Biofuel Research Journal 15 (2017) 704-712

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Biofuel Research Journal

Journal homepage: www.biofueljournal.com

Review Paper

Recent trends on techno-economic assessment (TEA) of sugarcane biorefineries

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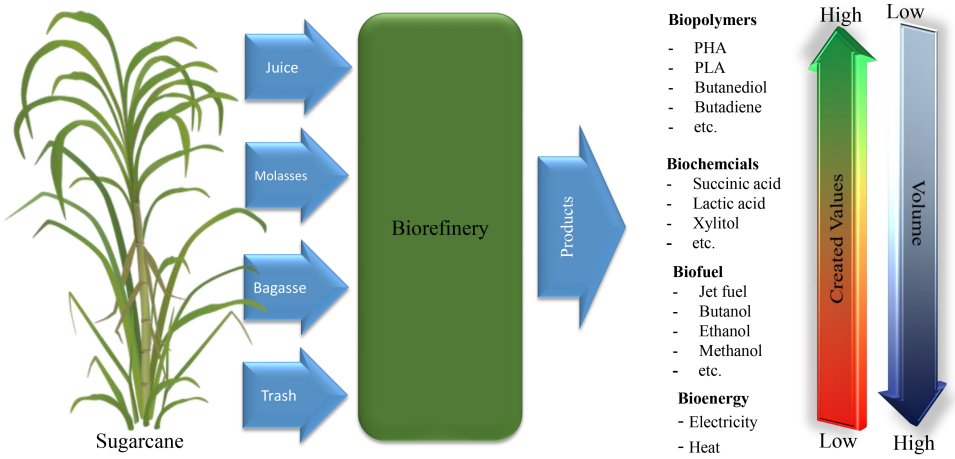
HIGHLIGHTS

- Sugar mills have opportunities to become economically-viable biorefineries.
- TEA of biofuels, biochemical, and biopolymers form sugarcane were reviewed.
- TEA is vital to sift through the product options to define investment opportunities.
- More research is required for biochemical and biopolymer production scenarios.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 June 2017
Received in revised form 5 August 2017
Accepted 17 August 2017
Available online 1 September 2017

Keywords:
Sugarcane
Biorefinery
Biofuel
Biochemical
Biopolymer
Techno-economic assessment

ABSTRACT

Sustainability challenges, e.g., climate change, resource depletion, and expanding populations, have triggered a swift move towards a circular bio-economy which is expected to evolve progressively in the coming decades. However, the transition from a fossil fuel-based economy to a bio-based economy requires the exploitation of scientific innovations and step changes in the infrastructure of chemical industry. Biorefineries have been extensively investigated for biofuel production from first and second generation feedstocks, whereas some research activities have been conducted on production of biochemical and biopolymers from renewable resources. Techno-economic evaluation of diverse technologies for production of biofuels and biochemical is a crucial step for decision making in the development of bio-economy. This contribution focuses on the economic studies carried out on biorefineries converting sugarcane bagasse, due to its availability and importance in the South African context, into value-added products. Recent studies on biofuel production *via* biochemical pathway, e.g., ethanol, butanol, or thermochemical pathway, e.g., methanol and bio jet fuel as well as production of biochemicals with high market demands and diverse applications such as lactic acid, succinic acid, and xylitol have been briefly reviewed. In addition, an overview on the production of biopolymers such as polyl-lactic acid and bio-based monomers, i.e., butanediol, from sugarcane bagasse is reported.

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Please cite this article as: Mandegari M.A., Farzad S., Görgens J.F. Recent trends on techno-economic assessment (TEA) of sugarcane biorefineries. Biofuel Research Journal 15 (2017) 704-712. DOI: 10.18331/BRJ2017.4.3.7

Contents

Abbreviations

ABE	Acetone, butanol and ethanol
BD	Butadiene
BDO	Butanediol
DM	Dry mass
EtOH	Ethanol
FP-H	Fast pyrolysis followed by hydroprocessing
1G-2G biorefinery	First and second generation biorefinery
1G biorefinery	First generation biorefinery
FT	Fisher-Tropsh
G-FTs	Gasification followed by Fischer–Tropsch synthesis
HD-PE	High density polyethylene
HTL	Hydrothermal liquefaction
IRR	Internal rate of return
LA	Lactic Acid
LLD-PE	Linear low density polyethylene
LD-PE	Low density polyethylene
MeOH	Methanol
MTBE	Methyl-tert-butyl ether
MESP	Minimum ethanol selling price
PA	Polyacetylene
PBR	Polybutadiene
PBS	Polybutylene succinate
PEG	Polyethylene glycol
PET	Polyethylene terephthalate
PHAs	poly-hydroxyalkanoates
PLA	Poly lactic acid
PS	Polystyrene
PVA	Polyvinyl acetate
PVC	Polyvinyl chloride
2G biorefinery	Second generation biorefinery
SBR	Styrene-butadiene rubber
TEA	Techno-economic assessment

1. Introduction

In recent years, environmental concerns, energy security issues, and global climate change have driven the development of biobased economy, where biorefineries and bio-products are identified as key pathways to decrease fossil fuel consumption. Different biorefinery routes (thermochemical and biochemical) for the production of biofuels and chemicals have been developed. Among biofuels, ethanol and butanol have been extensively studied, whereas bioethanol production has been used in large scale in countries such as Brazil (from sugarcane) and the USA (from corn). First-generation (1G) bioethanol derived from food crops, i.e., corn, wheat, sugar beet, as well as oil seeds, has been widely used for vehicle fuels, lowering net carbon dioxide emissions compared to fossil fuels. However, increasing demands of 1G biofuels has led to food *vs.* fuel concerns (Bezerra and Ragauskas, 2016) and consequently second-generation (2G) biofuels from lignocellulosic biomass, have received a huge deal of interest worldwide to overcome this challenge. Moreover, the co-production of integrated 1G-2G biorefinery for production of fuel, food, feeds, and value-added products have been investigated by many researchers (FitzPatrick et al., 2010).

In the global trend towards an increased use of renewable feedstocks, sugarcane, as a crop, has become more important. Sugarcane bagasse is one of the most commonly examined lignocellulosic materials due to its relative abundance, potential lower supply cost, and avoidance of land use competition with food crops (Farzad et al., 2017a). Sugarcane biorefineries convert sugar syrups, molasses, bagasse, and harvesting residues into a plethora of bio-products. The main challenge of 2G biorefineries is their ability to compete with fuel/chemical production through conventional pathways (Baeyens et al., 2015). In order to develop economically-viable biorefineries, production of value-added chemicals along with fuel is investigated by academics. Furthermore, interest in bio-based chemicals has risen due to increasing environmental problems and climate change concerns associated with the growing use of fossil resources (Bos and Sanders, 2013; Biddy et al., 2016). Bioethanol is the main product generated from sugar-based platforms, followed by n-butanol, acetic acid, and lactic acid, these occupy much smaller but still significant shares of the market though. In addition to those, Xylitol, sorbitol, and furfural, also generated through chemical conversion of sugars, have considerable markets too while these products have no petrochemical alternatives (Taylor et al., 2015). It should be mentioned that the 2G production of these products are close to commercialization with a few industrial or demonstration practices (Peplow, 2014; Taylor et al., 2015). Aviation fuel has a significant impact on CO_2 emission in the transportation sector, therefore, its production from biomass has become the focus of numerous research activities over the course of recent years (Wang and Tao, 2016). Moreover, succinic acid is one of bio-products, reported among the top twelve with near-term deployment potential based on its large projected

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market (Biddy et al., 2016), since it has been identified as a feedstock for higher value products (Shen et al., 2015).

Due to the wide spectrum of possible products from first and second generation feedstocks and the complexity of the processes involved, techno economic assessment (TEA) should be carried out to define the feasibility of the biorefineries. This study aims to represent a concise review on recent TEAs carried out considering different biofuels (e.g., ethanol, butanol, methanol, jet fuel, and Fischer–Tropsch (FT) syncrude), biochemical (e.g., lactic acid, succinic acid, and xylitol), as well as biopolymers (e.g., polylactic acid, polyhydroxyalkanoates, butadiene, and butanediol) from different parts of sugarcane (i.e., juice, molasses, bagasse, and trash). Comparison of available literature will help to identify the areas which require more attention by academic communities.

2. Sugarcane

Sugarcane, originated in Asia probably in New Guinea, has a large capacity to convert solar energy into biomass. Most of the rain-fed and irrigated commercial sugarcane is grown between 35°N and S of the equator. The crop flourishes under a long, warm growing season with a high incidence of radiation and adequate moisture, followed by a dry, sunny, and fairly cool but frost-free ripening and harvesting period (www.fao.com). The total cane energy content, excluding ash (about 2–3%) can be divided into three main parts including juice, fibrous residues (bagasse), and sugarcane agriculture residues, i.e., tops and trashes (Renó et al., 2014). Sugarcane is the main feedstock for sugar production all over the world with about 27 million ha area land used and total commercial world production of about 1900 million tonnes/year (t/y) cane (www.faostat.com). The distribution of sugarcane production around the globe is demonstrated in **Figure 1**. Brazil is the main producer with 38.8%, followed by India (18.8%), China (6.6%), Thailand (5.5%), and Africa (5.0%). The average production rate of sugarcane has increased by about 4% over the last 10 years, whereas this rate differs among countries.

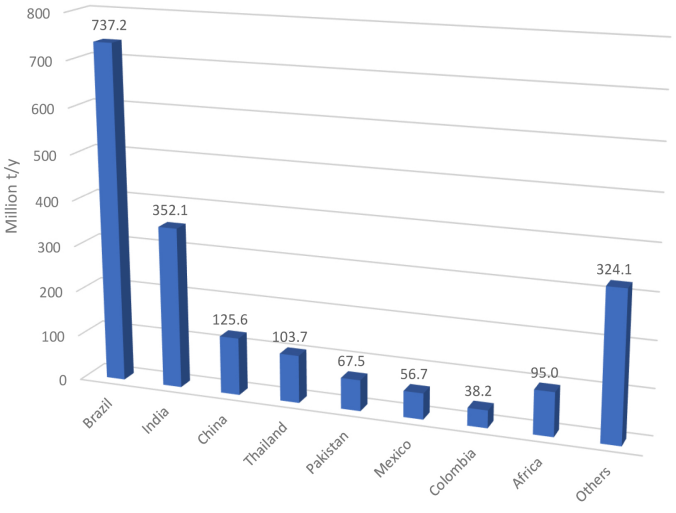

Fig.1. Sugarcane distribution based on countries in the year 2014 (www.faostat.com).

Although characterisation of sugarcane may differ in different seasons and regions, the average characteristics of sugarcane plant are represented in **Table1**. Dry mass (DM) of bagasse is about 15% of the total sugarcane weight. In the sugar industry context, bagasse is mostly burnt in boilers, to provide the steam and electricity demands of sugar mills (Mandegari et al., 2017a). Whereas, technical approaches are already available to improve energy efficiency in sugar cane processing, resulting in liberation of surplus bagasse. Furthermore, 7.5 wt.% of sugarcane is trash which can be collected *via* green harvesting of the sugarcane (Farzad et al., 2017a) leading to higher available feedstock. Brazil is currently in a transition from burning the whole cane for harvesting to unburned (green) harvest (Dias et al., 2015). Sugarcane bagasse and fibrous residues are typically composed of 39-43% cellulose, 21–23% lignin, 25–32% hemicelluloses, and minor amounts of organic extractives and ash (Oliveira et al., 2013; Clauser et al., 2016), which make them a proper carbon source for valorisation.

Table 1.
General characterization of the sugarcane plant.

Material	wt.% of sugarcane	Moisture content	Reference
Total sugar content	15%	-	Dias et al. (2013a)
Bagasse	30%	50%	Petersen et al. (2014); Smithers (2014)
Fibrous residues*	15 %	15%	Smithers (2014)

* Fibrous residues refers to brown leaves and green tops. Brown leaves (trash) are 50% of total residues. Only the brown leaf component of sugarcane harvesting residues will be available by a green-cane-harvesting approach, while the tops (green leaves) will be left in the field to maintain soil fertility (Smithers, 2014; Farzad et al., 2017b).

3. Techno-economic assessment (TEA)

To compare the feasibility of biorefineries following the thermochemical or biochemical pathways or biorefineries with different complexity based on the implemented technology, economic performance of each biorefinery should be thoroughly investigated. As common means used in techno-economic assessment, several predefined parameters or objectives (e.g., production cost and rate of return) which represent the techno-economic performance are evaluated and compared for different case studies. The evaluation is carried out by determining some common indicators, i.e., payback period, net present value, fixed capital cost, total manufacturing cost, after-tax rate of return, and break-even price. Some researchers have argued that the conversion of biomass to biofuels is strongly influenced by the cost of the feedstock and the technology used (Lange, 2007). For instance, FT syncrude production is technology dominated, whereas the vegetable-oil-based biofuel production is significantly influenced by feedstock cost (Parajuli et al., 2015). Several examples of techno-economic performance assessments for biofuel generation are available in the literature (Brown, 2015). However, comparison of the results is challenging because different approaches have been implemented by different research works. The available data on TEAs have been summarised based on the products, as follows.

3.1. Biofuels

Annually the transportation sector consumes 25% of the global primary energy and is responsible for the related greenhouse gas emissions. Currently, petroleum-derived liquid fuels are the dominant source of energy and biofuels can be appropriate options for their substitution (Bhutto et al., 2016). A summary of the recent TEA studies on conversion of sugarcane to biofuels is represented in **Table 2**.

3.1.1. Ethanol (EtOH)

Ethanol production has received an increasing deal of attention, mostly because of its major environmental benefits. It can be produced from different kinds of renewable feedstock mainly sugarcane (35%) and corn (65%) with world production of 110 billion L in the year 2015 (Chum et al., 2014; Baeyens et al., 2015). The USA, Brazil, and several EU member states have the largest programs promoting bioethanol in the world (Balan et al., 2013; Chum et al., 2014). Since the year 2014, two commercial sugarcane lignocellulosic bioethanol production plants with capacities of 40 and 84 Ml/y (about 0.4% of the production capacity in Brazil) have become operational (Chum et al., 2014; Peplow, 2014), while several other projects are still in progress worldwide (Balan et al., 2013).

The biorefinery converting sugarcane residues (bagasse and trash) of an autonomous distillery to ethanol has been studied for Brazil (Seabra et al., 2010) and Colombia (Sánchez and Cardona, 2012) which showed acceptable economic performances. The lignocellulosic ethanol production (i.e., 2G) from extracted residue of 1G autonomous distillery and

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Table 2.
Recent TEA studies on the sugarcane biorefineries aimed at biofuels production.

Location	Feedstock/s	Product/s	Capacity (t cane/h)	Reference
Brazil	Bagasse and trash	EtOH	1000	Seabra and Macedo (2011)
Colombia	Cane juice	EtOH	146	Sánchez and Cardona (2012)
South Africa	Bagasse and trash	EtOH	300	Mandegari et al. (2017)
Brazil	Cane juice and hemicellulose	EtOH	500	Dias et al. (2013b)
Hungary/ USA	Bagasse	EtOH	293*	Gubicza et al. (2016)
Brazil	Cane juice, bagasse, and trash	Butanol	500	Pereira et al. (2014)
Brazil	Cane juice	Butanol	500	Mariano et al. (2013)
South Africa	Bagasse and trash	Butanol	300	Farzad et al. (2017b)
Brazil	Cane juice, bagasse, and trash	Jet fuel / Chemicals	500	Alves et al. (2017)
South Africa	Cane juice, bagasse, and trash	EtOH / Jet fuel	222	Diederichs et al. (2016)
Brazil	Cane juice, bagasse, and trash	Jet Fuel	500	Santos et al. (2017)
South Africa	Bagasse and trash	MeOH / FT syncrude	300	Petersen et al. (2015)
Cuba	Bagasse and trash	EtOH / MeOH	1700	Renó et al. (2014)
Brazil	Cane juice, bagasse, and trash	EtOH / MeOH	500	Albarelli et al. (2015)
South Africa	Bagasse	Pyrolysis products	300	Nsaful et al. (2013)
China / UK	Bagasse	FT / Pyrolysis products	667*	Michailos et al. (2017)

* Calculated based on the reported data on bagasse as well as those reported in **Table 1**.

integration of 1G-2G have been investigated by Brazilian (Dias et al., 2013b), Cuban (Macrelli et al., 2012; Dias et al., 2013b; Renó et al., 2014) and Colombian researchers (Moncada et al., 2013), where better performances compared with the individual 2G biorefineries were achieved. Furthermore, different alternatives for annexing a 2G biorefinery into existing sugar mill in South Africa have been studied (Mandegari et al., 2017a) which proved that annexing biorefinery to the existing mill would improve the economic performance since the feedstock would be cheaper than a standalone biorefinery.

The majority of the produced EtOH worldwide is consumed as transportation fuel, whereas it is an important building block for other advanced biofuels and bio-chemicals as well. Some of the possible products from EtOH are shown in **Figure 2**. Among the possible products, only a few options have been studied.

3.1.2. n-Butanol

Although ethanol is a well-established biofuel for blending with petrol, there is a growing interest in butanol because of its superior fuel properties compared with those of ethanol, including a higher heating value, lower volatility, reduced ignition problems, ease of blending, a higher viscosity, safer to use, and easier distribution (Jin et al., 2011). Butanol is produced from either metabolic pathway, also known as acetone, butanol and ethanol (ABE) fermentation, or chemical synthesis from ethanol (Ndaba et al., 2015).

Although the first option (ABE process) has a long history of research and commercialization, the latter has also gained attention of researchers (Jiang et al., 2015). Techno-economic evaluation of ABE process production from 1G has been studied by Mariano et al. (2013) and from 2G by Farzad et al. (2017b). The results showed that butanol production by fermentation is economically uncompetitive and technically challenging compared with bioethanol production without improved microorganisms and not traded as a chemical (Mariano et al., 2013; Farzad et al., 2017b). Furthermore, conversion of EtOH into butanol has also been analysed by Dias et al. (2014), which showed that butanol sold as chemical has a limited market and as fuel presents economic constraints. Pereira et al. (2015) assessed two competing technological routes for the production of n-butanol (fermentative and catalytic route) as facilities annexed to a 1G-2G sugarcane biorefinery. Based on their study, ABE process despite its drawbacks performed better than the catalysis of ethanol to n-butanol and co-products (Pereira et al., 2015).

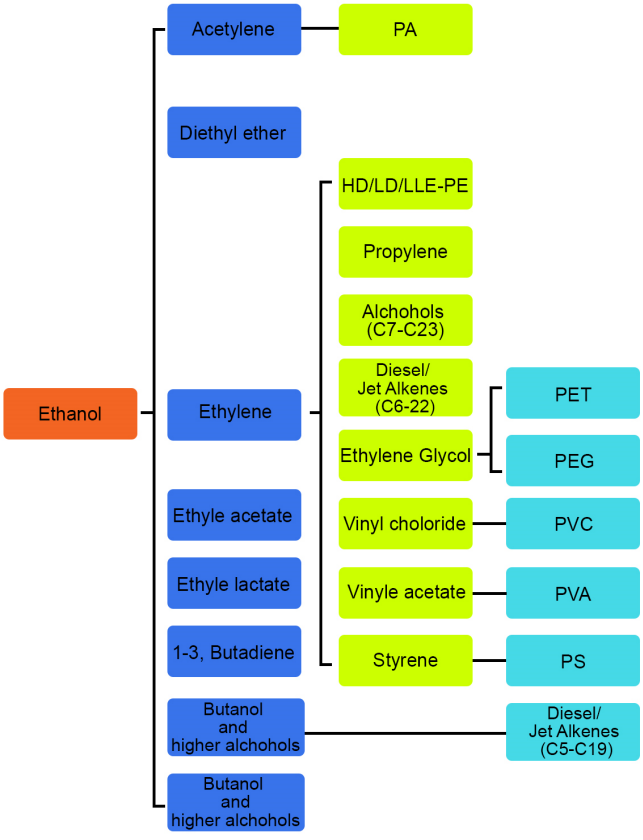

Fig.2. The possible products from EtOH (adapted from Taylor et al. (2015)).

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3.1.3. Biofuels from thermochemical pathway

Thermochemical conversion of lignocellulose to fuels/chemicals is an alternative pathway in contrast to biochemical pathway, as demonstrated in **Figure 3**. Size reduction of biomass along with drying is a preliminary step of this process. Gasification and pyrolysis are the most important technologies of this category followed by liquefaction as a less developed technology.

Gasification is the thermal decomposition of biomass at temperatures up to 1500 °C to a gaseous mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and small amounts of light hydrocarbons using a gasification agent (oxygen, air, steam or their combination). This intermediate product is known as syngas and can be converted into heat and power *via* combustion, or be catalytically-upgraded to liquid fuels such as ethanol, methanol, gasoline, diesel, jet fuels, etc. (Brown, 2015; Farzad et al., 2016).

Pyrolysis is the thermal decomposition of biomass in the temperature range of 350–700 °C to produce gases, liquids, and solids. There are four pathways for production of transportation fuels *via* pyrolysis including slow pyrolysis and upgrading of syngas, fast pyrolysis (FP) & hydroprocessing, catalytic pyrolysis & hydroprocessing, and hydropyrolysis & hydroprocessing (Brown, 2015; Dang et al., 2016).

Solvent liquefaction is the processing of biomass in a pressurized solvent at elevated temperatures to directly produce liquid products. Under relatively mild conditions, the products are sugars and partially deconstructed lignin. At more severe conditions, the products resemble the bio-oil produced from fast pyrolysis, although the product is reported to be more deoxygeated than pyrolysis-derived bio-oil (Brown, 2015; Huang and Yuan, 2015; Tan et al., 2015). There are a number of solvents appropriate for this process, whereas water is frequently used because of its low cost and the ability to directly process wet feedstocks. When water is used as a solvent, the process is known as hydrothermal liquefaction (HTL). The products of solvent liquefaction require further upgrading to finished fuels.

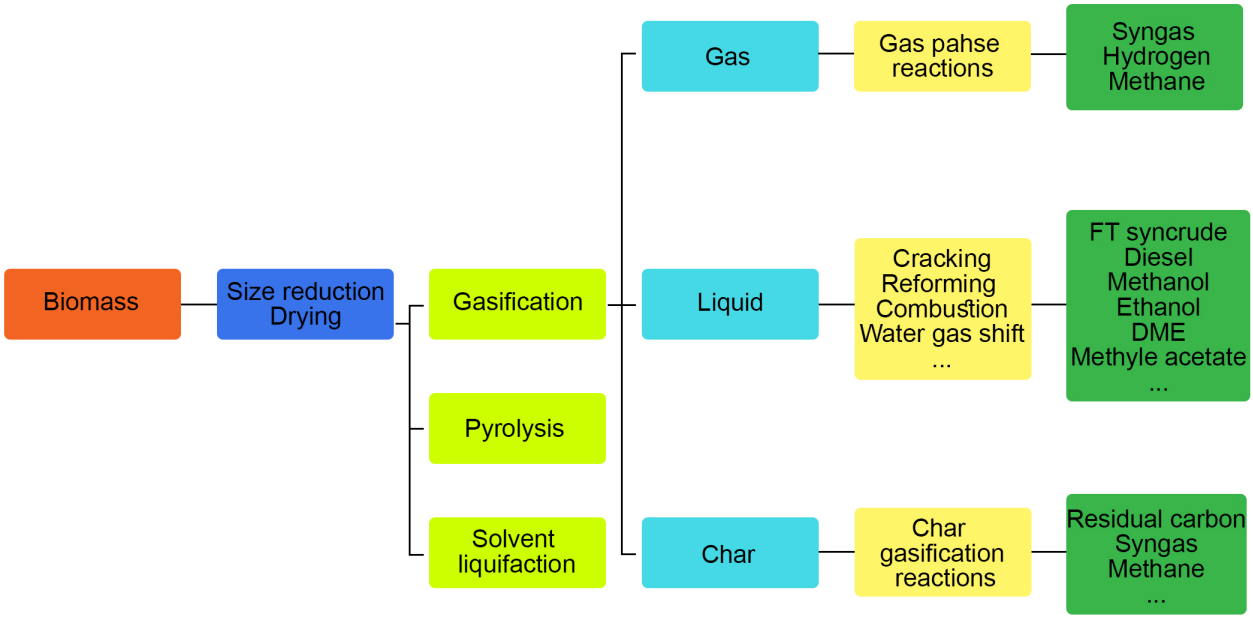

Fig.3. Overall flowchart of the thermochemical pathway for conversion of biomass to fuel/chemicals.

A sugar mill with an annexed 2G biorefinery has been investigated for methanol, FT syncrude, and bio oil production (Nsaful et al., 2013; Petersen et al., 2015), which showed that the combustion of biomass and electricity production was a more attractive option than applying a pyrolysis plant considering the current pyrolysis technology (Nsaful et al., 2013). Furthermore, investigations by Petersen et al. (2015) and Farzad et al. (2017b) proved that FT syncrude production was not an economically viable option, due to the relatively low volume of production with low cost of syncrude. Recently, Michailos et al. (2017) focused on the feasibility of gasification followed by FT synthesis (G-FTs) route, and fast pyrolysis followed by hydroprocessing (FP-H). Both energetically and financially, G-FTs synthesis found to be the more efficient option, with the payback period of 9 years (IRR=11%) considering USD15/t feedstock cost.

Techno-economic analysis of ethanol production from sugarcane bagasse using a mild liquefaction plus simultaneous saccharification and co-fermentation process has been carried out by Gubicza et al. (2016). They followed the minimum ethanol selling price (MESP) approach and the resulted MESP varied between 50.38 and 62.72 US cents/L which was comparable with the market price.

3.1.3.1. Methanol

Methanol (MeOH) is the simplest alcohol that acts as a hydrogen carrier or storage compound, with the total annual production capacity of 50 million t/y worldwide, of which 75% is produced from natural gas (Shamsul et al., 2014). Methanol is used as primary feedstock for a large variety of chemicals such as formaldehyde (70% of the total methanol produced), methyl-tert-butyl ether (MTBE, 20%), acetic acid, and dimethylether as well as a variety of intermediates exploited in manufacturing of chemicals and materials (Bozzano and Manenti, 2016).

There are several conventional and new processes for the production of biomethanol, such as pyrolysis, gasification, bio-synthesis, electrolysis, and photo electrochemical processes (Shamsul et al., 2014). However, among different technologies, gasification of sugarcane lignocellulosic residues for MeOH production has been more attractive. Albarelli et al. (2015) evaluated a sugarcane biorefinery producing EtOH through juice fermentation and MeOH *via* gasification of sugarcane lignocellulosic residues and liquid fuel synthesis. The cost analysis showed that the calculated MeOH production cost was 30% higher than its then market price. Petersen et al. (2015) and Farzad et al. (2017b) also investigated MeOH production annexed to a sugar mill. All these studies demonstrated that MeOH producing scenarios from sugarcane residues are not likely to be economically feasible under the current economic conditions (low oil price), without government subsidies (Albarelli et al., 2015).

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3.1.3.2. Jet fuel (aviation fuel)

Since aviation is responsible for 12% of the CO_2 emissions of all transportation sectors, a new alternative within the jet-fuel production chain could significantly affect the sustainability of the transportation sector (Alves et al., 2017). Bio jet fuel production technologies are at an early stage of development when compared with petrochemical processes. In general, sugarcane components (sucrose/molasses/bagasse/trash) can be converted into bio jet fuel *via* two pathways, 1: EtOH or butanol production and its upgrading into jet fuel (alcohol-to-jet; applicable for 1G and 2G) and 2: gasification/pyrolysis of biomass residues and upgrading into jet fuel (applicable for 2G only) (Mawhood et al., 2016; Wang and Tao, 2016). Direct sugars to hydrocarbons is also an applicable pathway which was investigated by a joint venture between the companies Amyris and Total. The first commercial plant of this technology, has been operational since December 2012 (Mawhood et al., 2016) in Brazil and the renewable jet fuel produced by the process from a sugarcane feedstock has been used in an Embraer E195 jet operated by the Azul Brazilian Airline (Wang and Tao, 2016).

Various studies have assessed the techno-economic feasibility of bio jet fuel production, covering a broad scope of feedstocks, technologies, and geographical regions (Alves et al., 2017). Although several research activities have been published about 1G-2G generation of bio jet fuel (Klein-Marcuschamer et al., 2013; Diederichs et al., 2016; Alves et al., 2017; Santos et al., 2017), the number of studies considering sugarcane as feedstock is limited.

In addition, upgrading lignin to bio jet was found to increase the complexity of the process without leading to a major reduction in the minimum selling price of the product. It is worth noting that, even considering premium fees, an integrated 1G-2G bio jet fuel from sugarcane did not achieve a minimum selling price competitive with the current fossil fuel prices (Santos et al., 2017) and it was 2-4 folds higher than the market prices (Diederichs et al., 2016). Techno-economic comparison of bio jet fuel production from lignocellulose, vegetable oil, and sugar cane juice (1G-2G) conducted by Diederichs et. al. (2016) proved G-FTs as the best 2G process.

3.2. Biochemicals

Production of chemicals from renewable resources offers a promising opportunity to reduce petroleum dependence, and improve the overall economics and sustainability of an integrated biorefinery. Overall, in petroleum refineries, 15% of the entire barrel of oil is consumed for the production of chemicals, whereas chemicals account for nearly 50% of the refinery profits (Biddy et al., 2016). During the last decade, biochemicals have gained the attention of the researchers and investors because of their respective environmental benefits and economic profitability (Biddy et al., 2016). In the following sub-sections, some remarkable techno-economic studies of sugarcane biorefineries for production of biochemicals are reviewed. The most recent TEA studies on conversion of sugarcane to biochemical/biopolymers are tabulated in **Table 3**.

3.2.1. Lactic acid

Lactic acid (LA) is the most frequently occurring carboxylic acid in nature, which is globally applied in food, pharmaceuticals, personal care products, industrial uses, and polymers (poly-lactic acid; PLA). LA can be produced from both hexoses and pentoses through homofermentative and hetrofermentative pathways, implementing different microorganisms (Gao et al., 2011). Most commercial production of LA is through microbial fermentation of 1G feedstocks (carbohydrates). However, there are a few examples of LA production plant form 2G feedstocks (Biddy et al., 2016). Corbion®, produces LA in a gypsum-free process from 2G feedstocks (Castro-Aguirre et al., 2016).

The results of a TEA study on LA production from sugarcane bagasse and trash, proved that utilization of the whole biomass (pentose and hexoses) for LA production annexed to a sugar mill, through homofermentative pathway was an economically attractive option (Mandegari et al., 2017b). However, further research particularly evaluating the effects of different microorganisms on economic viability of PLA production is necessary.

3.2.2. Succinic acid

Succinic acid ($C_4H_6O_4$) is a linear saturated di-carboxylic acid, considered as a building block for various chemicals, such as personal care products and food additives (used in the food and beverage industry as an acidity regulator), or bio-polymers (for example polybutylene succinate; PBS), plasticizers, polyurethanes, resins, and coatings (Taylor et al., 2015). Although, it is predominantly produced from butane through catalytic hydrogenation of maleic acid or maleic anhydride, its production *via* fermentation is already implemented by a number of industries, such as Bioamber and Reverdia, while several other companies, such as Myriant, BASF, and Purac, are constructing or are about to operate commercial-scale bio succinic acid plants (Koutinas et al., 2014). Bio-based succinic acid is most commonly produced through low pH yeast or bacterial fermentation.

Production of succinic acid from sugarcane bagasse has been investigated by Borges and Pereira, where they reported high conversion yields from sugarcane bagasse hydrolysate (Sindhu et al., 2016). In addition, it has been reported that the implementation of ultrasound pretreatment and hydrolysis of sugarcane bagasse led to succinic acid yields as high as 79% (Sindhu et al., 2016). There are a few techno-economic analyses on succinic acid production from glycerol (Koutinas et al., 2014) or corn stover as well (Luo et al., 2010).

3.2.3. Xylitol

Xylitol, pentahydroxypentane ($C_5H_{12}O_5$), is a sugar alcohol with diverse applications, i.e., sweetener (food and pharmaceutical industries), food preservative agent, antioxidant, moisturizer, stabilizer, and freezing point reducer (Mohamad et al., 2015). Xylitol is industrially-produced from xylan (a hemicellulose) extracted from hardwoods or corncobs, which is hydrolyzed into xylose and then hydrogenated into xylitol in the presence of a catalyst (Taylor et al., 2015). The biochemical/bioprocess alternative, with microbial conversion of xylose to xylitol, has also gained interests, partly due to the "natural" status of products from this route. Due to its application as a diabetic sweetener, its production from biomass has gained an increasing deal of attention and different microorganisms have been developed for its production. The most commonly investigated biomass for xylitol production include corn cobs, sugarcane bagasse, and rice straw, whereas oil palm, *Eucalyptus* wood, and corn leaves have also been examined (Mohamad et al., 2015). Although several microorganisms have been developed for xylitol production, fermentability of lignocellulosic streams and expensive separation of xylitol from fermentation broth are the technological areas which require further research.

Production of xylitol from sugarcane bagasse *via* the biochemical/microbial route has been investigated using dilute acid pretreatment, where post hydrolysis of dilute acid pre-treated hydrolysate

Table 3.
Recent TEA studies conducted on sugarcane with an aim to produce biochemicals/biopolymers.

Location	Feedstock/s	Product/s	Capacity (t cane/h)	Reference
Colombia	Bagasse / Molasses	EtOH/PHB	200	Moncada et al. (2013)
South Africa	Bagasse and trash	EtOH/Butadiene	300	Farzad et al. (2017a)
South Africa	Bagasse and trash	EtOH/Lactic acid	300	Mandegari et al. (2017)
Argentina	Bagasse (hemi fraction)	Furfural/Xyliltol	NA	Clauser et al. (2016)
Brazil	Molasses / Sucrose	BDO	*	Koutinas et al. (2016)

* Production rate of BDO 1.2 t/h.

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increased the xylitol production. The enzymatic production of xylitol from a sugarcane bagasse hydrolysate, as an alternative to conventional fermentation route, was also studied and 100% conversion was reported due to direct transformation of xylose to xylitol (Sindhu et al., 2016). A study on xylitol production from sugarcane straw *via* the biochemical route revealed that the supplementation of an inorganic nitrogen source such as $(NH_4)_2SO_4$, was important for increasing the productivity of the process and the type of nutrients as well as control of the oxygen availability were also necessary for bioprocess production of xylitol from a sugarcane straw hydrolysate (Kamat et al., 2013). Co-production of xylitol with biodiesel or EtOH has also been studied. However, there is a lack of information on the economic assessment of different technologies associating with xylitol production from biomass, specifically sugarcane bagasse.

3.3. Bio-based monomers and biopolymers

Biopolymers are generally considered an eco-friendly alternative to petrochemical polymers due to the renewable feedstock consumption. Furthermore, biodegradable polymers such as PLA, poly-hydroxyalkanoates (PHAs), and starch-based polymers, have been examined as a solution for the future of our planet (Crank et al., 2004). Apart from biodegradability, production of some polymers with high volume consumption from bio-based monomers such as butadiene (BD) and butanediol (BDO) are advantageous (Mussatto and van Loosdrecht, 2016).

3.3.1. Poly-lactic acid (PLA)

PLA is made of lactic acid and can be produced from sugars *via* fermentation. PLA is applied in the form of a bio-based plastic alone, in blends with other polymers, or it can be reinforced with cellulose fibres, mostly in packaging industry and textiles. There are three main methods available to produce PLA from LA including, 1) direct condensation polymerization, 2) direct polycondensation in an azeotropic solution, and 3) polymerization *via* lactide formation (Castro-Aguirre et al., 2016). Although several studies have considered LA production from sugarcane, PLA production is typically not included.

3.3.2. Poly-hydroxyalkanoates (PHAs)

PHAs are linear polyesters produced in nature by direct bacterial fermentation of sugars or lipids. They are produced by the bacteria to store carbon and energy, usually under conditions of physiological stress. A generic process for PHAs produced by bacterial fermentation consists of three basic steps namely fermentation, isolation, and purification followed by blending and palletising (Crank et al., 2004). Although PHAs have attracted widespread interests as alternatives to conventional plastics, their 20–80% higher production cost compared with petrochemical plastics is the key bottleneck (Fernández-Dacosta et al., 2015). Three main factors contribute to this relatively high production costs of PHAs: (i) the energy required for the sterilisation of the fermentation equipment, (ii) the PHAs yield on the substrate, and (iii) the efficiency of the downstream processing (Fernández-Dacosta et al., 2015). Therefore, cheap substrate such as industrial wastewater or activated slug could be promising (Mudliar et al., 2008). The study by Moncada et al. (2013) is one of the rare studies evaluating sugarcane molasses and juice for PHAs production. More specifically, they conducted a techno-economic analysis for a sugarcane biorefinery for different conversion pathways as function of feedstock distribution and technologies for sugar, fuel ethanol, polyhydroxybutyrate (PHB) (a common type of PHAs), anthocyanins, and electricity production. Their results showed that the best economic performance was achieved in a biorefinery producing fuel ethanol and PHB from combined cane bagasse and molasses (Moncada et al., 2013).

3.3.3. Butanediol (BDO)

BDO (1,4-butanediol or 2,3-butanediol) is a four-carbon primary alcohol, considered as a building block for the production of polymers, solvents, and specialty chemicals. Current demands for BDO is just under 2 million metric t/y. Genomatica has successfully demonstrated an integrated process for BDO production utilizing a range of lignocellulosic sugars that has a commercialization potential. Catalytic conversion of succinic acid to BDO is another promising conversion strategy, currently being scaled-up (Biddy et al., 2016). Koutinas et al. (2016) studied techno-economic evaluation of 2,3-butanediol production *via* fermentation, using glycerol, sucrose, and sugarcane molasses as carbon sources. They found that MSP varied from 2.6 to 4.8 USD/kg sugarcane molasses, based on the variation of molasses' price and fixed capital requirement. Considering the market price of BDO reported as 1,800 USD/t to 3,200 USD/t in the year 2013 (Taylor et al., 2015), this process has the potential to be economically profitable.

3.3.4. Butadiene (BD)

BD (1,3-butadiene) is one of the major building blocks used in the production of synthetic rubbers and polymers (Ochoa et al., 2016), with a global demand of 10 million t in the year 2012 (Makshina et al., 2014) and a rapid production growth, specifically in Asia (Sushkevich et al., 2015; Cespi et al., 2016). Polybutadiene (PBR) and styrene-butadiene rubber (SBR) are the main end applications for BD including 54% of total usage in the year 2014. Nowadays, the dominant technology for the production of BD is thermal cracking of naphtha, while catalytic and oxidative dehydrogenation of n-butane is also used on industrial scale (White, 2007). Nevertheless, naphtha still represents the primary material for BD production (55%), followed by ethane (30%) (Cespi et al., 2016). An alternative approach is the production of BD from EtOH applying one-stage (Lebedev) process or two-stage (Ostromisslensky) process. Considering the possibility of EtOH production from 1G and 2G feedstocks, produced BD can be assumed as bio-BD. Farzad et al. (2017b) have developed different scenarios for 2G biorefineries annexed to a sugar mill for BD production *via* a two-step process. Monte Carlo financial risk analysis demonstrated that BD production could be profitable, only if the average of ten-year historical price would increase by 1.9 fold (Farzad et al., 2017b).

4. Conclusions

The environmental challenges and depleting fossil fuel resources necessitate the transition toward bio-based economy. Sugar mills have the opportunities to become biorefineries, based on several feedstock conversion potentials. The easiest of these would be sugars/molasses conversion *via* the biochemical route, while newer 2G technologies for lignocelluloses conversion are also becoming a commercial reality (EtOH, LA, etc.). To emphasise on this possibility, the most recent studies on production of some biofules/biochemical/biopolymers from sugarcane bagasse have been reviewed in this study. Overall, it should be stressed that TEA remains essential to sift through the multitude of technology/product options, and to identify specific product/investment opportunities applicable to specific sugar mills.

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Please cite this article as: Mandegari M.A., Farzad S., Görgens J.F. Recent trends on techno-economic assessment (TEA) of sugarcane biorefineries. Biofuel Research Journal 15 (2017) 704-712. DOI: 10.18331/BRJ2017.4.3.7