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Integrated First and Second Generation Ethanol Production from Sugarcane

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Efficient conversion of biomass into energy resources remains one of the biggest challenges faced by humanity in the search for a sustainable energy future. Bioethanol, the most important biofuel, currently produced from first generation feedstock like sugarcane may also be produced from lignocellulosic materials like sugarcane bagasse and straw, which are not a primary food source. Efficient technologies for production of lignocellulosic (or second generation) ethanol, however, are still under development, and challenges concerning its technical, economic and environmental feasibility remain to be solved. Integration of first and second generation ethanol production processes can be more economical, efficient and present lower environmental impacts than stand-alone second generation; thus, integrated first and second generation ethanol production can improve the feasibility of lignocellulosic ethanol and foster its industrial implementation.

In this study the integrated production of first and second generation ethanol from sugarcane, including some of its technical, economic and environmental aspects are discussed. The biochemical route for second generation ethanol production, comprised by feedstock pretreatment and enzymatic hydrolysis, is taken as an example. Features of both first and second generation processes that are required to promote an adequate integration are discussed, providing guidance for development of experimental works, especially in second generation process.

1. Introduction

Sugarcane is currently the most efficient crop for ethanol production, and the feedstock for second generation ethanol (sugarcane bagasse and straw) is also available at plant site (Palacios-Bereche et al., 2011). These lignocellulosic feedstocks have either been sold or used for electricity production in Brazil, but may be used for second generation ethanol production; besides, some commercial lignocellulosic ethanol production units are starting to operate. Efficient processes from conversion of lignocellulosic materials to ethanol, however, remain to be developed (Barakat et al., 2014). Second generation ethanol production can be more competitive when considering its integration to a first generation distillery (Palacios-Bereche et al., 2011).

Since sugarcane bagasse is currently used as fuel for production of steam and electricity, second generation ethanol production from sugarcane bagasse may compete with its current use as a fuel (Dias et al., 2011a), so the configuration of the conventional production process must be adapted to include second generation ethanol production while guaranteeing self-sufficiency in energy and steam production. Therefore, unit operations of the first generation ethanol production process from sugarcane should be redesigned in order to increase feasibility of integration of a second generation ethanol production from

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sugarcane bagasse and straw. These operations and the most suitable characteristics of a second generation ethanol production from sugarcane bagasse and straw integrated to a first generation biorefinery are discussed in this paper.

2. First generation ethanol production from sugarcane

First generation ethanol production from sugarcane in an autonomous distillery consists of sugarcane cleaning and preparation, extraction of sugars, juice treatment, concentration and fermentation, distillation, dehydration and cogeneration, as described by Junqueira et al. (2011). Integrating second generation into this plant requires that steam demand of the first generation process be reduced, since the fuel is the feedstock for second generation; therefore, unit operations must be optimized regarding their energy consumption. The most important operations regarding this energy savings are described in sections 2.1 to 2.3. Cogeneration is a critical step of the integrated process and is also detailed in section 4.

2.1 Juice extraction and treatment

Juice extraction in Brazil is mainly carried out using mills, where sugarcane is pressed and split in two streams (juice and bagasse). Mills and other equipment in the section are usually driven by steam turbines, which require more energy as steam than electric energy in efficient electric engines. Therefore, electric engines are preferable for integrated first and second generation ethanol production processes. Diffusers can also be used in juice extraction with increased sugar recovery and less energy consumption than the mills (Palacios-Bereche et al., 2013).

In juice treatment, after impurities removal, juice is concentrated to achieve an adequate sugar concentration for fermentation. In ethanol production, standard evaporators are usually employed for juice concentration, but multiple effect evaporators have lower steam consumption (Dias et al., 2012a).

2.2 Alcoholic fermentation

Conventional fed batch or continuous fermentation processes are employed in ethanol production in Brazil; these processes lead to low ethanol concentration in the wine due to inhibitory effects, as described by Junqueira et al. (2009). Alternative fermentation processes such as low temperature and vacuum extractive fermentation decrease yeast inhibition towards ethanol and allow a more concentrated substrate, thus producing wine with higher ethanol content (Dias et al., 2012b) and decreasing energy consumption in the subsequent purification step, as well as vinasse generation. In the integrated first and second generation process, the amount of vinasse produced will be considerably higher than in conventional first generation plants, so its transportation to the field and use in fertirrigation can become a larger problem if no actions to reduce the amount produced are implemented.

2.3 Distillation and dehydration

In order to be used as a fuel, ethanol must be purified to at least 92.8 wt% (hydrated ethanol, used in neat ethanol engines) or around 99.3 wt% (anhydrous ethanol, mixed with gasoline). Since ethanol and water form an azeotrope with concentration around 95 wt%, distillation is used to produce hydrated ethanol, but alternative separation processes must be used to produce anhydrous ethanol.

Distillation is responsible for an important fraction of the steam consumption in ethanol production (Dias et al., 2011b). Multiple effect distillation systems allow thermal integration between columns reboilers and condensers, therefore decreasing energy consumption (Junqueira et al., 2009).

Alternative dehydration processes such as adsorption on molecular sieves have been used in new plants in Brazil, replacing energy intensive azeotropic distillation with cyclohexane. New processes based on membranes pervaporation tend to promote further reduction in steam consumption, if compared with molecular sieves adsorption, but membranes cost still hinders their use (Abels et al., 2013).

3. Second generation ethanol production from sugarcane bagasse and straw

Different processes may be used to convert sugarcane bagasse and straw to ethanol and other biofuels: gasification and pyrolysis are some of the thermochemical routes in which high temperatures are employed, while hydrolysis represents the biochemical route, in which cellulose is converted to glucose (and further converted to ethanol) using acid or enzymes prior to fermentation of sugars. Different authors have shown that integrating either thermochemical (Čuček et al., 2011) or biochemical (Palacios-Bereche et al., 2013) routes increases ethanol production significantly, when compared with first generation ethanol production from sugarcane and other feedstocks (Walter and Ensinas, 2010). Each route has its advantages and drawbacks; some of their main aspects are indicated in Table 1.

In this study the biochemical route for production of ethanol is discussed, since it has been intensely investigated in Brazil for conversion of sugarcane bagasse into ethanol and appears to be the most convenient way to use existing first generation ethanol facilities. In this route the lignocellulosic feedstock (surplus sugarcane bagasse and straw) undergo pretreatment to increase cellulose accessibility in the subsequent hydrolysis stage and also (partially) separate xylose obtained from hemicellulose degradation.

Table 1: Features of thermochemical and biochemical routes for biofuels production from lignocellulosic materials – adapted from (Damartzis and Zabaniotou, 2011) and (Kokossis and Yang, 2010)

	Thermochemical route	Biochemical route
Advantages	Robust technologies	High conversion and selectivity
	Flexibility in feedstock	Mild operation conditions
	Diversity of products	Unreacted lignin can be used as fuel
	Possibility of thermal integration with first generation ethanol production	Possibility of sharing infrastructure with first generation ethanol production (fermentation and distillation)
Drawbacks	Lack of efficient catalysts for selected products	Sugar degradation and energy consumption in pretreatment operations
	Gas cleaning in gasification prior to synthesis	Lack of efficient microorganisms for simultaneous C5 and C6 fermentation
	Extreme operating conditions	High enzymes costs

3.1 Lignocellulosic material pretreatment

Dilute acid, liquid hot water (hydrothermal), steam explosion and organosolv pretreatments have been investigated and constitute promising alternatives for sugarcane bagasse pretreatment. For use in the integrated first and second generation ethanol production process from sugarcane, the pretreatment operations should focus on four main aspects: reduced energy consumption, especially steam; decreased sugar losses; low solvent use; use of high solids loading. Additionally, care has to be taken with the inhibitors formation which will impact fermentation performance. Pretreatment research usually focuses on sugar yield, at the expense of energy, solvent and water use (Alvira et al., 2010). It must be taken in mind that in the integrated process the amount of feedstock processed will be extremely large (thousands of tons per day), so solvent and water use can have a significant impact in the environmental and economic sustainability of the process unless they are recovered and reused in the process. High energy use in the pretreatment operations can decrease the amount of feedstock available for second generation ethanol production, since sugarcane bagasse is the fuel used to supply thermal energy for the process. Dias et al. (2013) showed that the use of an additional delignification step after steam explosion pretreatment decreases overall ethanol production in the integrated process, in spite of increasing enzymatic hydrolysis yields, due to its high energy consumption.

During pretreatment, hemicellulose is usually converted to pentoses, while lignin structure is altered and cellulose remains mostly intact. Monomeric sugars released can undergo degradation, producing furfural and hydroxymethylfurfural depending on process conditions. A solid-liquid separation can be used to remove soluble solids (mostly pentoses) from the cellulignin mixture. This is typical of hydrothermal acid catalyzed pretreatment.

3.2 Cellulose hydrolysis

Enzymatic hydrolysis has been the preferred method for cellulose hydrolysis, producing monomeric C6 sugars (glucose); the alternative process (acid hydrolysis) requires relatively high temperature and produces fermentation inhibitors generated in sugar degradation, besides requiring corrosion-resistant equipment. Enzymatic hydrolysis is also more specific and high conversion rates can be achieved in long reaction times (48 – 72 h). Research in this area usually focuses on obtaining very high yields, mostly at the expense of long reaction times, using high enzymes and low solids loading. In the integrated process, enzymatic hydrolysis does not necessarily require maximum cellulose conversion; low solids loading with high conversion does not necessarily lead to the highest overall ethanol production in the integrated process, since it leads to high energy consumption in the subsequent concentration step (Dias et al., 2013a). On the other hand, high solids loading may require significant power for mixing. In addition, unreacted cellulose (along with lignin) can be used as fuels to produce steam for the process, thus displacing more sugarcane bagasse and straw for use as feedstock. Taking into consideration that most of the cellulose is converted under 24 h (Stephen et al., 2012), short reaction times can be beneficial for the integrated process. Similarly to pretreatment, a solid-liquid separation step can be carried out to remove unreacted solids from the glucose liquor.

3.3 Fermentation

Glucose produced in enzymatic hydrolysis can be fermented in a mixture with sugarcane juice, since it is consumed by *Saccharomyces cerevisiae* (the yeast used in conventional fermentation); hence, eventual inhibitors generated during pretreatment are diluted in sugarcane juice and do not affect fermentation yields. Fermentation of pure hydrolysate has shown to be less efficient than fermentation of this mixture (Andrade et al., 2013). Pentoses sugars obtained after pretreatment from the hemicellulosic fraction, however, cannot be fermented by the same yeast, requiring alternative microorganisms to be converted to ethanol. An alternative to fermentation, biodigestion can be used to produce biogas from pentoses sugars, producing additional energy that can displace more lignocellulosic materials to be used as feedstock in second generation process; it has been shown, however, that pentoses fermentation to ethanol is crucial for the economics of the integrated process (Dias et al., 2011a), but it has a great impact in the process steam demand due to its concentration prior to fermentation (Furlan et al., 2012). Pentoses can also be used as feedstock for other chemicals production such as butanol (Mariano et al., 2013), beyond others. After fermentation, ethanol produced is purified in the same processes used for conventional first generation ethanol production.

4. Cogeneration

In the integrated first and second generation ethanol production from sugarcane, sugarcane bagasse, straw and hydrolysis residues (unreacted cellulose, hemicellulose and lignin) can be used as fuels (if pentoses are biodigested, biogas can also be used as fuel). Therefore, efficient boilers that can use different fuels should be employed for production of steam and electricity. High pressure boilers (up to 100 bar) can be used to produce high pressure steam, which drives turbines and produce large amounts of electricity. Lower pressure boilers (22 – 42 bar), on the other hand, require less bagasse to generate the same amount of steam than high pressure boilers, at the expense of generating less electricity. In the integrated process, larger amounts of ethanol can be produced if modern and efficient, low pressure boilers are employed, since more bagasse could be available for use as feedstock. However, decrease in electricity production could outweigh the gains in ethanol production, comparing with high pressure boilers, depending on relative ethanol: bioelectricity market prices (Dias et al., 2013b).

5. Integrated first and second generation

The amount of lignocellulosic material available to be used as feedstock for second generation ethanol production depends both on process steam demand, which is determined by process operations described in sections 2 and 3, and on the cogeneration system. Therefore, the choice of the cogeneration system has a major impact on the performance of the integrated process.

A simplified scheme of the integrated first and second generation ethanol production process from sugarcane is shown in Figure 1.

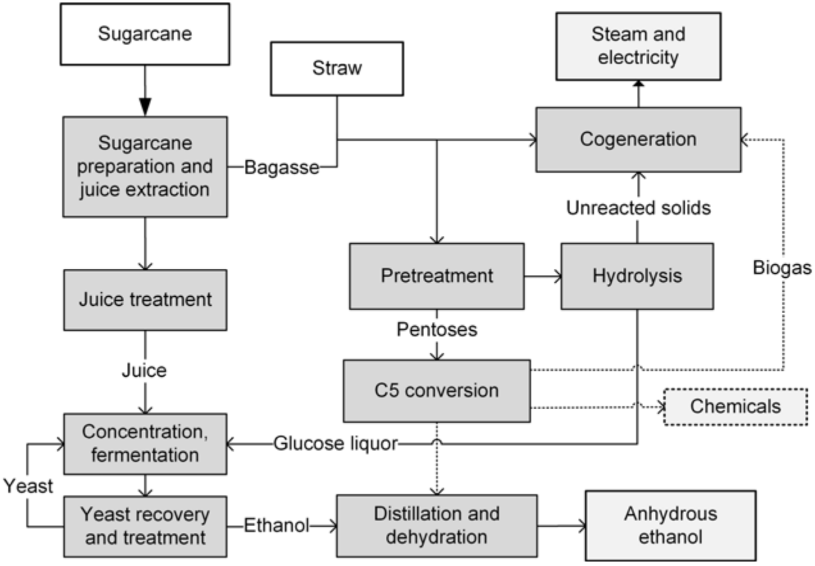

Figure 1: Simplified scheme of the integrated first (1G) and second (2G) ethanol production process from sugarcane

6. Economic and environmental aspects of integrated first and second generation

Second generation ethanol production through the biochemical route, integrated to a first generation sugarcane biorefinery, has several economic benefits when compared with stand-alone second generation units: reduced CAPEX (capital expenditure) due to the possibility of sharing infrastructure (fermentation, distillation, cogeneration and storage); possibility of reduced enzymes use, since unreacted solids from hydrolysis can be burnt and displace sugarcane bagasse and straw to be used as feedstock (thus decreasing enzyme costs); lower transportation costs for feedstock since it is already available at plant site.

Even though the agricultural phase is responsible for most of the environmental impacts of ethanol production, it was shown that process improvements such as the ones highlighted in this study can significantly decrease environmental impacts of sugarcane biorefineries. Therefore, integrating first and second generation can potentially reduce environmental impacts of bioethanol production from sugarcane in comparison to current first generation process (Cavalett et al., 2012), since a more intensified and extensive use of biomass is carried out.

7. Current projects in Brazil

Several companies are building plants for second generation ethanol production from sugarcane in Brazil: Granbio was the first company to announce a second generation plant in Brazil, to be completed in 2014 with production of 82 million litres of ethanol from sugarcane bagasse per year (Granbio, 2013); CTC, Odebrecht Agroindustrial, Raízen, Petrobras and other companies are also building demonstration and pilot scale plants (UNICA, 2013), most in partnership with European and North American companies. These plants will support technology development and cost reduction, starting second generation learning curve. Since some plants will be integrated with current first generation mills, aspects of their integration will also be better understood at demonstration and commercial scale.

8. Conclusions

Second generation ethanol production is not yet commercially feasible; first demonstration and commercial plants for second generation ethanol production from sugarcane bagasse and straw are under construction in Brazil. Integrating first and second generation from sugarcane seems an obvious choice, since feedstock is already available at current bioethanol production facilities. However, since sugarcane bagasse is currently used as a fuel in the process, current first generation bioethanol production must be improved in order to increase feedstock availability for second generation. Challenges regarding the technical, economic and environmental performances of the integrated first and second generation ethanol production process from sugarcane were highlighted in this study, and the main aspects of the most suitable process alternatives were introduced and discussed. These aspects must be included in research seeking the production of future sustainable second generation ethanol production in Brazil.

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