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Analysis of energy consumption in three systems for collecting sugarcane straw for use in power generation

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ABSTRACT

This work estimated the energy consumption of three straw-collection systems: baling, forager and whole-plant harvest system in which the chopped cane and straw are separated at the mill. About 12 t ha^{-1} yr^{-1} of straw can be collected for a typical sugarcane yield of 100 t ha^{-1} yr^{-1}. The system with the lowest energy consumption was whole-plant harvesting, which used 2.0 L of diesel fuel per tonne of straw collected for a harvest area 30 km from the mill and when 75% of straw is collected. This value is approximately 40% lower than of the specific consumption estimated for the other systems and just 1–2% of the energy available from the straw. However, for successful application of the whole-plant harvest system, it is needed significant improvements to the efficiency of cane cleaning systems for straw separation. The thermal energy available from the straw when 75% is recovered is 182 GJ ha^{-1} yr^{-1}, compared to 151 GJ ha^{-1} yr^{-1} of the ethanol that can be produced and approximately 174 GJ ha^{-1} yr^{-1} from the bagasse. If cane straw were used for electricity generation, an additional 12.6 MWh ha^{-1} yr^{-1} could be generated.

1. Introduction

The straw produced during sugarcane harvesting is potentially an important source of energy in Brazil. Over the past fifteen years, sugarcane production in Brazil grew more than 100%, from 302 million tonnes in 1997/1998 to about 648.1 million tonnes in 2012/2013 [1]. The sugarcane industry accounts for 2.3% of Brazilian GDP [2], 53.9% of the country's agricultural output and 17.5% of its primary energy production [3]. The energy products generated from sugarcane are ethanol and sugarcane bagasse. However, the latter is used almost entirely to produce thermal and electrical energy for the production of sugar and ethanol. The industry's contribution to the economy and its social impact—it is the largest employer of unskilled labor, which is used mainly for harvesting operations—make it one of the most important industries in Brazil [4].

Sugarcane is a gramineous plant with a root system, stem, leaves, and efflorescence. The stalk is the part that is of most commercial interest as it is from this that the juice and bagasse are extracted. Traditionally, and particularly before the 1990s, sugarcane was harvested manually. To ensure high yields during manual harvesting, the dried leaves of the plant are burned prior to harvesting, thereby avoiding the need for the leaves to be cut manually. Increasing concern with environmental issues has led to changes in legislation and harvesting practices, as the burning of sugarcane causes significant emissions of particulate matter and polyaromatic hydrocarbons [5]. A further problem associated with preharvest burning is that the sugar content of the harvested stalks is reduced by the high temperatures reached when the sugar cane is burnt [5]. Mechanized harvesting has increased gradually in recent years and currently accounts for around 89% of sugarcane harvested in the state of São Paulo [2]. As a result, not only has there been a significant reduction in the amount of sugarcane straw burnt before harvesting but the amount of straw, which is currently left in the soil and used as natural protection, has increased. Sugarcane straw consists of green leaves, dry leaves and tips (Fig. 1), and its availability after harvesting depends on several factors, such as the harvesting system used, the climate and the variety of sugarcane. In the technical literature sugarcane, waste is referred to as cane trash or cane straw. Average yields for this waste have been investigated, measured and reviewed by various authors [6–9].

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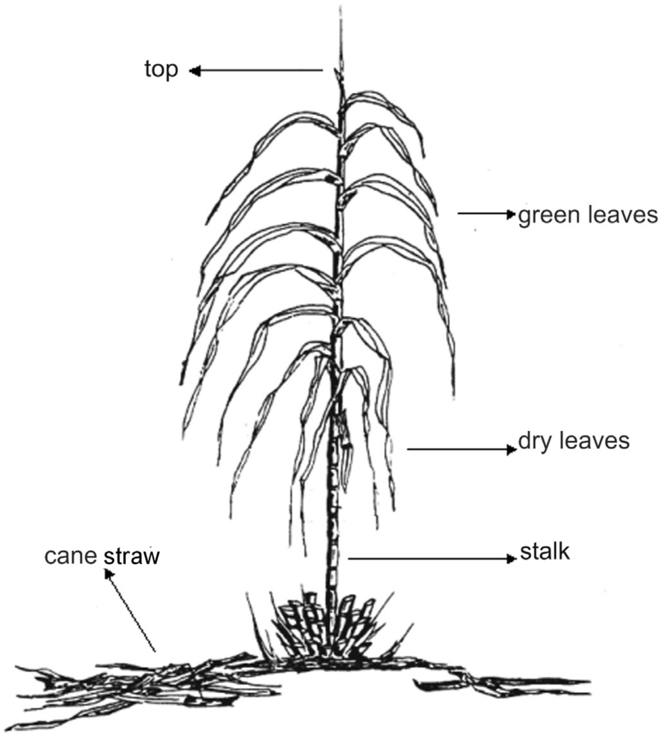

Fig. 1. A sugarcane plant showing the leaves and stalk and the cane straw on the ground.

An extensive field study was carried out by Hassuani et al. [10] to determine sugarcane straw yields and test several operations for collecting cane straw. The operations involved in the collection of sugarcane straw include essentially densification, loading, transportation, cleaning the cane and recovering the straw. Currently, these operations have limitations when applied on a large scale because of the need to adapt and develop specific harvesting equipment, generating uncertainty about the most technically efficient and economically viable solution for the recovery of cane straw.

Harvesting, loading and transport account for around one-third of the cost of sugarcane delivery to mills in Brazil [10]. Michelazzo and Braunbeck [11] studied six options for collecting and transporting cane straw to estimate its final cost after recovery and delivery to the processing plant. They concluded that the lowest-cost straw is obtained by harvesting cane and straw together and separating them at the mill. However, this method is not yet fully developed, and questions remain about its performance and energy requirements. A number of other straw-harvesting techniques were also evaluated in terms of their performance and energy needs in field studies by several authors [8,12,13]. These studies also evaluated sugarcane straw yield. In other countries, such as South Africa, cane straw collecting methods has also been investigated [14]. Other authors [15,16] also conducted technical and economic assessment of straw collecting systems, mainly focusing the integration with sugarcane biorefineries. However, the energy consumption was not estimated or not explained in these works.

Currently, cogeneration systems in sugar-alcohol plants use bagasse as the sole fuel for steam generation, which provides all the thermal and electrical energy for the industrial process and can be employed in some sugarcane mills to generate surplus electric power. Nevertheless, much greater amounts of surplus electrical energy could be generated if cogeneration systems used part of the sugarcane straw as fuel for steam generation.

In 2009, cogeneration in the sugar-alcohol industry produced 20×10^6 MWh of electricity, or 4.5% of all the electricity produced in Brazil [1]. However, as 12.5×10^6 MWh of this was used by the sugar-alcohol industry itself, the surplus left over for sale corresponded to only 1.65% of the electric energy generated in the country. Of the 393 sugar mills in Brazil, only 28% (which process 47% of all the sugarcane milled in the country) generate electrical energy for sale. As cane straw is produced in similar quantities to bagasse, it could potentially produce 5% of all the electricity currently generated in Brazil. Furthermore, if it were used as fuel in boilers instead of bagasse, this could be used exclusively to produce second-generation ethanol, significantly increasing ethanol production without any increase in the amount of land given over to sugarcane. In light of this, an analysis of different methods of collecting and transporting cane straw and taking advantage of its energy potential is required. However, energy consumption in straw collection is key information for environmental life cycle analysis and sustainability assessment. This becomes even more important when the primary energy input in the straw collection operations is a fossil fuel: the diesel fuel.

Here, we review data on cane straw yield, discuss methods for collecting and transporting cane straw and estimate energy consumption for these operations. In addition, we analyze the main challenges involved in the collection of cane straw, identify what technological developments are needed and estimate the energy-generation potential of this product of sugarcane.

1.1. Sugarcane and straw yield

Typically, yield data is given in terms of stalk production (wet basis) excluding tops and leaves. While the average yield in Brazil is 85 t ha^{-1} yr^{-1}, on some plantations where mechanized harvesting is used this figure can reach 132 t ha^{-1} yr^{-1} [17]. In a study of potential yield in the state of São Paulo, the region with the highest sugarcane production in Brazil, Gouvêa [18] estimated potential values of between 100 and 136 t ha^{-1} yr^{-1} based on the annual historical variation in water deficiency for the period 1927 to 2006. When measures for increasing performance were taken into account, Gouvêa [18] arrived at projected potential values of up to 212 t ha^{-1} yr^{-1} for the year 2080.

Table 1 shows sugarcane straw yield measured by various authors. Some of these authors report detailed data on yields for tops, green leaves, and dry leaves, while others do not give details for green leaves, in which case it can be assumed that this information is included in the yield data for tops. The considerable variability in the values can be attributed to the criterion used to define the top of a sugarcane, which was usually not explained in the reports consulted. A further explanation could also be the differences in soil characteristics and the variety of sugarcane used, which is also generally not stated. A description of a cane harvester and mechanized harvesting can be found in Bizzo et al. [19], where it can be seen that the height at which the top of the cane is cut can be regulated by adjusting the harvester cutting mechanism (topper). The moisture content of the straw when it is harvested is also reported by some authors [7,12,20]. This information is vital because moisture content has a significant influence on the lower heating value of cane straw.

In general, the straw yield is about 140–192 kg of dry matter per tonne of fresh stalk harvested. Tops and green leaves have a high moisture content (66–82%) while dry leaves moisture content is around 10–14%. Ten to fifteen days after the harvest, the moisture of the green leaves and tops left in the soil is usually reduced to 15–30% [11,20].