual fibre of the different pre-treatments has been studied for several applications, for example, absorbent of contaminants such as Cd(II), Pb(II) and Zn(II) ions from water (Velazquez-Jimenez et al. 2013), compostable and biodegradable composites (Kestur G. et al. 2013; Torres-Tello et al. 2017), and to elaborate cellulose hydrogel films (Tovar-Carrillo et al. 2013, 2014). All of these alternatives could improve the energy and economical balance of the integrated process of AB biorefinery.

5. BIOFUELS

The hydrolysate of AB is considered as an ideal feedstock for biofuels production since they are generally composed by a mixture of glucose and xylose (Arreola-Vargas et al. 2016a; Pérez-Pimienta et al. 2017). Anaerobic microorganisms, some of which can readily convert it into a wide range of energy sources, easily metabolize these sugars. Due to their economic potential, level of research, and technology status, this review is focused on the alcoholic fermentation (AF), dark fermentation (DF) and anaerobic digestion (AD).

Among these bioprocesses, the AF is the partial oxidation of carbohydrates that leads to the ethanol production and is commonly carried out by yeasts, mainly *Saccharomyces cerevisiae*. AF is the most mature and industrialized technology for biofuel production (bioethanol) in comparison with DF and AD. The DF is the partial oxidation of carbohydrates to volatile fatty acids (VFA), mainly acetate and butyrate, with the concomitant production of molecular hydrogen (H_2). This process is carried out by acidogenic microorganisms (e. g. *Clostridiaceae* and *Enterobacteriaceae* families). Finally the AD continues with the consumption of H_2 and acetate by hydrogenotrophic and acetoclastic methanogens, respectively. The metabolic pathways for these biotransformations are summarized in Fig. 2.

5.1 Ethanol from agave bagasse

AF of food crops (e.g. sugarcane or corn) has established as the main and one of the most developed alternatives for biofuels production worldwide. In 2015, the global production of fuel ethanol was above 97.2 x 10^6 m^3, being the USA (57%) and Brazil (27%) the leading producers (RFA 2017). Thus, the AF infrastructure is well known and it is relatively easy to adapt for second-generation ethanol production from

lignocellulosic hydrolysates.

Conversion of glucose to ethanol can be performed by *S. cerevisiae* with high efficiency of conversion. However, when non-model substrates such as AB hydrolysates are used as carbon source, the fuel production and energy yields can be affected (Table 3). Caspeta et al. (2014) used enzymatic hydrolysates of organosolv pretreated AB (12.4 $g_{Glucose}$/L) for ethanol production with *S. cerevisiae* and reached a maximum glucose conversion into bioethanol of 96%.The 64 g/L of ethanol obtained from the saccharification at 20% w/w organosolv pretreated solids of AB is the highest ethanol concentration reported for this lignocellulosic material. Overall the potential conversion of AB to fuel ethanol was 0.25 g/g, which is 85% of the maximum theoretical.

The main limitation of ethanol production processes is the presence of pentoses in lignocellulosic hydrolysates (e.g. xylose) since *S. cerevisiae* is not capable to transform them to ethanol; for this reason, researchers have explored the potential of other microorganisms. For example, Saucedo-Luna et al. (2011) used the native yeast *Pichia caribbica* UM-5 to ferment sugars (hexoses and pentoses) produced from acid and enzymatic hydrolysates. The final optimized process generated 8.99 g ethanol/50 g of AB, corresponding to an overall 56.75% of theoretical ethanol (w/w) (Saucedo-Luna et al. 2011).

In the same way, Pérez-Pimienta et al. (2017) evaluated ethanol production using a sequential enzymatic saccharification and fermentation of ionic liquid and organosolv pretreated AB with cellulolytic enzymes and the ethanologenic *Escherichia coli* strain MS04. This process achieved a conversion of 90% and 84% of glucan and xylan respectively for ionic liquid pretreatment bagasse, and 93% and 90% of glucan and xylan respectively for organosolv pretreatment bagasse. Ethanol production yields were 12.1 and 12.7 kg per 100 kg of untreated AB, with ionic liquid pretreatment and organosolv pretreatment respectively. Another alternative is the genetic modification of microorganisms to give them the capability to process pentoses, for instance, *E. coli* has been genetically modified in order to produce ethanol from pentose; nevertheless, implementation of ethanol production using modified microorganism represents high cost attributed to aseptic conditions (Ingram et al. 1987).

Other microorganism that can use xylose and glucose as carbon source for ethanol production is *Scheffersomyces stipitis* (formerly known as ***Pichia stipites***). ***Nakasu et al. (2016)*** used *S. stipitis* to study the ethanol production from xylose-enriched hemicellulose hydrolysate of sugarcane bagasse. They studied several pretreatments conditions, and found a maximum xylose conversion of 97.3% when sulfuric acid was used as pretreatment. In terms of ethanol production, they found a maximum ethanol concentration of 10.6 g/L, with a fermentation yield close to 60% with 33.5 g xylose/L. Interestingly, the authors showed that the presence of inhibitors (e.g. acetic acid, phenolic compounds, furfural, and others) precluded the ethanol production. Therefore, low generation of these inhibitory compounds or its previous detoxification is an important step of the AF process (see section 5.4 Inhibitors). In this regard, ethanol yields are dependent of pre-treatment and hydrolysate conditions. When xylose is found at high proportion, the ethanol yield is affected and decreases about 80% of the theoretical value (Olsson and Hahn-Hägerdal 1996; Nigam 2001; Klinke et al. 2004).

5.2 Hydrogen by dark fermentation

Hydrogen (H_2) production by DF is considered as a promising biotechnology that can be a central keystone towards the establishment of lignocellulosic biorefineries. The H_2 produced herewith can be highlighted by two principal reasons: its high energy content (120 kJ/g) and its high-efficient conversion to electricity. DF has been extensively explored in multiple reactor configurations, different substrates, inocula and operational conditions (Nissilä et al. 2014; Barca et al. 2015; Ghimire et al. 2015; Ren et al. 2016). In the last decade, DF started to be considered as part of a revalorization chain of lignocellulosic residues. In this sense, substrates such as sugarcane bagasse, oat straw, and AB have been investigated (Monlau et al. 2013).

Particularly, the use of AB for hydrogen production has been scarcely reported thus far. In batch experiments, Arreola-Vargas et al. (2016) used acid and enzymatic hydrolysates of *Agave tequilana* at different concentrations of 20-100% (v/v). They found that the highest H_2 production rate was obtained with 40% (v/v) enzymatic hydrolysates and it was equivalent to a volumetric hydrogen production rate (VHPR) of 2400 mL H_2/L-d. In contrast, when the acid hydrolysates were used, the H_2 production rate was limited by the increasing concentration of inhibitory compounds (see section 5.4). On the other hand, in continuous mode,

Contreras-Dávila et al. (2017) reported a maximum VHPR of 2530 mL H_2/L-d with a CSTR operated at an organic loading rate (OLR) of 52.2 g COD/L-d using enzymatic hydrolysates of AB. They also found that a notably higher productivity could be achieved with a trickling bed reactor (TBR). Using the TBR configuration, they found a maximum VHPR of 3450 mL H_2/L-d, at an OLR of 52.9 g COD/L-d.

In comparison with other lignocellulosic materials (Table 3), AB hydrolysates have demonstrated to be a feasible feedstock for hydrogen production. Nevertheless, there are important challenges in the DF systems that must be solved in order to improve the rate and efficiency of the H_2 production. In this regard, three important constraints are: 1) endogenous H_2 consumption, 2) incomplete substrate utilization and 3) presence of inhibitory compounds. Endogenous H_2 consumption is considered as any H_2 utilization either direct (i.e. molecular H_2) or indirect (i.e. NADH, Fd, and others) in the fermentation reactor that leads to the synthesis of different metabolites (e.g. propionate, ethanol, lactate, etc.) with inherent inefficiency of the process. Hereof, the metabolic diversification can be minimized with proper control of pH, OLR, temperature, etc. (Ghimire et al. 2015). The incomplete utilization refers to the fact that DF can only aim to a maximum hydrogen recovery of 4 molH_2/mol hexose which is only one third of the energy content in hexose-type carbohydrates. Therefore, it is necessary to use the DF effluents as feedstock for other biotechnologies such as electrochemical systems (H_2), photofermentation (H_2) and AD (CH_4) to enhance the energy recovery. Other alternatives to revalorize the DF residues are depicted in the following section. The third potential drawback of DF is its sensitivity to inhibitory compounds (e.g. Furfural, HMF, phenols, formic acid, etc.) which could result from aggressive treatment (Monlau et al. 2014). Thus, the implementation of a previous detoxification steps (briefly described in the next section) is probably required.

Although DF is considered as a promising alternative for the production of hydrogen energy, the current status of the technology suggests that further evaluation, especially at the large scale, is still necessary. Up to date, successful operation of pilot-scale reactors have only been carried out for a limited number of waste materials, i.e. as molasses (Ren et al. 2006) and food wastes (Licata et al. 2011; Sekoai and Gueguim Kana 2014; Elsamadony and Tawfik 2015). To the best of our knowledge, no studies of hydrogen production from AB or other lignocellulosic wastes in pilot- or full-scale have been conducted so far.

5.2.1 Dark fermentation byproducts

An important drawback of hydrogen production by DF is that most of the substrate entering the system is transformed to partially oxidized compounds, mainly volatile fatty acids (VFA). Thus, the feasibility of the AB biorefinery is expected to depend on the proper utilization or valorization of such effluents. The composition of DF effluents will change as function of the operational conditions, type of inoculum, and intrinsic characteristics of the hydrolysate. From AB enzymatic hydrolysates, literature reports have shown that acetic and butyric acid account for more than 80% of VFA produced in DF (Arreola-Vargas et al. 2016a; Contreras-Dávila et al. 2017). Considering such composition, the use of DF effluents as substrate for polyhydroxyalkanoates (PHA) production can be an attractive alternative that can also be coupled to additional H_2 production (Venkata Mohan et al. 2010; Venkateswar Reddy et al. 2014; Sarma et al. 2015; Cardeña et al. 2017). Nevertheless, the PHA production from dark fermentation effluents is still considered as a young technology that requires important efforts towards its use in the AB biorefinery.

5.3 Biogas

The biogas production by AD consists of four steps namely hydrolysis, acidogenesis, acetogenesis and methanogenesis (Fig. 2). It is an attractive process to integrate into a biorefinery framework that is gaining attention worldwide. Biogas production from lignocellulosic materials has an important approach due to carbon neutral concept. Furthermore, it can reduce more than 90% of organic matter of the bagasse/lignocellulosic waste, therefore it also contributes to reduce the associated pollution which is an environmental concern. Another important fact is that nowadays the feedstock of AD does not have a significant value as it is considered a residue from other processes.

Biogas can be produced all around the world, since it does not depends on the geographical position or weather conditions of each region. Besides, biogas is a stable process that is already working at full scale. For example, Dussadee et al. (2014) achieved an energy production of 343680 MJ/d. Actually, biogas facilities have gained attention as integral part of biorefineries, while biomethane/biogas plants have increased constantly around the world. Until 2015, in Europe existed 459 biogas plants (European Biogas Association) while in Mexico there were 16 biogas plants (SENER 2016).

In the biorefinery of AB, the pre-treated bagasse could be used for energy recovery in the form of biogas (Table 4). For example, Arreola-Vargas et al. (2015) achieved a biogas yield of 0.26 L/g COD and a biogas

production rate of 0.3 L/L-d from acid hydrolysates of AB in an ASBR with a OLR of 1.3 g COD/L-d. On the other hand, Hassan et al. (2016) achieved a biogas yield of 0.32 L/g VS in a digester with 5% TS feed with corn stover hydrolysates .

One of the most important problems of the AD is the acidification of the medium due to the VFAs accumulation, which causes the methanogenesis inhibition (Akuzawa et al. 2011). This problem arises for substrates with high carbohydrate content such as the case of AB hydrolysates. However, increasing the buffering capacity, adding alkali, regulating the OLR or lowering the substrate concentration can easily solve the inconvenient. Another potential problem of AD is the lack of important nutrients (e.g. N-compounds) in the biomass (e.g AB). This is of special relevance since the biogas production is strongly affected by the C/N ratio (Hassan et al. 2016a). For this problem, Alatriste-Mondragón et al. (2006) suggested the co-digestion of substrates (e.g. bagasse hydrolysate or DF effluent) with other high N-content residues that each industry in particular produce (e.g. sewage sludge or wastewater) allowing the nutrient balancing (e.g. ratio C/N) and besides, this strategy improve the biogas yield.

5.4 Fermentation inhibitory compounds

In general, fermentation inhibitors could be produced during the hydrolysis of AB, especially in the acidic hydrolysis, as result of the degradation of carbohydrates (Larsson et al. 1999). The presence of these compounds (e.g. 5-HMF, furfural, vanillin, syringaldehyde, acetic acid, formic acid, etc.) have different grade of constraints in AF and DF.

In the case of AF, Klinke et al. (2004) reported yields about 40 mg EtOH/g carbohydrate when acetic acid and Furfural/ 5HMF were in concentrations of 9 g/L and 1 g/L, respectively. They observed that after the inhibitors removal, the ethanol yields increased 80-90%. Nakasu et al. (2016) studied the ethanol production under high concentrations of inhibitors (4 g/L furfural). They found that *S. cerevisiae* could metabolize furfural, but the process does not stimulate ethanol production due to furfuryl-alcohol formation. In fact, ethanol production decreased to half of the initial value (about 50 %). For the case of DF, Lin et al. (2015) recently reported that furan derivatives and phenolic compounds at 15 mM decreased the H_2 yield and production rate in 4-15% and 20-44%, respectively. Quéméneur et al. (2012) performed a series of experiments to determine the inhibitory effects of furan derivatives, phenolic compounds and lignin (concentration, 1g/L each) on the hydrogen production performance. They found major impacts of furan

derivatives (69-76% lower hydrogen yield than control) in comparison with phenols (17-23 % lower hydrogen yield than control). In terms of hydrogen production potential, they reported that HMF, furfural, vanilline, phenol and syringaldehyde decreased the amount of hydrogen obtained as compared to the xylose control (1367 mL/L) by 82, 82, 67, 65, and 23%. In another study, Siqueira and Reginatto (2015) studied the effect of different concentrations of inhibitory compounds (organic acids, furan derivatives, and phenolic monomers) on the hydrogen production rate. They observed that the concentrations of inhibitors that reduced by half the maximum hydrogen production rate (IC50) were 0.38, 0.48, 0.62, 0.71, 1.05, and 5.14 g/L for 4-hydroxybenzoic acid, HMF, furfural, vanillin, syringaldehyde, and acetic acid, respectively.

In the case of AB, Arreola-Vargas et al. (2016) reported appreciable concentrations of total phenols (941.6 mg/L), 5-HMF (95.8 mg/L), and furfural (33.1 mg/L) in acid hydrolysates. These concentrations limited the utilization of the hydrolysate in the biological production of H_2 in two-stage processes. Specifically, authors found that H_2 production rate decreased by 85% when the concentration of hydrolysate reached 100% in comparison with the maximum rate of 35 mL H_2/h found at 20% hydrolysate.

Concerning the effects of these compounds on the anaerobic digestions, Barakat et al. (2012) reported that they cause no inhibition of the process; rather, the presence of such byproducts can increase the methane production. Similarly, Ghasimi et al. (2016) reported that concentrations of 0.8 g/L of furfural and HMF slightly decreased the rate of methane production, but the methane production was similar. At a concentration of 2 g/L, furfural and HMF strongly inhibited the methanogenesis process. Using AB hydrolysates, Arreola-Vargas et al. (2016) reported that the methane production rate decreased from 12.5 mL CH_4/h to 2.5 mL CH_4/h when the hydrolysate concentration changed from 20 to 100% i.e. 2200, 7700, 941.6, 95.8, and 33.1 mg/L for formic acid, acetic acid, total phenol, HMF, and furfural, respectively.

As alternative, inhibitory molecules could be removed through different strategies such as adsorption onto activated carbon (Chandel et al. 2007; Lee and Park 2016; Saini et al. 2016; Sambusiti et al. 2016), ion exchange (Gao and Rehmann 2016; Chen et al. 2017), enzymatic treatment (Saravanakumar et al. 2016), and combined approaches (Vallejos et al. 2016). In an interesting investigation, Gupta et al. (2016) evaluated different inhibitory abatement methods and found that the use of activated carbon was the most suitable for

the process. In addition, they also showed the feasibility of the strategy at a pilot scale. However, optimization is required to minimize the carbohydrates adsorption on the activated carbon.

6. CONCLUSIONS AND REMARKS

The AB biorefinery is a conceptual approach towards the full revalorization of the residual lignocellulosic biomass produced in one of the most representative industries in Mexico. In general, the route depicted in this review resulted to be the most suitable due to delignification yields (oxidative pretreatment), saccharification yield (enzymatic hydrolysis) and energy recovery (dark fermentation → anaerobic digestion). Moreover, along the proposed route, byproducts generated can be used in several applications (cement production, adsorbent materials, bioplastics, etc.). Overall, the AB biorefinery is an opportunity to revalorize a residue and obtain energy and valuable products through a sustainable process.

However, there are still important aspects to be considered. Such is the case of separation and purification technologies as well as storing and transportation issues. Although these topics were not discussed in this review, they play relevant roles in the overall techno-economical balance of the biorefinery. Special attention is being gained by the separation of H_2 from CO_2 as well as the dehydratation of ethanol.

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8. CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

9. REFERENCES

Akuzawa M, Hori T, Haruta S, et al (2011) Distinctive Responses of Metabolically Active Microbiota to Acidification in a Thermophilic Anaerobic Digester. Microb Ecol 61:595–605. doi: 10.1007/s00248-010-9788-1

Alatriste-Mondragón F, Samar P, Cox HHJ, et al (2006) Anaerobic Codigestion of Municipal, Farm, and Industrial Organic Wastes: A Survey of Recent Literature. Water Environ Res 78:607–636. doi: 10.2175/106143006X111673

Alvira P, Tomás-Pejó E, Ballesteros M, Negro MJ (2010) Pretreatment technologies for an efficient

bioethanol production process based on enzymatic hydrolysis: A review. Bioresour Technol 101:4851–4861. doi: 10.1016/j.biortech.2009.11.093

Arreola-Vargas J, Alatriste-Mondragón F, Celis LB, et al (2015a) Continuous hydrogen production in a trickling bed reactor by using triticale silage as inoculum: effect of simple and complex substrates. J Chem Technol Biotechnol 90:1062–1069. doi: 10.1002/jctb.4410

Arreola-Vargas J, Celis LB, Buitrón G, et al (2013) Hydrogen production from acid and enzymatic oat straw hydrolysates in an anaerobic sequencing batch reactor : Performance and microbial population analysis. Int J Hydrogen Energy 38:13884–13894.

Arreola-Vargas J, Flores-Larios A, González-Álvarez V, et al (2016a) Single and two-stage anaerobic digestion for hydrogen and methane production from acid and enzymatic hydrolysates of Agave tequilana bagasse. Int J Hydrogen Energy 41:897–904. doi: 10.1016/j.ijhydene.2015.11.016

Arreola-Vargas J, Jaramillo-Gante NE, Celis LB, et al (2016b) Biogas production in an anaerobic sequencing batch reactor by using tequila vinasses: Effect of pH and temperature. Water Sci Technol 73:550–556. doi: 10.2166/wst.2015.520

Arreola-Vargas J, Ojeda-Castillo V, Snell-Castro R, et al (2015b) Methane production from acid hydrolysates of Agave tequilana bagasse: Evaluation of hydrolysis conditions and methane yield. Bioresour Technol 181:191–199. doi: 10.1016/j.biortech.2015.01.036

Arriaga S, Rosas I, Alatriste-Mondragón F, Razo-Flores E (2011) Continuous production of hydrogen from oat straw hydrolysate in a biotrickling filter. Int J Hydrogen Energy 36:3442–3449. doi: 10.1016/j.ijhydene.2010.12.019

Ávila-Lara AI, Camberos-Flores JN, Mendoza-Pérez JA, et al (2015) Optimization of alkaline and dilute acid pretreatment of Agave bagasse by response surface methodology. Front Bioeng Biotechnol 3:1–10. doi: 10.3389/fbioe.2015.00146

Badshah M, Lam DM, Liu J, Mattiasson B (2012) Use of an Automatic Methane Potential Test System for evaluating the biomethane potential of sugarcane bagasse after different treatments. Bioresour Technol 114:262–269. doi: 10.1016/j.biortech.2012.02.022

Barakat A, Monlau F, Steyer JP, Carrere H (2012) Effect of lignin-derived and furan compounds found in lignocellulosic hydrolysates on biomethane production. Bioresour Technol 104:90–99. doi: 10.1016/j.biortech.2011.10.060

Barca C, Soric A, Ranava D, et al (2015) Anaerobic biofilm reactors for dark fermentative hydrogen production from wastewater: A review. Bioresour Technol 185:386–398. doi: 10.1016/j.biortech.2015.02.063

Barrera I, Amezcua-Allieri MA, Estupiñan L, et al (2016) Technical and economical evaluation of bioethanol production from lignocellulosic residues in Mexico: Case of sugarcane and blue agave bagasses. Chem Eng Res Des 107:91–101. doi: 10.1016/j.cherd.2015.10.015

Cardeña R, Valdez-Vazquez I, Buitrón G (2017) Effect of volatile fatty acids mixtures on the simultaneous photofermentative production of hydrogen and polyhydroxybutyrate. Bioprocess Biosyst Eng 40:231–239. doi: 10.1007/s00449-016-1691-9

Carvajal JC, Gómez Á, Cardona CA (2016) Comparison of lignin extraction processes: Economic and environmental assessment. Bioresour Technol 214:468–476. doi: 10.1016/j.biortech.2016.04.103

Caspeta L, Caro-Bermúdez MA, Ponce-Noyola T, Martinez A (2014) Enzymatic hydrolysis at high-solids loadings for the conversion of agave bagasse to fuel ethanol. Appl Energy 113:277–286. doi: 10.1016/j.apenergy.2013.07.036

Cedeño-Cruz M, Alvarez-Jacobs J (1991) Production of tequila from agave: historical influences and contemporary processes. alcohol Textb a Ref beverage, fuel Ind alcohol Ind 225–242.

Chandel AK, Kapoor RK, Singh A, Kuhad RC (2007) Detoxification of sugarcane bagasse hydrolysate improves ethanol production by Candida shehatae NCIM 3501. Bioresour Technol 98:1947–1950. doi: 10.1016/j.biortech.2006.07.047

Chen K, Hao S, Lyu H, et al (2017) Ion exchange separation for recovery of monosaccharides, organic acids

and phenolic compounds from hydrolysates of lignocellulosic biomass. Sep Purif Technol 172:100–106. doi: 10.1016/j.seppur.2016.08.004

Cheng HH, Whang LM, Chung MC, Chan KC (2016) Biological hydrogen and methane production from bagasse bioethanol fermentation residues using a two-stage bioprocess. Bioresour Technol 210:49–55. doi: 10.1016/j.biortech.2015.12.084

Cherubini F (2010) The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. Energy Convers Manag 51:1412–1421. doi: 10.1016/j.enconman.2010.01.015

Contreras-Dávila CA, Méndez-Acosta HO, Arellano-García L, et al (2017) Continuous hydrogen production from enzymatic hydrolysate of Agave tequilana bagasse: Effect of the organic loading rate and reactor configuration. Chem Eng J 313:671–679. doi: 10.1016/j.cej.2016.12.084

Corona-González RI, Varela-Almanza KM, Arriola-Guevara E, et al (2016) Bagasse hydrolyzates from Agave tequilana as substrates for succinic acid production by Actinobacillus succinogenes in batch and repeated batch reactor. Bioresour Technol 205:15–23. doi: 10.1016/j.biortech.2015.12.081

Crespo MR, González DR, Rodríguez R, et al (2013) Evaluación de la composta de bagazo de agave como componente de sustratos para producir plántulas de agave azul tequilero. Rev Mex Ciencias Agrícolas 4:1161–1173.

CRT (2016) Consumo de Agave para tequila y tequila 100% de Agave. 2016.

Dan Jiang, Fang Z, Chin S, et al (2016) Biohydrogen Production from Hydrolysates of Selected Tropical Biomass Wastes with Clostridium Butyricum. Sci Rep 6:27205. doi: 10.1038/srep27205

Dussadee N, Reansuwan K, Ramaraj R (2014) Potential development of compressed bio-methane gas production from pig farms and elephant grass silage for transportation in Thailand. Bioresour Technol 155:438–441. doi: 10.1016/j.biortech.2013.12.126

Elsamadony M, Tawfik A (2015) Potential of biohydrogen production from organic fraction of municipal solid waste (OFMSW) using pilot-scale dry anaerobic reactor. Bioresour Technol 196:9–16. doi: 10.1016/j.biortech.2015.07.048

Fache M, Boutevin B, Caillol S (2016) Vanillin Production from Lignin and Its Use as a Renewable Chemical. ACS Sustain Chem Eng 4:35–46. doi: 10.1021/acssuschemeng.5b01344

Gao K, Rehmann L (2016) Combined Detoxification and In-situ Product Removal by a Single Resin During Lignocellulosic Butanol Production. Sci Rep 6:1–10. doi: 10.1038/srep30533

Ghasimi DSM, Aboudi K, de Kreuk M, et al (2016) Impact of lignocellulosic-waste intermediates on hydrolysis and methanogenesis under thermophilic and mesophilic conditions. Chem Eng J 295:181–191. doi: 10.1016/j.cej.2016.03.045

Ghimire A, Frunzo L, Pirozzi F, et al (2015) A review on dark fermentative biohydrogen production from organic biomass: Process parameters and use of by-products. Appl Energy 144:73–95. doi: 10.1016/j.apenergy.2015.01.045

Gupta R, Mehta G, Kuhad RC (2016) Scale-up of abatement of fermentation inhibitors from acid hydrolysates for efficient conversion to ethanol as biofuel. J Chem Technol Biotechnol 91:1826–1834. doi: 10.1002/jctb.4775

Hassan M, Ding W, Shi Z, Zhao S (2016a) Methane enhancement through co-digestion of chicken manure and thermo-oxidative cleaved wheat straw with waste activated sludge: A C/N optimization case. Bioresour Technol 211:534–541. doi: 10.1016/j.biortech.2016.03.148

Hassan M, Ding W, Umar M, et al (2016b) Methane Enhancement through Liquid Ammonia Fractionation of Corn Stover with Anaerobic Sludge. Energy and Fuels 30:9463–9470. doi: 10.1021/acs.energyfuels.6b01745

Hassan M, Ding W, Umar M, et al (2017a) Methane enhancement and asynchronism minimization through co-digestion of goose manure and NaOH solubilized corn stover with waste activated sludge. Energy 118:1256–1263. doi: 10.1016/j.energy.2016.11.007

Hassan M, Ding W, Umar M, Rasool G (2017b) Batch and semi-continuous anaerobic co-digestion of goose

manure with alkali solubilized wheat straw: A case of carbon to nitrogen ratio and organic loading rate regression optimization. Bioresour Technol 230:24–32. doi: 10.1016/j.biortech.2017.01.025

He Y, Pang Y, Liu Y, et al (2008) Physicochemical characterization of rice straw pretreated with sodium hydroxide in the solid state for enhancing biogas production. Energy and Fuels 22:2775–2781. doi: 10.1021/ef8000967

Hendriks ATWM, Zeeman G (2009) Pretreatments to enhance the digestibility of lignocellulosic biomass. Bioresour Technol 100:10–18. doi: 10.1016/j.biortech.2008.05.027

Hernández-Salas JM, Villa-Ramírez MS, Veloz-Rendón JS, et al (2009) Comparative hydrolysis and fermentation of sugarcane and agave bagasse. Bioresour Technol 100:1238–1245. doi: 10.1016/j.biortech.2006.09.062

Ingram LO, Conway T, Clark DP, et al (1987) Genetic engineering of ethanol production in Escherichia coli. Appl Environ Microbiol 53:2420–5.

Iñiguez-Covarrubias G, Lange SE, Rowell RM (2001) Utilization of byproducts from the tequila industry: Part 1: Agave bagasse as a raw material for animal feeding and fiberboard production. Bioresour Technol 77:25–32. doi: 10.1016/S0960-8524(00)00137-1

Jiang L, Wu N, Zheng A, et al (2016) The integration of dilute acid hydrolysis of xylan and fast pyrolysis of glucan to obtain fermentable sugars. Biotechnol Biofuels 9:1–10. doi: 10.1186/s13068-016-0612-0

Jong E De, Jungmeier G (2015) Biorefinery Concepts in Comparison to Petrochemical Refineries.

Kafle GK, Kim SH (2013) Anaerobic treatment of apple waste with swine manure for biogas production: Batch and continuous operation. Appl Energy 103:61–72. doi: 10.1016/j.apenergy.2012.10.018

Kalliola A, Vehmas T, Liitiä T, Tamminen T (2015) Alkali-O2 oxidized lignin - A bio-based concrete plasticizer. Ind Crops Prod 74:150–157. doi: 10.1016/j.indcrop.2015.04.056

Kestur G. S, Flores-Sahagun THS, Dos Santos LP, et al (2013) Characterization of blue agave bagasse fibers of Mexico. Compos Part A Appl Sci Manuf 45:153–161. doi: 10.1016/j.compositesa.2012.09.001

Klinke HB, Thomsen AB, Ahring BK (2004) Inhibition of ethanol-producing yeast and bacteria by degradation products produced during pre-treatment of biomass. Appl Microbiol Biotechnol 66:10–26. doi: 10.1007/s00253-004-1642-2

Larsson S, Palmqvist E, Hahn-Hägerdal B, et al (1999) The generation of fermentation inhibitors during dilute acid hydrolysis of softwood. Enzyme Microb Technol 24:151–159. doi: 10.1016/S0141-0229(98)00101-X

Lee SC, Park S (2016) Removal of furan and phenolic compounds from simulated biomass hydrolysates by batch adsorption and continuous fixed-bed column adsorption methods. Bioresour Technol 216:661–668. doi: 10.1016/j.biortech.2016.06.007

Li H, Ye C, Liu K, et al (2015) Analysis of particle size reduction on overall surface area and enzymatic hydrolysis yield of corn stover. Bioprocess Biosyst Eng 38:149–154. doi: 10.1007/s00449-014-1253-y

Li M, Pu Y, Ragauskas AJ (2016) Current Understanding of the Correlation of Lignin Structure with Biomass Recalcitrance. Front Chem 4:1–8. doi: 10.3389/fchem.2016.00045

Licata B La, Sagnelli F, Boulanger A, et al (2011) Bio-hydrogen production from organic wastes in a pilot plant reactor and its use in a SOFC. Int J Hydrogen Energy 36:7861–7865. doi: 10.1016/j.ijhydene.2011.01.096

Lin R, Cheng J, Ding L, et al (2015) Inhibitory effects of furan derivatives and phenolic compounds on dark hydrogen fermentation. Bioresour Technol 196:250–255. doi: 10.1016/j.biortech.2015.07.097

Monlau F, Sambusiti C, Barakat A, et al (2014) Do furanic and phenolic compounds of lignocellulosic and algae biomass hydrolyzate inhibit anaerobic mixed cultures? A comprehensive review. Biotechnol Adv 32:934–951. doi: 10.1016/j.biotechadv.2014.04.007

Monlau F, Trably E, Barakat A, et al (2013) Two-stage alkaline-enzymatic pretreatments to enhance biohydrogen production from sunflower stalks. Environ Sci Technol 47:12591–12599. doi: 10.1021/es402863v

Montiel C, Hernández-Meléndez O, Vivaldo-Lima E, et al (2016) Enhanced Bioethanol Production from Blue Agave Bagasse in a Combined Extrusion–Saccharification Process. Bioenergy Res 1–10. doi: 10.1007/s12155-016-9747-x

Murillo-Alvarado PE, Ponce-Ortega JM, Castro-Montoya AJ, et al (2014) Biofuels from residues of the tequila industry of Mexico. Elsevier

Mussatto SI, Roberto IC (2004) Alternatives for detoxification of diluted-acid lignocellulosic hydrolyzates for use in fermentative processes: A review. Bioresour Technol 93:1–10. doi: 10.1016/j.biortech.2003.10.005

Nakasu PYS, Ienczak LJ, Costa AC, Rabelo SC (2016) Acid post-hydrolysis of xylooligosaccharides from hydrothermal pretreatment for pentose ethanol production. Fuel 185:73–84. doi: 10.1016/j.fuel.2016.07.069

Nigam JN (2001) Ethanol production from wheat straw hemicellulose hydrolysate by Pichia stipitis. J Biotechnol 87:17–27. doi: 10.1016/S0168-1656(00)00385-0

Nissilä ME, Lay CH, Puhakka JA (2014) Dark fermentative hydrogen production from lignocellulosic hydrolyzates - A review. Biomass and Bioenergy 67:145–159. doi: 10.1016/j.biombioe.2014.04.035

Nualsri C, Kongjan P, Reungsang A (2016a) Direct integration of CSTR-UASB reactors for two-stage hydrogen and methane production from sugarcane syrup. Int J Hydrogen Energy 41:17884–17895. doi: 10.1016/j.ijhydene.2016.07.135

Nualsri C, Reungsang A, Plangklang P (2016b) Biochemical hydrogen and methane potential of sugarcane syrup using a two-stage anaerobic fermentation process. Ind Crops Prod 82:88–99. doi: 10.1016/j.indcrop.2015.12.002

Olsson L, Hahn-Hägerdal B (1996) Fermentation of lignocellulosic hydrolysates for ethanol production. Enzyme Microb Technol 18:312–331. doi: 10.1016/0141-0229(95)00157-3

Ouyang X, Tan Y, Qiu X (2014) Oxidative degradation of lignin for producing monophenolic compounds. J Fuel Chem Technol 42:677–682. doi: 10.1016/S1872-5813(14)60030-X

Perez-Pimienta JA, Flores-Gómez CA, Ruiz HA, et al (2016) Evaluation of agave bagasse recalcitrance using AFEX, autohydrolysis, and ionic liquid pretreatments. Bioresour Technol 211:216–223. doi: 10.1016/j.biortech.2016.03.103

Perez-Pimienta JA, Lopez-Ortega MG, Chavez-Carvayar JA, et al (2015) Characterization of agave bagasse as a function of ionic liquid pretreatment. Biomass and Bioenergy 75:180–188. doi: 10.1016/j.biombioe.2015.02.026

Perez-Pimienta JA, Lopez-Ortega MG, Varanasi P, et al (2013) Comparison of the impact of ionic liquid pretreatment on recalcitrance of agave bagasse and switchgrass. Bioresour Technol 127:18–24. doi: 10.1016/j.biortech.2012.09.124

Pérez-Pimienta JA, Vargas-Tah A, López-Ortega KM, et al (2017) Sequential enzymatic saccharification and fermentation of ionic liquid and organosolv pretreated agave bagasse for ethanol production. Bioresour Technol 225:191–198. doi: 10.1016/j.biortech.2016.11.064

Quéméneur M, Hamelin J, Barakat A, et al (2012) Inhibition of fermentative hydrogen production by lignocellulose-derived compounds in mixed cultures. Int J Hydrogen Energy 37:3150–3159. doi: 10.1016/j.ijhydene.2011.11.033

Quintero M, Castro L, Ortiz C, et al (2012) Enhancement of starting up anaerobic digestion of lignocellulosic substrate: Fique's bagasse as an example. Bioresour Technol 108:8–13. doi: 10.1016/j.biortech.2011.12.052

Ren N-Q, Zhao L, Chen C, et al (2016) A review on bioconversion of lignocellulosic biomass to H2: Key challenges and new insights. Bioresour Technol 215:92–99. doi: 10.1016/j.biortech.2016.03.124

Ren N, Li J, Li B, et al (2006) Biohydrogen production from molasses by anaerobic fermentation with a pilot-scale bioreactor system. Int J Hydrogen Energy 31:2147–2157. doi: 10.1016/j.ijhydene.2006.02.011

Rencoret J, Pereira A, del Río JC, et al (2016) Laccase-Mediator Pretreatment of Wheat Straw Degrades

Lignin and Improves Saccharification. Bioenergy Res 9:917–930. doi: 10.1007/s12155-016-9745-z

Reungsang A, Sittijunda S, Sreela-or C (2016) Methane production from acidic effluent discharged after the hydrogen fermentation of sugarcane juice using batch fermentation and UASB reactor. Renew Energy 86:1224–1231. doi: 10.1016/j.renene.2015.09.051

RFA (2017) BUILDING PARTNERSHIPS|GROWING MARKETS 2016 ETHANOL INDUSTRY OUTLOOK.

Rios-González LJ, Morales-Martínez TK, Rodríguez-Flores MF, et al (2017) Autohydrolysis pretreatment assessment in ethanol production from agave bagasse. Bioresour Technol. doi: 10.1016/j.biortech.2017.03.039

Saha BC (2004) Lignocellulose biodegradation and applications in biotechnology. In: ACS symposium series. pp 2–34

Saini JK, Patel AK, Adsul M, Singhania RR (2016) Cellulase adsorption on lignin: A roadblock for economic hydrolysis of biomass. Renew Energy 98:29–42. doi: 10.1016/j.renene.2016.03.089

Sambusiti C, Monlau F, Antoniou N, et al (2016) Simultaneous detoxification and bioethanol fermentation of furans-rich synthetic hydrolysate by digestate-based pyrochar. J Environ Manage 183:1026–1031. doi: 10.1016/j.jenvman.2016.09.062

Sannigrahi P, Pu Y, Ragauskas A (2010) Cellulosic biorefineries-unleashing lignin opportunities. Curr Opin Environ Sustain 2:383–393. doi: 10.1016/j.cosust.2010.09.004

Santos JRA, Lucena MS, Gusmão NB, Gouveia ER (2012) Optimization of ethanol production by Saccharomyces cerevisiae UFPEDA 1238 in simultaneous saccharification and fermentation of delignified sugarcane bagasse. Ind Crops Prod 36:584–588. doi: 10.1016/j.indcrop.2011.10.002

Saravanakumar T, Park HS, Mo AY, et al (2016) Detoxification of furanic and phenolic lignocellulose derived inhibitors of yeast using laccase immobilized on bacterial cellulosic nanofibers. J Mol Catal B Enzym 134:196–205. doi: 10.1016/j.molcatb.2016.11.006

Sarma SJ, Pachapur V, Brar SK, et al (2015) Hydrogen biorefinery: Potential utilization of the liquid waste from fermentative hydrogen production. Renew Sustain Energy Rev 50:942–951. doi: 10.1016/j.rser.2015.04.191

Saucedo-Luna J, Castro-Montoya AJ, Martinez-Pacheco MM, et al (2011) Efficient chemical and enzymatic saccharification of the lignocellulosic residue from Agave tequilana bagasse to produce ethanol by Pichia caribbica. J Ind Microbiol Biotechnol 38:725–732. doi: 10.1007/s10295-010-0853-z

Saucedo-Luna J, Castro-Montoya AJ, Rico JL, Campos-Garcia J (2010) Optimization of Acid Hydrolysis of Bagasse from Agave tequilana Weber. Rev Mex Ing Química 9:91–97.

Sekoai PT, Gueguim Kana EB (2014) Semi-pilot scale production of hydrogen from Organic Fraction of Solid Municipal Waste and electricity generation from process effluents. Biomass and Bioenergy 60:156–163. doi: 10.1016/j.biombioe.2013.11.008

Silva EAB da, Zabkova M, Araújo JD, et al (2009) An integrated process to produce vanillin and lignin-based polyurethanes from Kraft lignin. Chem Eng Res Des 87:1276–1292. doi: 10.1016/j.cherd.2009.05.008

Siqueira MR, Reginatto V (2015) Inhibition of fermentative H2 production by hydrolysis byproducts oflignocellulosic substrates. Renew Energy 80:109–116. doi: 10.1016/j.renene.2015.01.070

Stewart D (2008) Lignin as a base material for materials applications: Chemistry, application and economics. Ind Crops Prod 27:202–207. doi: 10.1016/j.indcrop.2007.07.008

Su Y, Du R, Guo H, et al (2015) Fractional pretreatment of lignocellulose by alkaline hydrogen peroxide: Characterization of its major components. Food Bioprod Process 94:322–330. doi: 10.1016/j.fbp.2014.04.001

Sun RC, Sun XF, Fowler P, Tomkinson J (2002) Structural and physico-chemical characterization of lignins solubilized during alkaline peroxide treatment of barley straw. Eur Polym J 38:1399–1407. doi: 10.1016/S0014-3057(01)00303-2

Taherzadeh MJ, Karimi K (2008) Pretreatment of Lignocellulosic Wastes to Improve Ethanol and Biogas

Production: A Review. Int J Mol Sci 9:1621–1651. doi: 10.3390/ijms9091621

Torres-Tello E V., Robledo-Ortíz JR, González-García Y, et al (2017) Effect of agave fiber content in the thermal and mechanical properties of green composites based on polyhydroxybutyrate or poly(hydroxybutyrate-co-hydroxyvalerate). Ind Crops Prod 99:117–125. doi: 10.1016/j.indcrop.2017.01.035

Tovar-Carrillo KL, Nakasone K, Sugita S, et al (2014) Effects of sodium hypochlorite on Agave tequilana Weber bagasse fibers used to elaborate cyto and biocompatible hydrogel films. Mater Sci Eng C 42:808–815. doi: 10.1016/j.msec.2014.06.023

Tovar-Carrillo KL, Sueyoshi SS, Tagaya M, Kobayashi T (2013) Fibroblast compatibility on scaffold hydrogels prepared from agave tequilana weber bagasse for tissue regeneration. Ind Eng Chem Res 52:11607–11613. doi: 10.1021/ie401793w

Valenzuela A (2011) A new agenda for blue agave landraces: food, energy and tequila. GCB Bioenergy 3:15–24. doi: 10.1111/j.1757-1707.2010.01082.x

Vallejos ME, Chade M, Mereles EB, et al (2016) Strategies of detoxification and fermentation for biotechnological production of xylitol from sugarcane bagasse. Ind Crops Prod 91:161–169. doi: 10.1016/j.indcrop.2016.07.007

Velazquez-Jimenez LH, Pavlick A, Rangel-Mendez JR (2013) Chemical characterization of raw and treated agave bagasse and its potential as adsorbent of metal cations from water. Ind Crops Prod 43:200–206. doi: 10.1016/j.indcrop.2012.06.049

Velázquez-Valadez U, Farías-Sánchez JC, Vargas-Santillán A, Castro-Montoya AJ (2016) Tequilana weber Agave Bagasse Enzymatic Hydrolysis for the Production of Fermentable Sugars: Oxidative-Alkaline Pretreatment and Kinetic Modeling. Bioenergy Res 9:998–1004. doi: 10.1007/s12155-016-9757-8

Venkata Mohan S, Venkateswar Reddy M, Venkata Subhash G, Sarma PN (2010) Fermentative effluents from hydrogen producing bioreactor as substrate for poly(??-OH) butyrate production with simultaneous treatment: An integrated approach. Bioresour Technol 101:9382–9386. doi: 10.1016/j.biortech.2010.06.109

Venkateswar Reddy M, Amulya K, Rohit MV, et al (2014) Valorization of fatty acid waste for bioplastics production using Bacillus tequilensis: Integration with dark-fermentative hydrogen production process. Int J Hydrogen Energy 39:7616–7626. doi: 10.1016/j.ijhydene.2013.09.157

Wilkinson S, Smart KA, Cook DJ (2014) Optimisation of alkaline reagent based chemical pre-treatment of Brewers spent grains for bioethanol production. Ind Crops Prod 62:219–227. doi: 10.1016/j.indcrop.2014.08.036

Xuebing Z, Zhang L, Liu D (2012) Biomass recalcitrance. Part I: the chemical compositions and physical structures affecting the enzymatic hydrolysis of lignocellulose. Biofuels, Bioprod Biorefining 6:465–482. doi: 10.1002/bbb

Zhao X, Cheng K, Liu D (2009) Organosolv pretreatment of lignocellulosic biomass for enzymatic hydrolysis. Appl Microbiol Biotechnol 82:815–827. doi: 10.1007/s00253-009-1883-1

Zhou S, Xue Y, Sharma A, Bai X (2016) Lignin Valorization through Thermochemical Conversion: Comparison of Hardwood, Softwood and Herbaceous Lignin. ACS Sustain Chem Eng 4:6608–6617. doi: 10.1021/acssuschemeng.6b01488

Zhu L, O'Dwyer JP, Chang VS, et al (2008) Structural features affecting biomass enzymatic digestibility. Bioresour Technol 99:3817–3828. doi: 10.1016/j.biortech.2007.07.033

FIGURE CAPTIONS

Fig. 1 Agave bagasse biorefinery scheme

Fig. 2 Metabolic pathways for the production of ethanol, hydrogen and methane by anaerobic processes

Figure 1

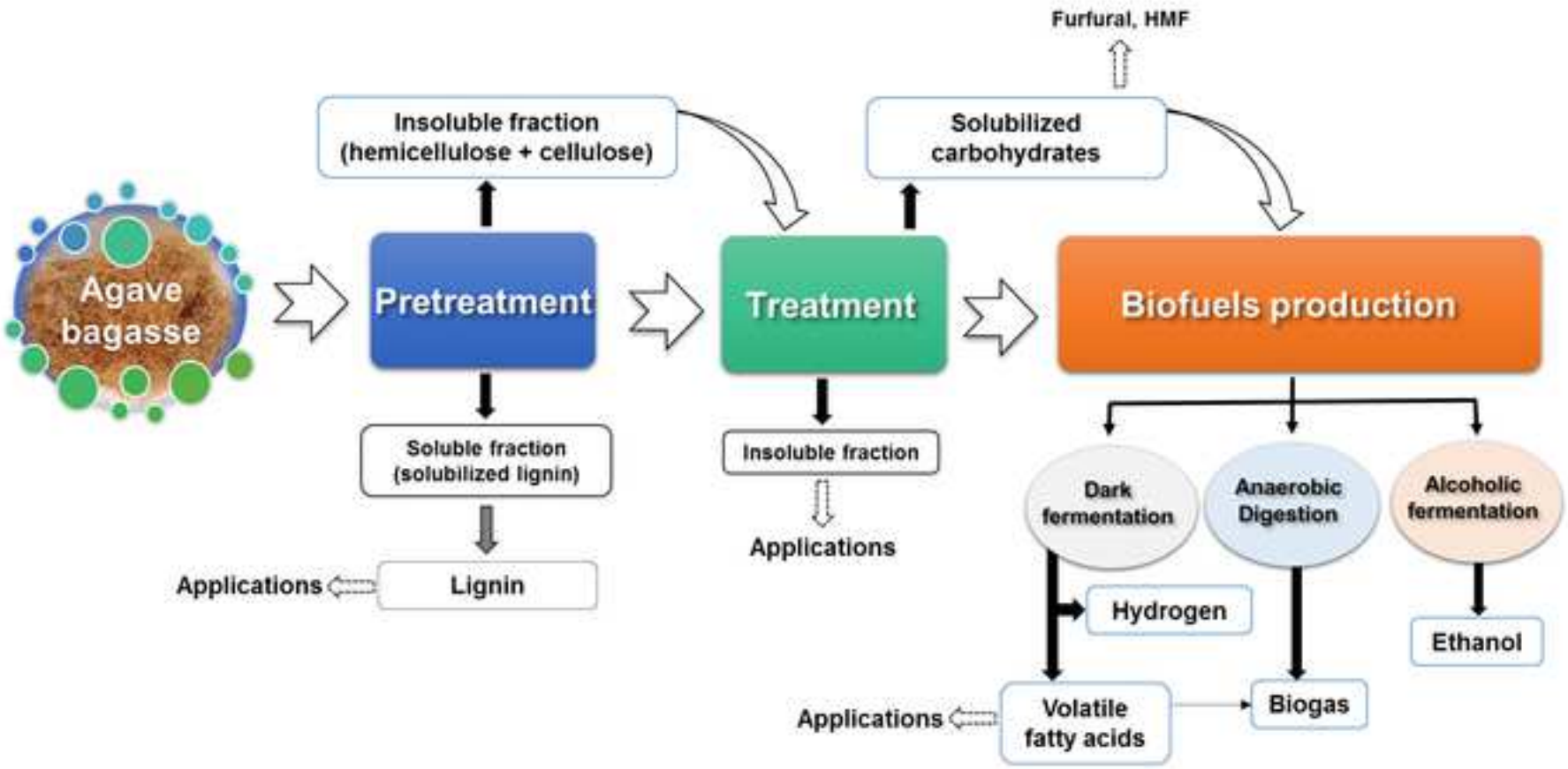
Furfural, HMF
Insoluble fraction
(hemicellulose + cellulose)
Solubilized
carbohydrates
Agave
bagasse
Pretreatment
Treatment
Biofuels production
Soluble fraction
(solubilized lignin)
Insoluble fraction
Applications
Applications
Lignin
Dark
fermentation
Anaerobic
Digestion
Alcoholic
fermentation
Hydrogen
Ethanol
Applications
Volatile
fatty acids
Biogas

Figure 2

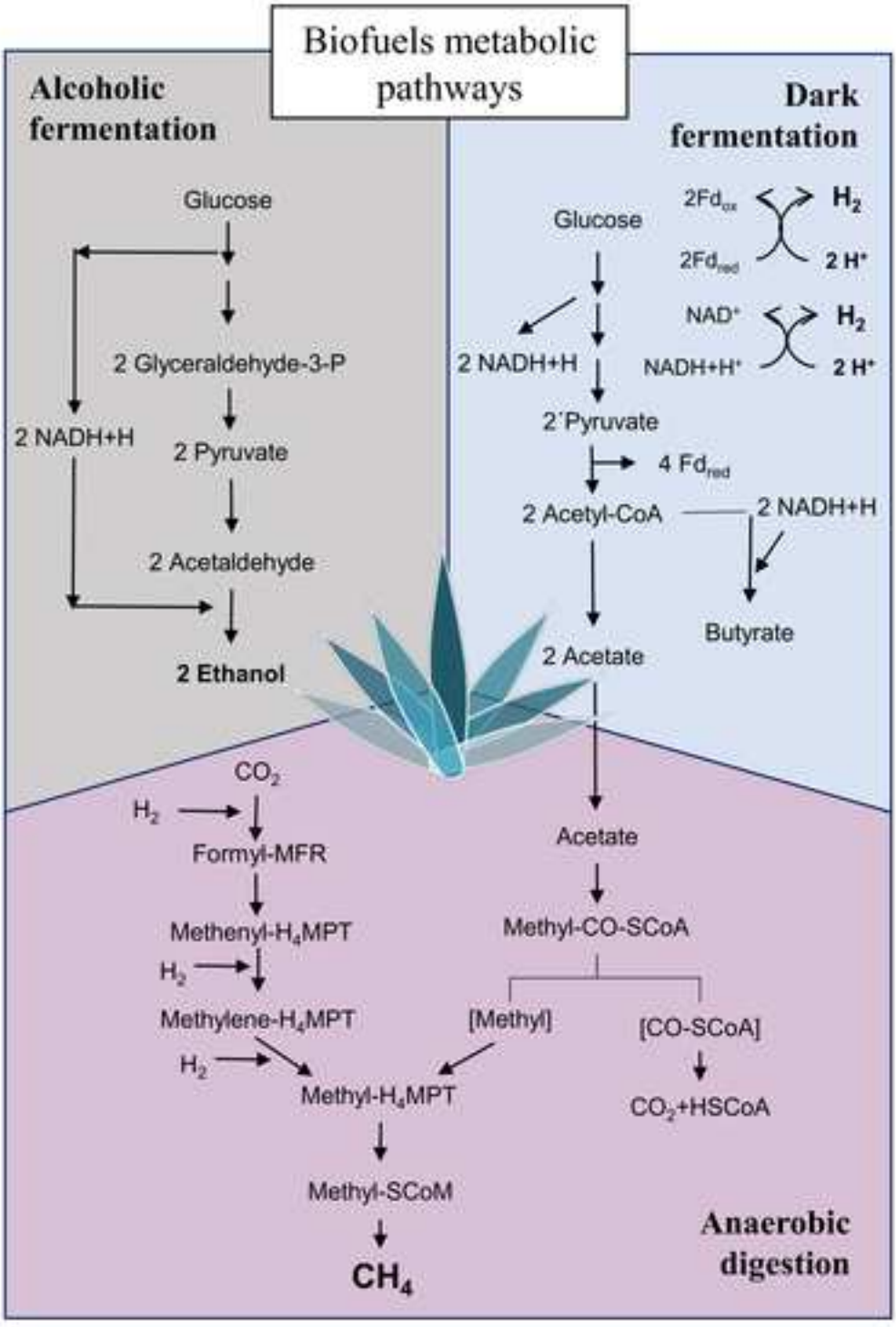
Biofuels metabolic pathways
Alcoholic fermentation
Dark fermentation
Glucose
2 Glyceraldehyde-3-P
2 NADH+H
2 Pyruvate
2 Acetaldehyde
2 Ethanol
Glucose
2Fd$_{ox}$
2Fd$_{red}$
H$_2$
2 H$^+$
NAD$^+$
NADH+H$^+$
H$_2$
2 H$^+$
2 NADH+H
2´Pyruvate
4 Fd$_{red}$
2 Acetyl-CoA
2 NADH+H
Butyrate
2 Acetate
CO$_2$
H$_2$
Formyl-MFR
Methenyl-H$_4$MPT
H$_2$
Methylene-H$_4$MPT
H$_2$
Methyl-H$_4$MPT
Methyl-SCoM
CH$_4$
Acetate
Methyl-CO-SCoA
[Methyl]
[CO-SCoA]
CO$_2$+HSCoA
Anaerobic digestion

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Table 1. Delignification pretreatments for lignocellulosic biomass.

Lignocellulosic biomass	Delignification pretreatment	Delignification yield (%)	Disadvantages	Reference
Wheat straw	Enzymatic (laccases)	48	Their use are restricted by lignin content in lignocellulosic biomass	Rencoret et al. 2016
Agave bagasse[a]	Alkaline	N.R	High temperature and pressure	Hernández-Salas et al. 2009
Agave bagasse	Alkaline	N.R	High temperature and pressure	Ávila-Lara et al. 2015
Rice straw	Alkaline	28.4	Low delignification yields even with high NaOH concentrations (6%) Removal of hemicellulose (36.8%)	He et al. 2008
Agave bagasse	Ethanosolv (similar to organosolv)	69	Removal of hemicellulose by use of sulfuric acid High temperature and pressure	Caspeta et al. 2014
Agave bagasse	Organosolv	45	Removal of hemicellulose (86%) by use of sulfuric acid High temperature and pressure	Pérez-Pimienta et al. 2017
Agave bagasse	Alkaline-oxidative	82.62	High amounts of reagents and temperature Long reaction time	Velázquez-Valadez et al. 2016
Agave bagasse	Oxidative	19.6	Long reaction time (48 h)	Perez-Pimienta et al. 2016
Corncob	Oxidative	74	Removal of hemicellulose (39%)	Su et al. 2015

N. R: Not reported
[a]*Agave atrovirens*

Table 2. Enzymatic hydrolysis of agave bagasse after pre-treatment

Pretreatment	Enzymatic hydrolysis conditions	Enzyme	Sugars concentration	Saccharification yield	References
Acid hydrolysis (25.8 g/L of sugars)	pH 5, 40 °C, 72 h	Celluclast 1.5L[1] (80 U/g of TS*) + Novozyme 188[2] (100 U/g of TS)	41 g/L	73.6 %	Saucedo-Luna et al. 2011
Ionic liquids	pH 5.5, 55 °C, 72 h, solid loadings 15%	40 mg of Cellic® CTec2[3]/g glucan + 4mg of Cellic® HTec2[4]/g xylan	7.6 g/L		Perez-Pimienta et al. 2013
Ethanosolov	pH 4.8, 50 °C, 72 h, solid loadings of 3 % (w/w)	NS50013[5] 10 PFU/g TS + NS50010[6] 20 CBU/g TS	225 g/L	91 % 0.51 g/g bagasse	Caspeta et al. 2014
Alkaline Acid hydrolysis	pH 4.8, 55 °C, 72 h, solid loadings of 3 % (w/w)	Cellic® CTec2[3] 35 FPU/g + Cellic® HTec2[4] 60CBU/g biomass		460 mg/g dry matter 457 mg/g dry matter	Ávila-Lara et al. 2015
Alkali extrusion	pH 5.5, 50 °C, 24 h, solid loadings of 2.5 % (w/w)	80% Cellic CTec2[3] + 20% Viscozyme[7] 10 mg/g DM	69.5 g/L	73 %	Montiel et al. 2016
Alkali-Oxidative	pH 5.0, 50 °C, 72 h	6% Cellic® CTec3[3] + 6% Cellic® HTec3[4]	165.7 g/L 136.4 g/L of glucose and 29.2 g/L of xylose	82.2 %, 352.2 g/kg	Velázquez-Valadez et al. 2016
Ionic liquids	pH 4.8, 55 °C, 48 h, solid loadings 5 g glucan/L	Cellic® CTec2 + Cellic® HTec2: 20 g protein per kg glucan and 2 g protein per kg xylan, respectively	6.7 g/L		Perez-Pimienta et al. 2015
Ionic liquids	pH 4.8, 50 °C, 24 h, solid loadings 20 g/L	Cellic® CTec2 + Cellic® HTec2 40 mg protein per g glucan and 4 mg protein per g xylan, respectively	25.5 g/L	397 g/kg	Perez-Pimienta et al. 2016
Ammonia fiber expansion			21.4 g/L	425 g/kg	
Autohydrolysis			14.4 g/L	269 g/kg	
Ionic Liquids	pH 4.8, 50 °C, 18 h, solid loadings 10% (w/w)	Cellic® CTec2 8 FPU/g + Cellic® HTec2 15 CBU/g	36.3 g glucose/L and 14.4 g xylose/L	71.2 %	Pérez-Pimienta et al. 2017
Organosolov			67.7 g glucose/L and 5.6 g xylose/L	53.8 %	

[1]Celluclast 1.5L, [3]Cellic® CTec, [5]NS50013 (Cellulases); [2]Novozyme 188, [6]NS50010 (Cellobiase); [4]Cellic® HTec2, [7]Viscozyme (Hemicellulase) *TS – Total Solids

Table 3. Selection of AF, DF, and AD of lignocellulosic materials.

Biofuel process	Type of system	Inoculum	Substrate	Operational conditions	Fuel production rate	Energy production rate kJ/gCOD-d	Fuel production yield	Energy yield kJ/gCOD	Reference
DF	Batch	Anaerobic sludge	Agave bagasse (EH)	40 % (v/v) hydrolysate, S^0: 16 gCOD/L, 37 °C, pH: 7	2.4 L/L-d	1.6	3.4 $molH_2/molHex$	4.25[a]	Arreola-Vargas et al. 2016a
DF	CSTR	Anaerobic sludge	Agave bagasse (EH)	HRT: 6 h, S^0: 13 gCOD/L, OLR: 52.5 gCOD/L-d, 37 °C, pH: 5.5	2.53 L/L-d	2.1	0.79 $molH_2/molHex$	0.99[a]	Contreras-Dávila et al. 2017
DF	TBR	Anaerobic sludge	Agave bagasse (EH)	HRT: 4 h, S^0: 8.8 g COD/L, OLR: 52.9 gCOD/L-d, 37 °C, pH: 5.5	3.45 L/L-d	4.2	1.53 $molH_2/mol\ Hex$	1.91[a]	Contreras-Dávila et al. 2017
DF	BTF	Anaerobic sludge	Oat straw (AH)	HRT: 12 h, S^0: 35 gCOD/L, OLR: 70 gCOD/L-d, 28 °C, pH: 5.5	1.95 L/L-d	0.60	0.4 $molH_2/molHex$	0.5[a]	Arriaga et al. 2011
DF	ASBR	Anaerobic sludge	Oat straw (EH)	HRT: 8 h, S^0: 5 gCOD/L, OLR: 15 gCOD/L-d, 35°C, pH: 4.5	0.71 L/L-d	1.52	0.81 $molH_2/molHex$	1.01[a]	Arreola-Vargas et al. 2013
DF	TBR	Triticale silage	Oat straw (EH)	HRT: 12 h, S^0: 5 gCOD/L, OLR: 10 gCOD/L-d, 35°C, pH: 5,	0.624 L/L-d	1.33	2.3 $molH_2/molHex$	2.87[a]	Arreola-Vargas et al. 2015a
DF	Batch	*C. butyricum*	Jatropha hulls (AH)	S^0: 15.64 gRS/L, 35°C, pH: 6.5	4.29 L/L-d	2.9	1.95 $molH_2/molHex$	2.44[a]	Dan Jiang et al. 2016
DF	Batch	*C. butyricum*	Sugarcane bagasse (AH)	S^0: 15.64 gRS/L, 35°C, pH: 6.5	4.52 L/L-d	3.1	2.06 $molH_2/molHex$	2.58[a]	Dan Jiang et al. 2016
AD	Batch	Anaerobic sludge	Goose manure + corn stover (Alk)	37 °C, pH: 7.0-7.8	0.01 L/g VS-d[b]	-	0.39 L/gVS	13.96	Hassan et al. 2017a
AD	Semi-continuous STR	Anaerobic sludge	Goose manure + wheat straw (Alk)	S^0: 30 gVS/L, OLR: 3 gVS/L-d, HRT: 10 d	~ 8 L/L-d	-	0.26 L/gVS	9.31	Hassan et al. 2017b
AD	Batch	Anaerobic sludge	Agave bagasse → DF Effluent	S^0: 20 % (v/v), pH:8, 37°C	0.96 L/L-d	34.4	0.24 L/gCOD	8.60	Arreola-Vargas et al. 2016a

AD	Continuous	Anaerobic sludge	Agave bagasse → DF Effluent	HRT: 8.7 h, S^0: 0.9 gCOD/L, OLR: 2.5 g COD/L-d, 37°C, pH: 7	0.9 L/L-d	35.8	0.35 L/gCOD	12.53	Cheng et al. 2016
AD	ASBR	Anaerobic sludge	Tequila vinasses	S^0: 8 gCOD/L, X^0: 16.5g VSS/L, 32°C, pH:7	2.25 L/L-d	15.8	0.29 L/gCOD	10.38	Arreola-Vargas et al. 2016b
AD	Batch	Anaerobic sludge	Sugarcane syrup → DF effluents	S^0: 25 gCOD/L, 30 °C, pH: 7	0.022 L/gCOD-d	0.78	0.31 L/gCOD	11.10	Nualsri et al. 2016b
AD	UASB	Anaerobic sludge	Sugarcane syrup → DF effluents	HRT: 3 d, S^0: 25 gCOD/L	2.25 L/L-d	3.24	0.27 L/gCOD	9.66	Nualsri et al. 2016a
AD	UASB	Anaerobic sludge	Sugarcane syrup → DF effluents	HRT: 4 d, OLR: 5.25 g COD/L-d, S^0: 20 g COD/L	1.27 L/L-d	2.27	0.35 L/gCOD	12.53	Reungsang et al. 2016
AD	ASBR	Anaerobic sludge	A. tequilana bagasse (AH)	S^0: 5 g COD/L, VSS/L, pH: 7.5, 32 °C	0.3 L/L-d	2.14	0.26 L/gCOD	9.31	Arreola-Vargas et al. 2015b
AD	Batch	Anaerobic sludge	Sugar cane bagasse→ AH + EH	S^0: 5.5 g VS/L, pH: not controlled (7-8.1), 37°C	-	-	0.2 L/gVS	7.16	Badshah et al. 2012
AD	Batch	Ruminal liquid + pig waste sludge	Fique`s bagasse (*Furcraea* sp.)	39°C	0.14 g COD-CH_4/g VSS	-	0.3 L/gVS_{added}	10.74	Quintero et al. 2012
AD	CSTR	Anaerobic sludge	Apple waste (25% VS) + swine manure (75% VS)	HRT:30 d, OLR: 1 g VS/L-d, 36-38 °C, pH:7.8	-	-	0.24 L/gCOD_{added}	8.59	Kafle and Kim 2013
AF	Batch	*S. cerevisiae*	Agave (AH)	S^0: 35.4 g RS/L, 30ºC, pH 5	3.7 g/L-d[b]	0.35	0.14 g/gCH	0.6	Hernández-Salas et al. 2009
AF	Batch	*P. caribbica*	Agave bagasse (EH)	S^0: 25.8 gCHs, 30 ºC, pH 5	3.2 g/L-d [b]	0.5	0.56 g/gCH	0.91	Saucedo-Luna et al. 2011
AF	Batch	*S. cervisiae*	Agave bagasse (EH)	S^0: 93 $g_{glucose}$/L, 30 °C, pH 5	38.4 g/L-d [b]	0.61	0.96 g/gGlucose	0.58	Caspeta et al. 2014
AF	SSF	*E. coli*	Agave bagasse (Organosolv)	37 ºC, pH 7	28.8 g /L-d	1.12	0.85 g/gCH	1.52	Pérez-Pimienta et al. 2017
AF	SSF	*E. coli*	Agave bagasse (IL)	37 ºC, pH 7	16.3 g/L-d	1.02	0.82 g/gCH	2.52	Pérez-Pimienta et al. 2017
AF	Batch	*S. cerevisiae*	Agave bagasse (Autohydrolysis)	S^0: 130 $g_{glucose}$/L, 32 °C, pH 5.5	156 g/L-d [b]	2.64	0.95 g/gGlucose	1.0	Rios-González et al. 2017
AF	Batch	*S. cerevisiae*	Sugarcane bagasse (EH)	S^0: 88.8 g delignificated bagasse/L, 37 °C, pH 4.8	13.8 g/L-d [b]	2.45	0.12 g/gBagasse	0.93	Santos et al. 2012

DF: Dark fermentation; AD: Anaerobic digestion; AF: Alcoholic fermentation.

BTF: Biotrickling filter; ASBR: Anaerobic sequencing batch reactor; CSTR: Continuous stirred tank reactor; TBR: Trickling bed reactor; UASB: Up-flow anaerobic sludge blanket; STR: Stirred tank reactor; SSF: Simultaneous saccharification and fermentation.

EH: Enzymatic hydrolysate; AH: Acid hydrolysate; Alk: Alkaline hydrolysate; CH: Carbohydrates; RS: Reducing sugars; S^0: initial substrate concentration;

VFA: Volatile fatty acids; VS: Volatile solids; VSS: Volatile suspended solids; X^0: Initial microorganism's concentration.

[a] Calculated from COD of hexoses; [b] computed using the total fermentation/digestion time