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Research paper

A vertical integration simplified model for straw recovery as feedstock in sugarcane biorefineries

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ABSTRACT

Mechanized sugarcane green harvesting has been increasingly adopted in Brazil, rising straw availability at the field. Computer-aided tools are used to predict the optimum conditions for straw recovery systems. This study aims at developing a model-based method for optimization of sugarcane straw recovery costs and internal rate of return (IRR), as a function of sugarcane productivity, straw recovery fractions and transport distances considering two recovery systems: integral harvesting (*IS*) and baling system (*BS*). A simulation procedure using the Virtual Sugarcane Biorefinery (VSB), according to a Central Composite Design (CCD) is used in this study. The scenarios were based on an autonomous ethanol plant, with milling capacity of four million tons per year. The influence of these agricultural parameters on the sugarcane straw recovery costs and internal rate of return was evaluated through this approach, where the CCD was used for the development of an empirical model for optimization as well as a statistical evaluation of results. An optimized IRR (26.3%) was obtained for integral system, with low transport distance (20 km), maximum sugarcane stalk productivity (100 t ha^{-1}) and maximum recovery fraction (70%). The same conditions lead to higher IRR (26.2%) for baling system. Results showed that the IS promotes the highest reduction of the agricultural components of straw recovery cost and the optimum IRR considering the vertical integration of sugarcane biorefineries was observed by adopting this system.

1. Introduction

Brazil is the highest world producer of sugarcane. The production of sugar, ethanol and bioelectricity has an important part in the Brazilian economy. Seeking to increase the sustainability of the sector, in the recent years, the mechanized sugarcane harvesting without previous burning (green harvesting) has been increasingly adopted in Brazil, rising straw availability at the field. The amount of available straw changes according to sugarcane variety and productivity, crop age, climate, soil and other factors, ranging from 10 to 20 tonnes of dry matter per hectare per year [1]. Without sugarcane burning before harvesting, the straw left on the soil may bring several benefits to sugarcane fields: increase of soil organic matter content, reduction of soil erosion, recycle of nutrient, maintenance of stable soil temperatures, reduction of water losses by evapotranspiration, and reduction of weed infestation [2–5].

On the other hand, it is a valuable raw material for biorefineries, to produce electricity in first generation or biofuels in second generation plants. If large amounts of straw are left on the field some negative aspects needs to be considered, such as the increased risk of accidental burning, the increased incidence of pests and reduction of ratoon sprouting leading to the reduction on sugarcane productivity [1,6].

Technical parameters and economic impacts of different straw recovery systems and types of equipment have been studied by different authors [7–12]. The main systems analysed are the integral harvesting and the baling system (Fig. 1). In the first one straw is harvested, chopped and transported together with the sugarcane stalks, while in baling system it is left in the field for about 15 days after sugarcane harvesting to decrease its water content. After that period, straw is windrowed, collected and compacted in bales,

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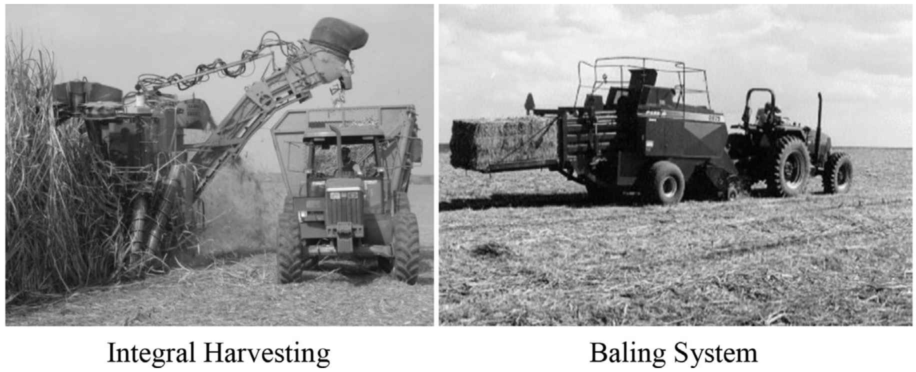

Fig. 1. Main straw recovery systems.
Source: Hassuani et al. (2005) [11].

which are subsequently loaded and transported to the mill separately from the stalks.

Each system presents advantages and drawbacks that need to be analysed in order to find the best one for each particular situation. Straw recovery along with sugarcane stalks leads to lower load density in the transport trucks, and recovery costs are strongly dependent on distances. The transport cost represents about 25%–35% of total cost of sugarcane production [8]. In addition to that, not separating the straw in the field reduces losses of stalks, increasing sugarcane yield per hectare. Baling system needs more agricultural operations, and straw recovery can become very expensive, mainly if recovery fractions are low. Nevertheless, this system does not decreases stalks' transport efficiency, and can be an interesting option for longer distances and high straw recovery fractions [7,8].

However, in addition to the straw recovery cost, the effects that sugarcane straw brings to biorefineries can not be ignored. Therefore, the valorisation of sugarcane straw as a raw material for the production of electricity and/or second generation ethanol in sugarcane biorefineries depends on a set of agricultural (transport distance and load density, straw recovery fraction and system, sugarcane productivity, among others) and industrial parameters (dry cleaner station, juice extraction and boiler efficiencies), which may have to take into consideration in order to optimize the sustainability impacts. Some scenarios with sugarcane straw recovery may present positive economic results in the agricultural phase and disadvantages in industrial phase [7,8]. The assessment of vertical integration on sugarcane biorefineries (including both agricultural and industrial phases) enables analysing the combined results. In this sense, it is worth to analyse the benefits of straw recovery systems considering both agricultural and industrial aspects together; this is the novelty provided in this article.

For this purpose, an integrated approach is applied in this study, employing mathematical modelling and computer simulation of processes. These tools are very powerful for predicting technical parameters and indicators of sustainability of different technologies, and computer-aided techniques can be used to predict the optimum conditions for straw recovery systems previously to its effective implementation.

In order to evaluate technical, socioeconomic and environmental issues of new technologies in sugarcane production (agricultural phase) and its processing (industrial phase), the Technological Assessment Program of the Brazilian Bioethanol Science and Technology Laboratory (CTBE) of the Brazilian Center of Research in Energy and Materials (CNPEM) has been developing and improving the Virtual Sugarcane Biorefinery (VSB) [13], which consists in a simulation platform for this purpose.

The VSB relies on several commercial tools, for example Aspen Plus® and SimaPro® software, as well as on own-developed tools like the CanaSoft and other Excel spreadsheets. This framework has been successfully used in several studies, as the ones described by Cardoso et al. (2013), Bonomi et al. (2012), Cavalett et al. (2012) and Dias et al. (2012) [7,13–15]. The production and transport of sugarcane (agricultural phase) are evaluated using the model named CanaSoft, and the industrial processes of sugarcane are simulated using Aspen Plus®; financial and economic analyses are carried out using Excel spreadsheets (throughout a cash flow approach), and environmental assessment are based on Life Cycle Assessment methodology and run on SimaPro®.

The CanaSoft model has been developed for simulation and measurement of important agricultural parameters for technical and sustainability assessment of agricultural practices in the sugarcane production system. This model was developed on spreadsheets and integrates several calculation modules. It contains an interface in which the main parameters of production system are defined (yield, type of planting and harvesting, fertilizer application rates, among others factors that defines the sugarcane production system). These parameters are considered for the life cycle inventory calculation and also for economic assessment. Both economic and life cycle inventory calculations are linked to an agricultural database which involves comprehensive information about all agricultural operations used in sugarcane production, such as agricultural performance parameters for different types of harvesters, tractors and implements, as well as their weight, costs, diesel consumption, annual use, life span and depreciation, among others, as main parameters [13].

The process simulation software Aspen Plus® is used in the VSB for technical assessment of industrial phase and includes all the unit operations for ethanol and electricity production from sugarcane. This software has been successfully used to simulate different biorefinery configurations, providing information for energy and mass balances and economic analysis. Other raw materials and products are also covered by VSB using Aspen Plus®, allowing the evaluation of different technologies [13,15].

In techno-economic studies, in most cases, it is not applied a systematic approach to define the production system; only a very limited number of variations are considered leading, as a consequence, that the best technology options are not considered. In this sense, this study has proposed to apply a Central Composite Design (CCD) coupled to VSB simulations as a more systematic analytical tool, as it is possible to map a larger space of technology options, using a design planning. CCD coupled to VSB simulations allowed the identification of a correlation among operational parameters