Chapter 4

Sugarcane Bagasse Valorization Strategies for Bioethanol and Energy Production

Elias Martinez-Hernandez,
Myriam Adela Amezcua-Allieri,
Jhuma Sadhukhan and Jorge Aburto Anell

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http://dx.doi.org/10.5772/intechopen.72237

Abstract

The use of sugarcane bagasse pith as solid substrate for fungi and microbial growth is well known, as well as a source of microorganisms that can be isolated from it. Pith has also been used as a bulking agent for soil bioremediation. More recently, bagasse pith has been used for bioethanol production involving pretreatment and hydrolysis followed by fermentation and dehydration. However, little is reported about biomass valorization for the development of environmentally sound and innovative strategies to process sugarcane bagasse from sugar mills. Incineration of sugarcane bagasse pith is a very common and mature technology for waste disposal and generation of electrical and thermal energy. However, this approach may not be satisfactory in organic waste management due to pollutant emissions, economic and labor costs, loss of energy, and bad odor. In addition, no valuable product is generated from its decomposition process. Instead of incineration, recent research has focused on its utilization as biofuel source. In this chapter, the use of sugarcane bagasse pith as a waste material for incineration versus biomass to produce bioethanol is discussed in terms of energy ratio and emissions, in addition to elucidate the potential of sugarcane bagasse valorization for a more sustainable society.

Keywords: lignocellulosic materials, lignin, biorefinery, bioeconomy, heat and thermal power, bio-based chemicals, biofuels

1. Introduction

Sugarcane is one of the most widely cultivated crops in the world, with the major producing countries being in the tropics, including Brazil, India, China, Thailand, Pakistan and Mexico.

The extraction of sugar from this crop generates several residues that are often disposed improperly especially where sugar mills use basic process technology. The huge quantities of solid waste are often destroyed or burned inefficiently causing environmental pollution [1]. Sugarcane solid residues include bagasse and filter cake. Bagasse is the solid residue resulting after the juice extraction from the sugarcane stalks and contains the fibrous lignocellulosic material of the stalks. The precipitate in the form of sludge slurry after filtration of the sugarcane juice is the filter cake. Every 1000 tons of processed sugarcane generates about 270 tons of bagasse and 34 tons of cake [2]. Approximately, 1.81 billion tons of sugarcane were produced worldwide in 2015, and this is expected to reach more than 2.21 billion tons by 2024 [3]. Based on these values, the world's potential generation of sugarcane bagasse will reach 0.6 billion tons, which could be valorized into bioenergy, biofuels, and other products.

The expected increase in bagasse availability is driven by the increasing demand for sugar, and sugarcane is the most important source of sugar in the world. However, sugar industries are one of the most polluting ones in view of the generated solid wastes, wastewater, and gaseous emissions of carbon monoxide, volatile organic compounds, and also greenhouse gases during crop cultivation phase [1]. Transforming all by-products obtained from sugar mills (bagasse, filter mud, fly ash and molasses) into value-added products will minimize the pollution to a large extent. Treating sugar industry effluent for reuse in agriculture and other applications is another strategy to reduce the environmental impacts. In summary, sugar industry wastes should be seen as economic resources that can be converted into valuable products in progressing toward resource recovery as a sustainable solution that could generate social welfare and economic development from the sugarcane industry and its residues. In this chapter, the use of sugarcane bagasse as a raw material for energy generation versus bioethanol production is discussed.

2. Uses and trends for sugarcane bagasse valorization

Bagasse consists of fibers (48%), water (50%) and soluble solids such as sugars (2%) [4]. Bagasse is an important lignocellulosic material containing cellulose 42%, hemicellulose 28%, lignin 20%, 4.6% of other polysaccharides, 3% of saccharose and 2.4% of ash, on a dry weight basis [5]. Lignocellulosic biomass has been used to produce second-generation ethanol and other by-products such as xylitol by sugarcane agroindustries. Various energy products can be generated from the lignocellulosic composition using biochemical and thermochemical processes. For example, sugarcane bagasse is an economically viable and promising raw material for bioethanol and biomethane production [6, 7]. Bagasse is typically used to produce heat and electricity in sugar mills (cogeneration), but can also be used for paper making, as cattle feed and for manufacturing of disposable food containers. Currently, bagasse is mainly used as a fuel in the sugarcane industry to satisfy its own energy requirements. However, there is a surplus of this bagasse which could be diverted to other uses such as the production of single cell protein, ethanol, enzymes and food additives such as vanillin [8] and xylitol [9, 10]. The sugarcane bagasse surplus is used in more than 40 different applications, including pulp and paper, boards, animal feed, and furfural [11, 12]. **Figure 1** shows some of the various uses of the sugarcane bagasse.

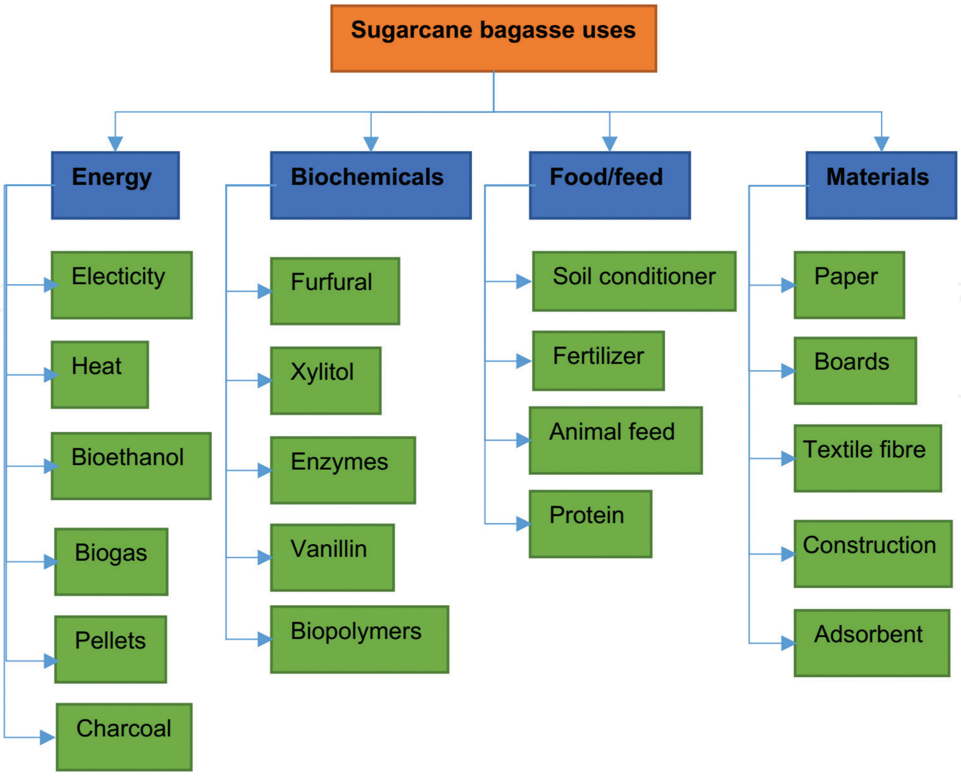

Figure 1. Uses of sugarcane bagasse in energy, biochemical, food and feed, and materials applications.

Bagasse is used as a more sustainable source of diverse paper products including toilet, tissue, corrugating medium, news print and writing paper [13–15]. Poopak and Reza described the process of paper making which starts by separating bagasse fibers from the pith by mixing it with water and using a dewatering unit [15]. Fibers are then cooked approximately 10–15 min in a steam boiler, where a black liquor or pulp remains in container. This pulp is washed to remove the color and then sand and undesired fibers are removed by screening and cleaning. Afterwards, pulp thickening reduces the water to about 12%, and it is further processed for whitening the pulp by using chlorine gas and NaOH. This pulp is then ready to supply to a paper mill where the pulp will go through several processes to create paper products. The use of sugarcane bagasse as a renewable raw material can be a sustainable option to reduce deforestation and impacts of the pulp and paper industry.

Charcoal from sugarcane bagasse is another possible source of heating and cogeneration of energy, and can be produced according to the following simplified process [1]. Bagasse is collected and passed through a pyrolysis step where it gets fully carbonized. The resulting powder is mixed with a binding material such as starch and then boiled with water so that it can be extruded to form briquettes or other desirable shapes of charcoal to be sold as a solid fuel.

Recent trends in the use of sugarcane bagasse include new and improved applications in the areas of materials. For example, the bagasse has been used as an excellent soil conditioner to improve sugarcane plant productivity and health [16]. Sugarcane bagasse can also be used for products that improve the durability and mechanical properties of construction materials and as a binder [17]. The bagasse fibers can also be conditioned to be used in the textile industry [18], and as an effective adsorbent material to remove toxic metals and dyes from wastewater [19, 20]. More recently, sugarcane bagasse has been used as a raw material to produce carbon quantum dots which can be used as biosensors in light-emitting diodes and even in drug delivery [21]. This chapter concerns the two most common applications of energy and bioethanol production from sugarcane bagasse, which are described in the following sections.

3. Sugarcane bagasse incineration for energy generation in sugar mills

Burning or incineration in a boiler for steam generation is the most common application of bagasse using a cogeneration system for steam and power generation [22]. This allows supplying heat and power to the sugar and ethanol process and exporting any excess. In countries such as Brazil, where sugarcane industry is well developed, power generation has been largely supported by the government incentives and can be a major revenue component, after sugar and ethanol sales. **Figure 2** shows the two simplified typical cogeneration systems used.

The backpressure steam turbine (BPST) system in **Figure 2a** is more common. In this system, only the amount of bagasse necessary to match the heat required for the process is burned, thus leaving some excess bagasse that can be used for other purposes or needs to be disposed of. The steam is produced from water treated to remove some minerals and is called boiler feed water. The less efficient old systems generate steam at medium pressure of 22 bar and a temperature of 300°C, while the most modern systems can operate at up to 100 bar and 530°C [22]. The steam is then passed through the BPST with a discharge pressure of 2.5 bar and 140°C to meet the low-pressure steam required by the sugar refinery. The condensing

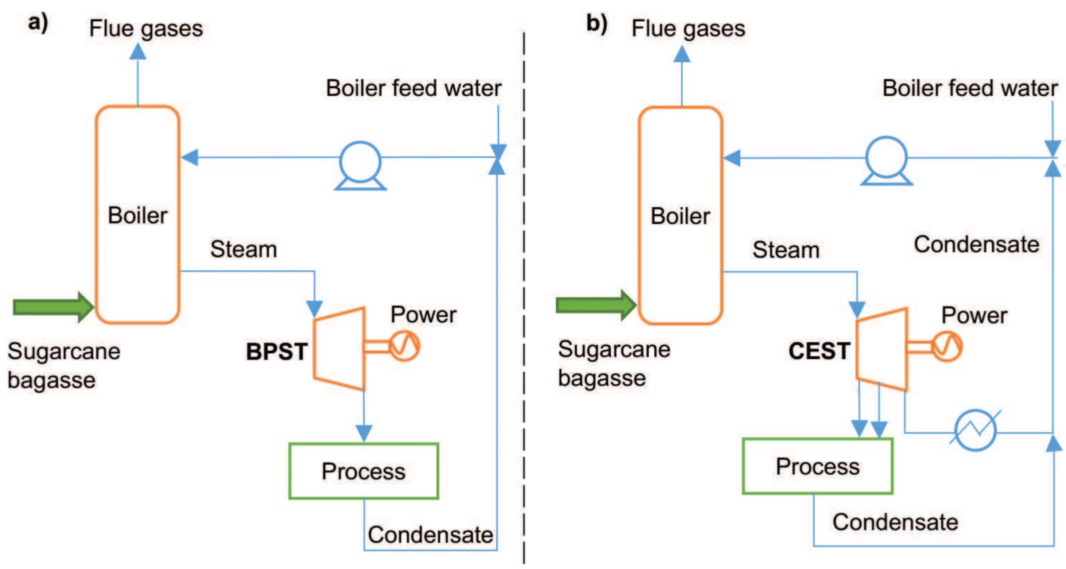

Figure 2. Typical cogeneration systems in sugarcane refineries using (a) a backpressure steam turbine (BPST) and (b) a condensing extraction steam turbine (CEST).

extraction steam turbine (CEST) system in **Figure 2b** is more complex and more expensive than BPST, but achieves higher efficiencies and higher electricity surplus, have more flexibility and can operate the whole year. In this system, the high-pressure steam can be expanded at different lower pressure levels and extract the steam required for process or produce further electricity. Typically, the high-pressure steam is at 65–100 bar and can be expanded at 22 and 2.5 bar with a final condensing stage at 0.135 bar.

4. Valorization of sugarcane bagasse for bioethanol production

The use of sugarcane bagasse for bioethanol production has been extensively researched in recent years [23, 24]. The processing of sugarcane starts with the cleaning of sugarcane and extraction of sugars: juice treatment, concentration and sterilization [25]. Sugar extraction is carried out using mills to produce a sugarcane juice which follows a series of treatment, clarification and dewatering until the crystallization and centrifugation of sugar crystals. The production of ethanol from the juice, molasses or bagasse includes additional processing units of fermentation, that is, distillation and dehydration.

Ethanol can be prepared by the fermentation of molasses which contain 60% of fermentable sugars as described in [1]. Molasses is first diluted with water in 1:5 (molasses/water) ratio by volume. If molasses lack sufficient amount of nitrogen, it is fortified with ammonium sulfate to provide adequate supply of nitrogen to yeasts. Fortified solution of molasses is then acidified with a small quantity of sulfuric acid. The addition of acid favors the growth of yeasts and hinders the growth of unwanted bacteria. The resulting solution is then transferred to a large tank, and yeast is added to it at 30°C and left to ferment for 2–3 days. During this period, sucrase and zymase present in yeasts convert the sugars in molasses into ethanol according to the following simplified chemical reactions [26]:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6 \tag{1}$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \tag{2}$$

The alcohol concentration in the fermentation broth is only 15–18%. The broth is sent to a distillation system to obtain 92% pure alcohol, also known as rectified spirit or commercial alcohol. A further purification step by molecular sieves or pervaporation is needed to produce anhydrous bioethanol for blending with gasoline.

An additional pretreatment step is needed in the production of bioethanol from bagasse. Pretreatment of the sugarcane bagasse is important because it helps to separate lignin and hemicellulose from cellulose, reduce cellulose crystallinity and increase the porosity of bagasse, thus improving cellulose hydrolysis [27]. Lignocelluloses are made up of three main polymer types: lignin encasing cellulose in cell walls provides rigidity of cell walls, hemicelluloses cover the cellulose and strengthen cell walls by interaction between lignin and cellulose, while encased cellulose microfibrils gives tensile strength to cell walls [28]. Celluloses and hemicelluloses are polysaccharides of C6 and C5 monomers, respectively, connected by β-(1–4)-glycosidic linkages. The main lignin compounds are polymers of para-hydroxyphenyl (H lignin), guaiacyl (G lignin) and syringyl (S lignin) alcohol. Pretreatment liberates hemicelluloses first because these are hydrolyzed at a faster rate. Liberation of hemicellulose separates lignin and cellulose. β-(1–4)-glycosidic linkages are broken down by pretreatment, liberating glucose from celluloses. The various methods for pretreatment of lignocellulosic materials such as sugarcane bagasse include acid hydrolysis, alkaline hydrolysis, steam or ammonia fiber expansion, organosolv, enzymatic hydrolysis, microwave and ultrasonication, and thereof combinations between these. The most common method is the dilute acid. Ozonolysis has also been used to pretreat sugarcane and agave bagasse [5].

Table 1 shows values for bioethanol yields reported for various systems. The key to high ethanol yield is to enable the conversion of both hexoses and pentoses into ethanol. This requires the search for new microorganisms and their metabolic engineering. A leading second-generation bioethanol plant using sugarcane bagasse is operating in Brazil by the company Raizen, a joint venture between Shell and Cosan. This highly advanced integrated facility is able to boost bioethanol production by up to 50%, in addition to the first-generation plant and without expanding cultivation land use. The use of bagasse and straws allows production even during off-season for sugarcane harvest. The progressive scaling-up has allowed producing 7 million liters in its first year and planned to reach a groundbreaking 40 million liters by 2018 [29].

Ethanol is used as an alternative energy source in top sugarcane-producing countries such as Brazil, India and China. World production of ethanol in 2013 was about 89 GL, with 74% of the world supply coming from Brazil and the USA [1]. The increasing biofuel production causes an increase in the biomass demand for energy purposes, which poses the challenge of the fuel versus food dilemma. The use of biomass has also raised some questions about the real benefits to decrease environmental impacts of the bioenergy systems that seek to replace fossil fuels due to the greenhouse gas emissions generated during crop cultivation and processing. To avoid unintended consequences and the translocation of issues of using biomass resources, a comprehensive analysis taking into account emissions and externalities related to energy and material consumption in the whole life cycle of sugarcane-based bioenergy systems is essential to ensure their sustainability.

System	Total electricity production (GJ/t)	Steam production for process (GJ/t)	Total (GJ/t)	Energy ratio (output/input)	Direct process emissions (kg CO_2/GJ)
BPST system	0.854	2.9	3.75	0.20	118.8
CEST system	1.507	2.9	4.4	0.24	101.2

Table 1. Energy ratio and direct process CO_2 emissions for bagasse use in power generation.

5. Energy balance and emissions

The current major use of sugarcane bagasse is for power supply in sugar refineries, making this facilities energy self-sufficient. Depending on the process configuration and energy requirements, some of them even export electricity to grid due to the excess bagasse available [23]. As commented in the previous section, an alternative use extensively researched nowadays is in bioethanol production [24]. In this section, the energy balance and emissions of the two alternative uses of bagasse are discussed. The indicator used to compare energy balance is the energy ratio which is defined as the energy output per unit of energy input. Energy input includes the energy originally contained in the bagasse based on its higher heating value. In the case of bagasse for power generation, the only input is the bagasse itself, in the case of the bioethanol production, the input also includes steam and electricity to run the second-generation bioethanol plant.

To perform an energy balance using sugarcane for power generation, it is necessary to know the amount of steam and electricity required for the main sugar factory process. A typical electricity demand is 28 kWh/t cane and the process steam consumption of 500 kg/cane with low efficiency factory, or about 280–340 kg/t cane for modern efficient factories [33]. The balance also depends on the pressure at which the steam is generated and fed to the turbines. Using data from [22], the energy balance of a BST and CEST system on the basis of 1 ton of bagasse is shown in **Table 2**. Current efficiencies are quite low, only 20–24% and, as expected, the CEST system performs better with higher energy ratio and lower CO_2 emissions per GJ of energy delivered. These values can be improved further through reduction of steam required in the sugar factory by better energy integration as well as by replacing old equipment with more efficient one. Highly efficient cogeneration systems can achieve up to more than 80% efficiency. Improvements can lead to a significant amount of surplus bagasse becoming available for other purposes such as production of bioethanol. In such a case, approximately 50% of the bagasse is sufficient to supply the energy needs of sugar mills [33].

Given the wide availability of bagasse as an agroindustrial residue, its use for bioethanol production has been widely investigated. The energy balance for this process may be less favorable as the ethanol yields can be relatively low and may require additional energy inputs. Strategies to achieve higher efficiencies in integrated systems combine (1) higher ethanol production can be achieved by the proper pretreatment and hexoses and pentoses fermentation

System	Ethanol yield (L/t bagasse)	Reference
Pretreatment + enzymatic hydrolysis	149.3	[30]
Two-stage dilute acid pretreatment + organosolv	192	[31]
With pentoses also fermented to ethanol	335	[32]

Table 2. Reported bioethanol yields from sugarcane bagasse.

process and (2) the lignin and solid residuals are used for energy production. This can be achieved by adopting a biorefinery concept in which several process technologies are combined to convert biomass into multiple products [28]. A simplified diagram of an integrated biorefinery system is shown in **Figure 3**.

Table 3 shows the energy ratios reported for several integrated bioethanol processes in biorefineries. It can be observed that an energy ratio of up to 0.5 can be achieved using a simultaneous saccharification and fermentation process, including strategies (1) and (2) aforementioned. Energy integration using pinch analysis is also essential to reduce process utility requirements and increase energy efficiency [35, 37].

It is important to examine the life cycle emissions as the bioethanol process uses additional inputs, including enzymes, nutrients, salts, neutralizers, and so on. An average value of 6.2 kg CO_2/kg ethanol has been reported [35]. More comprehensive results of life cycle assessment environmental impacts are shown in **Table 4** for the impact categories of global warming potential (GWP-100 years), abiotic resource depletion (fossil fuels), eutrophication and acidification potentials of the integrated biorefinery system in **Figure 3**. These results show that the amount of GWP can be negative due to the savings by replacing fossil fuels by ethanol and grid electricity by the power generated from lignin and biogas.

Comparing the two options for bagasse utilization, a study shows that the use of bagasse for power generation results in lower global warming, acidification and eutrophication potentials, whereas the bioethanol production provides resource conservation (by replacing fossil fuel) and lower human- and eco-toxicity [33]. In terms of energy balance, with the use of advanced technologies and process integration, both systems are able to achieve high efficiency level up to 50% in the bioethanol case. Up to 65% of the energy from bagasse incineration can be recovered by the biorefinery system in **Figure 3**, while only 32–33% of the energy is recovered by stand-alone bioethanol production [39]. Therefore, the use of multistage steam condensing turbines, efficient boilers, as well as the integrated first-generation + second-generation system with energy recovery from solid residues and biogas from wastewater treatment is highly recommendable to achieve high efficiency levels and environmental benefits from sugarcane bagasse and sugarcane as an energy crop.

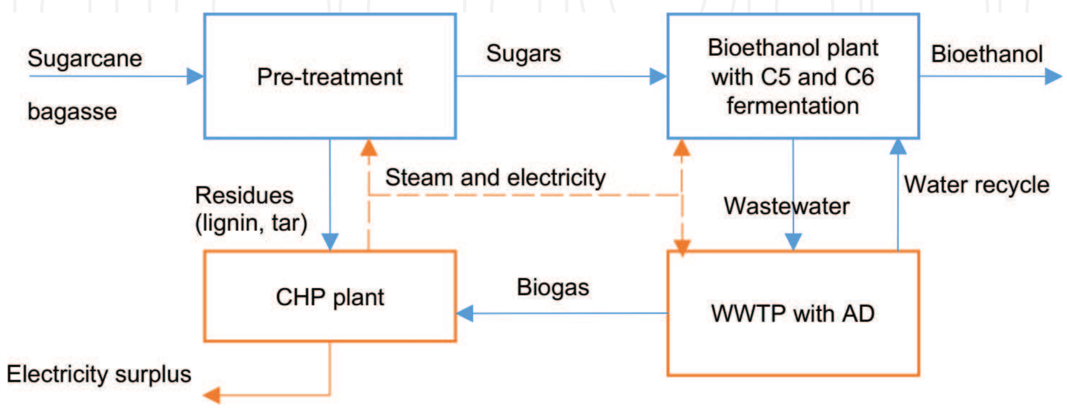

Figure 3. Integrated system for bioethanol production from sugarcane bagasse.

System	Reference	Energy ratio
Separate hydrolysis and fermentation	[34]	0.474
Separate hydrolysis and fermentation	[35]	0.419
Separate hydrolysis and fermentation	[35]	0.391
Simultaneous saccharification and fermentation	[36]	0.5
Simultaneous saccharification and fermentation	[35]	0.438

Table 3. Energy ratios reported for second-generation bioethanol production.

Impact category	Abiotic resource depletion (fossil fuels), MJ/t biomass	Global Warming Potential kg CO_2-eq/t biomass	Acidification, kg SO_2/t biomass	Eutrophication, kg PO_4^{3-}/t biomass
Value	1586.16	−176.29	0.46	0.03

Table 4. Life cycle assessment (LCA) results for bioethanol production from sugarcane bagasse [38].

A flexible biorefinery that can adapt production to electricity and bioethanol can be more effective and achieve economic profitability [40]. Integrated first- and second-generation ethanol production process from sugarcane leads to better economic results, especially when advanced hydrolysis technologies and pentoses fermentation are included [32]. Novel ethanol separation and purification processes such as a combination of vacuum, atmospheric and extractive distillation systems for efficient dehydration of ethanol will also help to improve the feasibility of the bioethanol route from bagasse [41]. Other sugarcane bagasse biorefinery concepts have also been studied for production of bioethanol, methane and heat [39], as well as for chemicals, electricity and fuels with succinic acid being competitive in comparison to the petrochemical-based products [42]. Thermochemical processes via gasification and Fischer Tropsch process [23], as well as gasification for cleaner electricity production from syngas has also been reported [43]. A simultaneous economic and environmental impact assessment of biorefinery systems should be performed to enable an informed decision-making as to which process technology to adopt [44].

Although there is no clear winner in terms of energy balance and emissions, the current market has made the use of bagasse for power generation as the focus of some companies to make profits from sales for the grid. Other leading companies, such as Raizen Energy in Brazil, consider second-generation ethanol from the bagasse as a more attractive option [45].

6. Final remarks

Sugarcane mills are one of the major industrial facilities in tropical and developing countries, generating income and jobs in the rural agricultural sector. These important industrial systems are evolving from single product process producing sugar to sweeten drinks and food, to sugar and bioenergy generation in the form of electricity and also biofuels. The valorization of sugarcane bagasse as a resource for energy and bioethanol production has been reviewed in this chapter from the perspective of energy ratio and emissions. Trade-offs between the two bagasse applications have been found with incineration for power generation being favorable toward reducing potential impacts of global warming while bioethanol being more favorable toward resource conservation and lower toxicity. Advanced integrated biorefineries can achieve energy ratios similar to those in incineration for power-only systems, especially if second-generation bioethanol production from cellulose and hemicellulose and electricity from lignin are combined in the sugar mill facilities. Sugarcane mills have the potential to be retrofitted and converted into advanced biorefineries being energy self-sufficient and co-producing other value-added products from sugarcane bagasse in a wide range of applications such as energy, biochemicals, food and feed and materials sectors. Comprehensive energetic, economic and environmental assessment of the various alternative uses and process technologies need to be carried out considering the various efficiencies of the value chain, from cultivation to processing and end use, in order to find the best alternative in a given socioeconomic context.

Author details

Elias Martinez-Hernandez[1], Myriam Adela Amezcua-Allieri[1]*, Jhuma Sadhukhan[2] and Jorge Aburto Anell[1]

*Address all correspondence to: mamezcua@imp.mx

1 Biomass Conversion Division, Instituto Mexicano del Petróleo, Mexico City, Mexico

2 Centre for Environment and Sustainability, University of Surrey, Guildford, UK

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