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Energy consumption evaluation of fuel bioethanol production from sweet potato

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HIGHLIGHTS

- Evaluation of an experimental promising raw material for ethanol production.
- Identification of key operative conditions which optimize the use of energy.
- Energy evaluation on drying of sweet potato for ethanol production.
- Selection of optimal range of the dry matter ratio of sweet potato to water.

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ABSTRACT

The energy consumption for different operative conditions and configurations of the bioethanol production industrial process from an experimental variety of sweet potato (*Ipomea batatas*) K 9807.1 was evaluated. A process simulation model was developed using SuperPro Designer® software. The model was based on experimental data gathered from our laboratory experiments and technology and equipment suppliers. The effects of the dry matter ratio of sweet potato to water, the fermentation efficiency, and sweet potato sugar content, on the energy consumption (steam and electricity) were respectively evaluated. All factors were significant. The best ratio of dry matter to total water to work with fresh sweet potato was 0.2 kg dry sweet potato/kg water, as for greater ratios was not found a significant reduction in energy consumption. Also, the drying of the sweet potato previous its processing was studied. It presented an energy consumption greater than the energetic content of the bioethanol produced.

1. Introduction

The bioethanol production has as major cost factors the raw material and the energy demand (Bai et al., 2008; Kwiatkowski et al., 2006; Vučurović et al., 2012). Hence, raw materials with high carbohydrate content, efficient transformation processes energetically optimized, and an accessible, low cost energy source are needed. Sugar stalk crops, such as sugarcane and sweet sorghum, offer more advantages than other crops since they produce a residue (bagasse) which can be burnt for steam production to satisfy the energy demand of the industrial processes. It can also generate surplus energy that can be commercialized as electricity (Dias et al., 2011; Soccol et al., 2010). Starch-based materials, such as sorghum grain and sweet potato, require the use of an external energy source (fuel oil, natural gas, wood, lignocelullosic residues). An energy balance is favorable when the energy required to produce a biofuel unit, including both agricultural and industrial phases, is less than the energy leaving the system. If this does not happen, it must be evaluated what kind of energy should be used to meet energy needs, in order to ensure real replacement of fossil source for renewable energy source (Kwiatkowski et al., 2006; Nghiem et al., 2011).

Computer simulations have been used successfully to understand processes and the physical an economical implications of experimental modifications, and to model and predict the energy consumption for many industrial processes. They provide the ability to estimate the effect of variations in material composition, changes in operational conditions, process configurations, the incorporation of different processing steps or the use of new technologies. Various authors have reported models for bioethanol production from different feedstock using well-known process softwares such as SuperPro Designer® (Intelligen Inc., Scotch Plains, NJ) (Kwiatkowski et al.,2006; Nghiem et al., 2011) and Aspen Plus®, Aspen Technologies Inc., Cambridge, MA (Cardona and Sánchez, 2006; Dias et al., 2012; Humbird et al., 2011; Kazi et al., 2010; Krajnc and Glavič, 2009; Sánchez and Cardona, 2012; Tasić and Veljković, 2011; Wingren et al., 2008).

Sweet potato (*Ipomea batatas*) has been considered a promising substrate for alcohol fermentation since it has a higher starch yield

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per unit land cultivated than grains (Duvernay et al., 2013; Kim and Hamdy, 1985; Lee et al., 2012; Srichuwong et al., 2009; Ziska et al., 2009). It also contains simple fermentable sugars such as glucose, fructose and sucrose, minimal quantities of fibers and proteins. Sweet potato has several agronomic characteristics that determine its wide adaptation to marginal lands such as drought resistant, high multiplication rate and low degeneration of the propagation material, short grow cycle, low illness incidence and plagues, and covers rapidly the soil and therefore protects it from the erosive rains (Cao et al., 2011). There is a national program of sweet potato genetic improvement for bioenergy production that seeks to obtain varieties with high yields of dry biomass and starch (Vilaró et al., available on line). The industrial sweet potatoes developed for the production of bioenergy are selected for their higher content of starch and better agricultural yields. They are not intended to be used as a food crops (Duvernay et al., 2013). Their appearance, color and flavor are not attractive for use as food.

Starch, a glucose polymer, must be converted into fermentable sugars. Generally, this takes place in two enzymatic steps: liquefaction using thermal-stable alpha-amylase (~86–90 °C) and saccharification by addition of amyloglucosidase (AMG) (~50–60 °C). The glucose from the starch hydrolysis is fermented together with the free soluble sugars presents in the sweet potato.

An important aspect of the process is the water balance. The distillation is one of the most energy consuming steps, and the energy consumption increases as the amount of water to be eliminated increases. Energy saving on distillation can be achieved with high ethanol concentration by adding a minimal quantity of water to the raw material, that is a very high gravity (VHG) fermentation, where the initial fermentable sugar concentration is high (Bai et al., 2008). In the case of ethanol production from root and tuber crops, the use of a VHG medium implies manipulation of a material with high solid content and high viscosity. The high viscous nature causes several handling difficulties during process, and may lead to incomplete hydrolysis of starch to fermentable sugars (Shanavas et al., 2011; Wang et al., 2008; Watanabe et al., 2010), and to an incomplete fermentation since the yeast are exposed to stress conditions due to the high osmotic pressure produced by the high soluble solid concentration. Also, the high ethanol concentrations reached can be toxic for the cells (Bai et al., 2008; Breisha, 2010). Simultaneous saccharification and fermentation (SSF) has been considered a good choice to reduce the osmotic pressure caused by high initial concentration of dissolved sugars in batch ethanol fermentation (Cao et al., 2011; Shen et al., 2011; Srichuwong et al., 2009; Zhang et al., 2011), and the feedback inhibition that the AMG could present by the presence of high concentrations of glucose (Cao et al., 2011; Mojović et al., 2006). Using this technology, the time and energy of the complete process can be reduced since the saccharification step separated from fermentation at temperatures above 50 °C is eliminated (Zhang et al., 2010).

Sweet potato has high water content (~75%). Previous transformation of the sweet potato into chips or flour (powder) can be done in order to (i) facilitate its transport and/or plant conservation (Vilaró et al., available on line), (ii) reach high ethanol concentrations, since media with higher ratio of dry material to water than fresh sweet potato can be prepared, (iii) improve the plant flexibility, since the material can be conserved for longer times and it occupies less space than fresh, and (iv) improve the performance of the starch hydrolysis at high ratios of dry material to water. In this case, the saving in the manipulation of less material, high viscosity, the extra cost of drying and the effect of the drying on the performance of the process (conversion of starch to glucose) should be evaluated. In our laboratory (Lareo et al., 2012), it was found experimentally that ethanol yields were similar for fresh sweet potato and sweet potato flour.

This work seeks to gather information on the energy use in the ethanol production from sweet potato as a guideline for the execution of agricultural programs of genetic improvement and for making decisions on the commercial-scale implementation of processes that allows net replacement of fossil fuels in the automotive sector. The industrial energy consumption in the ethanol production from an experimental variety of sweet potato selected for the bioenergy production, fresh and dried (flour), was evaluated for different process configurations and operative parameters. A process simulation software and experimental data of material composition, kinetic parameters and process yields obtained in our laboratory (Lareo et al., 2012) were used. Sensitivity studies were performed to examine the effects of variations in the dry matter ratio of sweet potato to water, the fermentation efficiency and sweet potato sugar content, on the energy consumption.

2. Methods

2.1. Base case simulation

The analysis of the fuel bioethanol production process from a variety of sweet potato (*Ipomea batatas)* K 9807.1 (fresh and flour) was performed using the software SuperPro Designer®, Intelligen Inc. versión 8.0. The base case of study was an annual production of anhydrous ethanol of 90,000 m^3 (expressed as ethanol 100%). The quality of the ethanol to be obtained was 99.2% v/v. It was assumed that the plant works 24 h per day, during 320 days per year, and 45 days were used for operations such as provision, cleaning, maintenance and repair of equipment. The nominal plant capacity was 130 t/h sweet potato. The use of the non-fermentable material recovered from the bottom of the beer column was not considered in the analysis. This could be considered as a value-added coproduct, in a similar way than the distiller's dried grains with solubles (DDGS) produced during ethanol production from corn which can be used as animal feed. However, in the case of sweet potato, the solids generated have minor feed value since it has low nitrogen content: 4% (dry basis) of residual non-fermentable sweet potato solids (Lareo et al., 2012) and 27.8% for DDGS (Kwiatkowski et al., 2006), and experience about its use is not available according to our knowledge. Therefore, the analysis done in this work could give conservative values since the energy consumption was assigned exclusively to the ethanol production.

2.2. Process design

The simulator used (SuperPro Designer®) quantifies energy requirements of the process being considered. The energy consumption was calculated considering the electric consumption of the each equipment and the steam consumption used in the process. Data of composition and physical properties of the raw material and chemical products, equipment maximum volumes, maximum areas of exchange coefficients of heat and mass transfer, among other specific parameters of input and output streams for each device were entered to the simulator. For the different situations defined, the input streams of the raw material, the number of the equipments used, the number of batches per year, the number of batches in the sequence of multiples batches, maximum useful volumes among others, were adjusted to reach the fixed processing capacity parameters (described in Section 2.1). The equipment was selected directly from the SuperPro Designer software data base, choosing the most used within the bioethanol production industry for a similar scale. To select the equipment, the processes were integrated by recirculation of streams to minimize the consumption of materials and energy. The energy consumption values were