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Evaluation of Different Harvesting and Storage Practices: Sweet Sorghum and Energycane

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EVALUATION OF DIFFERENT HARVESTING AND STORAGE PRACTICES: SWEET SORGHUM AND ENERGYCANE

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ABSTRACT

Two attractive potential feed stocks for biofuel production are energycane and sweet sorghum due to the environmental adaptability, sugars concentration and yield. Evaluation and development of harvesting, transportation and storage practices is critical for bringing the production of these crops to industrial levels.

This research aims to analyze the supply system of energy crops and evaluate the effect of different harvesting and storage in the yields of the feedstock and the efficiencies of the processes. Harvesting trials were conducted at St. Gabriel, LA for evaluating the feasibility of using energy crops as inputs for ethanol production. The parameters that were varied during the trials were: billet size, fan speed of the extraction system. Several operational indicators were estimated in the study: material yield (tons/acre), sugars yield (ton/acre), ethanol yield (liter/acre) and agronomic and efficiencies indicators of the supply stages of the system.

A simulation of the conceived supply system was performed in order to measure and determine the feasibility of the operation. The objective function of the model was defined as the profit maximization of ethanol production. Twenty four scenarios were simulated and evaluated for determining the optimal solutions.

It was evidenced that for increasing the sugars and ethanol yield from the energy crops, it was necessary to reduce the lead times of the operations, enabling to process the material shortly after harvesting. A feasible operation of the system was guarantee when a maximum distance of 35 miles was defined for transportation logistics and when an area of 100 acres was covered for collecting the feedstock.

CHAPTER 1: INTRODUCTION

The necessity of generating alternative options for the production of energy and bio-fuels for the future replacement of traditional fuels was established in the Energy Independence and Security Act of the United States, 2007. It was also stated the importance of developing new alternative solutions for reducing the dependence of crude oil due to the risks related in the instability of oil prices and policies established by the countries that belong to the OPEC (non-Organization of the Exporting Countries).

According to the "Annual Energy Outlook 2013" of the US Energy Information Administration, there are certain key factors that determine the long term prices of petroleum and others fuels, which are classified in four categories:

1. The economics of non-Organization of the Petroleum Exporting Countries (OPEC).
2. OPEC investment and production decisions.
3. The economics of other fuels and world demand for petroleum and other fuels (United States Energy Information Administration, 2011).

This formulation shows the uncertainty on prices and risks related to the future of this commodity and it indicates that most of the policies and critical decisions are mostly established by producers. In addition, because of the high predominant cost of acquisition and its critical value as an input to many economic activities and industrial processes, the competitiveness of any business can be affected if there is no stability on prices in a long term scenario.

The Energy Independence Security act of 2007 stated that around 36 billions of gallons of renewable fuels will need to be produced by the year 2022. One alternative for the production of biofuels is the implementation of lignocellulosic biomass plant; specifically, from grassy crops (USDA, 2010) due to their environmental adaptability and agronomic characteristics (A.Ribera,

2013), (Mark, 2009). It was determined that was viable to transfer and use the already established methods and infrastructure of sugarcane with crops such as the energycane and sweet sorghum(Zegada-Lizarazu and Monti, 2012).

Energycane and sweet sorghum are being considered as a new alternative source for producing biofuels and alternative products thanks to their suitability for growth, high yields of lignocellulosic and fermentable saccharides, and low agronomic requirements (Whitfield, 2013). However, despite of the advantages that can be gained from the use of alternative feedstock and biomass, there still are some barriers that, have not been clearly defined and solved, as was mentioned in the "Roadmap for Agricultural Biomass Feedstock Supply in the United States" (USDA, 2012). Some of the barriers defined are the following:

1. The risks related to the availability of adequate biomass supply to a bio refinery, and the possible risks of success and costs implied in the infrastructure and equipment for the supply system required (Kaldellisc, 2011).
2. The agricultural residues, such as the residues that can be obtained from the energycane and sweet sorghum, have lower yields of biomass per acre compared to other crops (e.g. switch grass, *miscanthus*). This particularity leads to the necessity of increasing the area of harvesting, collecting and transporting the feedstock; as a result, the total cost of operations can increase (Mapemba, 2005).
3. The lignocellulosic biomass is a renewable energy alternative that faces challenges such as availability and logistics constraints, due to low bulk density and delivery issues. Additionally, the transportation operation represents a high component cost of the production of biofuels, near to 35-50% (Kumar *et al.* 2006).

For a profitable and successful utilization of agricultural feedstock and its biomass for their conversion into alternatives products, it is necessary to link all the operations required throughout the system, which starts from acquiring the feedstock, harvesting, transporting, delivering, storing and processing. All these activities collectively define the basic structure required for the agricultural supply chain system (SCS) needed for the production of alternative products, and conforms the main factors that determine the structure of a supply chain system, as was proposed by Porter (Porter, 1987).

The harvesting and the transportation are considered critical stages for an agricultural supply chain that utilizes perennial grasses as inputs for the production system, because the operational cost can vary as a function of the distance needed to cover for collecting and harvesting the feedstock (Gan *et al*. 2011), (Mapemba, 2005), (Mark *et al.* 2009), (Sharma *et al.* 2013), (Cock *et al.* 2000).

For the case of sugar cane, it is established that transporting the material over large distances is not a feasible option, mainly because the material is perishable, bulky and there is no tradeoff with the costs (Cook *et al.* 2000); some of the main considerations formulated by the author are summarized below:

1. The biomass from agricultural residues is characterized by a low bulk density when it is been harvested and collected.
2. The moisture level of the biomass can affect the quality and the efficiency of the system.
3. The quality characteristics of the biomass and feedstock can be variable and inconsistent depending on: the type of feedstock selected to work, the weather conditions, the technologies and practices implemented, etc.
4. The calculation of the maximum distance for obtaining the feedstock should consider the operational costs vs. the potential profit of the outputs.

In this way is possible to determine the feasibility of the system and the maximum distances for transporting the material (the transportation costs can easily arise based on the distance needed to obtain the material).

All these considerations affect the supply of the feedstock, any change can affect the costs of the operations, the consistency of the feedstock as well as the quality, the efficiency of conversion and the possible yields. It is indispensable to evaluate different alternatives to determine the feasibility of establishing the system in industrial levels.

CHAPTER 2: LITERATURE REVIEW

In the Energy Independence and Security Act of 2007 (United States Energy Information Administration, 2007), the necessity of producing considerable quantities of renewable fuels as an alternative resource for the next decades was established. It was stated the necessity of producing around 36 billions of gallons by the year 2022.

One of the alternatives for the replacement of traditional fuels is the production of biofuels from lignocellulosic biomass plants, projecting the goal of producing around 530 million tons of Lignocellulosic biomass for satisfying the production demand and ensuring a continuous supply. The policy suggest the necessity of promoting and improving technologies and methodologies for the collection and converting the material as well as a definition of the logistics practices for the system. This integration needs to be efficient and cost effective in order to determine the optimal configuration that the system will require for the supply, the management and the transformation of alternative resources for the production of bio-fuels.

2.1 Importance of ethanol production from energy crops

The implementation of the energycane and the sweet sorghum as inputs for the production of ethanol are alternative options for contributing to the independence of fossil fuels. Ethanol is a high octane fuel used primarily as a gasoline additive (Salassi, 2007) that can be produced from grain crops (corn and wheat) and sugar crops (sugar cane, molasses and beets).

There are several similarities of sugarcane crop with sweet sorghum and energycane, and as a result, these crops are considered to be processed as inputs for the production of ethanol by implementing the sugarcane operational infrastructure. The energycane and sweet sorghum are similar in gross and shape to the sugar cane, and can be handled with the current operational

structure and infrastructure used for harvesting and processing sugar cane (Misook *et al.* 2011), (Ribera *et al.* 2013). Energycane and sweet sorghum are considered potential biofuel crops due to the environmental adaptability and capability of producing high yields of sugars (Amosson, et al. 2010).

For the production of ethanol from energy crops, it is necessary to remove the sugar through the implementation of processes such as crushing, sacking and chemical treatment, with these processes, the sugars can be fermentable to alcohol by the implementation of yeast and microbes. Finally, the product is distilled until achieving the desired concentration (USDA, 2009); for implementing ethanol with gasoline, water needs to be removed for producing "*anhydrous ethanol".* Currently, the ethanol is being used as an additive for gasoline because it is a renewable fuel, while gasoline is a derivate of crude oil, hence, the net emissions of Green House Gases, GHG's, (mainly CO2), can be significantly lowered (Goldemberg, *et al.* 2008).

In the United States, approximately 3.9 billion gallons of ethanol are produced every year, where 97% of it is produced from corn, while the remaining is produced from sorghum, cheesy whey and beverage waste (Renewable Fuel Association), (USDA, 2006).

For the production of ethanol, there are two main processes used, these are: the wet milling process, which consists in fractioning the corn into starch, fiber, corn germ and protein, where only the starch is the component used for ethanol production. The other process is called dry milling, and basically consist of grounding the corn kernels by adding water, then the product is cooked and enzymes are added for converting the material into sucrose. Around 40% of the production of corn in the U.S. is utilized for the production of fuels and because the high demand, the price of a bushel has increased by 20%, generating an increment in the prices of the food products that are produced from this commodity (Cendrowski, 2012), (Elobeid et al. 2006).

The utilization of corn as an input for fuel production is already established in industrial levels in the U.S., and several benefits are provided by the U.S. government for incentivizing the production of corn (0.60/gal) (EIA, 2012). The utilization of this commodity for fuel purposes compete drastically with the utilization of the crop for food production (McPhail *et al.* 2008), (McPhail *et al.* 2012), hence, a dedicated utilization of the commodity for purposes different from food may be constrained in the future. This suggest the necessity of finding sources for the production of biofuels that not compete as a food commodity.

According to the Energy Policy Act of 2005, the "Renewable Fuel Standard (RFS)", defined that the gasoline sold in the U.S. need to contain a minimum value of renewable fuel; for this purpose, the utilization of ethanol has been implemented.

In 2012, approximately 7.5 billion gallons of renewable fuel was used for this purpose, it was stated by the USDA that for 2013, it was necessary the production of 250 million gallons of cellulosic derived ethanol (USDA, 2006).

2.2 Energycane and Sweet sorghum as an alternative for biofuels production

Producing alternative products from lignocellulosic biomass is an alternative that has been promoted by the U.S. Department of Energy (DOE); for this purpose, an alternative to work with is the use of grassy crops. According to the USDA Roadmap on Biofuels (USDA, 2010) the utilization of lignocellulosic biomass was a trending option because was possible to transfer technologies and practices. It is expected to achieve the capacity of producing about 13.4 billion gallons of advanced biofuels by 2022.

The states of the south of the U.S. are the main producers of sugarcane, specifically Florida and Louisiana, producing around 375,000 and 390,000 acres respectively (Tyler, 2006).

Approximately 20% of the national sugar production is produced by the Louisiana sugar industry achieving an economic activity of 2.2 billions of dollars (ASCL, 2011).

According to the report, "The Economic Feasibility of Ethanol Production from Sugar in the United States" presented by the USDA, it was estimated that the average national yield of sugar cane was around 28.8 tons per acre harvested with a recovery rate of 12.3%.

The report mentioned that the estimated sugar yield per acre was of approximately 3.55 tons of raw sugar harvested per acre. This suggests that the current infrastructure used for collecting, handling and transforming the material provide an effective development of the system suggesting that the practices used for the sugar production are efficient and provide a feasible operation.

It has been mentioned that is viable to transfer and use the already established infrastructure of sugarcane, with crops such as energycane and sweet sorghum, these alternative feedstock are being considered as a potential source for producing biofuels and alternative products.

Energy crops are becoming an attractive option for the Southern States of the U.S. due to the agronomic characteristics and adaptability to environmental conditions as well as the non-competitiveness with food or fiber crops (Ribera, 2013), (Mark, 2009), (Zegada-Lizarazu *et al*. 2012).

The energycane and sweet sorghum provide a high biomass productivity per unit area, are non-competiveness with food commodities and because of the similarities with sugar cane crops, its suitable to use the already establish infrastructure (Kaldellisc, 2011).

The energycane is a crop classified as a perennial grass, which is a variety of the commercial sugar cane and is characterized with a lower content of sucrose but a higher content of fibers, which can be utilized as an input for the production of lignocellulosic ethanol (Misook *et al.* 2010).

Another important characteristic of the energycane, is that the crop can resist different weather conditions and present desirable characteristics such as high material yield, appropriate geographic adaptability, non-competitiveness with food, feed or fiber and low input requirements (Ribera *et al*. 2013). On the other hand, the sweet sorghum is an annual crop that is well adapted to warm and dry growing regions; it has been identified as a possible input for producing ethanol because of its biomass yield and high concentration of readily fermentable sugars (Bennett & Anex, 2009). The sweet sorghum requires fewer quantities of fertilizer and water and is high adapt to different environmental conditions (Misook *et al.* 2010), (Montross *et al.* 2009), (Zegada-Lizarazu *et al.* 2011). Sweet sorghum produces lignocellulose that can be used for the production of second generation of biofuels and because of its high content of soluble sugars and structural carbon, the crop can be also used for the production of first generation biofuels (Zegada-Lizarazu et al. 2011). Despite the advantages and benefits that can be obtained from the energy crops, Montross et al. mentioned that the shelf life of the juice is short and because the high concentration of sucrose, the juice cannot be stored for a long period of time.

It was suggested by Montross the necessity of improving the conversion methods in order to increase the concentration of the ethanol so the storage and transportation costs can be reduced (Montross *et al.* 2009). Similarly, Rooney *et al.* mentioned that even with the agronomic advantages of the crop, the implementation of sweet sorghum as an energy crop is still behind of maize, sugar cane or beet (Rooney *et al.* 2007).

The search for new biofuels alternatives is focused in cellulose-based plant material, mainly because it is an abundant material that represents around 13.4% of the global energy supply for the United States (Sims, Hastings, Schlamadinger, Taylor, & Smith, 2006). Biomass material represents a highly viable option as a solution for finding alternative resources from the already

established crops; also a variety of by-products can be obtained; some of these are heat, power and/or biofuels (Kaldellisc, 2011).

2.3 Logistics and operational practices for energy crop supply chain system

The utilization of energy crops for the production of biofuels is an option that lately has been strengthened due to the requests stated by governmental entities in the United States (USDA, 2006).

Currently, there is no commercial scale of cellulosic plants of neither energycane nor sweet sorghum for their use as inputs for biofuels production; hence, there is not a real measure of the economic feasibility or a definition of the parameters and practices necessary to ensure a continuous and efficient system operation (Zhang *et al*. 2012).

The supply chain system focusses in the design, planning, production and delivery of products to the final costumer (Durand, 2012); therefore, it is necessary to define and establish the conditions, parameters and practices for each of the stages that integrate the supply chain system.

For the case of an agricultural system that implements energy crops as inputs for biofuel production, it has been defined that the system may be limited by the logistics of harvesting, collection, storage and transportation (Leboreiro *et al.* 2011). It is necessary that each of the stages integrating the supply chain system (SCS) need to be well-defined, and measured in order to determine the flow of the processes, identify the critical variables necessary for assuring an optimal development of a productive system (Porter, 1987).

Currently there is not a full scale implementation of energy crops as inputs for biofuel production, the main stages of the supply system are not well defined (design, planning, logistics, technology and operational practices). It is indispensable to determine the structure of these stages and the

feasibility of implementing the production system in industrial levels, is requested in order to ensure the future utilization of energy crops. It is important to determine how a greater benefit can be obtained from both, agronomic and economic so the minimization of the operational-logistics costs, the maximizing of the products (obtain high yields from the feedstock), and the profitability of the business can be a feasible and a competitive option for the industry.

These considerations are critical for structuring and establishing the future success of the cellulosic industry, which at the moment stills in the design phases; consequently, the data and technical procedures are uncertain (Tyner, 2009).

Harvesting and transportation are considered critical stages in an agricultural supply chain system that implements alternative crops for the production of biofuels because the operational costs can varies as a function of the distances needed to cover for collecting and harvesting the material (Gan *et al.* 2011), (Mapemba, 2005), (Mark *et al.* 2009), (Sharma *et al*. 2013).

Even though the search for alternative sources for biofuel production is a promising trend, Iman mentioned that there are serious logistic issues for the production of biofuels due to feedstock availability and the economics of the feedstock supply (Iman *et al.* 2010). Iman suggested that the material yield is a key factor for its utilization in the conversion to ethanol as well as the delivery costs (they include the feedstock production, the harvesting, and the processing steps).

Finally, the author points out, that these two considerations are key factors that affect the selling price of the final product and the overall sustainability of the bioethanol production. It was mentioned by Badger, that the transportation costs and the operational efficiency of an agricultural system mainly depends on the type of feedstock being transported; the density of the material; the transportation modes; and the distances for covering (Badger, 2003). Similarly, it was stated that

the feedstock cost can be affected by the type of material, the field conditions, the climate and the efficiency of the logistic processes (Larasati *et al*. 2012), (Kumar *et al.* 2012).

Additionally, for collecting and transporting the material, in most of the cases, the dependency of consuming traditional fuels for the operation, is almost an unavoidable aspect (operation of machines and trucks), representing higher costs for the fraction of the production process (Ashron *et al.* 2007).

In the production of ethanol, around 20 to 40% of the total cost, is originated by the cost of feedstock supply to the bio refineries, and 90% of these costs are based on the logistics for delivering the material (Ekşioğlu, 2008). On the other hand, the feedstock acquisition cost can be approximately 35-50% from the total production cost of the ethanol (Larasati *et al.* 2012). Similarly, Hess estimated that approximately 30% of the feedstock cost was due to the transportation cost.

For the case of sugar cane, it was mentioned by Srivastava that the current supply management practices used for harvesting and transporting the material, present an impediment for the successful recovery of sugars.

This phenomena occurs due to the exposure time that the feedstock have before processing and the total loss weight that can occur during these two stages of the supply system. It was found that a decrease of approximately 2 units of sucrose can occur by not processing the material during the first 72 hours after harvesting (Srivastava *et al.* 2009).

Similarly, Larrahondo reported that for every 10% of extraneous matter on harvested cane, a reduction of 3.7% of juice extraction occurred, consequently, a reduction of 0.9% of sucrose was generated (Larranhondo *et al.* 2009). Legendre estimated that that these losses represented approximately 15 kg of sugar losses per ton of cane (Legendre, 1973). Likewise, Saska *et al.*

reported sugar losses as a function of the time the material was stored before processing taking special attention for the fluctuations of the internal temperature of the material stored.

In the research titled as “Determination of Sucrose Loss in Storage of Clean Unburnt Billet Cane” it was showed that for a 24 hour period of storage, the internal temperature ranged between 17°C, 17-22°C, 22-27°C and >27°C, the sucrose losses calculated in terms of tons of sucrose for each 100 tons of initial sucrose per hour, was approximately 0.01, 0.01, 0.03 and 0.32, respectively. It was observed that the weight loss of the material was measured, and it was concluded that the weight losses (tons of cane per 100 tons initial per hour) when the temperature was in the two highest ranges (22-27°C and >27°C), was approximately of 0.08 and 0.22 (Saska *et al.* 2009).

Based on the complex conditions that are required to consider for ensuring an efficient and continuous supply of feedstock (harvesting, transportation, and storage), the following considerations are necessary to contemplate for the economic success and feasibility of system:

1. Ensure minimum operating costs in the system (harvesting, transportation, delivery, storage and processing) (Ribera *et al.* 2013), (Gan *et al.* 2011), (Sultana *et al.* 2011).
2. Maintain feedstock availability in order to ensure a continuous supply of the input and a continuous operation; enabling production maximization and profitability of the business. (Homem *et al.* 2010).
3. Implement practices for increasing the bulk density of the material (Leboreiro *et al.* 2011).
4. Due to low bulk density and low content of sugars that can be obtained, the transportation stage is critical and expensive; therefore it should be evaluated and analyzed in detail.
5. The quality characteristics of the biomass and feedstock can be variable and inconsistent depending on the type of feedstock selected to work, the weather conditions, the technologies and practices implemented.

6. For acquiring the feedstock, it is necessary to harvest, transport and store the material before processing. Depending on the duration of these activities the biomechanical conversion process to ethanol can be affected (Iman *et al.* 2010).
7. The energy crops are perishable feedstock that requires to be processed in a short period of time before deterioration become critical (port harvest sugar losses, chemical and physical deterioration), (Solomon, 2009).

   When the storage time and temperature increase, the physical and chemical deterioration tend to increase over time, and the appearance of bacteria and physiological changes might occur more rapidly (Watt *et al.* 2009).

2.4 Supply chain logistics for agricultural productive systems

There are several considerations that are needed to be studied in order to determine how different practices can provide better results for handling the material before processing. It has been mentioned that the harvesting, the transportation and the storage phases of the operational supply are considered critical stages because of both, the criticality of the economics and the agronomics. The quality of the material can be affected depending of the procedures implemented for acquiring and handling the feedstock and the economics can be affected according to the parameters defined for obtaining, collecting and handling the material before processing.

It is important to highlight that the energy crops are perishable and present physical and chemical deterioration due to the exposure to environmental conditions, the practices used for handling the material and the time elapsed before processing it. Also, it is important to evaluate different supply practices that can reduce these impacts, and can increase the yield and quality of the material, and maximize the potential conversion of the feedstock into the final outputs.

The complexity of structuring and defining the overall operational structure of any supply chain is a challenge, specially, when a full scale industrial implementation has not been developed. Currently, because there is not a full scale implementation of the crops in industrial levels, these practices are unknown or are not well defined. There are different challenges to face, some of them are: the operational structure of the supply; the logistics used for the supply; the practices for acquiring and handling the material; the procedures and technologies utilized for the conversion process.

It is important to analyze the variables, constraints and requirements that are needed to take into consideration in an agricultural system for defining the network flow and structure of the system, different considerations have been studied for the model formulation of the system and the identification of the critical paths. Some of these are: spatial and temporal relationships, geographical conditions, distances to cover, and the effect of different practices on the quality characteristics of the feedstock (Mapemba, 2005).

At the moment, different mathematical models have been developed in the attempt of representing the behavior of the system taking into consideration a wide range of parameters used for specific stages of the system; some of these approaches are based on:

1. Analyze different types of feedstock such as wood, straw, sorghum and sugarcane, where the potential yield and availability of the feedstock is analyzed based on the practices used for obtaining and handling the feedstock before the processing (Mapemba, 2005), (Sultana *et al.* 2011).
2. Different studies are focused in the biomass availability (Perlack *et al.* 2005), (Gant *et al.* 2006) where the necessity of ensuring a continuous supply is an important and critical factor for a long term scenario.

3. The necessity of relating and establishing coordination of the activities between the harvesting, the transportation and the delivery of the feedstock to the factory is a necessity that should be defined for the efficient operation of the supply chain system, as was mentioned by Grunow (Grunow *et al.* 2007). Due to the similarities of the sugarcane with the energycane and sweet sorghum, this can be taken into account for analyzing the system.
4. Different technologies for the conversion of feedstock have been evaluated; some of these technologies are: the thermochemical conversion, combustion, gasification, and pyrolysis to biochemical conversion (Brechbill *et al.* 2008), (Charlton *et al.* 2009) (Sharma *et al.* 2013).

   In these approaches the evaluation and the tradeoff between the energy required for producing the final products and the energy obtained at the end of the process, is analyzed.
5. Evaluating the optimal location for the facility and the plant capacities has also been of great interest for different authors aiming to define the optimal distances to travel for acquiring the feedstock, and scheduling the operations (Gan *et al.* 2010), (Mapemba 2005).
6. Evaluation of different sources of lignocellulosic biomass for ensuring continuous supply for biofuel production (wheat straw, corn stover, forest biomass), (Sultana, *et al.* 2011).
7. Determination of optimal plant size based on the possible quantity of biomass supply can be obtained for ethanol production, where the biomass transportation is modeled based on truck scheduling and transportation capacity (Leboreiro *et al.* 2011).
8. Biomass supply simulation where the feedstock cost is evaluated, as well as, the energy consumption for acquiring the material and the energy consumed for the conversion process (Zhang *et al.* 2012).

9. Determination of best locations for the construction and operation of bio refineries for the production of biofuels and bioenergy. For these approaches, the availability of the material is a critical parameter, the geographical conditions, and the transportation infrastructure (Judd *et al.* 2012).

Supply chain system network: Due to the importance of a well-defined network of the supply chain, a body of literature related to an efficient supply management has been developed; several considerations and assumptions have been analyzed by different authors, focusing on:

1. Defining optimal location of multiple bio refineries using multiple feedstock (agricultural crops, woody biomass, and perennial grasses).

   For this approach, several types of feedstock were evaluated in order to define the optimal material combination for the supply to a single bio refinery; the yields of the feedstock were analyzed and were a decision factor for the selection.

2. Epplin developed a linear programing model for the definition of the optimal selection of different types of grasses and agricultural residues, the area for harvest, and the quantity of equipment was calculated and defined (Epplin *et al.* 2007).

3. Defining an optimal single bio refinery location using a single feedstock, where the low cost of delivery of individual feedstock was defined based on mathematical programing models. The author concluded that if the area of harvesting increases, the bio refinery capacity also needs to increase. (Wang *et al.* 2009).

4. Other economic models have been developed in the attempt of relating the economic feasibility of the utilization of biomass, Beeharry evaluated the utilization of sugarcane residues for the production of energy.

The author concluded that by using all the leaf matter generated from the sugarcane, it was feasible to obtain an increment near to a 50% more on the production of energy from this resource, compared to the current practices that not included all the residues (14%) (Beeharry, 2001).

5. Analyzing a long term investment and an economic feasibility of producing alternative products, such as ethanol from lignocellulosic material, from crop residues like woody biomass and energy crops, has also been studied.

   Kaylen used the Net Present Value (NPV) to estimate the net income over a long term period; similarly, Tembo and Epplin developed a multi period, multi region, mixed integer mathematical programming model to analyze the investment by maximizing the NPV value for a biomass bio refinery facility (Kaylen *et al.* 2000).

6. Other considerations for modeling biomass have been also analyzed, where the relationship between the environmental and geographical implications were performed by the implementation of the Geographical Information System (GIS).

   This approach was studied by English and Graham (English *et al.* 2000); they estimated the variability of the cost of handling biomass as a result of the environmental and geographical conditions.

In general, it was identified by the authors that the current practices do not completely satisfy the potential necessities that might require the implementation of alternative energy crops as inputs for biofuels production, and its implementation in industrial levels. The necessity of improving the practices and integrating the main components of the system will allow the definition of strategies and methods that can help to reduce the logistics costs, enabling to obtain a sustainable and feasible productive operation.

According to the literature, the utilization of biomass plants will require the evaluation of the material availability, quality characteristics, and the distances to cover for obtaining and transporting the material.

These critical factors must be considered, in order to carefully establish a system capable of ensuring a continuous supply to the factory, where the quality of the material, the yield and the operational costs can provide efficient conditions along the entire productive system, enabling the industry to become economically sustainable. However, special attention should be taken to the stages of harvesting, transportation and storage due to their impact to the supply system (Pantaleo *et al.* 2013).

Even though different approaches have been studied, it is necessary to focus special attention to the practices and methods defined for the supply stages of the system, so efficient practices can be determined for obtaining benefits from both, the economics and the agronomics.

CHAPTER 3: ENERGY CROPS SUPPLY SYSTEM

3.1 Supply chain system

Due to the advantages and similarities of sweet sorghum and energycane with sugarcane, it is expected to integrate and implement the current infrastructure and practices used for sugar cane with the energy crops. It is necessary to evaluate the current operational structure used by the sugar cane industry in order to identify and understand each of the processes that integrate the supply system, specially the stages of acquiring, handling and processing the feedstock.

This research will take special consideration to the harvesting, transportation and storage stages in order to evaluate how different practices can affect the yield of the sugars and the operational efficiencies of the processes.

The research will consider the already established supply system used for the sugar cane, in order to implement the energy crops for it conversion into ethanol.

The following sections will describe the current supply processes used by the sugar can industry; these same system will be considered for the model and current work

3.2 Sugar cane supply system

The main structure of the operational flow for acquiring the material (sugar cane) and processing through the system is shown in Figure 3.1. The main structure for the supply system of sugar cane, starts with the agronomic phases, which consist of the land preparation, the planting, the growth and management.

The logistics stages for supplying the material to the factory takes place according to the maturity of the plant, hence, the harvesting, loading, transporting and unloading processes are programed and executed for the delivery of the material to the mill.

Land preparation

•

Planning

•

Crop growth and management

•

Harvesting

•

Loading

•

Transportation

•

Unloading

•

Juice extraction

•

Conversion: Electricity, sugar and ethanol

Figure 3.1 Process flow diagram of sugar, ethanol and electricity (Woods, 2000)

Finally, after collecting the material, the processing and conversion operation can be developed in order to obtain as inputs electricity and/or sugar and/or ethanol. In the following sections, each of the stages previously mentioned will be described.

3.3 Supply of sugar cane to factories

The supply chain system of sugar cane for the production of raw sugar is primarily composed of the following stages.

Harvesting and loading the material: There are different harvesting methods that are currently used by the sugar industry. One of the methods is manual harvesting; this practice is used in some countries due to the low costs of labor and also because the field conditions can make difficult the mechanical harvesting.

It has been established, that by implementing manual harvesting, some advantages can be achieved; some of them are: lower field losses and better quality cane (Rein, 2007). The process for performing manual harvesting is followed by cutting the whole stalk from the bottom of the plant. The leaves and the top are manually removed with a tool called "machete", then, the material is grouped in rows so that it can be collected and loaded for it transportation to the factories (Figure 3.2).

Figure 3.2 Manual harvesting of the sugarcane (Carl Frank/Photo Researchers, 2013).

The loading process can be performed manually or mechanically, depending on the field conditions and the equipment and design of the operations that the cane growers or mills commonly use.

It has been established that manual loading provides better quality cane; for mechanical loading, special care should be taken in order to reduce the amount of soil and rocks that can be loaded with

the material by the grab loader (Rein, 2007). The mechanical harvesting is performed using a harvester which collects row by row the material planted (Figure 3.2); cut the top of the plant; chop the stalks into billets; and removes the leaves with an internal cleaner system.

For most of the harvester's equipment, the cutting system can be adjusted in order to modify the size of the billet, as well as, the fan speed used for removing the leaf matter from the material.

The material that is removed and expulsed by the extractor, forms a layer of leaf matter and trash on the ground (Figure 3.3).

There are some requirements needed before using a mechanical harvesting system, some considerations are: regular conditions of the field, a specific row length, spacing and distribution.

When the mechanical harvesting system is implemented, a collector truck needs to be parallel to the harvester in order to collect the billets processed by the harvester.

Figure 3.3 Mechanical harvesting of the sugarcane (ABE, 2011).

Transportation of the material from the field to the factory: After the cane is harvested and collected on the trucks, different mechanisms for transporting the material can be implemented. Tractors and trailers are commonly used for delivering the material to the factories; however, some countries implement the rail trucks or tramway systems. Normally, haul tractors and trailers

without a significant capacity, tend to cover as a maximum distance of 10 or less kilometers to transport the material. When tractors with capacities from 15 to 20 tons are used, the distances for transporting the material increases.

It is common to implement a trans-loading area to supply the material harvested and transported by smaller trucks to the trucks with greater capacity (Rein, 2007). The system employed to transport the feedstock can be vary depending of: field and road conditions, safety policies for roads, mills and growers' logistical operation.

The bulk density of the material harvested is a parameter that is highly related to this stage of the supply system and can affect the efficiency of the operation. It has been defined by several researches that different methods for harvesting can impact the density of the load being transported.

When more leaf matter is attached to the material during harvesting, the bulk density of the load decreases and some quality effects can be produced during the processing of the cane. When green cane is employed, this means that the cane is not burned in the field before harvesting, more tops and leaves are expected to be collected, affecting the load density of the trucks and affecting the logistical operation. It is expected to have more material but not all the material might have the same yield during the processing operation and will affect the efficiencies of the crushing and conversion operation.

Employing the green cane method, other effects can be produced: the harvester performance might be reduced; moderate billeting losses in the field will occur; more material to process in the factory; and more soil and trash will be included in the loads, (Rein, 2007). Despite of some negative effects, some advantages can be obtained: the material is fresher and it takes more time to degrade during the transportation and storage stages (Rein, 2007).

Harvesting efficiency: Another important parameter that can affect the efficiency of the harvesting operation is the length of the billet. It is important to obtain a well cut billet of an appropriate size that can allow a maximum load capacity of the trucks and minimize material deterioration and proportion of leaf matter (Fuelling *et al.* . 1978).

It has been defined that the shorter the billet, the higher the load density of the truck, however, the deterioration of the material might increase (Ripoli, 1996).

1. Weighing and unloading the material: After the cane is transported to the mill, the load of the truck needs to be weighted in order to calculate the payment rate of the material.

   This operation normally occurs using a weighbridge platform that registers the total weight of the truck when it is fully loaded. Then the material is unloaded and the truck is weighted again for defining the total amount of cane delivered.

2. Storing the material in the facility: When the cane is unloaded, the material is usually stored in a yard next to the processing facility. Because the material is handled in billets, the area of exposure of the material is greater compared to a whole stalk.

   The deterioration of the material increases depending on the time and conditions of exposure; this leads to increasing the possibilities of acquiring bacteria and having sugar losses.

   The gap of time between the harvesting and the processing stages is a critical period for the efficiency of all the system, it is recommended that the time that should elapsed in between these stages should be as short as possible, in order to reduce the losses of sucrose in the material. It has been illustrated that for burned cane, the losses of sucrose can become up to 0.4% for every hour elapsed after harvesting the material (Cock, 1995).

3. Conversion of the material into final products: After the cane is unloaded and moved for starting the conversion process, the cane is cleaned and washed in order to eliminate, as much as possible, any attachment of leaf matter or trash. The cane is processed by the following main stages: milling or diffusion, heating, flashing, defecation, clarification, evaporation, boiling and centrifuging (Grimaldo, 2013). After all the stages are performed, the output of the system is the raw sugar, which later passes through a series of refining processes in the refineries for direct consumption.

3.4 Chemical and physical deterioration

Due to the importance of finding alternative sources for biofuels production, it is necessary to identify the critical path of the system in order to improve efficiencies of the supply operation, the quality of the inputs and outputs and minimize the costs. It was mentioned that the harvesting, transportation and storage are critical stages for an agricultural system that implements energy crops as inputs for the biofuel production.

It is required to define and adjust the conditions of the already established system of the sugar cane for its utilization with energycane and sweet sorghum.

The harvesting, transportation and storage practices need to ensure a continuous supply of the material to the processing facility, where the quality of the material and the yield of the crop are factors that should be carefully considered and analyzed.

The current research will study and evaluate how different harvesting, transportation and storage practices affect the yield of the material, the yield of the recoverable sugars, and the efficiencies of each of the main supply processes (harvesting, transportation and storage).

3.5 Sugar losses

It is important to evaluate methods that can reduce physical and chemical deterioration in order to minimize the sugar losses and maximize quality of the material during the supply stages.

Several studies of harvesting practices, storage practices, physical and chemical deterioration have been conducted for the case of the sugar cane, some of these approaches are described below.

For the case of the sugar cane, Srivastava evaluates different post-harvest storage methods in his research titled as “Studies on Minimizing Quality and Quantity Losses in Stale cane”. The author implemented five different treatments after harvesting for evaluating the sugar and weight losses. The study analyzed the sugars and weight losses during a period of 120 hours after harvesting.

The following treatments were developed: cane stored under shade, cane water sprayed, canes with trash cover, cane with trash cover + water spray, that include a solution of mercuric chloride, salicylic acid, zinc sulphate, ammonium bifluoride and sodium acid, and cane stored in an open

The author conclude that changes in the temperature and in the relative humidity might rapidly affect the weight losses of the material stored; especially, for the first 48 hours. In the other hand, the result of the % pol tended to decrease more when the cane was stored without any storing treatment; the authors concluded that by implementing these storage treatments a minimization of sugar losses might be achieved.

Another approach developed for evaluating different harvesting practices was reported by Larrahondo. The main objective was to determine levels of extraneous matter obtained after harvesting manually and mechanically; determine the sucrose losses due to the amount of leaf matter; the grinding efficiency; and the quality of the juice. Brix, pol, purity was measured in the field before harvesting, and after the juice extraction, a complete sugar analysis was developed, as well as brix test, and color, purity and turbidity tests (Larrahondo *et al.* 2009).

The pre harvest tests showed the following results: pol% cane of 14.5%, a purity of 91% a fiber % of 17%; after harvesting manually and storing the material during a period of 48 hours, the %pol was 14.6%, and the purity was reduced to 86%; while by the mechanical harvesting the purity was of approximately 84.9%.

By harvesting manually it was determined that the % of extraneous matter was around 5%, while by harvesting mechanically the percentage of extraneous matter increased up to 16%.When the manual harvesting practice was used, the % of fiber tended to be lowered compared to the mechanical harvesting. However, the brix and purity percentages of the juice were higher, it was concluded that a reduction of approximately 0.18 units of sucrose occurred for every 1% increment of leaf matter.

A different approach was studied by Pope in his research titled as “The Effect of Cane Factors on Bin Weight”; basically the research focusses on determining the relationship of bin weight and extraneous matter (EM). The author points out that the transportation cost represents a significant portion of the total production cost of sugar, and that the presence of leaf matter due to green harvesting is associated with a reduction of the weight of the bins after harvesting.

It was mentioned that a reduction of approximately 0.1-0.2 tons can occur by every 5% increase in EM (Pope, 1998); it was also found that as the age of the ratoon increased, the bin weight tended to decrease mainly because the billet becomes lighter on older ratoons. It was concluded that the bin weight reduction was produced as result of effects of lighter cane and higher amount of EM.

According to the study conducted by Cerqueira, it was established that due to the necessity of increasing the production of energy crop, it was indispensable to implement significant changes to the current supply chain used for the sugar cane.

Similarly, the author mentioned that it was necessary to determine how can different practices can be used for obtaining the maximum benefit for sugars recovery from the bagasse and the leaf matter, thus, a better utilization of the resources can be implemented.

The main objective of the research was to evaluate and predict the impact of sugarcane trash recovery and it potential use through the implementation of a crop simulation model (APSIM) and the environmental life cycle assessment (LCA).For the study, all the requirement needed for the preparation of the land in order to produce the feedstock (energy inputs, fertilizers) were measured, in the same way, the potential transportation modes (rail and road) and the equipment needed for collecting and transporting the cane were evaluated. Similarly, the farm requirements and the potential profit obtained from the final products, that were produced as a result of the yield and quality of the material collected (Cerqueira *et al.* 2013).

Saska reported sugar losses as a function of the time the material was stored before processing. Special attention was taken for the fluctuations of the internal temperature of the material stored. In the research titled as "Determination of Sucrose Loss in Storage of Clean Unburnt Billet Cane". The results from the study suggested that for a 24 hour period of storage, were the internal temperature ranged between 17C°, 17-22 C°, 22-27 °C and >27°C, it was calculated that the sucrose losses in terms of tons of sucrose for each 100 tons of initial sucrose per hour was approximately 0.01, 0.01, 0.03 and 0.32, respectively.

In the other hand, the weight losses of the material was measured, and it was concluded that the weight losses (tons of cane per 100 tons initial per hour) when the temperature was in the two highest ranges (22-27 °C and >27°C), was approximately of 0.08 and 0.22 (Saska *et al.* 2009).

3.6 Sugarcane post-harvest deterioration

A different study was conducted by Bhatia in India. The research titled as "Post-Harvest Quality Deterioration in Sugarcane under Different Environmental Conditions" evaluated how the post-harvest practices can affect the juice quality, especially when the material was stored before processing.

The research defined a period of storage of 12 days, in which each of the following tests were performed every two day: weight losses %, juice extraction %, sucrose %, purity and ph. As a result of the period of storage, the results of the test tended to decrease over time, especially, the cane weight losses %, the purity %, sucrose %, the yield juice extraction % and ph.; consequently, the total fermentable sugars was reduced.

It was evidenced that as the cane losses tended to increase, the percent of juice extracted tended to be reduced over time; it was also found that the TFS tended to increase. The author mentioned that a possible reason of this phenomena was primarily because of the moisture losses and due to the increment of the viscosity of the juice.

Similarly, a significant reduction of the sucrose % and purity occurred as the storage period progressed; one of the reasons of this phenomena was attributed to the presence of bacteria which reduced the sugar purity (Bathia *et al.* 2009).

For evaluating the chemical and physical effect of cutting the stalk of cane during harvesting, Watt *et. al*, developed a research titled as "Post-Harvest Biology of Sugar Cane." The author point out that the composition of the stalk might change when the stalk is portioned, especially when the storage period before juice extraction is long.

The author stated that the chemical deterioration was due to the bacteria and fungi appearance mainly because the microbes used the sugars as energy, and because they produced metabolic by-

products that cause processing problems in the factory. In the research conducted it was evidenced that the balance of the plant was disrupted at harvesting, generating that the supply of sucrose to the leaves stopped.

The plant respiration effect continues after harvesting; this phenomenon basically consume the sugar available in the plant and produces energy, resulting in sugar losses (Watt *et al.* 2009).

The authors concluded that the sugar losses after harvesting were due to microbial presence and ongoing plant respiration. It was found that the respiration process was highly related to the internal temperature of the material stored, with an environmental temperature of 23°C, approximately 0.27mg of carbohydrate (sugars) are consumed per gram of stalk over a day of storage.

It was concluded that if the material presented higher levels of damage after harvesting, the bacteria presence might increase, consequently, the physical and chemical deterioration increased, especially when the material was stored over a long period of time and the internal temperatures tended to increase.

Similarly to the previous research, Salomon mentioned in his research titled as "Post-Harvest Deterioration of Sugarcane", that most of the post harvesting practices implemented by the sugar industry are linked to sugars losses and low sugar recovery.

Some of the factors that accelerate these effects during the post-harvest operation and contribute to a lower sugar recovery are: harvest delays, processing delays, ambient temperature, methods of harvesting, supply system, environmental conditions, and cane variety, period of storage and bio deterioration (Solomon *et al.* 2009).

The author mentioned that the deterioration of the material after harvesting affect directly both, the industrial processing of the material, the economics of the processes and the final profit.

When the material was stored for a long period before processing, a direct effect occurred in the sugars recovery, the micro bacterial presence increase, as well as the sugar losses.

The condition of the material under these circumstances generates processing problems at the factory, and based on an economic perspective, the author mentioned that it was not totally worth to process material that presents chemical and physical deterioration, due to the low quality.

3.7 Main factors to feedstock deterioration

The author attributes the deterioration of the material after harvesting to different factors, these are:

1. Varieties: besides the adaptability and potential yield of each variety other factors such as environmental conditions and handling practices can affect drastically the sugar recovery. It has been evaluated that fibrous varieties show higher reduction in sucrose compared to less fibrous type.
2. Crop maturity: mature material tend to not deteriorate at the same rate of the immature cane over mature cane.
3. Green and burnt cane: according to the literature, the author mentioned that the green cane tends to deteriorate slower than chopped and burnt cane.
4. Environmental factors: it has been mentioned by Solomon (Solomon *et al.* 2009) and Uppal (Uppal *et al.* 2000) that when the material is exposed to high temperatures and a high % of humidity, the deterioration of the material tends to be greater.

   In addition to the bacterial presence, as a consequence of high temperatures and humidity, it was mentioned that the weather conditions can affect the practices implemented for collecting and handling the material as well as the quality.

5. Transportation logistics: the main factors that affect the quality and yield of the material during the transportation operation are basically: the time during transporting; the degree of damage of the feedstock after harvesting and the storage time.

   The author mentioned that due to some handling practices with different types of equipment (grab loaders, chains, pile rakes) in conjunction of high temperatures and mud presence, it was more likely the acceleration and population of the *leucunostoc* phenomena. Finally it was determined that by transporting and storing the material in smaller storage containers, the material was less susceptible to physical and chemical deterioration.

6. Magnitude of sugar losses: the author points out that some of the critical factors during the post-harvest stage were the exposure to different temperatures, the bacteria presence and propagation, and the plant respiration process that occur after the material is harvested.

According to the previous factors mentioned, the author associates them with an economic implication. In general, the author mentioned that material deterioration after harvesting is a critical parameter for the efficiency of the conversion process and the competitiveness of the business.

In the same way, as the deterioration occurs, a reduction in the cane tonnage takes place mainly because a rapid loss of moisture is produced. The author emphasizes that cane growers are affected by this issue mainly because if the cane quality is lower and the yield of the cane tonnage is reduced, the payment performed based on a weight basis will be significant reduced.

Reduction of material deterioration in post-harvest operations: In order to reduce all the issues involved in the post-harvest operation, the author concluded the following strategies for minimizing sugar losses, these are:

1. The material harvested should be processed as soon as possible; therefore, the reception policies of the mills should be planned and synchronized with the supply process (cane suppliers).

   The author stated that for the case of full green cane, the material should be milled within a period of 48 hours, when burnt full cane is used, the storage time should not be greater than 24 hours. When billets are implemented during the harvesting operation, the material should be processed no later than 12 hours after harvesting.
2. The material used for processing should contain a minimum amount of extraneous matter if production of sugar is the objective; the author recommends to use varieties with high fiber, in this way, sugar and moisture losses are minimized.
3. Avoid processing muddy cane.
4. While harvesting is recommended to no removal of the crown of leaves; otherwise, the material will deteriorate faster.
5. Practices for handling and transporting should be improved in order to reduce the level of damage of the material; in that way, dextran formation can be reduced.
6. Implement FIFO management policies for crushing, where the cane that firstly arrived should be the firstly used for processing.

Another important approach for evaluating how different practices of harvesting and storing can affect the yield of the sugars from sugarcane was performed by Legendre and Birkett in their research titled “Deterioration of sugar cane in overnight sleeper loads”.

The authors mentioned that the sugar industry faced critical challenges in the harvesting system because of the practices used and its effects in the yield of the material and efficiencies of the conversion processes at the factory. The authors suggested the necessity of improving the

coordination of harvesting schedules and deliveries as well as the minimization of the time the material is stored after harvesting.

The goal of the study was to determine the effect of the dextran concentration after storing billets in sleeper loads during a period of 24 hours. For determining the concentration of dextran, the Rapid Haze method and the ASI II was used; the average results from the results for each method were 650ppm and 850ppm respectively.

The results suggested that between 17 to 20 hours after harvesting, the concentration of dextran was expected to be higher; as a result, a penalty for the seller due to the condition of the material was highly associated. The authors suggested that cane billeted should not exceed more than 20 hours before processing, they point out that the material should be processed in an interval between 5 to 8 hours.

Eggleston, reported the effect of sugar cane deterioration due to harvest and storage methods. The author states that deterioration of sugar cane is associated to level of trash, billeted cane, material exposition between harvesting and crushing phases. The study conducted 8 cane supply treatments used for storing the material during 3 days; samples were collected every 24 hours. The treatments included hand cut cane (green and burnt), harvested cane (green and burnt) and burnt whole stalks. The results indicated that glucose and fructose were greater in billeted cane than whole stalk cane in the sample. It was evidenced that the cane that was billeted presented an earlier deterioration compared to whole stalk cane, especially when cane was burnt (Eggleston *et al.* 2012).

Similarly, in another study performed by Eggleston titled “How Combine Harvesting of Green Cane Billets with Different Levels of Trash affects Production and Processing Part I: Field Yields and Delivered Cane Quality”.

The research evaluated the effect of using different speeds in the extractor system fan in relation to the potential amount of trash that can be obtained after harvesting; also, it the effects in the downstream and upstream processing were evaluated.

Three fan speeds were used (650 rpm, 850 rpm and 1050 rpm) at a constant speed of 3.5mph; trash tissues were collected, juice extraction % was measured as well as sugars analyses, pol, purity, fiber % and others more.

The results indicated that the leaf matter composition obtained after implementing a fan speed of 650 rpm, 850 rpm and 1050 rpm was approximately of 22.7%, 18.9% and 12.1% (Eggleston *et al.* 2012).

It was observed that the TRS decreased when lower fan speeds were used; similarly the yield of the material measured in tons of cane/acre tended to increased, however the % of leaf matter was higher for these treatments (lower fan speeds). It was also evidenced that as the % of leaf matter increased in the material that was harvested, the quality indicators tended to decrease. The authors point out that obtaining lower quality indicators was not only due to the amount of leaf matter attached to the material after harvesting, but also due to weather conditions, cutter height and varieties.

Post-harvest quality indicators: In the second part of the research, Eggleston reported different quality indicators were measured (soluble solids, sucrose, color, ash starch, mud volume during clarification).

The results indicated that the quality indicators tended to be progressively worse as the amount of leaf matter attached to the material harvested increased; it was determined by the authors that for every additional 1% of trash, a decrease of approximately 0.15% occurred in the purity of the

mixed juice. It was also mentioned that with the increase of trash while processing, the yield of juice extraction tended to decrease.

Inderbitzin mentioned in the article titled “Improving the Harvesting and Transport of Whole Crop harvested Sugar Cane” mentioned that by using billeted cane instead of whole stalk cane, the mass of the material transported and the bulk density might increase. In the research, the authors used a shredder fan in addition to the primary extractor fan in order to reduce the particle size of the extraneous matter, while the material was harvested into billets; with this procedure it was intended that the particles of extraneous matter were reintroduced with the material harvested in order to be transported with the cane.

The results indicated that the bulk density of the material increased approximately by 17%. Finally, the authors concluded that with the implementation of the additional shredder fan in the harvester, an increase of the bulk density of the material was obtained as well as a reduction of billet losses in the field.

Despite different approaches have been developed at the moment, it is necessary to provide additional strategies for improving the operational efficiencies of the harvesting and transportation in order to improve the quality of the material.

It is evidenced that different studies have been conducted for improving the practices of the harvesting, transportation and storage for the case of the sugarcane. This research will focus specifically on these initial stages of the supply chain.

CHAPTER 4: PROBLEM STATEMENT

According to the literature review that so far has been cited, it was mentioned that the implementation of alternative sources for the production of biofuels brings together complex considerations that should be analyzed and evaluated before establishing the feasibility of the operation.

So far, it has been mentioned the necessity and importance of implementing energy crops for the future replacement of fossil fuels. It was highlighted that energy crops such as energycane and sweet sorghum were potential sources for this purpose.

Energy crops provide greater benefits compared to other energy crops, however, it was concluded that before implementing the current supply chain structure used for the sugar cane it was necessary to study, analyze and improve some considerations of the system.

Especial attention should be provided to the stages of harvesting, transporting, delivery and storage due to the critical impact that can be generated in both, the material efficiency utilization and the economics.

In the same way, it was shown that some of the approaches that at the moment have been developed seek to evaluate the operational, the logistic and the agronomic challenges that the biofuel trend bring to the industry and to governmental entities. Some of these approaches attempt to evaluate the operational structure and the logistics that should be reflected for this type of agricultural system. In this approach, different topics have been evaluated, some of them are: transportation network, inventory policies, plant location and capacity, transportation capacity policies and time studies.

The main goal of the research conducted was to determine the structure, the strategies and the policies that this type of supply chain system should integrate in order to provide better and greater benefits from the operational development.

Similarly, different approaches have been carried out for analyzing the agronomic challenges involved in the handling, transportation and the processing; these topics are carefully evaluated in order to determine if the strategies for handling these alternative crops can ensure the sustainability of the system and determine if it can be implemented in economic scales.

4.1 Justification

The objectives of this approach are followed by the identification of practices, methods and strategies that can allow to greater yields, better quality characteristics and better processing performances of the conversion processes.

Some of the main topics mentioned in the literature review were:

1. Evaluation of different parameters for harvesting in order reduce sugar losses in sugar cane.
2. Effect of extraneous matter on the yield of sugar and can affect the processing performance; sugar cane trash recovery.
3. Storage effect in relation to weight bin losses.
4. Sucrose losses due to storage for the case of the sugar cane.
5. Post-harvest deterioration; post-harvest biology of the sugar cane.
6. Effect of the storing period and some others.

According to the literature, it was evident that considerations related to the material availability; the necessity of improving the quality characteristics of energy crops; the harvesting-transportation-storage practices for minimizing sugar losses.

Also it was critical to determine the distances to cover, are some of the key factors that should be considered for the successful implementation and development of an agricultural system based on energy crops.

The considerations that were mentioned before are necessary for the definition of a system capable to ensure continuous supply to the processing facilities, where the quality of the material is a critical factor due to the economics and the performance of the processing effects.

To establish a feasible biofuel production system from alternative sources, it is important to well define the network of the system and the logistics needed for the development of the operations, in order to minimize the total cost and set the optimal parameters that will lead to the maximize the efficiencies for the supply system.

It is indispensable to determine which practices for harvesting, transporting and storing the material can provide greater benefits for both, agronomics (material and sugars yields) and economics, for the case of the energycane and sweet sorghum.

Even though different approaches have been developed at the moment, it is necessary to provide additional strategies for improving the operational efficiencies of the harvesting and transportation when alternative energy crops are implemented in a productive system. It is evidenced that different studies have been conducted for improving the practices of the harvesting, transportation and storage for the case of the sugarcane.

The necessity of developing a similar approaches for alternatives energy crops such as energycane and sweet sorghum is indispensable; therefore, this research will focus specifically on these initial stages of the supply chain for these specific crops.

4.2 Main objectives

The main objective of the research is:

To evaluate the feasibility of implementing energy crops as inputs for the production of ethanol by the evaluation of different harvesting practices in order to determine the sugars yield, the material yield and the efficiencies of the processes.

4.3 Specific objectives

The following objectives were defined in order to accomplish the main objective of the research.

1. To measure the yield of the fermentable sugars that can be obtained from the energy crops after implementing different practices for harvesting and storing the feedstock.
2. To calculate the processes efficiencies of the initial stages of the supply system after implementing different harvesting and storage.
3. To determine the ethanol yield that can be obtained after implementing different harvesting and storage practices.
4. To perform an economic analysis between the operational costs and the potential profit of the ethanol production that can be obtained from the harvesting practices in order to determine the feasibility of the supply process.

CHAPTER 5: MATERIALS AND METHODS

This project investigates and evaluates different harvesting and storage practices for the energycane and the sweet sorghum, and the effect of these practices on the yield of the sugars, the yield of the material and operation efficiencies of the processes. Finally, the research will conduct an economic analysis for determining the feasibility of implementing the harvesting crops based on the operational costs and the potential profit form the ethanol production. This research attempts to develop a set of harvesting trials in which different parameters of the operation are going to be varied. According to the results obtained, an economic analysis will be performed in order to determine the economics of the supply system implemented in the harvesting trials and will evaluate the feasibility of the productive system according to the production costs and the potential profit from the ethanol production. The experimental work performed in this research is intended to be part as a preliminary study of the implementation of energy crops as inputs for the ethanol production, hence, the indicators and analyzes performed are presented as preliminary findings, further research will be conducted.

5.1 Experimental design

The methodologies, procedures and parameters used in the harvesting trials were taken from a document prepared by Aragon (2013) in keeping with the USDA AFRI–CAP award No. 2011-69005-30515 (Kochergin, 2012). Specifically, the procedures used in the harvesting protocols included harvesting efficiency and transportation density, convertible sugar losses and leaf matter; the harvesting trials were conducted by the direction of Dr. Aragon from the Audubon Sugar Institute. Additional information on the protocols used in this study can be found in Day (2013 and 2014).

The design of the experimental trials were developed in order to implement different harvesting and storage methods with the purpose of evaluating the effect of these methods on the %Brix and Total fermentable Sugars (%sucrose, % glucose, % fructose). It was intended to measure and determine the following indicators: potential losses of the material during storage, harvesting and transportation, composition of the plant before and after harvesting, the temperature and %RH effect of the feedstock after storing the material during 24 hours as was proposed by Aragon (Aragon, 2013) and cutting system accuracy of the harvester. A statistical analysis was developed in order to determine the existence of significant differences between the results obtained from the variables of response based on the combination of factors evaluated in each of the treatments executed and tested in the trials. The experimental trials design consisted in a factorial combination where three treatments for harvesting and storing the material were defined; these factors were: (a) fan extractor speeds (1100 rpm, 900 rpm and 0 rpm), (b) storage time of the material before been processed (24 hours of storage), (c) billet size (6 and 8 inches). All these factors were varied in the harvesting trials in order to measure and determine the effect on the variables of response defined for the experiment. The variation of the parameters mentioned (fan speed, billet size, storage time) were taken from the harvesting protocol reported from Aragon and used in the trials (Aragon, 2013). For testing the combination of factors in the harvesting trials, a Factorial design was developed for measuring the variable of response. Through the implementation of this statistical design, it was possible to determine the descriptive statistics of the results for each of the trials and determine if there were significant differences in the response variables according to the factors implemented in each of the treatments. The dependent variables defined for the study were assumed from the harvesting protocol defined by Aragon (Aragon, 2013). The dependent variables defined for the trials of the study were:

1. Analysis of sugars (% sucrose, %fructose, %glucose, total fermentable sugars and brix).
2. Harvesting efficiency (potential losses of the material in the field after harvesting).
3. Transportation density (ton/m3).
4. Composition of the material before and after harvesting.
5. Cutting harvesting system accuracy.
6. Effect of the temperature (C) and %RH on the feedstock after 24 hours of storage.

The independent variables defined for the trials were:

1. Speed of the fan – cleaning system of the harvester (1100 rpm, 900 rpm and 0 rpm).
2. Billet size – cutting system of the harvester (billet of 6 and 8 inches).
3. Brix and Sugars effect on the juice after storing samples during 24 hours before been processed (samples taken at time = 0 hours and at time = 24 hours).

5.2 Importance of the experimental trials

The experimental trials contributed to the work that is being developed for the USDA grant awarded by the LSU Agcenter "A regional program for production of multiple agricultural feedstock and processing to biofuels and bio based chemicals". The experimental trials that were performed in the research were alienated with the following outline project tasks:

1. Evaluate the efficiencies of the harvesting and transportation operations of the feedstock from the field to the factory.
2. Evaluate the potential biomass recovery that can be obtained from the feedstock based on the different parameters for handling, harvesting and transporting the feedstock.
3. Evaluate and determine the viability of using lignocellulosic material to obtain sugars based on the optimal conditions to harvest and transport the material.

5.3 Description of the Experimental trials

The experimental trails are planned to be performed in order to collect the data for analyzing the operational efficiencies, the logistics and economics of the harvesting and transportation of the energycane and sweet sorghum.

Table 5.1 and Figure 5.1 illustrate the variation of parameters implemented in the harvesting treatments.

Table 5.1 Harvesting and storage treatments (Aragon, 2013)

Treatment	Fan speed rpm	Billet size (inches)	
1	1100	8	6
2	900	8	6
3	0	8	6

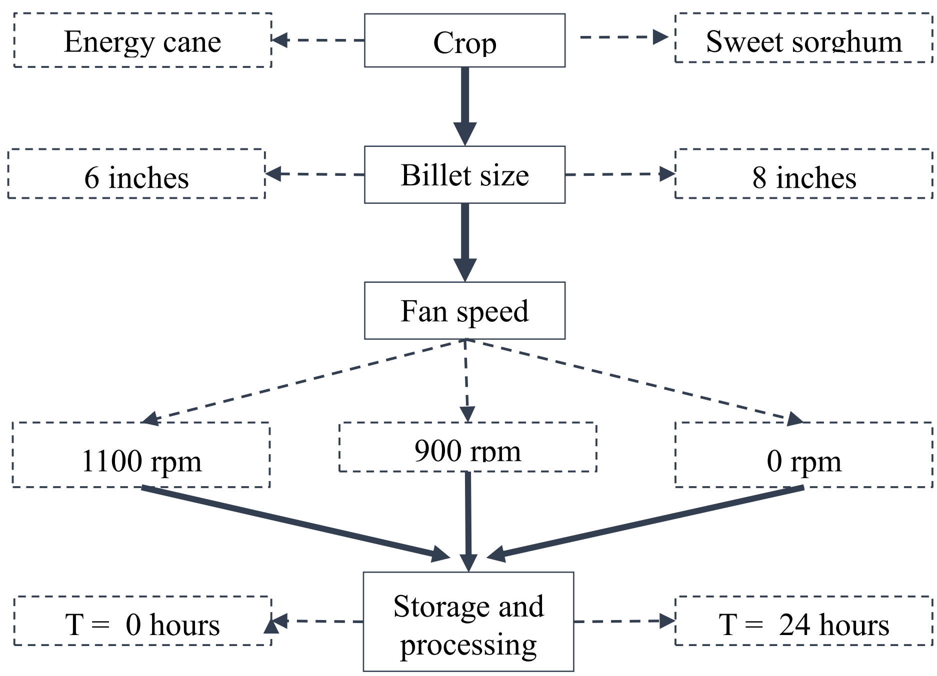


Figure 5.1 Treatment combination

The trials defined for the research are described below. The concept of the trials considered the procedures and methodologies of the Harvesting protocol proposed and conducted by Aragon (Aragon, 2013):

1. Material yield during harvesting (ton/acre).
2. Harvesting efficiency.
3. Transportation density.
4. Composition of the biomass plant before harvesting without treatments.
5. Composition of the biomass plant after harvesting implementing the treatments.
6. Convertible sugar losses during harvesting and storage.
7. Juice Yield.
8. Material losses due to storage.
9. Harvesting cutting system accuracy.
10. Temperature and %RH effect after storing the feedstock during 24 hours.

5.4 Energycane and Sweet sorghum plot characteristics

The energycane plot characteristics:

1. Variety: energycane variety 113.
2. Area of the field: 1.5 acres.
3. Number or rows: 19 rows. 8 rows were assigned to be harvested with a billet size of 6 inches and the others 8 rows were assigned to be harvested with a billet size of 8 inches.

Sweet Sorghum plot characteristics:

1. Variety: Dura Sweet 120 days hybrid.
2. Area of the field: 2 acres.
3. Number or rows: 37 rows. 18 rows were assigned to be harvested with a billet size of 6 inches and the others 18 rows were assigned to be harvested with a billet size of 8 inches.

5.5 Experimental trials and Sampling protocol

The activities proposed for this study considered the parameters, methodology and procedures defined in the Harvesting protocol proposed by Aragon (Aragon, 2013). The execution of the harvesting trials presented in this study were conducted by Dr. Aragon from the Audubon Sugar Institute.

Each of the crops was cultivated with the characteristics mentioned in Table 5.2.

Table 5.2. Plot Distribution

Description	Energycane	Sweet sorghum
area	1.5 acres	2 acres
rows	19	37
rows per size	8	18
rows for 1100 rpm	2	6
rows for 900 rpm	2	6
rows for 0 rpm	2	6

After harvesting the rows assigned for each of the treatments, the material was loaded, transported and stored in Audubon Sugar Institute – ASI (3845 Hwy 75 St. Gabriel, LA 70776).

The plots where the crops were planted and harvested were located about 0.5 miles away from the institute. The harvesting process initially started by harvesting the material according to the rows assignation for the different harvesting treatments. A John Deere harvester - 3520 model was used for the trials (Figure 5.2).

The material was collected by a “Weight wagon” which was located parallel to the harvester. The “Weight Wagon” collected and weighted the material harvested; then, the material was transferred into a “Dump Wagon” in order to be transported to ASI.

Figure 5.2 3520 John Deere harvester and weight wagon

After transporting and unloading the material to ASI facility, the samples for the experimental trials were taken.

The following basket distribution was assigned according to the harvesting treatments performed during the trials (Table 5.3).

Table 5.3 Baskets distribution according to harvesting treatments

Basket	Treatment (fan sped in rpm)	Crop	
1	1100	Energycane	Sweet sorghum
2	1100	Energycane	Sweet sorghum
3	1100	Energycane	Sweet sorghum
4	900	Energycane	Sweet sorghum
5	900	Energycane	Sweet sorghum
6	900	Energycane	Sweet sorghum
7	0	Energycane	Sweet sorghum
8	0	Energycane	Sweet sorghum
9	0	Energycane	Sweet sorghum

The baskets used for the trials are shown in Figure 5.3. After filling the baskets with the material collected from the harvesting treatments, samples of approximately 3 to 4 kilograms from each of the baskets were taken in order to perform sugars analysis (%sucrose, %fructose and % glucose,

and brix), same way that was proposed and conducted in the Harvesting protocol (Aragon, 2013). A total of n = 27 samples were collected before the storage trials started, and another n = 27 samples were collected after 24 hours.

The samples collected from each of the baskets at time t = 0 hours, were processed for juice extraction in order to perform Sugar analysis. 24 hours later, other set of 27 samples were collected for the same purpose.

At the end of the storage period, a total of N = 54 samples were taken (N = 54 samples for harvesting treatments composed of 8 inches billets and N = 54 samples for harvesting treatments composed of 6 inches), completing a total of N = 108 samples per crop.

Figure 5.3 Basket distribution.

It was expected that by using the harvesting treatment that used a fan speed of 1100 rpm in the extraction system, had the lowest amount of leaf matter compared to the other treatments (900 rpm and fan off – 0 rpm).

Figure 5.4, illustrates the condition of the samples that were taken according to each of the fan speeds used. As it can be evidenced in Figure 5.4, it can be evidenced that the sample contained the lowest amount of leaf matter and dust compared to other samples.

Figure 5.4 Samples with 1100, 900 and 0 rpm, respectively

After harvesting and collecting the material, another set of samples was taken in order to measure the real billet size obtained after harvesting and determine the accuracy of the cutting system of the harvester when the machine was configured for cutting the billets with a length of 6 and 8 inches (Figure 5.5).

Figure 5.5 Hydraulic Press and shredding machine

For extracting the juice from the samples, a hydraulic press was used; the mean pressure exerted by the press was of approximately 2500 psi during 30 seconds.

The sugar analysis was performed under the guideline of ICUMSA by the method GS7/4/8-23 “Determination of Sucrose, Glucose and Fructose by HPLC in cane molasses. It has been shown, that this method can be used for juice analysis instead of using molasses (ICUMSA, 2005),

(Schaffler, 1990), (Waldorf *et al.* 2004). This technique can be developed through a Chromatographic separation of sucrose, glucose and fructose which is achieved by the implementation of the High Performance Liquid Chromatography (HPLC).

Figure 5.6 illustrates the color of the juice collected after implementing each of the harvesting treatments defined for the experiment. The samples illustrated in Figure 5.6, correspond to the juice extracted from Sweet Sorghum after using each of the fan speeds from the extraction system (the juice was collected from the samples processed after harvesting, no storage time took place).

Figure 5.6 Sweet Sorghum juice samples – color

As can be evidenced in Figure 5.6, sample 1 corresponds to the sample collected after harvesting with a fan speed of 1100 rpm. By using this speed, it is expected that the billets contains the lowest amount of leaf matter, hence, during the juice extraction process, the juice extracted is not completely exposed and mixed with leaf matter and dust, obtaining as a result, a cleaner juice.

Finally, it can be evidenced that as the fan speed of the harvester is reduced (sample 2 and sample3), the juice can become darker because more leaf matter and dust can be attached to the billet.

CHAPTER 6: RESULTS AND STATISTICAL METHODOLOGY

A Factorial experimental design was implemented for performing the statistical analysis; the analysis was performed using the statistical software "SAS 9.3., SAS institute, Cary, NC.".

The experimental design employed for analyzing the data was selected because of the necessity of evaluating the effect of the combination of factors on the variables of response. By implementing this experimental design, all possible interactions and effects between the factors could be tested and analyzed in order to determine the existence of significant statistical differences between the factor interactions from the harvesting treatments.

The statistical method implemented in the software for analyzing the data, was a Two-Way ANOVA analysis. This procedure was performed by the implementation of a *Proc Mixed* statement, which allowed to test if there were significant differences in the results obtained from the factorial arrangement from each of the harvesting treatments.

A level of significance was tested at a P-value ≤ 0.005. The statistical analyses were executed to the results of the variables of response obtained from the factorial combination of the harvesting treatments. The variables of response proposed and defined in this study were followed from the parameters and methodologies established in the Harvesting Protocols (Aragon, 2013).

In order to guarantee a correct implementation of the statistical methods and data analyses, a normality distribution test was performed to all the results from the variables of response. The normality test was developed in SAS by the implementation of the statement procedure *Proc univariate* and through the analysis of the *Shapiro-Wilk test*, which guarantee the normality of the data when the P-value is equal or greater than 0.005. By using the average results from the treatments, the normality of the data was guaranteed; therefore, the implementation of the

statistical methods for identifying significant differences from the results was statistically valid for all variables.

6.1 Results and Discussion

In the following section, the results obtained from the harvesting trials defined in Section 5 from both of the crops are presented. The results were analyzed with a statistical analysis using a "Factorial Design" for evaluating the interaction between the variables that were measured. The statistical results are explained and interpreted under the considerations of the design of the experiment defined in Section 5. The methodologies and indicators explained in the following section considered the procedures and conceptual definitions established by Aragon in the Harvesting Protocols (Aragon, 2013); the methodologies used in the study were followed from the Harvesting Protocols proposed by Aragon (Aragon, 2013); the harvesting trials were conducted by Dr. Aragon. Finally, a summary of the results is shown in each of the sections.

6.2 Weight losses of the material during storage (24 hours)

The samples were stored in baskets during a period of 24 hours under normal environmental conditions (material protected from rain and sun). After each basket was filled with the material collected from each of the harvesting treatments, the basket was weighted and 24 hours later, the basket was weighted again, for calculating the material weight differences and determine the % of material losses during a storage period of 24 hours.

The calculations were performed by using Equation 6.1 material losses:

$$\%Material\ losses\ =\ 1-\frac{final\ weigth(weigth\ of\ the\ basket\ after\ 24h)}{Initial\ weight\ (weight\ of\ the\ basket\ at\ t=0hours)} \qquad (6.1)$$

6.3 %Weight losses during storage for the case of the energycane

For the case of the energycane samples, the mean results obtained from the material weight losses during a 24 hours period of storage are shown in Table 6.1.

Table 6.1 Material losses during storage energycane (24 hours)

Fan speed (rpm)	Basket #	Wt. losses (kg)	Sample weight (kg)	Material losses (kg)
1100	1-2-3	4.7	144.5	7.2
900	4-5-6	5.9	131.5	8.0
0	7-8-9	6.6	43.0	3.1
1100	1-2-3	3.3	149.4	5.0
900	4-5-6	3.9	127.4	5.2
0	7-8-9	11.7	50.4	6.7

6.4 %Weight losses during storage for the case of the Sweet Sorghum

The % of material losses obtained during a period of time of 24 hours in storage for the Sweet Sorghum samples are shown in Table 6.2.

Table 6.2 Material losses during storage for Sweet Sorghum (24 hours)

	8 inches billet			6 inches billet		
Fan speed (rpm)	Wt. losses (%)	Sample weight (kg)	Material losses (kg)	Wt. losses (%)	Sample weight (kg)	Material losses (kg)
0	10	103.9	12.1	16	106.4	24.4
900	8	104.4	9	14	113.3	22.7
1100	7	71.8	5.7	13	121.1	30.3

6.5 Discussion of results

Energycane: the results from the statistical analysis indicated that the *Material Losses due to storage* were significantly different when the fan speed and the length of the billet varied (Figure 6.1 and Figure 6.2). It was concluded that as the fan speed increased, the losses produced in the

material stored for 24 hours decreased, especially when billets of a length of 6 inches were harvested.

The results suggested that by having lower amounts of leaf matter and dirt attached to the material harvested, the billets preserve better during a 24 hours storage period. The results suggest that as the fan speed increase, the % material losses during a period of 24 hours of storage is reduced, especially when the material is harvested with a billet length of 6 inches.

For Sweet Sorghum, the ANOVA results did not indicate that the “Material Losses due to storage” were significantly different between the results obtained from the different harvesting treatments. However, the results suggested that as the fan speed of the extractor system increased, the material losses on storage decreased (Figure 6.3).The results indicate that by using the highest fan speed while harvesting, a reduction of approximately 20% of material losses due to storage can occur, in comparison of not using the fan.

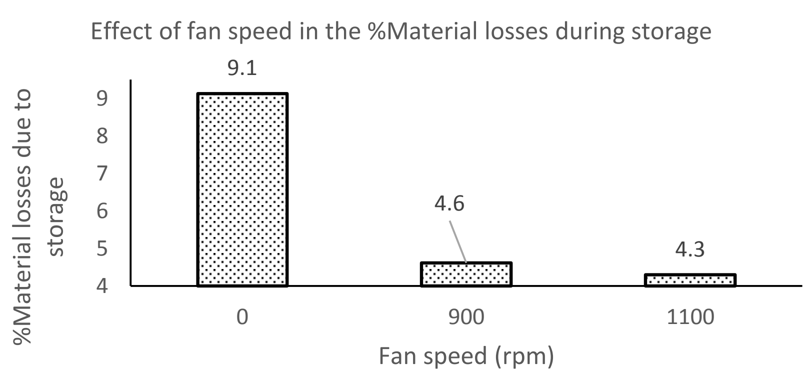


Figure 6.1 Billet size effect in the %material losses

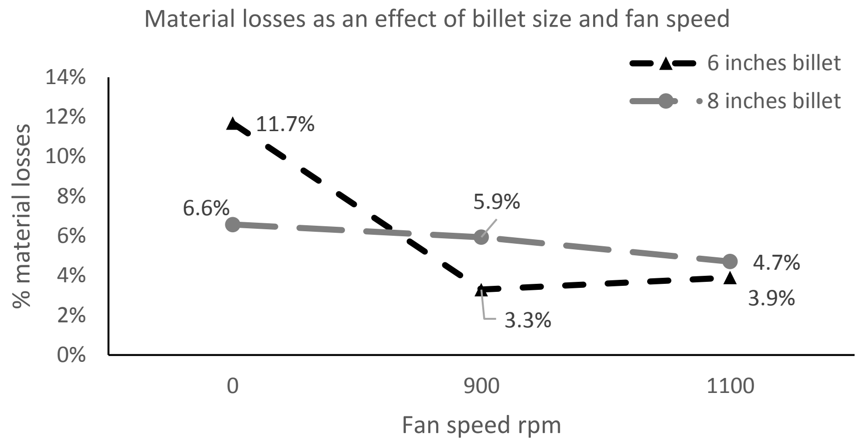


Figure 6.2 Billet size and fan speed effect in material losses%

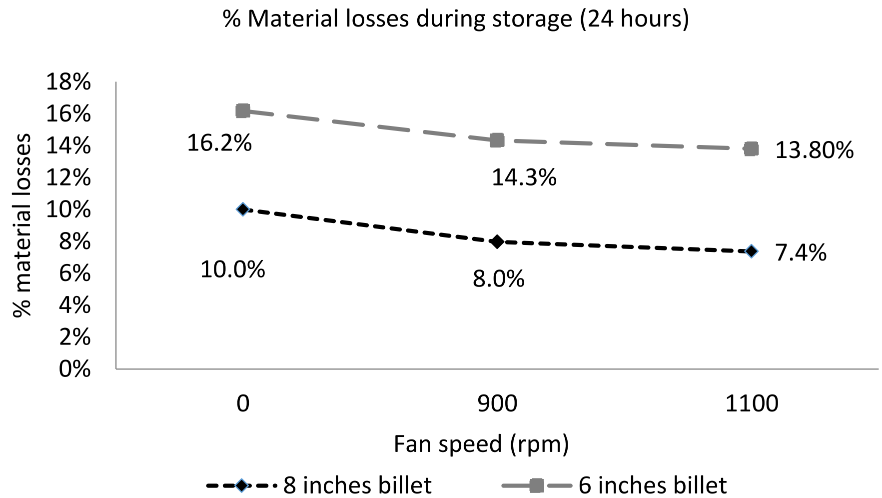


Figure 6.3 % Material losses during storage for Sweet sorghum

6.6 % Juice Yield

After collecting the samples from each of the harvesting treatments (each sample of approximately 1 kg), the material was pressed in a hydraulic press at 2500psi during 30 seconds. By the implementation of the Hydraulic press, it is expected to extract the highest amount of juice as possible from the sample (Procedure followed from the Harvesting protocol reported by Aragon).

The juice and the bagasse were collected and weighted for further analysis. The samples were collected after harvesting (t = hours of storage) and 24 hours later. The results obtained from the energycane are shown in Table 6.3.

Table 6.3 Percent of juice and bagasse obtained by press method for energycane

	8 inches billet				6 inches billet			
	T = 0 hours		T = 24 hours		T = 0 hours		T = 24 hours	
Speed (rpm)	Juice	Bagasse	Juice	Bagasse	Juice	Bagasse	Juice	Bagasse
1100	57	34	53	34	61	30	48	34
900	58	35	55	34	54	20	49	23
0	52	43	49	59	39	42	36	38

The statistical analysis indicated that by the variation of the fan speed of the extractor system and the storage periods, the yield of the juice presented significant differences. Table 6.4 illustrates the results from the treatments that indicate significant differences. The results suggest that the shorter the period of time the material is stored for processing, the higher the % of juice that can be collected; approximately and increase of 5% of juice can occur if material is processed in a short time before processing.

Table 6.4 Juice yield estimation energycane

Speed (rpm)	Estimate % juice
1100	0.56
900	0.55
0	0.47

The results obtained from the sweet sorghum are shown in Table 6.5 and Table 6.6. The statistical analysis indicated that by the variation of storage time, the % juice yield presented significant differences.

Table 6.5 Percent of juice and bagasse obtained by press method

	8 inches billet				6 inches billet			
	T = 0 hours		T = 24 hours		T = 0 hours		T = 24 hours	
Speed(rpm)	Juice	Bagasse	Juice	Bagasse	Juice	Bagasse	Juice	Bagasse
1100	65	22	57	23	60	25	58	26
900	65	21	56	21	56	25	37	20
0	56	29	44	31	54	29	35	32

Table 6.6 %juice extracted from sweet sorghum

Time (hours)	Estimate % juice
0	0.61
24	0.51

The results suggest that the sooner the material is processed after harvesting, the higher the % juice that can be extracted, obtaining an increment of approximately 10% compared when the material was processed after 24 hours of storage.

6.7 Bulk Density of the material (ton/m3)

Description: According to the dimensions of the basket where the material was stored, the volume (m3) was calculated (0.600163 m3). All baskets were filled up to the top with the material according to each of the harvesting treatments developed in the trials.

The density of the basket was calculated based on the total weigh of the material collected in the basket. By the implementation of Equation 6.2 (Density equation), the density of each of the treatments was calculated. The term “mass” of the equation was implemented in Tons, and the term “volume” in cubic meters.

$$\rho = \frac{mass(ton)}{volume\ (m3)} \tag{6.2}$$

6.8 Energycane Bulk Density (ton/m3)

The bulk density results obtained for each of the treatments for the energycane are summarized in Table 6.7.

Table 6.7 Average summary results of Bulk Density (ton/m3) for energycane

Fan speed (rpm)	Billet 8 inches	Billet 6 inches
1100	252	254
900	231	220
0	77	99

6.9 Sweet Sorghum Bulk Density (ton/m3)

The bulk density results obtained from each of the harvesting treatments performed with Sweet Sorghum are summarized in Table 6.8. According to the billet size, the indicator was measured for each of the treatments defined for the experimental trials.

Table 6.8 Summary results of Bulk Density (ton/m3) for Sweet Sorghum

Fan speed (rpm)	Billet 8 inches	Billet 6 inches
1100	190	220
900	180	240
0	120	220

6.10 Bulk density (ton/m3) results and discussion

For energycane, the results from the statistical analysis indicated that the Bulk Density was significantly different when the fan speeds used during harvesting were varied (Figure 6.4).The results showed a reduction of the bulk density occurred as the fan speed decreased. The results showed that by using the fan speeds of 1100 rpm, 900 rpm and 0 rpm, on average the bulk density of the material collected was 0.25 ton/m3, 0.22ton/m3 and 0.134ton/m3 respectively.

For the Sweet sorghum the results suggested that as the fan speed increased, the bulk density increased (a similar pattern compared to the results obtained with the energycane), and the shorter the length of the billets, the higher the bulk density obtained in the loads (Figure 6.5).

The results indicated that by using the fan speeds of 1100 rpm, 900 rpm and 0 rpm, on average the bulk density of the material collected was 0.212 ton/m3, 0.215ton/m3 and 0.177ton/m3 respectively.

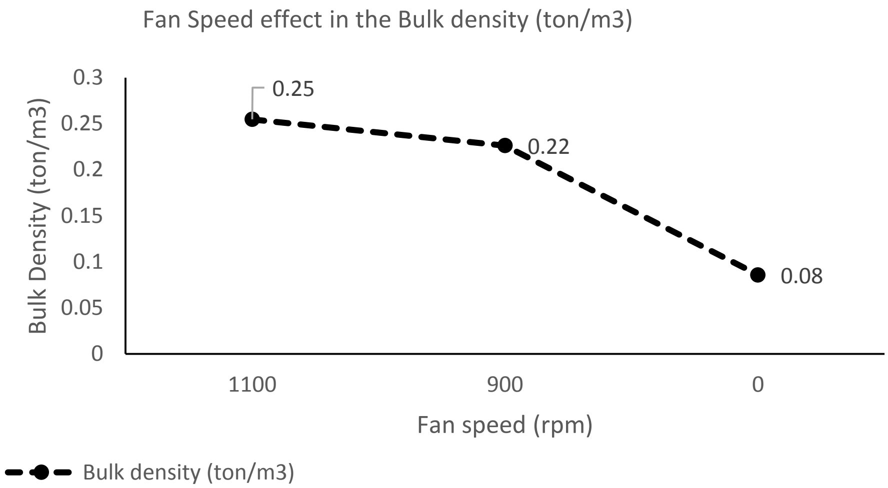


Figure 6.4 Fan Speed effect for Bulk density for energycane

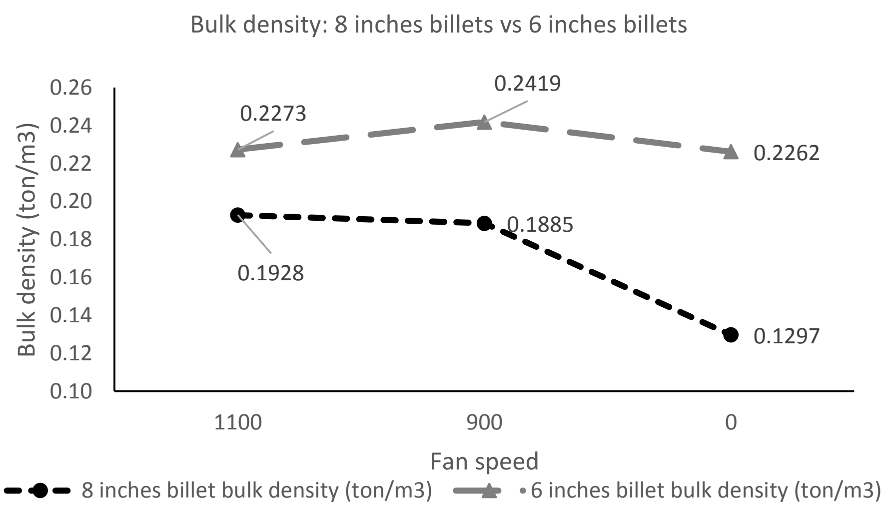


Figure 6.5 Comparison of material Bulk density composed of 8 inches billets vs 6 inches billets

6.11 Brix and sugars (%sucrose, %glucose, %Fructose, Total fermentable sugars)

After collecting the juice samples, a sugar analysis test was performed in order to measure the % Sucrose, %Glucose, % Fructose, Brix and the % of total fermentable sugars.

Table 6.9 and Table 6.10 shows the results of the normality test for all variables of response for both of the crops, Energy Can and Sweet Sorghum; all P-Values obtained from the *Shapiro Wilk Analysis* are greater than 0.005, which guarantee that the data is normal and can be used for further analysis without any transformation.

Table 6.9 Normality tests "Shapiro Wilk" for all variables of response (Energycane)

Variable	Test	Statistic		*p* Value	
Brix	Shapiro-Wilk	W	0.94	Pr < W	0.07
Sucrose	Shapiro-Wilk	W	0.97	Pr < W	0.73
Glucose	Shapiro-Wilk	W	0.94	Pr < W	0.06
Fructose	Shapiro-Wilk	W	0.95	Pr < W	0.12
TFS	Shapiro-Wilk	W	0.98	Pr < W	0.82

Table 6.10 Normality tests "Shapiro Wilk" for all variables of response (Sweet Sorghum)

Variable	Test	Statistic		*p* Value	
Brix	Shapiro-Wilk	W	0.94	Pr < W	0.07
Sucrose	Shapiro-Wilk	W	0.97	Pr < W	0.73
Glucose	Shapiro-Wilk	W	0.94	Pr < W	0.06

6.12 Sugars analysis for energycane

The summary mean results obtained from the Brix, %Sucrose, %Glucose, %Fructose and Total fermentable Sugars of the juice obtained from the different harvesting treatments executed in the experiment are shown in Table 6.11 and Table 6.12.

Table 6.11 Summary data for energycane - 8 inches billet size (Sugars and Brix)

Size (inch)	Speed (rpm)	Time *t* (hours)	Brix (%juice)	SUCR (%RDS)	GLUC (%RDS)	FRUC (%RDS)	Tfs (%juice)
8	1100	0	11.41	6.81	0.98	0.87	8.66
8	900	0	10.66	5.67	1.18	1.01	7.87
8	0	0	11.52	3.74	1.31	1.24	6.29
8	1100	24	11.62	6.46	1.18	1.08	8.72
8	900	24	11.48	6.21	1.43	1.26	8.89
8	0	24	10.84	4.23	1.47	1.31	7.01

Table 6.12 Summary data for energycane - 6 inches billet size (Sugars and Brix)

Size (inch)	Speed (rpm)	Time *t* (hours)	Brix (%juice)	SUCR (%RDS)	GLUC (%RDS)	FRUC (%RDS)	Tfs (%juice)
8	1100	0	11.49	7.76	1.26	1.16	10.17
8	900	0	11.75	7.61	1.36	1.20	10.17
8	0	0	11.23	5.41	1.33	1.22	7.96
8	1100	24	11.16	5.82	1.77	1.61	9.20
8	900	24	10.73	5.67	1.75	1.63	9.06
8	0	24	10.78	2.39	1.87	1.76	6.02

6.13 %Brix energycane

For energycane, statistical analysis did not show significant differences due to variation of parameters measured in the trials. However the results suggested that when the samples were processed shortly after harvesting, the %Brix present in the juice tended to be higher, especially when the material was harvested using a fan speeds of 1100 rpm or 900 rpm, obtaining on average 11.4 %Brix (Figures 6.6 and 6.7).

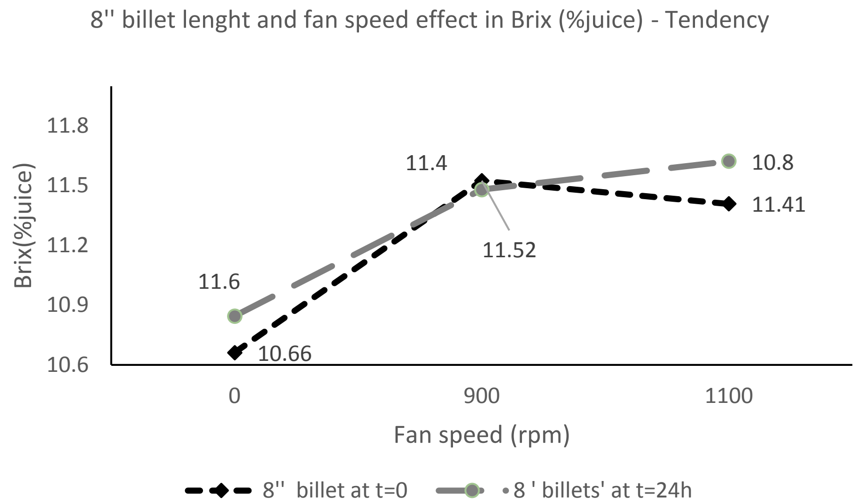


Figure 6.6 Billet 8 inches size - Brix comparison between treatments

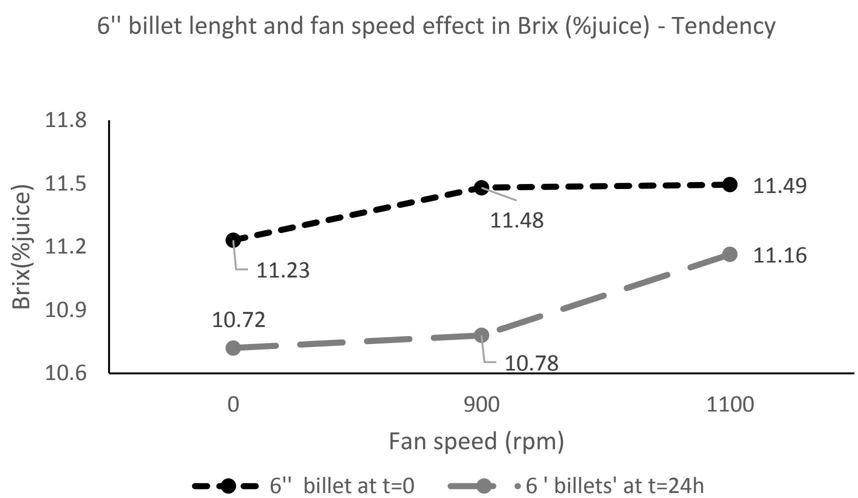


Figure 6.7. 6 inches billet size - Brix comparison between treatments

6.14 %Sucrose energycane

The results suggest that the higher the fan speed and the cleaner the billets, the %Sucrose tend to significantly increase (Figure 6.8).The statistical analysis suggested that there were significant differences on the %Sucrose as a result of the fan speed and storage time variation.

By using a fan speed of 1100 rpm, approximately an increase of 41% of Sucrose can occur in comparison of not using the fan extractor (0 rpm) (Figure 6.9).

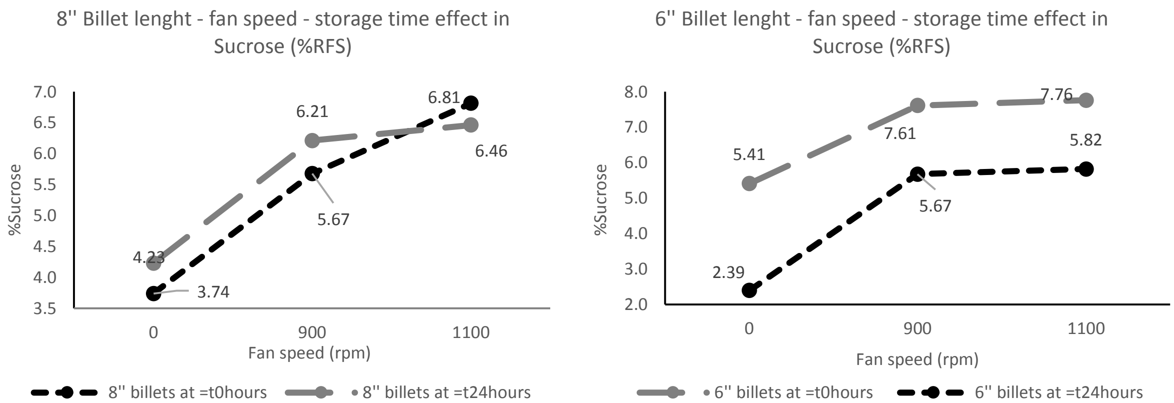


Figure 6.8 Comparison of % Sucrose between billets 8 inches vs billets of 6 inches

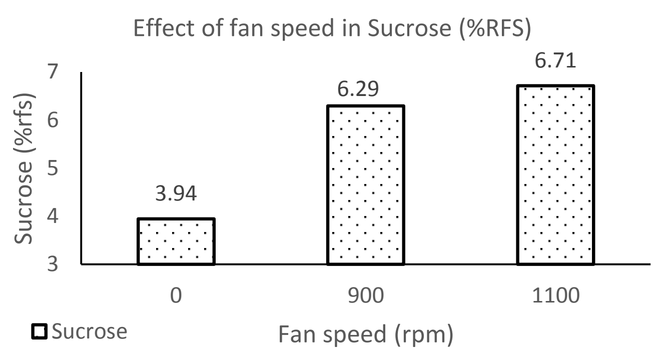


Figure 6.9 Fan speed effect in Sucrose (%RDS) for energycane

In Figure 6.10, the results suggest that as the storage time increase, the %Sucrose tend to decreased. The mean % Sucrose between both billet sizes at $t = 0$, is approximately 6.16%Sucrose, while after 24 hours of storage, the %Sucrose decrease to 5.1%, obtaining a difference of 16%.

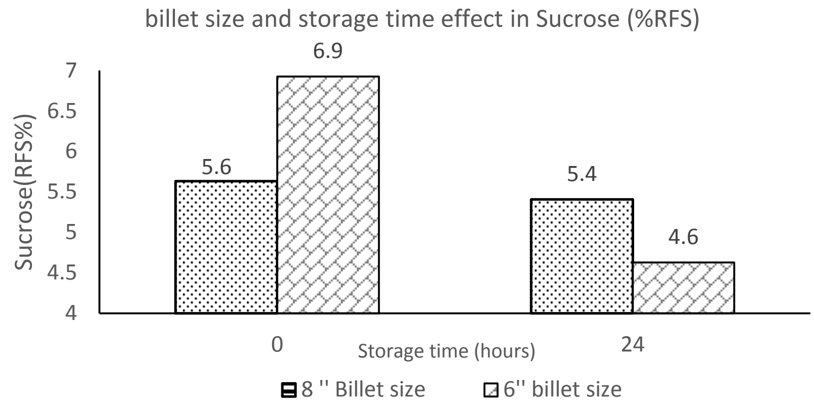


Figure 6.10 “Time*size” interaction effect in Sucrose (%RDS) for energycane

6.15 %Glucose energycane

The results of Glucose for the energycane suggested that as the fan speed of the extractor increased and the cleaner the billets for processing, the %Glucose tended to decrease.

The statistical analysis illustrate that there was statistical differences on the %Glucose as an effect of the billet size and storage time variation (Figure 6.11).

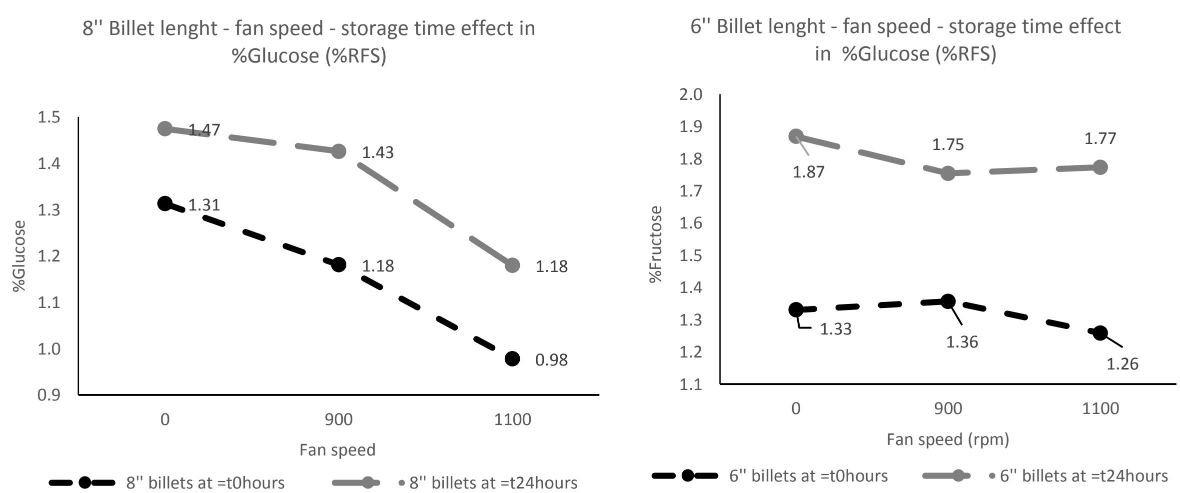


Figure 6.11 Comparison of % Glucose between billets 8 inches vs billets of 6 inches

Figure 6.12 illustrates a comparison between the mean results obtained from the % Glucose as an effect of the billet size and the period of time the sampled were stored.

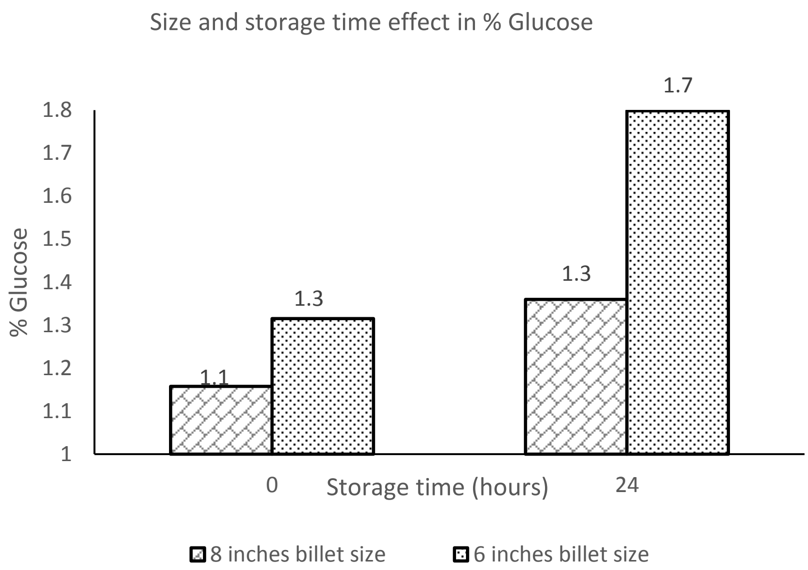


Figure 6.12 Comparison of the %Sucrose obtained in a period of 24 hours

The results suggest that the shorter the billet is harvested, the higher the %Glucose present in the juice; approximately an increase of 20% of %Glucose can occur when a billet size of 6 inches is used instead of using a billet of 8 inches.

Finally, the longer the material is sored, the higher the %Glucose in the juice; approximately an increase of 21% of Glucose can occur by storing the material during a period of 24 hours before processing.

6.16 %Fructose energycane

The results suggest that as the fan speed of the extractor increased, the %Fructose tended to decrease (Figure 6.13).

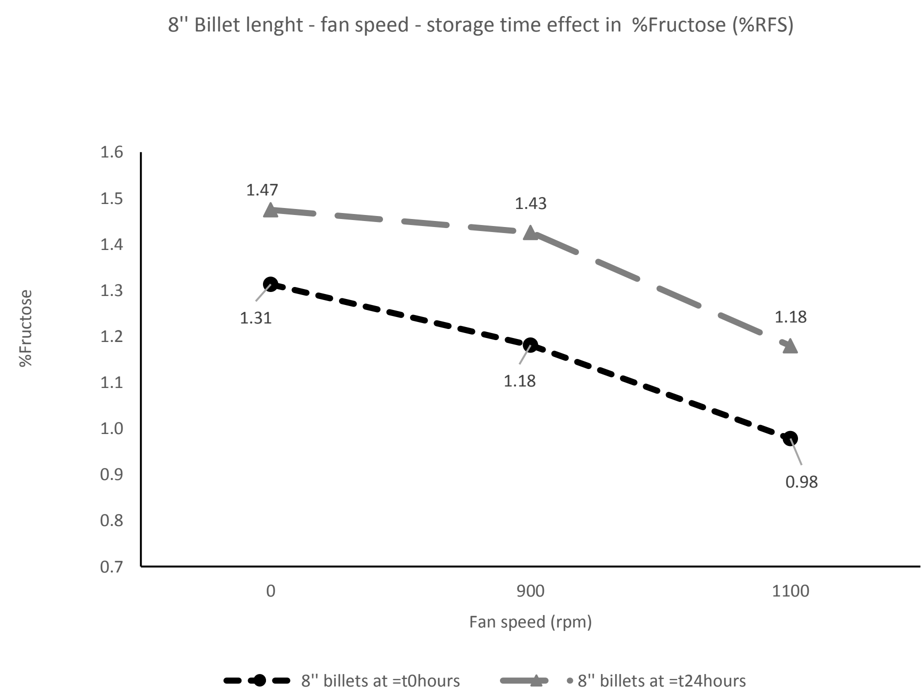


Figure 6.13. %Fructose between billets 8 inches.

The ANOVA results obtained in the statistical analysis indicated that the %Fructose was significant different. Approximately an increase of 14% of %Fructose can occur by not using the fan extractor instead of using the highest fan speed (1100 rpm). Figure 6.14 illustrates the mean results of the %Fructose as a result of the fan speed variation.

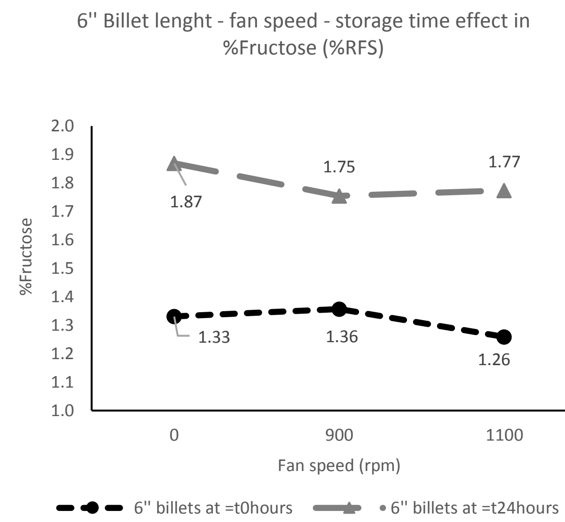


Figure 6.14. %Fructose between billets 6 inches.

Figure 6.15 illustrates the results of the %Fructose as an effect of billet size and storage time variation.

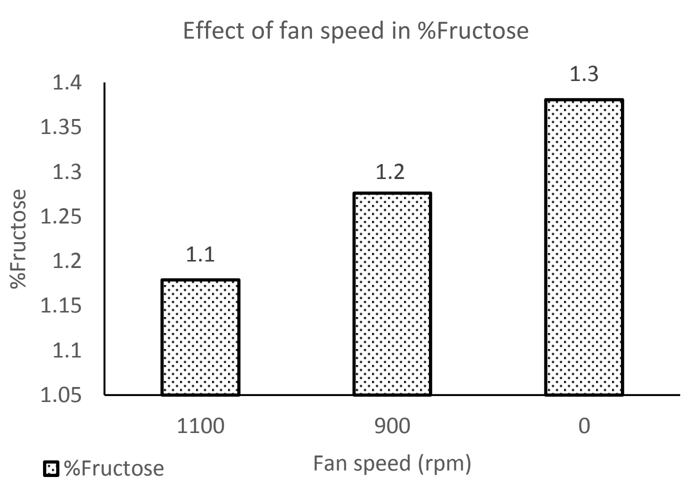


Figure 6.15 Fan speed effect in the %Fructose

According to Figure 6.16, the results suggest that the shorter the fan speed, the higher the % Fructose, obtaining an increase of 21.6% by using a billet length of 6 inches.

It can be evidenced that the longer the time of storing the material, the higher the %Fructose; approximately an increase of 22%Fructose can occur by storing the material for 24 hours before processing.

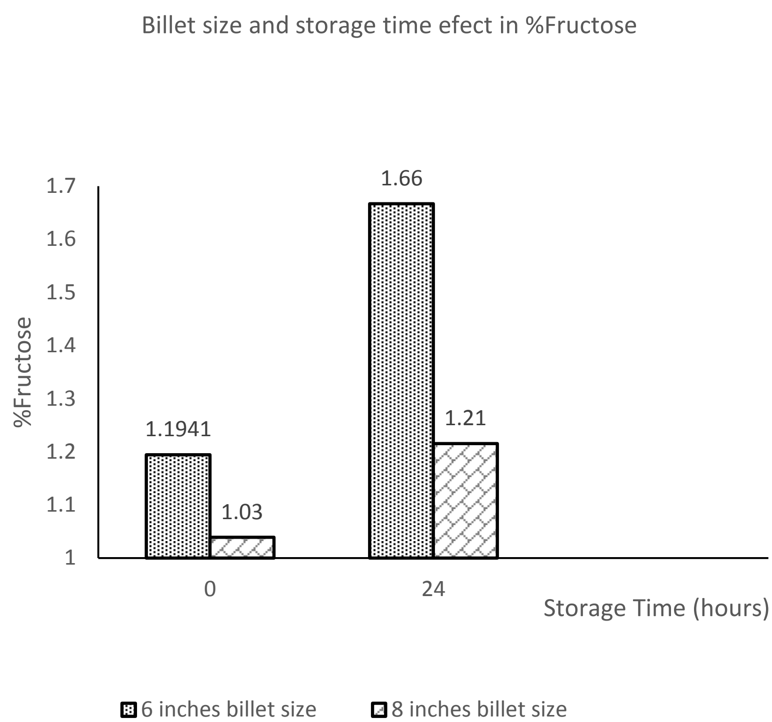


Figure 6.16 Billet size and storage time variation effect in the %Fructose

6.17 %Total fermentable sugars energycane

The results suggested that as the fan speed of the extractor increased, the %Fructose tended to decrease; it was also evidenced that the longer the storage time, the higher the %TFS.

The %TFS present in the juice significantly increased when the material was harvested with a billet length of 6 inches, representing an increment of approximately 9.8% TFS.

Figure 6.17 illustrates the comparison of the results obtained from the samples harvest with a length of 8 and 6 inches.

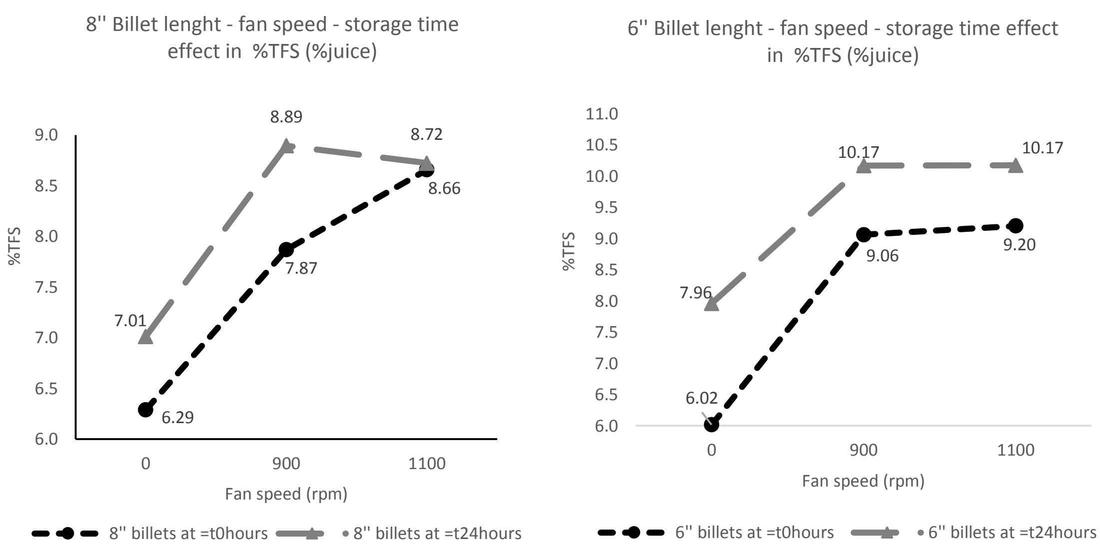


Figure 6.17 Comparison of %TFS between billets 8 inches vs billets of 6 inches.

From the Figure 6.18 it can be evidenced that as the fan speed of the extractor system increased, the %TFS present in the juice increased as well (9.1 TFS%), obtaining an increment of approximately 25% compared to the %TFS obtained by harvesting without fan (0 rpm).

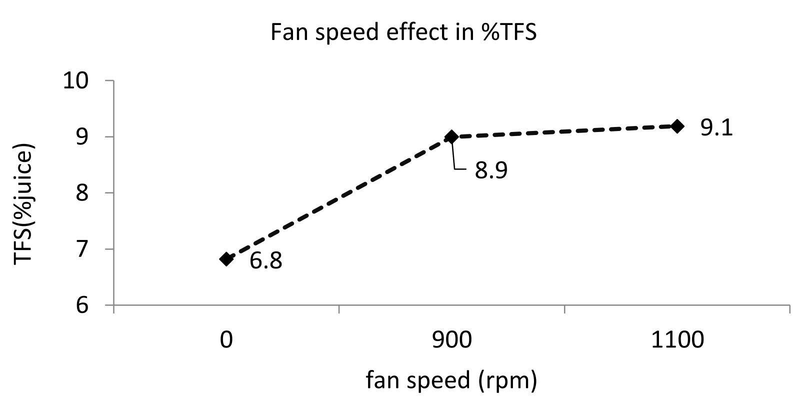


Figure 6.18 Fan speed effect in the %TFS

6.18 %Brix sweet sorghum

The results suggested that as the fan speed of the extractor increased, the %Brix tended to increase (Figure 6.19 and Figure 6.20). The longer the storage time, the higher the %Brix present in the juice. The results from the statistical analysis (ANOVA) indicated that the %Brix increased when the billets were harvested with a length of 6 inches, obtaining on average 10.2 %Brix, approximately 11% higher compared to the %Brix obtained from billets of 8 inches.

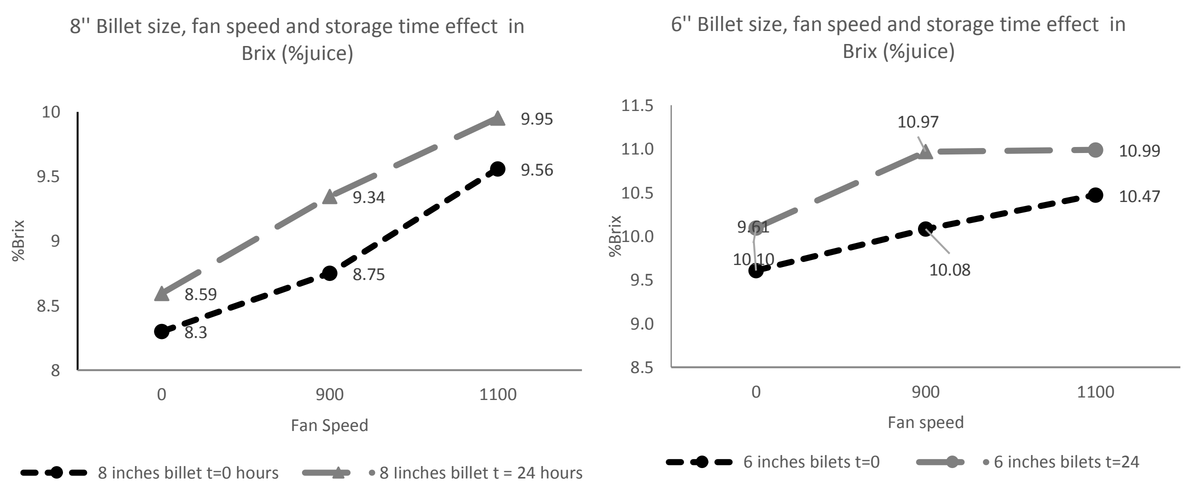


Figure 6.19 Comparison of %Brix between billets 8 inches vs billets of 6 inches

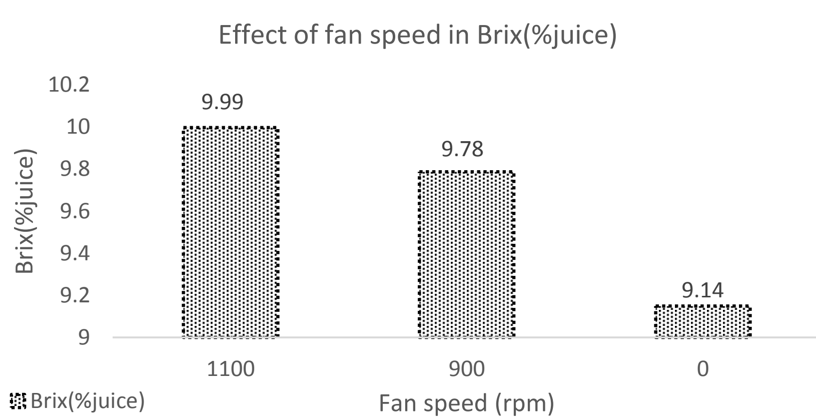


Figure 6.20 Effect of fan speed in the %TFS – energycane

6.19 %Sucrose sweet sorghum

The results from the %Sucrose present in the juice extracted form sweet sorghum suggested that as the fan speed of the extractor increased, the %Sucrose tended to increase (Figure 6.21). It was also evidenced that the shorter the storage time before processing, the higher the %Sucrose present in the juice.

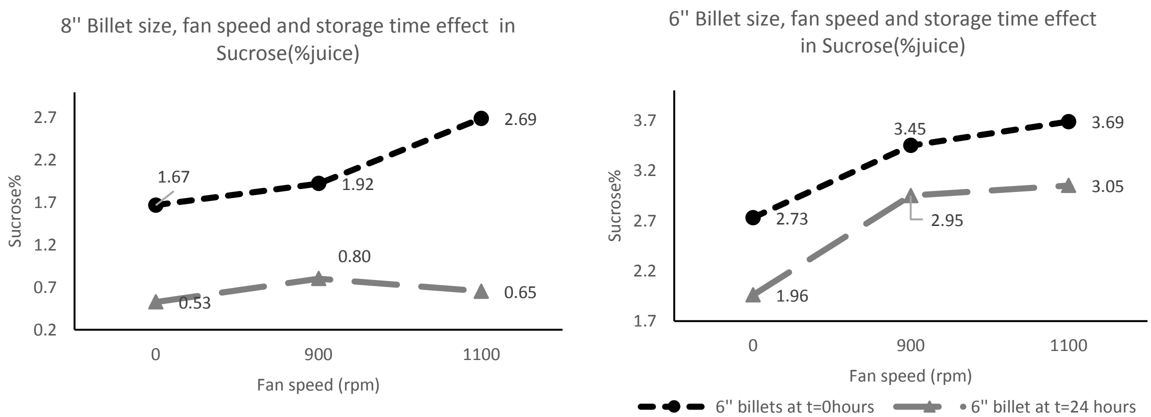


Figure 6.21 Comparison of %Brix between billets 8 inches vs billets of 6 inches

The results from the ANOVA analysis indicated that by the variation of the billet length and the period of storage, the result presented significant differences. The results suggest that the shorter the billet is harvested and processed, the higher the %Sucrose that can be present in the juice; an increment of approximately 53% of Sucrose might occur when 6 inches billets are harvested and processed in comparison of using 8 inches billets.

From Figure 6.22, it can be evidenced that the sooner the material is processed, the higher the %Sucrose present in the juice; an increase of approximately 38.6% of the %Sucrose might occur if the material is processed shortly after harvesting, in comparison if the material is stored for 24 hours.

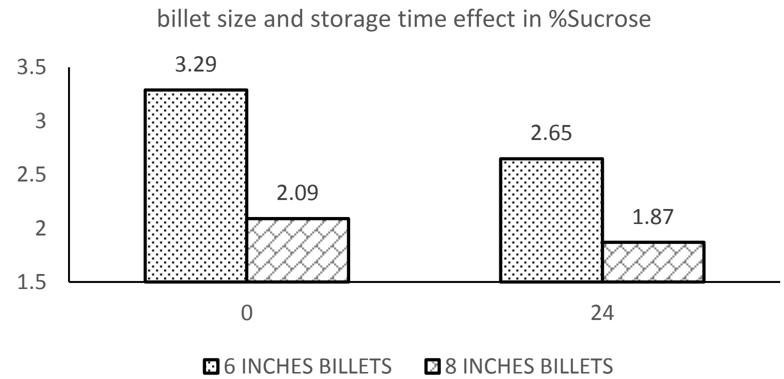


Figure 6.22 Billet size and storage time effect in the %Sucrose

6.20 %Glucose sweet sorghum

The results from the %Glucose present in the juice extracted form sweet sorghum suggested that as the fan speed of the extractor increased, the %Glucose tended to decrease (Figure 6.23). The results suggest that the shorter the billet is harvested and processed, the higher the %Glucose that can be present in the juice; an increment of approximately 9.8% of Glucose might occur when 6 inches billets are used instead of 8 inches billets (Figure 6.24).

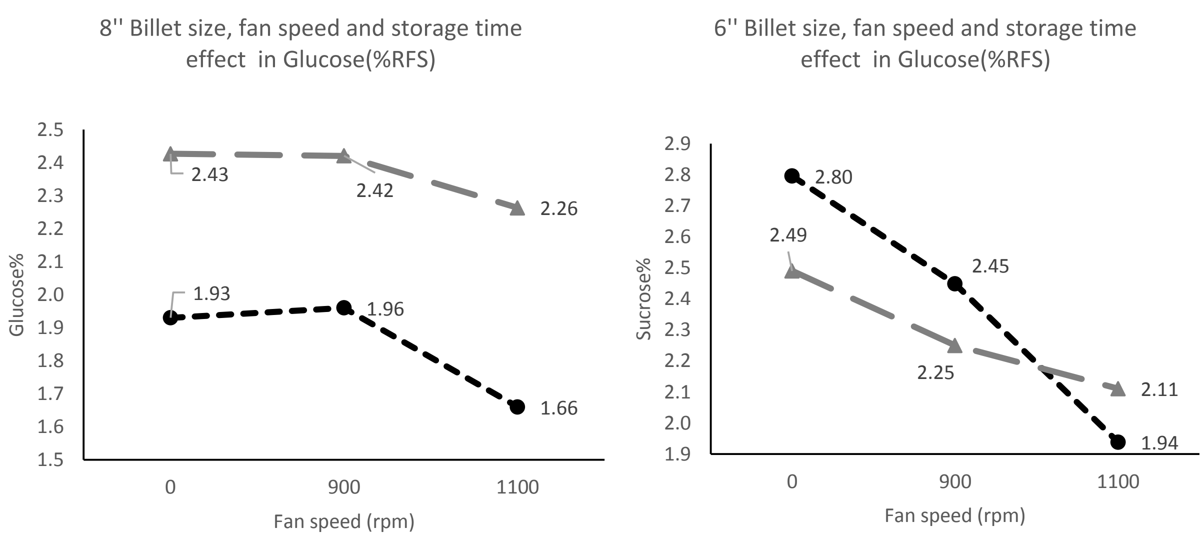


Figure 6.23 Glucose losses

As it can be evidenced, when the material is stored for a period of 24 hours, the %Glucose tended to increase, especially when the billets were harvested with a size of 6 inches.

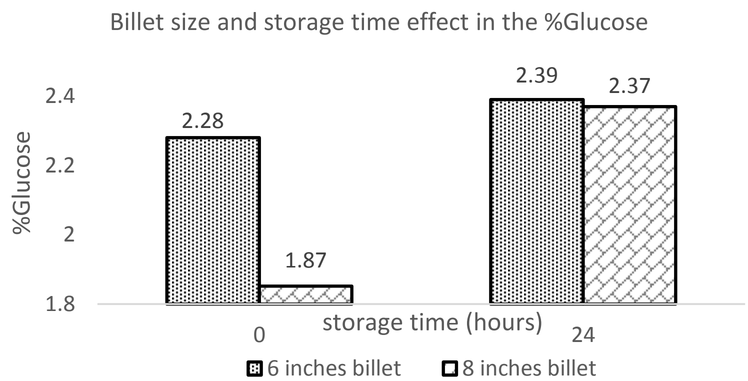


Figure 6.24 Billet size and storage time effect in the %Glucose, Sweet Sorghum

6.21%Fructose sweet sorghum

The results from the %Fructose present in the juice extracted from sweet sorghum suggested that, as the fan speed of the extractor system increased, the %Fructose tended to increase (Figure 6.25).

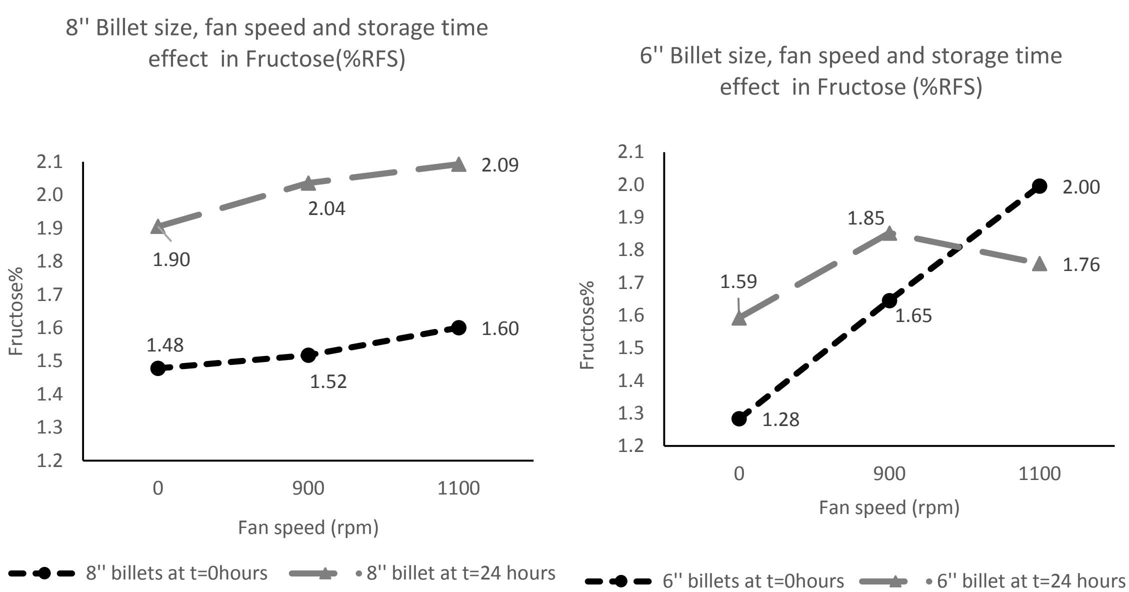


Figure 6.25 Comparison of %Fructose between billets 8 inches vs billets of 6 inches

The results from the ANOVA analysis indicated that by the variation of the fan speed and the period of storage, the results presented significant differences. As it can be evidenced in Figure 6.26, as the storage time increase, the %Fructose tended to increase; an increase of approximately 18.7% of %Fructose can occur when the material is stored for 24 hours before processing.

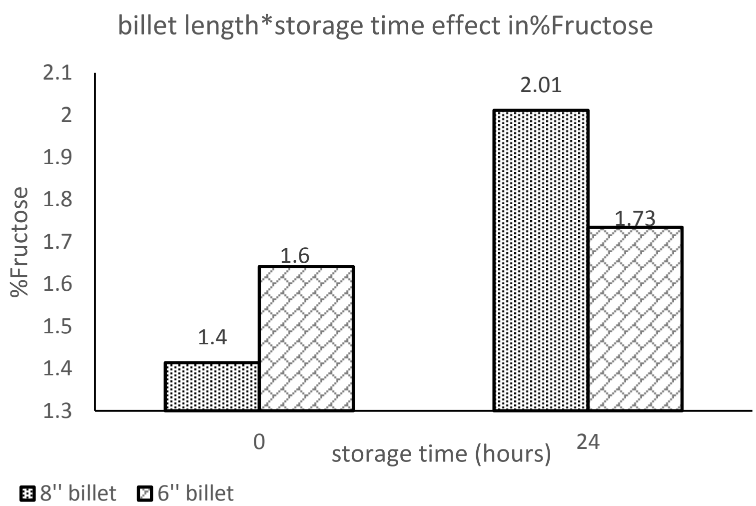


Figure 6.26 Billet length and storage time effect in the %Fructose

6.22 Total fermentable sugars sweet sorghum

For Sweet Sorghum, the results from the statistical analysis indicated that the % Total fermentable Sugars significantly change when the billet size and fan speed varied.

It was found that the smaller the billet, the higher the %TFS present in the juice (Figure 6.27), obtaining on average a maximum value of 6.9%TFS, presenting 25% more than the expected %TFS when 8 inches billets are processed.

The results indicate, that as then fan speed of the extractor system increase and the cleaner the billet, the higher the %TFS present in the juice, suggesting that by having less leaf matter attached to the billets, the higher the %TFS.

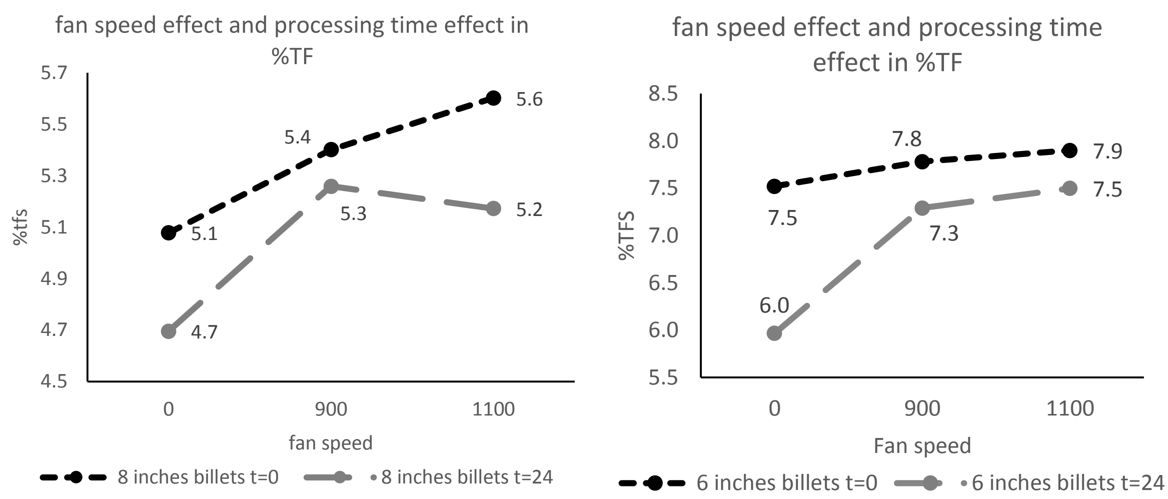


Figure 6.27 Comparison of %TFS between billets 8 inches vs billets of 6 inches

6.23 Harvester cutting system accuracy

The harvesting trials were performed with a John Deere harvester model 3520 (Figure 6.28). During the execution of the harvesting trials, two different billet sizes were implemented for harvesting the feedstock, 6 and 8 inches billets as was proposed in the Harvesting Protocols (Aragon, 2013).

A sample of approximately 42 billets was collected from each of the harvesting treatments executed in the experiment. The objective was to analyze the accuracy of the cutting system from the harvester by comparing “real length of the billets harvested” vs. the “theoretical length defined for the billet”.

Figure 6.28 Harvester used in the trials (John Deere 3520)

A statistical analysis was developed with the objective of calculating the descriptive statistics of the data and to implement a "One sample T-test" in order to compare the sample mean with a standard value. A *proc ttest* statement was used in the SAS code, in order to process the statistical analysis.

6.23.1 Harvester cutting accuracy – energycane 8 inches billet size

After collecting the material according to the different harvesting treatments, a sample of 42 billets of energycane was collected with a theoretical size of 8 inches. After measuring the length of each of the billets, the descriptive statistics from the sample were calculated.The sample mean of the sample was 7.54inches, indicating that the mean of the sample was under the length of the standard value. It can be evidenced that the majority of the billets from the sample, present a smaller size than the expected value, which indicates, that the mean size of the billets did not totally match the expected billet size (Table 6.13 and Figure 6.29).

Table 6.13 Summary results – billet length energycane (inches)

Theoretical length	Mean	Standard Deviation	Minimum	Maximum
8	7.54	0.68	6	9

The accuracy of the harvester for cutting billets with an expect size of 8 for energycane was of approximately of 94.25%.

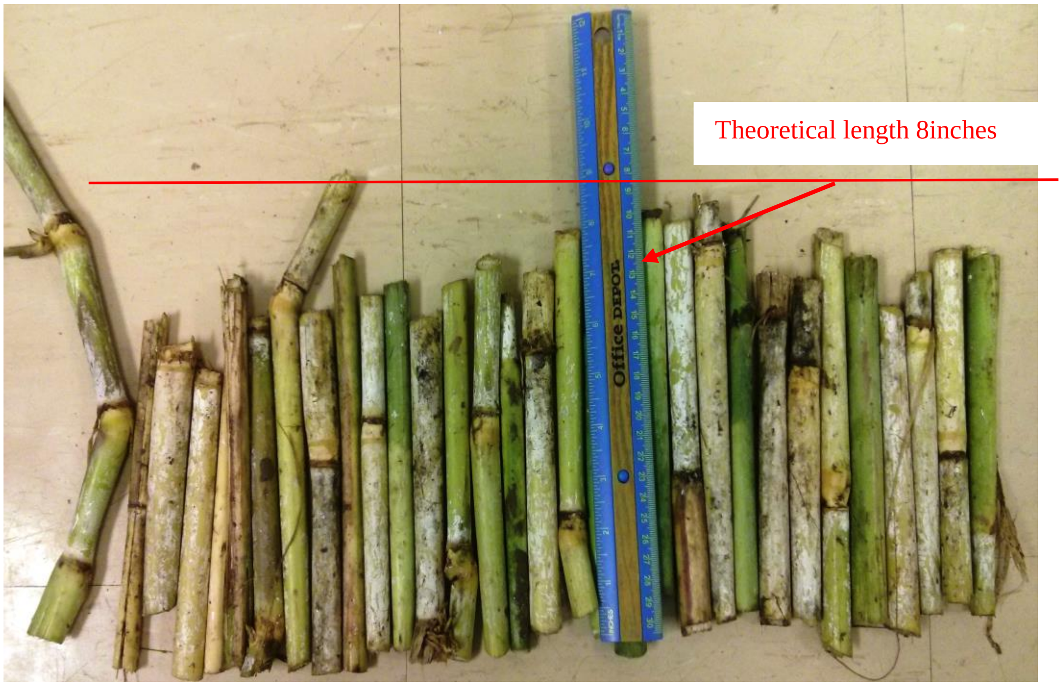


Figure 6.29 Energycane sample (8 inches)

Figure 6.30 illustrates the tendency of the results from the measurement of the billets. A one sample *t* – test was performed in order to compare the sample mean with the expect value; the results are shown in Table 6.14.

Based on the results obtained from the t-test, the results suggest that the mean length of the billets from the sample is significantly different from the expected length (standard value of 8 inches).

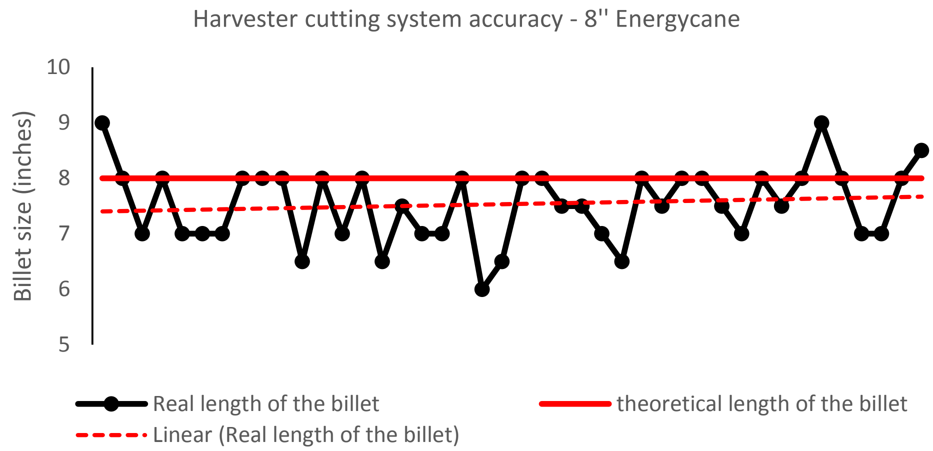


Figure 6.30 Accuracy for billets of 8 inches – energycane

Table 6.14 T- Test results for 8 inches billet size

Test	Statistic	*p* Value		
Student's t	t	72.320	Pr > |t|	<.0001
Sign	M	21	Pr > = |M|	<.0001
Signed Rank	S	451.5	Pr > = |S|	<.0001

6.23.2 Harvester cutting accuracy – energycane 6 inches billet size

After collecting the material according to different harvesting treatments, a sample of 42 billets of energycane were collected with a theoretical size of 6 inches (Table 6.15 and Figure 6.31). After measuring the length of each of the billets, the descriptive statistics were calculated.

Table 6.15 Summary results – billet length energycane

Theoretical length (inch)	Mean	Std. Dev	Minimum	Maximum
6	6.46	1.04	4.5	10

The sample mean was 6.46 inches, which indicates that the actual mean of the sample was over the expected billet length. In the sample was found billets with a larger size than the expected value, reaching up to 10 inches, and smaller billets of approximately 4.5 inches long.

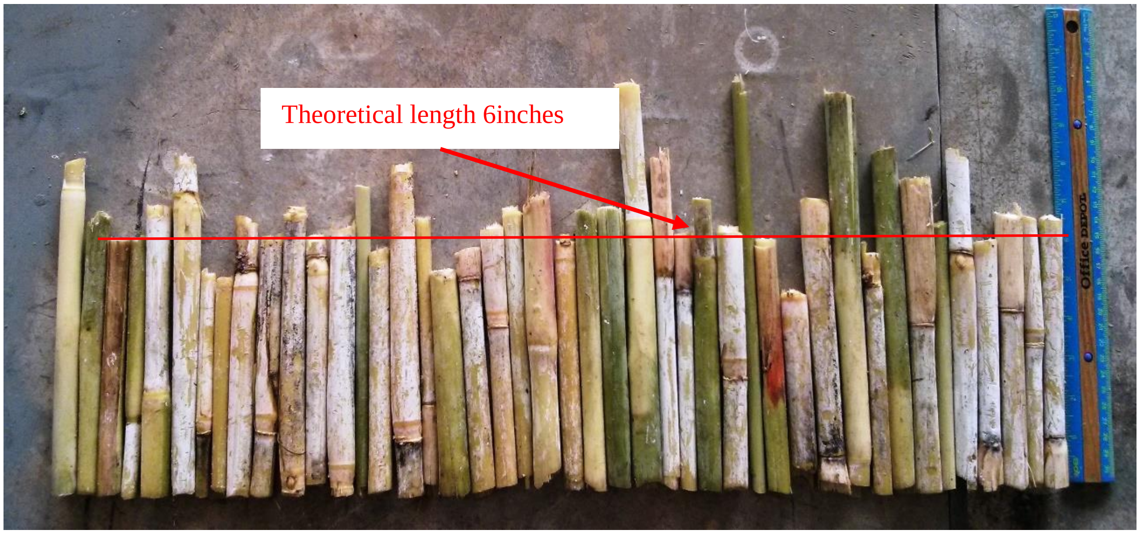


Figure 6.31 Energycane sample (6 inches).

From Figure 6.32 it can be evidenced that the majority of the billets from the sample had a larger size than the expected value (over the red line from the figure), which indicates, that the mean billet size from the sample did not match the expected billet size at all. The accuracy of the harvester for cutting billets with an expected size of 6 for energycane was of approximately of 92.87%.

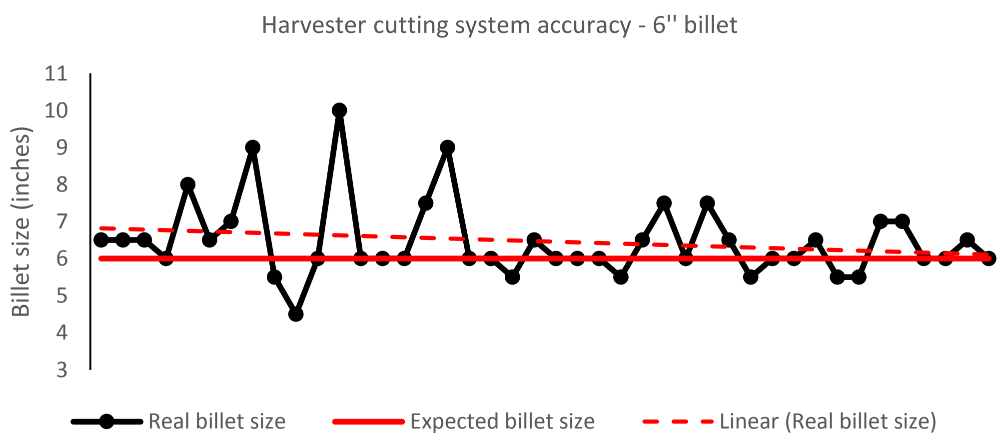


Figure 6.32 Accuracy for billets of 6 inches – energycane

A one sample *t* – test was performed in order to compare the sample mean with the expect value; the results are shown in Table 6.16. Based on the results obtained from the t-test, the results suggest that the mean of the real length of the billets is significantly different from the expected length (6 inches). Based on the results obtained from the t-test, the results suggest that the mean of the real length of the billets is significantly different from the expected length (6 inches).

Table 6.16 T- Test results for 8 inches billet size

Test	Statistic		*p* Value	
Student's t	t	40.1	Pr > |t|	<.0001
Sign	M	21	Pr > = |M|	<.0001
Signed Rank	S	451	Pr > = |S|	<.0001

6.23.3 Harvester cutting accuracy – Sweet Sorghum 8 inches billet size

After harvesting the material according to different harvesting treatments, a sample of 42 billets of Sweet Sorghum was collected with a theoretical size of 8 inches; after measuring the length of the billets, the following descriptive statistics were calculated (Table 6.17 and Figure 6.33).

Table 6.17 Summary results – billet length Sweet Sorghum

Theoretical length (inch)	Mean	Standard Deviation	Minimum	Maximum
8	7.54	0.95	5.5	9.5

The sample mean was 7.54 inches, which indicates that the sample had an actual mean that was under the length of the expected billet size. In the sample was found billets with a larger size than the expected value, reaching up to 9.5 inches, and smaller billets of approximately 5.5 inches long.

Figure 6.33 Sweet Sorghum sample (8 inches).

According to the measurements obtained it can be evidenced that the majority of the billets from the sample tend to be smaller than the expected value (under the red line from the figure), indicating that the mean size did not totally match the expected billet size (Figure 6.34).

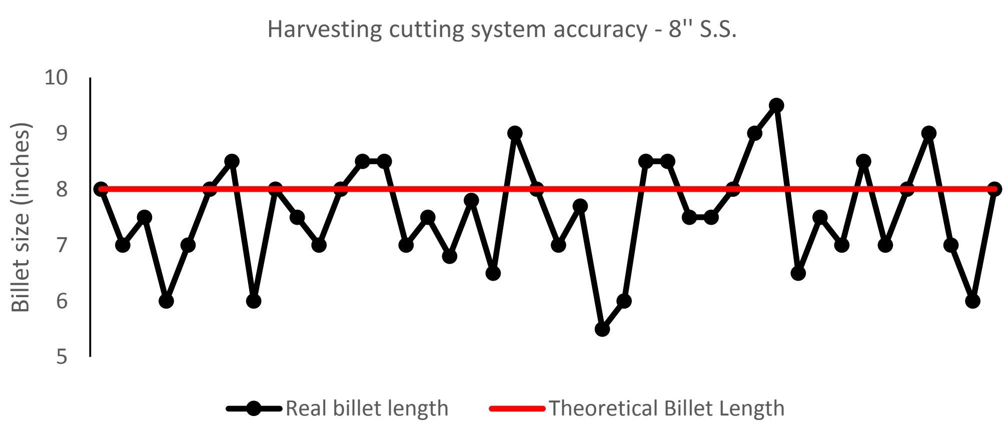


Figure 6.34 Harvesting cutting accuracy for 8 inches billet – Sweet Sorghum

The accuracy of the harvester for cutting billets with an expected size of 8 for Sweet Sorghum was of approximately of 94.25%.

A one sample *t* – test was performed in order to compare the sample mean with the expect value; the results are shown in Table 6.18.Based on the results obtained from the t-test, the results suggest that the mean length of the billets are significantly different from the expected length (8 inches).

Table 6.18 T- Test results for 8 inches billet size for Sweet Sorghum

Test	Statistic		*p* Value	
Student's t	T	50.88851	Pr > |t|	<.0001
Sign	M	20.5	Pr > = |M|	<.0001
Signed Rank	S	430.5	Pr > = |S|	<.0001

6.23.4 Harvester cutting accuracy – Sweet Sorghum 6 inches billet size

After harvesting the material according to different harvesting treatments, a sample of 42 billets with a theoretical size of 6 inches of Sweet Sorghum was collected for the trial (Table 6.19 and Figure 6.35).

Table 6.19 Summary results – billet length Sweet Sorghum

Theoretical length (inch)	Mean	Standard Deviation	Minimum	Maximum
6	5.79	1.11	3.5	9

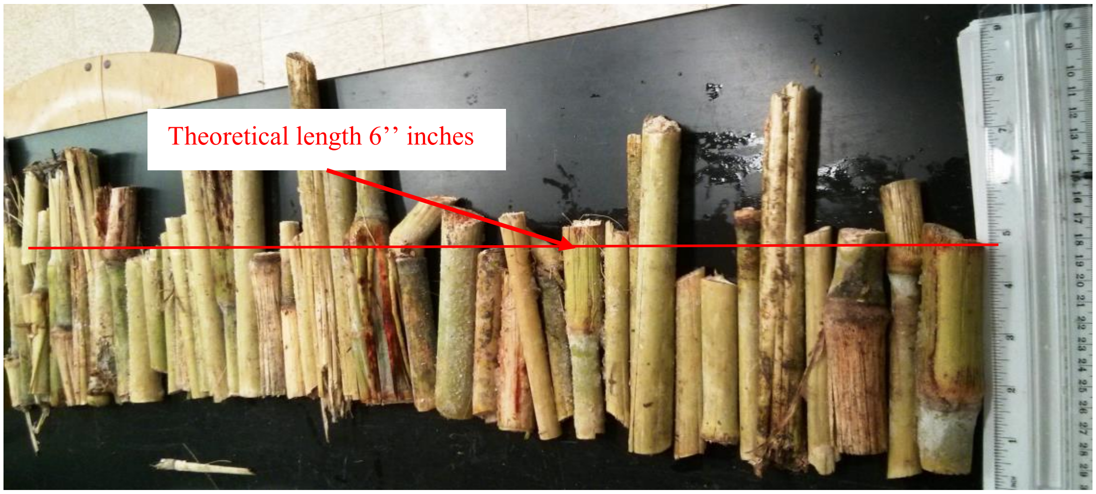


Figure 6.35 Sweet Sorghum sample (6 inches)

The sample mean of the sample was 5.79 inches, indicating that the sample mean of the sample was under the length of the expected billet size (theoretical billet size).

Figure 6.36 illustrates the tendency of the results from the measurement of the billets. According to the measurements illustrated in Figure 6.36, it can be evidenced that the majority of the billets from the sample tend to be smaller than the expected value (under the red line from the figure), indicating, that the mean size of the billets did not totally match the expected billet size.

The accuracy of the harvester for cutting billets with an expected size of 6 inches for the case of the Sweet Sorghum was of approximately of 96.5%.

A one sample *t* – test was performed in order to compare the sample mean with the expected value; the results are shown in Table 6.20.

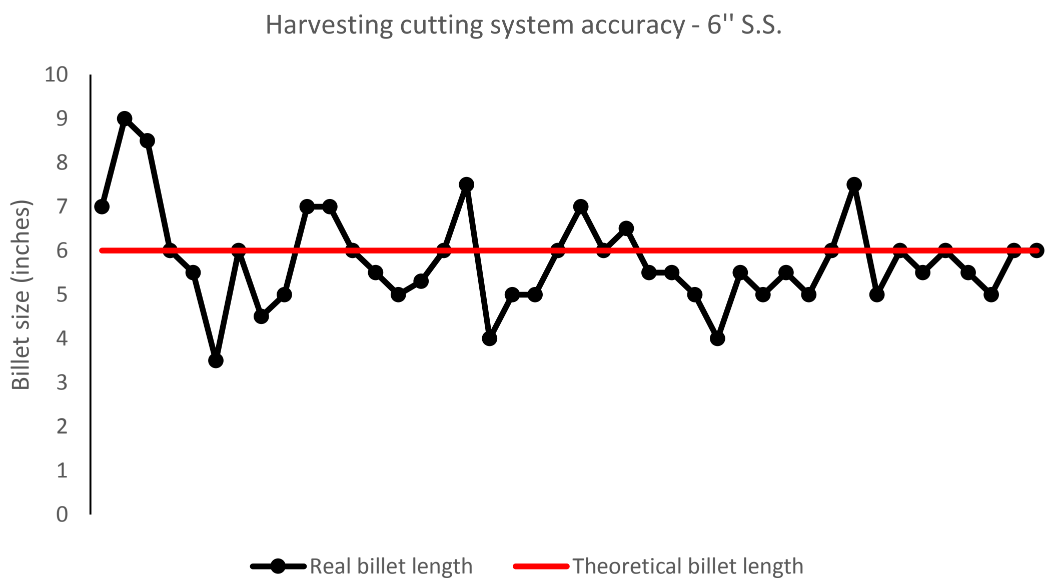


Figure 6.36 Harvesting cutting accuracy for 6 inches billet – Sweet Sorghum

Table 6.20 T- Test results for 6 inches billet size for Sweet Sorghum

Test	Statistic		*p* Value	
Student's t	t	33.9	Pr > |t|	<.0001
Sign	M	21	Pr > = |M|	<.0001
Signed Rank	S	451.5	Pr > = |S|	<.0001

Based on the results obtained from the t-test, the results suggest that the mean length of the billets obtained from the sample significantly different from the expected length (standard value of 6 inches).

6.24 Plant composition before harvesting (%Stalk, %Leaf matter and % Seeds)

In order to charcaterizethe material composition of the plant, samples were taken for material characterization. Equation 6.3, Equeation 6.4 and Equation 6.5 were used for calcultaing the potential %stalks, %leaff mater and %seeds obtained from the plant.

$$\%seed = \frac{Weight\ of\ seeds\ (kg)}{total\ weight\ of\ the\ sample\ (kg)} \quad (6.3)$$

$$\%Stalk = \frac{Weight\ of\ stalk\ (kg)}{total\ weight\ of\ the\ sample\ (kg)} \quad (6.4)$$

$$\%Leaf\ matter = \frac{Weight\ of\ leaf\ (kg)}{total\ weight\ of\ the\ sample\ (kg)} \quad (6.5)$$

6.25 Energycane plant composition before harvesting

A sample of 12 stalks of energycane was collected from the field for the trial. The total weigth of the sample was 15.6 kilograms. The results obtained from the physical characterization of the plant before harvesting is showed in Table 6.21.

Table 6.21 Energycane composition before harvesting

Energycane	Total weight (kg)	%
seeds	-	-
stalk	11.8	75.6
leaf matter	3.8	24.3

From the total weigth of the sample collected (15.6 kilograms), the total weigth categorized as stalk was approximately 11.8 kilograms, representing 75.6% of the plant composition, and a total weigth of 3.8 kilograms corresponded to leaf matter, representing a 24.3%, of the plant composition.

6.26 Sweet Sorghum plant composition before harvesting

A sample of 38 stalks of Sweet Sorghum was randomly collected from the field. The total weigth of the sample was 52.3 kilograms. The results obtained from the physical characterization of the plant before harvesting are shown in Table 6.22.

Table 6.22 Sweet Sorghum composition before harvesting

Sweet sorghum	Total weight (kg)	%
seeds	1.9	3.6
stalk	38.2	73
leaf matter	12.2	23.3

From the total weigth of the sample collected (52.3 kilograms), the total weigth categorized as stalk, was approximately 38.2 kilograms, representing 73% of the plant composition.

6.27 Material composition discussion

Comparing the result obtained from the plant composition of the energycane and Sweet Sorghum, the results suggest that the composition of each of the crops is relatively similar.

Table 6.23, shows a coparison between the final results obtained from the plant composition for both of the crops.

Table 6.23. Plant composition summary

Plant component	Energycane	Sweet sorghum
%stalk	75.6	73
%leaf matter	24.3	23.3
%seed	-	3.6

Despite the similarities of the plant composition between the crops, the energycane present a higher % of stalks and leaf matter compared to the Sweet sorghum, obtaining a difference of 2.6% for stalks and 1% for leaf matter, the seed components represented 3.6%.

6.28 Material composition after harvesting

After the separation, all components were weigthed in order to determine the potentail material that can be obtained after implementing different harvesting treatments (different fan speeds used in the fan extraction system and different billet sizes).

The harvesting treatments developed in the trials were composed of two different factors that were varied in the development of the trials, these factors are: fan speeds (fan extraction system) and billet size. The variation of these parameters were followed from the Harvesting protocol defined by Aragon (Aragon, 2013).

For the first factor, 3 different speeds were used (1100 rpm, 900 rpm and 0 rpm). For the second factor, 2 different billet sizes were selected for the length of the billet (6 and 8 inches).

6.28.1 Material composition after harvesting energycane 8'' billets

After harvesting with a theoreticall billet size of 8 inches and after implementing the harvesting treatments, the results obtained of the plant composition for the case of the energycane, are shown in Table 6.24.

Table 6.24 Summary – energycane 8 inches billet size

Average (kg)				Average (%)			
Speed (rpm)	Leaf	Billets	Total	Speed (rpm)	Leaf	Billets	Total
1100	0.3	3.6	3.9	1100	8.1	91.9	100
900	0.3	3.2	3.6	900	10.8	89.2	100
0	0.5	1.2	1.7	0	28.9	71.1	100

6.28.2 Material composition after harvesting energycane 6'' billets

After harvesting with a theoreticall billet size of 6 inches and after implementing the harvesting treatments, the results of the plant composition are shown in Table 6.25.

Table 6.25 Summary plant composition – energycane 6 inches billet size

Average (kg)				Average (%)			
Speed (rpm)	Leaf	Billets	Total	Speed (rpm)	Leaf	Billets	Total
1100	0.2	3.0	3.379	1100	8.1	91.9	100
900	0.5	4.0	4.630	900	11.6	88.4	100
0	0.8	1.8	2.670	0	31.4	68.6	100

6.28.3 Material composition after harvesting Sweet Sorghum 8'' billets

After harvesting with a theoreticall billet size of 8 inches and after varaying the fan speeds from the extraction system during the harvesting phase, the results obtained of the material composition for Sweet Sorghum are shown in Table 6.26 and Table 6.27. For the case of the Sweet Sorghum, the Seed component was considered and included for the analysis.

Table 6.26 Summary plant composition– Sweet Sorghum 8 inches billet size

Total weight - kg					% of the total weight				
Replica	Leaf	Billets	Seed	Total	Replica	Leaf	Billets	Seed	Total
1	0.09	6.11	0.02	6.22	1	1.5	98.1	0.4	100
2	0.18	4.23	0.04	4.46	2	4.2	94.9	0.9	100
3	0.29	4.97	0.03	5.29	3	5.5	93.8	0.7	100
4	0.27	5.16	0.01	5.45	4	5.0	94.7	0.3	100
5	0.28	5.06	0.06	5.42	5	5.3	93.5	1.1	100
6	0.26	4.84	0.06	5.17	6	5.1	93.6	1.3	100
7	0.80	2.24	0.04	3.09	7	25.8	72.6	1.6	100
8	0.77	2.45	0.11	3.34	8	23.3	73.3	3.4	100
9	0.69	2.35	0.15	3.20	9	21.8	73.5	4.7	100

Table 6.27 Summary– Sweet Sorghum 8 inches billet size

Average (kg)					Average %				
Speed (rpm)	Leaf	Billets	Seed	Total	Speed (rpm)	Leaf	Billets	Seed	Total
1100	0.190	5.105	0.032	5.328	1100	3.7	95.6	0.6	100
900	0.274	5.028	0.049	5.352	900	5.1	94.0	0.9	100
0	0.759	2.351	0.103	3.214	0	23.6	73.2	3.2	100

6.28.4 Material composition after harvesting Sweet Sorghum 6’’ billets

After hrvesting with a theoreticall billet size of 6 inches and after varaying the fan speeds from the extraction system during the harvesting phase, the results obtained of the material composition for Sweet Sorghum are shown in Table 6.28. For Seet Sorghum the Seed component was included.

Table 6.28 Summary – Sweet Sorghum 6 inches billet size

Average (kg)					Average %			
Speed (rpm)	LEAF	BILLETS	SEED	Total	Speed (rpm)	LEAF	BILLETS	SEED
1100	0.294	3.834	0.045	4.173	1100	7.5	91.4	1.2
900	0.382	3.350	0.107	3.838	900	11.3	85.7	3.1
0	0.622	1.550	0.089	2.261	0	29.0	67.3	3.7

6.29 Discussion Material composition after harvesting energycane

The results showed that the plant compositions after harvesting two different billet sizes with three fan speeds of the extraction system.Comparing the results obtained after implementing different harvesting treatments, the results suggest that as the fan speed increase, the percentage of leaf matter tend to bereduced and the percentage of billets tend to increase.

From the results obtained in all harvesting treatments, it can be concluded that by using a billet size of 6 inches, the % of leaf matter tend to increase more compared to the results obtained by harvesting billets of 8 inches.

6.30 Material composition after harvesting Sweet Sorgum

It can be evidenced that the treatments composed of billets of 8 inches indicate that a higher % of billets was collected from the material harvested compared to the harvesting treatments that used a billet length of 6 inches. The results indicates that as increasing th fan spedd from the extraction system while harvesting, the %of leaf matter collected from tha material harvested tend to decrease while the %billets tendo to increase.

6.31 Harvesting efficiency (material losses after harvesting ton/acre)

The Material Losses indicator was calculated in terms of the total quantity of material losses left in the field after harvesting. The material losses were measured by collecting all the material from random areas with a dimension of 10ftx10ft. After harvesting the material from each row, the total weight of the load was measure, then according to the area demarked for material losses, the material left by the harvester after harvesting, was collected and weighted. The total yield of the

material according to each of the harvesting treatments was as well calculated using Equation 6.6 (Aragon, 2013).

$$Harvesting\ Efficiency\% \ = \frac{potential\ material\ losses\ (\frac{ton}{acre})}{yield\ of\ the\ feestock\ (\frac{ton}{acre})} \tag{6.6}$$

Expected material losses %, this indicator was calculated as a proportion of the material losses found per acre over the yield of the material (Equation 6.7).

$$Material\ losses\% \ = \ 1 - \left(\frac{potential\ material\ losses\ (\frac{ton}{acre})}{yield\ of\ the\ feestock\ (\frac{ton}{acre})}\right) \tag{6.7}$$

6.31.1 Material losses and harvesting efficiency for the case of the energycane

After harvesting the material according to different harvesting parameters, the results obtained are illustrated in Table 6.28.1 and Table 6.29.

Table 6.28.1 Yield of material harvsted and field losses (ton/acre)– energycane

Fan speed (rpm)	8 inches billet	6 inches billet
1100	26.8	15.6
900	27.2	19.4
0	30.5	29.4

Table 6.29 Percent Harvesting efficiency and potential losses

Billet size	8 inches billets		6 inches billets	
Fan speed rpm	Harvesting efficiency	Potential losses	Harvesting efficiency	Potential losses
1100	98.98	1.02	99.05	0.95
900	99.55	0.45	99.46	0.54
0	99.84	0.16	99.91	0.09

The results obtained from Table 6.28.1 and Table 6.29 suggest that as the fan speed of the extractor system is reduced the yield of the material increased. It can be evidenced that by harvesting with

a billet length of 6 inches, the harvesting efficiency tend to increase as the fan speed is reduced; as a result the material losses decrease as the fan speed decrease.

6.31.2 Material losses and harvesting efficiency for the case of Sweet Sorghum

After harvesting the material according to different harvesting parameters, the results obtained are illustrated in Table 6.30 and Table 6.31. The results obtained from Table 6.30 and Table 6.31 suggest that as the fan speed of the extractor system is reduced the yield of the material increase.

Table 6.30 Yield of material harvsted and field losses – Sweet Sorghum

	Mean material harvested (ton/acre)		Material losses (ton/acre)	
Fan speed rpm	8 inches billet	6 inches billet	8 inches billet	6 inches billet
1100	19.15	16.24	0.44	0.37
900	18.68	20.12	0.29	0.19
0	30.36	34.50	0.11	0.08

It can be evidenced that as the fan speed increase, the amount of material losses increase, suggesting that by using a higher fan speed in the cleaning system of the harvester, the amount of material that is left in the field increase.

Table 6.31 Harvesting efficiency and potential losses (percent)

Billet size	8 inches billets		6 inches billets	
Fan speed rpm	Harvesting efficiency	Potential losses	Harvesting efficiency	Potential losses
1100	97.6	2.3	97.7	2.2
900	98.4	1.6	99.0	0.9
0	99.6	0.3	99.7	0.2

In the same way, it can be evidenced that by harvesting with a billet length of 6 inches, the harvesting efficiency tend to increase as the fan speed is reduced; as a result the material losses decrease as the fan speed decrease.

6.31.3 Harvesting efficiency and material losses discussion

For the case of the energycane the results shows that as the fan speed of the fan extractor system is reduced, the total weight of the material harvested increased. When the fan is not used a yield of approximately 30 ton/acre was obtained, however, from the total material harvested, 29% of the total load corresponded to leaf matter and 71% corresponded to billets. When the extractor system is not used, most of the material in the field was collected and as a result, the material losses in the field were lower. When the extractor fan was operated at a fan speed of 900 rpm, a yield of approximately 24ton/acre was obtained; for this case, the % leaf matter was reduced to 11% of the total material collected and the % billets increased to 89%. At the highest fan speed (1100 rpm), the yield of the material was approximately 21ton/acre; but the %leaf matter represented only 8% and the %billets represented 92%, indicating that even a higher % leaf matter was left in the field and cleaner billets were recovered from the harvesting operation (Figure 6.37).

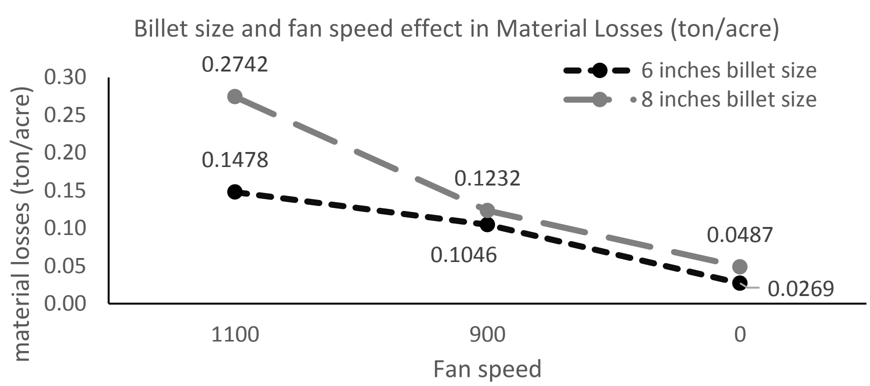


Figure 6.37. Material losses – energycane

When the extractor fan was operated at a fan speed of 900 rpm, a yield of approximately 24ton/acre was obtained; for this case, the % leaf matter was reduced to 11% of the total material collected and the % billets increased to 89%. At the highest fan speed (1100 rpm), the yield of the material

was approximately 21ton/acre; but the %leaf matter represented only 8% and the %billets represented 92%, indicating that even a higher % leaf matter was left in the field and cleaner billets were recovered from the harvesting operation.

Approximately 1% of the harvested material was left in the field when the highest fan speed was used (1100 rpm); in contrast, when the harvesting operation used a fan speed of 900 rpm or 0 rpm, the %material losses were approximately of 0.5% and 0.15% of the total material harvested.

When a billet length of 6 inches was used for harvesting, the %material losses left in the field were lower compared to the %material losses obtained after harvesting billets of 8 inches, a reduction of approximately 35%; the losses in the field were reduced as the fan speed was reduced (0 rpm). The %material losses increased as the fan speed increased, indicating that the higher the fan speed, the cleaner the billets and the higher the losses of leaf matter in the field. The yield from harvesting of Sweet Sorghum were similar to the results obtained with the energycane. As the fan speed of the fan extractor is reduced, the total weight of the material harvested increased while the material losses decreased.

At a fan speed of 0 rpm, the composition of the material harvested consisted of: 25.5% of leaf matter, 70.9% of billets and 3.5% of seeds.

By not using the extractor system, most of the material harvested was collected and as a result, the material losses left in the field were lower, obtaining just 3.7% of losses from the material harvested. Approximately 27% of the material harvested was left in the field when the highest fan speed was used (1100 rpm), the %material losses were reduced to 15% and 3% respectively from the total material harvested. For the case of the energycane, when a billet length of 6 inches was used for harvesting, the %material losses were lower compared when a billet length of 8 inches was used (Table 6.32).

Table 6.32 Harvesting efficiency and potential losses (in percentage)

	8 inches billets		6 inches billets	
Fan speed rpm	Harvesting efficiency	Potential losses	Harvesting efficiency	Potential losses
1100	97.68	2.32	97.71	2.29
900	98.40	1.60	99.06	0.94
0	99.63	0.37	99.75	0.25

On average from the 3 fan speeds used while harvesting, approximately 17.28% corresponded to material losses when a billet size of 8 inches was used and 13.9% of losses when a billet size of 6 inches was used while harvesting.

CHAPTER 7: ECONOMIC MODEL FORMULATION

A representation of the supply chain model for an agricultural system based on energycane and sweet sorghum will consider the following activities and processes: production of the crop, harvesting, transportation, storage and processing. The production of the feedstock (input: crop) and the conversion processes (output: ethanol) are considered for the economic assumptions.

The model used as input the data obtained from the harvesting trials proposed and conducted by Aragon (Aragon, 2013), however some economic assumptions from the sugar cane supply system will be integrated in this model. The model was developed for evaluating the supply costs (production, harvesting, transportation and conversion cost) of the energy crops and the potential sale value of ethanol. With the estimation of the potential ethanol sale value, the ethanol profit that can be calculated.

Different practices used in the harvesting and storage phases, are expected to produce different yields of the material (ton/acre), sugars (%TFS) and ethanol yield (lt/acre); the system will handle different production costs according to the practices and parameters defined for each scenario.

After simulating the scenarios, the results were analyzed in order to determine which treatments provided the lowest production cost, the highest ethanol yield and as a result, the minimum cost for the production system. Figure 7.1 illustrates the flow of the supply system evaluated in this current research. From the simulation of the supply system, the following indicators were measured:

1. Plant composition before and after harvesting (%leaf matter, %stalk, %seeds).
2. Material yield (tons/acre or ton/hectare)
3. Harvesting efficiency (material losses, ton/acre or ton/hectare)
4. Transportation density (bulk density, ton/m3).

5. Weight losses due to storage.
6. Material temperature and RH% during storage.
7. %TFS and brix (shortly after harvesting and after 24 hours of storage).
8. Ethanol yield (lt/acre or gal/hectare).

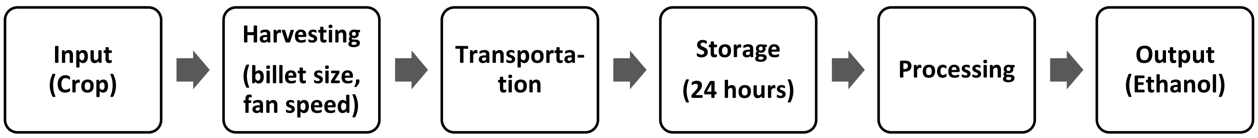


Figure 7.1 Supply chain diagram

Figure 7.2 illustrate the economic structure used in the model; according to the practices and parameters used in each of the scenarios, the operational costs varied.

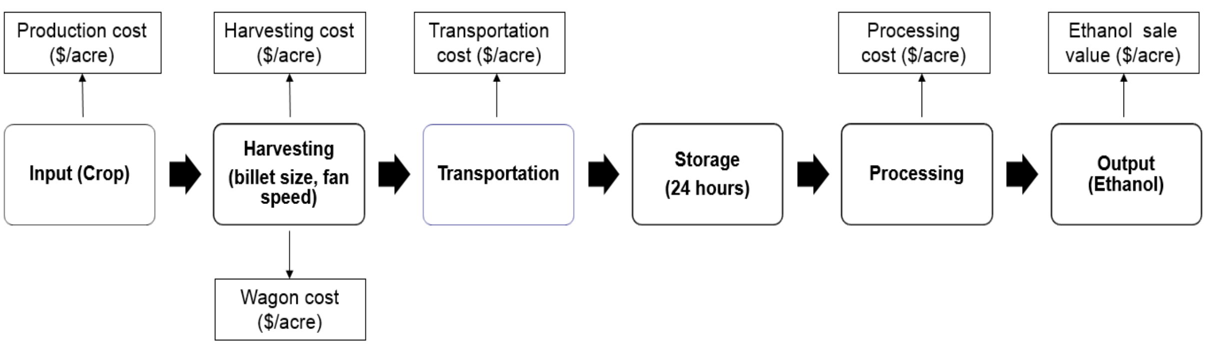


Figure 7.2 Economic components of the supply system

The supply chain system is integrated by operational units, which depends on factors defined for the system. Some of the variable parameters in the model are given in Table 7.1.

Table 7.1 Variable parameters of the model

Variable parameters	Variations	
Crop	energycane	sweet sorghum
Billet size (inches)	8	6
Fan speed	0 rpm, 900 rpm, 1100 rpm	
Processing time	0 hours	24 hours
Area for harvesting	X acres or hectares	
Distance for transporting	X miles or kilometers	

A set of scenarios were defined for simulating the economic model. The results were collected and analyzed in order to determine which scenario provided the highest yield of the material and the lowest operational costs. The model is formulated based on the maximization of the profit that can be obtained after harvesting, transporting and processing simple and complex sugars. The maximization of the profit is expected to provide the lowest total supply costs required for the production of ethanol.

7.1 Agricultural production cost

The production cost is calculated based on the production cost per wet ton reported by Hallam and Tyler, for both, the energycane and the sweet sorghum. The production cost was calculated as a function of the material yield obtained from each of the harvesting treatments. The mathematical formulation for the production cost is illustrated in Equation 7.1.

$$PC = X_a PC_{crop} \quad (7.1)$$

where $0 < X_a < 100$ acres (7.1.1)

The notation implemented in Equation 7.1 and the assumptions for the production cost, are illustrated and explained in Table 7.2.

Table 7.2 Input data for Production cost equation

Notation	Value	Unit	Description
PC(ss)	-	($/acre)	Production cost sweet sorghum
PC(ec)	-	($/acre)	Production cost energycane
X_{area}	-	(ton/acre)	Area for harvesting
$AC_{S.S.}$	208	($/acre)	Production cost per acre or hectare (Hallam *et al.* 2001)(Ribera *et al.* 2013).
AC_{EC}	411	($/acre)	Production cost per acre or hectare (Tyler *et al.* 2009), (Ribera *et al.* 2013), (Salassi *et al.* 2014).

Table 7.3 illustrates the production cost reported in the literature for both of the crops; an average of the production cost was calculated as an assumption for the model; these values represent the agronomic production cost of sweet sorghum and energycane in the model.

Table 7.3 Production cost assumptions

Feedstock production cost	Sweet Sorghum	Energycane	Description
	$/acre	$/acre	-
Ribera *et al.* 2013	181	613	-
Tyler,20009	-	827	Yield = 45 ton/acre
Hallam, 2001	235	-	Yield = 7.192 ton/acre
Salassi, 2014	-	50	4th stubble, Yield = 9.2 ton/acre
average	208	496	Feedstock production cost

7.2 Harvesting cost

The harvesting cost is calculated based on the fuel consumption of the harvester at each to the fan speed used in the extractor system; Table 7.3.1, describes the fuel consumption of the harvester after varying the rpm's of the fan extractor speed.

Table 7.3.1 Harvester characteristics

Standard characteristics of harvester (John Deere, 3520)		
Fan speed	800 rpm	
Speed	4miles/hour	
Fuel rate	35liters/hour	9.21gal/hour
Increment: 1rpm	0.0075 (lt/hour)/rpm	0.0020 (gal/hour)rpm

The standard assumptions of the harvester were defined by John Deere engineers at Thibodaux, LA (Kyle Trosclair – USA sugar territory manager, Cristobal Báez – Product Support representative).

The harvester used in the experimental trials was a John Deere harvester, model 3250; the standard set up for this harvester is as follow: fan speed of 800 rpm; machine speed of 4 miles per hour. According to these conditions, the fuel consumption of the machine is 35 liters per hour or 9.21 gallons per hour. The specifications for the harvester indicate that by increasing the speed of the fan extractor by 1 rpm, an increment of 0.0075 (lt/hour)/rpm occur; this formulation was incorporated in the harvesting cost. The procedure is illustrated on Figure 7.3.

(1) Fuel consumption increment = $0.0075(X_{RPM}\text{-}800) + 35$

Expression (1) represents the fuel consumption increment in terms of liters per hour. The term X_{RPM} refer to the rpm's that the harvester will implement in the fan extractor system of the harvester.

Figure 7.3 Fuel consumption increment

In the harvesting trials, 3 different fan speeds were used, the highest fan speed was 1100 rpm, the medium speed was 900 rpm and the minimum speed was 0 rpm.

The mathematical expression for harvesting includes the following factors: fuel consumption based on the increment of rpm's used in the fan extractor system; fuel consumption per liter or gallon per hour (regular gas); cost of labor per hour for harvesting; fixed expense cost of harvesting

per acre or hectare; time required for harvesting an acre or a hectare; and the total acres or hectares that are going to be harvested.

The mathematical formulation of the harvesting cost is expressed in Equation 7.2.

$$Y_{HFC} = [F_{inc}[F_s - 800] + F_{cons}]P_f t_h X_{area} + \left\{[C_{mh} + C_{fh}]\left(\frac{1}{t_h}\right) + C_{lh} t_h\right\} X_{area} \qquad (7.2)$$

where $F_s > 0, 0 < X_{area} \leq 100, t_h > 0$ (7.2.1)

The notation and assumptions considered for the harvesting costs are illustrated and explained in Table 7.4.

Table 7.4 Harvesting cost component description

Notation	value	unit	Description
Y_{HFC} =			Harvester cost based on the fuel consumption.
F_{Inc} =	0.0075	(lt/hour)/rpm	Fuel increment after adding 1 rpm over 800 in the fan system of the harvester.
F_s =		rpm	Fan speed from the extractor system used for harvesting
F_{Con} =	35	(lt/hour)	Fuel consumption constant = 35 (lt/hour) when using a speed of 4 miles/hour and a fan speed of 800 rpm (standard fuel consumption) or 9.4 (gal/hour) when the harvester use a fan speed of 6.45 km/hour
P_F =	1.076	$/lt	Fuel Price per gallon or per liter (http://www.eia.gov/petroleum/gasdiesel/).
C_{fh} =	32.93	$/acre	Fixed expense costs fixed value): cost per acre or hectare (Salassi *et al.* 2013).
t_h =	0.77	hour/ acre	Time required for harvesting an acre or a hectare (Salassi *et al.* 2013).
X_{area} =		acres	# Acres or hectares that are plan to be harvested (variable value).

7.3 Wagon cost

The harvesting model assumes the operational structure used for harvesting and collecting sugar cane, which consists of one harvester and three wagons, each with a capacity of 10 tons each. These wagons collect the material that is being harvested in parallel to the harvester (Figure 7.4).


Figure 7.4 Harvesting operation (wagon and harvester)

After a wagon is completely loaded, the next wagon will start collecting the material, such that the operation will not stop until a specific area is completely harvested. The operational structure and costs are taken from the "Project Commodity Costs and Returns 2013, Sugar Cane Production in Louisiana", developed by Michael Salassi and Michael Deliberto.

The main components of the wagon cost include: direct expenses (power unit and equipment cost), fixed costs (power unit and equipment cost), time required per acre or hectare and cost of labor per acre or hectare. The wagon cost is calculated based on the number of acres or hectares that are going to be harvested.

Equation 7.3 and Equation 7.3.1 illustrates the mathematical formulation of the wagon cost. The notation and assumptions considered for Equation 7.3 are illustrated in Table 7.5.

$$Y_{CTwagon}(\$) = 3\left[(C_{direct} + C_{fixed}) + C_{lwv}t_h\right]X_{area} \tag{7.3}$$

where, $0 < X_{area} \leq 100,\ t_h > 0.$ (7.3.1)

Table 7.5 Wagon cost components

Notation	Value	Unit	Description
$Y_{CTwagon}$	-		Estimated cost of transportation of the dump wagon based on the yield density of the material
C_{lwv}	9.60	(\$/hour)	Cost of labor for dump wagon per acre (constant cost, 9.60/h). 0.6(hours/acre) = 1.5(hours/hc).
C_{direct}	24.94	(\$/acre)	Direct costs (/acre or (/hectare)1: Power unit costs = 19.61 (/acre) or 49 (/hc) Equipment cost = 5.33 (/acre) or 13.3 (/hc)
C_{fixed}	20.91	(\$/hour)	Fixed expenses costs[1]: Constant cost for a wagon of 10 ton capacity.
			Power unit costs = 16.79 (/acre) or 41.9(/hc) Equipment costs = 4.12 (/acre) or 10.3(/hc).
t	0.6	(hour/acre)	Hours required by dump wagon to operate in 1 acre or hectare.
			The wagon requires 06(hour/acre) = 1.5 (hour/hc)
X_{area}		acres	# Acres or hectares that are going to be harvested (variable value).

7.4 Transportation cost

The transportation component cost for the model is calculated based on: the quantity of trucks required for transporting the material; the distance for transporting; and the cost per mile, which increase as the distance increases. For calculating the quantity of trucks needed to transport the feedstock, the material yield per acre or hectare was evaluated as well as the total volume of the truck and the bulk density of the loads (ton/ft3 or ton/m3).

7.4.1 Material yield

The yields of the material were obtained from the results collected from the harvesting trials. The yield of the material from both energy crops are reported in Table 7.6 and Table 7.7.

Table 7.6 Material yield sweet sorghum

Fan (rpm)	Material yield (ton/acre) (8 inches billet)		Material yield (ton/acre) (6 inches billet)	
1100	19.1	1100	16.2	40.6
900	18.6	900	20.1	50.3
0	30.3	0	34.5	86.2

Table 7.7 Material yield energycane

Fan (rpm)	Material yield (ton/acre) (8 inches billet)		Material yield (ton/acre) (6 inches billet)	
1100	26.8	67.5	15.6	39
900	27.2	68.5	19.4	48.6
0	30.5	76.5	29.46	73.6

7.4.2 Bulk density yield (ton/ft3 or ton/m3)

The results of bulk density obtained under different harvesting treatments are illustrated in Table 7.8 and Table 7.9. The results obtained were used for the simulation of the model according to the scenarios defined.

Table 7.8 Bulk density for sweet sorghum

Sweet sorghum	Density yield (8 inches billet)		Density yield (6 inches billet)	
Fan (rpm)	ton/ft3	ton/m3	ton/ft3	ton/m3
1100	0.0071	0.252	0.0072	0.255
900	0.0066	0.232	0.0063	0.221
0	0.0022	0.078	0.0027	0.095

Table 7.9 Bulk density energycane

Energycane	Density yield (8 inches billet)		Density yield 6 inches billet)		
Fan (rpm)	ton/ft3	ton/m3	Fan (rpm)	ton/ft3	ton/m3
1100	0.0055	0.192	1100	0.0064	0.227
900	0.0053	0.188	900	0.0068	0.241
0	0.0037	0.129	0	0.0064	0.226

7.4.3 Truck volume

The volume of the truck was calculated according to the dimensions of the most common type of truck used in Louisiana for transporting sugar cane. The regular capacity for this type of truck is 28 ton and the dimensions are = 42ft x 10ft x 8ft = 3360 ft3 or 95m3 (Legendre, 2014).

7.4.4 Transportation distances and costs

Based on the transportation system used by the sugarcane industry in Louisiana, the following ranges of costs and distances were assumed in the model and the simulation (Table 7.10).

Table 7.10 Costs and distances for transporting energy crops (Legendre, 2014)

Range in miles		$/mile
1.0	5.0	1.81
6.0	10.0	2.05
11.0	15.0	2.36
16.0	20.0	2.40
21.0	30.0	3.00
31.0	35.0	4.23
36.0	64.0	7.00
65.0	75.0	7.50

According to the transportation system used in Louisiana, covering distances greater than 75 miles or 120 kilometers is not a feasible option because of the high cost of the operation; however, in the analysis of the model, a simulation with greater distances was be performed in order to evaluate the economic impact.

The model considered each of the scenarios defined for the study (24 scenarios) and the objective function was simulated for all of them; the simulation varied the transportation distance from 1 to 100 miles and the area for harvesting from 1 to 100 acres.

Equation 7.4 and Equation 7.4.1 illustrates the mathematical expression that represents the transportation operation of the energy crops.

$$Y_{CTransp} = X_m X_{area} (\rho)^{-1} \left(\frac{1}{V_{truck}} \right) [X_{dist} TC_{dist}] \tag{7.4}$$

where, $0 < X_{area} \leq 100, X_m > 0, \rho > 0, 0 < X_{dist} \leq 100$ (7.4.1)

Table 7.11 describes each of the components defined in Equation 7.4 used for calculating the transportation cost.

Table 7.11 Transportation cost components

Notation	Value	Unit	Description
$Y_{CTransp}$		($/acre)	Transportation cost.
X_m		ton/acre	Material yield after implementing different harvesting treatments.
ρ		ton/ft3	Density yield of the material harvested.
V_{truck}	3360	ft3	Truck capacity:
			Truck volume with a capacity of 28 ton and a volume of 3360ft3 or 95.157m3
X_{dist}		miles	Radial distance for transporting the material from the field to the factory.
TC_{dist}		$/mile	Cost of transporting the material from the field to the factory per mile or km.

7.4.5 Processing costs

The processing cost for the model considered the cost of pre-processing the material (sweet sorghum or energycane) for juice extraction (simple sugars) and the conversion of complex sugars

extracted from the fiber and the biomass; the model assumed both sugars, the complex and simple sugars. The simple sugars are recovered from the juice, and the complex sugars could be recovered from the fiber and the biomass of the feedstock.

The component costs of the processing cost consider the costs of processing and conversion. The treatment assumed in the model for recovering complex sugars was *lime pretreatment*; the cost and the assumption were taken from the research developed by Day, 2012 titled Bio refinery Development Using Multiple Feedstock's.

The cost of the treatment for recovering and converting complex sugars reported in the literature were found very high and in order to simulate feasible solutions in the study, it was assumed that the complex sugars treatment cost was 0.022 $/ton produced, leading to a total of $48.40 per ton processed for the case of the sweet sorghum.

For the case of the energycane, the treatment cost for the conversion into complex sugars 0.023$/lb produced and a total of $50.60 per ton processed for the case of the energycane.

The model assumed a conversion cost lower compared to the data reported in the literature; this was assumed in order to obtain feasible solutions in the model. It is important that the conversion costs of simple and complex in the future should be reduced in order to have a feasible system operation. For the complex sugars recovery, it is assumed that the fiber and biomass that is processed shortly after harvesting contains approximately 50% moisture and when the material is processed after 24 hours, the moisture level is less than 50%. Finally, for the complex sugars recovery, the model assumed that approximately 60% of the total fermentable sugars can be recovered from the fiber for both of the energy crops. Equation 7.5 and Equation 7.5.1 illustrates the mathematical formulation of the processing cost.

$$C_{proc} = \{[X_m X_{fs} X_j C_{milling}] + [X_{db} X_{cs} C_{milling} C_{bio}]\} X_{area} \qquad (7.5)$$

Where $$0 < X_{area} \leq 100, X_m > 0, X_{fs} > 0, X_J > 0, X_{db} > 0, X_{cs} > 0 \qquad (7.5.1)$$

Table 7.12 shows the main assumptions taken into consideration for the yield of the simple and complex sugars in the model and simulation. The yield of the simple and complex sugars obtained from the harvesting trials are reported in Table 7.13.

Table 7.12 Processing cost

Notation	Value	Unit	Description
X_m =		ton/(acre)	Material yield
X_{fs} =		TFS%/100	Total fermentable sugars yield
X_j =		juice%/100	Juice yield
X_{area} =		acres	Area defined for harvesting
X_{db} =		ton/acre	Dry bagasse yield
X_{cs} :	60%	ton/acre	Complex sugar recovery rate
$C_{milling}$ =	6.02	($/ton processed)	Include: milling cost 3.52 (/ton processed), employee's expenses 1 (/ton process), administrative costs 0.50 (/ton process) and depreciation 1 (/ton processed).
C_{bio} =	48.4	($/ton sugar produced)	Conversion cost of complex sugars, Sweet sorghum: 0.071/lb sugar produced - lime = 156.2 /ton. Assumption: 0.022/lb complex sugars - 48.4 /ton
C_{bio} =	50.6	($/ton sugar produced)	Conversion cost of complex sugars energycane : 0.08/lb sugar produced - lime = 176 /ton. Assumption: 0.023 /lb complex sugars - 50.6/ton

Table 7.13 Simple and complex sugars yield assumptions and results

Crop	Billet (inch)	Fan speed (rpm)	Material yield ton/(acre)	Juice yield %		Simple sugars yield TFS%		Wet bagasse yield		Dry bagasse yields (ton/acre)		Bagasse moisture %		Complex sugars yields	
				t=0h	t=24 h	t=0h	t=24h	t=0 h	t=24 h	t=0h	t=24 h	t=0 h	t=24 h	t=0 h	t=24 h
Sweet sorghum	8	1100	19.15	66	57	5.60	5.20	34	43	6.51	8.23	50	38	2.6	2.45
Sweet sorghum	8	900	18.68	65	56	5.40	5.30	35	44	6.54	8.22	50	39	2.6	2.48
Sweet sorghum	8	0	30.36	56	44	5.10	4.70	44	56	13.3	17.00	50	39	4.8	4.64
Sweet sorghum	6	1100	16.24	60	55	7.90	7.50	40	45	6.50	7.31	50	38	2.7	2.33
Sweet sorghum	6	900	20.12	55	40	7.80	7.30	46	60	9.15	12.07	50	38	3.6	3.34
Sweet sorghum	6	0	34.50	52	39	7.50	6.00	48	61	16.5	21.05	50	39	6.3	5.72
Energycane	8	1100	26.83	57	53	8.72	8.66	43	47	11.5	12.61	50	43	4.7	4.48
Energycane	8	900	27.22	58	55	8.60	7.87	42	45	11.4	12.25	50	45	4.7	4.46
Energycane	8	0	30.50	51	49	7.01	6.27	49	51	14.9	15.56	50	45	5.5	5.14
Energycane	6	1100	15.60	57	50	10.17	9.20	43	50	6.71	7.80	50	43	2.9	2.71
Energycane	6	900	19.45	54	49	10.16	9.06	46	51	8.95	9.92	50	44	3.7	3.49
Energycane	6	0	29.46	48	44	7.96	6.02	52	56	15.3	16.50	50	46	5.7	5.33

7.4.6 Ethanol expected profit

After testing different harvesting and storage practices, the simple and complex sugars yields were determined from the material yield (ton/acre or ton/hectare), %juice yield, dry bagasse yield (ton/acre or ton/hectare). As a result of the combination of parameters used during the development of the harvesting trials (crop, billet size, and fan speed), the results of the recovery rate of the total fermentable sugars from the juice and the fiber varied, hence, it is expected that ethanol yield from these sugars will vary.

The results of the ethanol yield obtained from each of the treatments evaluated in the harvesting trials are illustrated on Table 7.14; these results were the input data for the simulation of each of the scenarios defined for the model.

Table 7.14 Material yield (sweet sorghum and energycane)

Crop	Billet (inches)	Fan speed (rpm)	Total sugars yields (ton/acre)		Ethanol yield (lt/acre)		Ethanol yield (gal/hec)	
			t = 0h	t = 24h	t = 0 h	t = 24 h	t = 0 h	t = 24 h
Sweet sorghum	8	1100	2.66	2.45	1606	1476	1048	963
Sweet sorghum	8	900	2.62	2.48	1579	1495	1031	976
Sweet sorghum	8	0	4.87	4.64	2942	2798	1920	1827
Sweet sorghum	6	1100	2.72	2.33	1640	1407	1071	918
Sweet sorghum	6	900	3.60	3.34	2173	2016	1419	1316
Sweet sorghum	6	0	6.31	5.72	3810	3451	2487	2253
Energycane	8	1100	4.79	4.48	2893	2702	1889	1764
Energycane	8	900	4.79	4.46	2889	2689	1886	1755
Energycane	8	0	5.57	5.14	3364	3103	2196	2026
Energycane	6	1100	2.92	2.71	1760	1636	1149	1068
Energycane	6	900	3.75	3.49	2264	2105	1478	1374
Energycane	6	0	5.72	5.33	3453	3219	2254	2101

The model assumed the following conversion rate of total fermentable sugars for the production of ethanol (Figure 7.5).

Input	*conversion*	Output
13.8 lb TFS	→	1 gallon ethanol
6.27 kg TFS	→	1 gallon ethanol
3.7 lb TFS	→	1 liter ethanol

Figure 7.5 Conversion rate of sugars into ethanol (Day, 2014).

Equation 7.6 and Equation 7.6.1 illustrates the mathematical formulation for the ethanol expected profit. The notation and assumptions considered for Equation12 are illustrated in Table 7.15.

$$Y_{ERA} = [(X_m X_{FS} X_J)ab + cX_{db}](X_{area} SP_{ethanol}) \quad (7.6)$$

where, $0 < X_{area} \leq 100, X_m > 0, X_{fs} > 0, X_J > 0, X_{db} > 0$ (7.6.1)

Table 7.15 Ethanol expected profit

Notation	value	unit	Description
Y_{ERA}			Expected ethanol profit.
X_m		ton/(acre)	Material yield.
X_{FS}		TFS%/100	Total fermentable sugars yield.
X_j		juice%/100	Juice yield %
a	2200	lb/ton	Conversion factor of tones into pounds or kilograms.
b	0.26	lt/lb	For producing 1 gallon of ethanol is required 13.8 lb of FS. - 1lt ethanol require = 3.7297lb
SP(e)	0.78	$/lt	Constant value that represents the selling value of ethanol.
X_{db}		ton/acre	Dry bagasse yield (Assuming 50% moisture from fiber) (Day, 2014)
X_{cs}	60%	%	Recoverable complex sugars rate of dry biomass (Day, *et al.* 2014)

7.4.7 Objective function

The objective function defined for the model consists of the maximization of profit from ethanol that can be obtained from recovering simple and complex sugars from energycane and sweet sorghum under different harvesting treatments.

Equations 7.7, 7.7.1, 7.7.2, 7.7.3, 7.7.4, 7.75 and 7.7.6 illustrate the objective function defined for the model and each of the component cost incorporated.

$$MAX \sum EP = \sum \{ Y_{ERA} - [PC + Y_{HFC} + Y_{CTwagon} + Y_{CTransp} + C_{processing}] \} \quad (7.7)$$

Subject to

$$Y_{ERA} = [(X_m X_{FS} X_J)ab + cX_{db}](X_{area} SP_{ethanol}) \quad (7.7.1)$$

$$PC = X_P PC_{crop} \quad (7.7.2)$$

$$Y_{HFC} = [F_{inc}[F_s - 800] + F_{cons}]P_f t_h X_{area} + \left\{ [C_{mh} + C_{fh}] \left(\frac{1}{t_h} \right) + C_{lh} t_h \right\} X_{area} \quad (7.7.3)$$

$$C_{proc} = \{ X_m X_{fs} X_j C_{milling} + X_{db} X_{cs} C_{milling} C_{bio} \} X_{area} \quad (7.7.4)$$

$$Y_{CTwagon}(\$) = 3(C_{direct} + C_{fixed} + C_{lwv}) t_h X_{area} \quad (7.7.5)$$

$$Y_{CTransp} = X_m X_{area} (\rho)^{-1} \left(\frac{1}{V_{truck}} \right) [X_{dist} TC_{dist}] \quad (7.7.6)$$

where, $0 < X_{area} \leq 100$, $0 < X_{dist} \leq 100$ $X_m > 0$, $X_{fs} > 0$, $X_J > 0$, $X_{db} > 0$, $X_{cs} > 0$, $\rho > 0$, $t_h > 0$,

The objective function is integrated by six different components, Equation 7.7 represents the objective function defined for the model. Equation 7.7.1 represents the ethanol expected profit that can be after using as input the energy crops, Equation 7.7.2 represents the agronomic production cost of the energycane and the sweet sorghum, Equation 7.7.3 and Equation 7.7.4 represents the

harvesting and wagon cost. Equation 7.7.5 and Equation 7.7.6 represents the cost of transporting the material from the field to the bio refinery and the processing cost. Finally the non-negativity and boundary limits are given.

CHAPTER 8: MODEL SIMULATION

The model considered the economics of the harvesting, collection, transportation, processing and conversion of simple and complex sugars into ethanol, and its estimates the ethanol expected profit that can be obtained under different harvesting practices.

Finally, the objective function of the model was defined in terms of the profit maximization that can be obtained after simulating different scenarios.

After implementing different harvesting and storage practices, it was expected that the previous indicators would change between treatments, especially when the area for harvesting and the distance for transporting the material was varied during the simulation.

The main parameters that were varied in the scenarios were the followings:

1. Type of crop (sweet sorghum – energycane).
2. Billet size (8 and 6 inches).
3. Fan speed of the extractor system (0, 900 and 1100 rpm's).
4. Processing time or the period of time in which the material was stored before been processed for simple and complex sugars recovery (processing time at t = 0 hours and processing time after 24 hours).
5. Area for harvesting
6. Distance for transporting the material from the field to the factory.

A total of 24 scenarios were defined and simulated using the model, 12 of these scenarios considered the simple and complex sugars recovered from sweet sorghum for ethanol production and 12 scenarios, considered the sugars recovered from the energycane.

The execution and simulation of the model was developed in Microsoft Excel, version 2010. The model included all the mathematical formulation for each of the component costs shown in Section8 that integrate the supply system used for the production of ethanol defined in the study.

The mathematical formulation developed in Microsoft Excel used as input for the simulation of the scenarios, all the results obtained from the harvesting trials; this data that was used for the calculation of the simple and complex sugars yield from the crops and the agronomic and efficiency indicators defined in the study; these results are reported in Section 7.

The model simulated the 24 scenarios that were defined for the study. The simulation considered an area for harvesting between 1 to 100 acres and a distance for transporting the material from the field to the factory that ranged between 1 to 100 miles.

The total cost of the supply system was calculated first, as well as the potential ethanol sale value, then, the ethanol profit was calculated in the matrixes based on the distances and area covered for transporting and harvesting the material.

Table 8.1 and Table 8.2 illustrates each of the scenarios defined for the model and the parameter configuration established for the simulation of each of the scenarios.

Finally, after simulating the scenarios, an analysis of the results was performed in order to determine which parameters and condition satisfied the objective function.

Table 8.1 Description of the scenarios simulated for sweet sorghum

Treat.	CROP	Billet size (inches)	storage time *t* (hours)	fan speed (rpm)	Material yield (ton/acre	simple sugars (ton/acre)	Complex sugars (ton/acre)	Total fermentable sugars (ton/acre)	ethanol yield (lt/acre)
T1	SWEET SORGHUM	8	0	1100	19.15	0.71	1.95	2.66	1605
T2	SWEET SORGHUM	8	24	1100	19.15	0.57	1.88	2.45	1475
T3	SWEET SORGHUM	8	0	900	18.68	0.66	1.96	2.62	1579
T4	SWEET SORGHUM	8	24	900	18.68	0.55	1.92	2.48	1495
T5	SWEET SORGHUM	8	0	0	30.36	0.87	4.01	4.87	2941
T6	SWEET SORGHUM	8	24	0	30.36	0.63	4.01	4.64	2798
T7	SWEET SORGHUM	6	0	1100	16.24	0.77	1.95	2.72	1640
T8	SWEET SORGHUM	6	24	1100	16.24	0.67	1.66	2.33	1407
T9	SWEET SORGHUM	6	0	900	20.12	0.86	2.75	3.60	2173
T10	SWEET SORGHUM	6	24	900	20.12	0.59	2.75	3.34	2016
T11	SWEET SORGHUM	6	0	0	34.5	1.35	4.97	6.31	3810
T12	SWEET SORGHUM	6	24	0	34.5	0.81	4.91	5.72	3451

Table 8.2 Description of the scenarios simulated for energycane

Treat.	CROP	Billet size (inches)	storage time *t* (hours)	fan speed (rpm)	Material yield (ton/acre)	simple s. (ton/acre)	complex s. (ton/acre)	total sugars (ton/acre)	ethanol yield (lt/acre)
T13	ENERGYCANE	8	0	1100	26.83	1.33	3.46	4.79	2893
T14	ENERGYCANE	8	24	1100	26.83	1.23	3.25	4.48	2701
T15	ENERGYCANE	8	0	900	27.22	1.36	3.43	4.79	2889
T16	ENERGYCANE	8	24	900	27.22	1.18	3.28	4.46	2689
T17	ENERGYCANE	8	0	0	30.51	1.09	4.48	5.57	3363
T18	ENERGYCANE	8	24	0	30.51	0.94	4.21	5.14	3103
T19	ENERGYCANE	6	0	1100	15.6	0.90	2.01	2.92	1760
T20	ENERGYCANE	6	24	1100	15.6	0.72	1.99	2.71	1636
T21	ENERGYCANE	6	0	900	19.45	1.07	2.68	3.75	2263
T22	ENERGYCANE	6	24	900	19.45	0.86	2.62	3.49	2105
T23	ENERGYCANE	6	0	0	29.46	1.13	4.60	5.72	3452
T24	ENERGYCANE	6	24	0	29.46	0.78	4.55	5.33	3219

8.1 Simple and complex sugars yield calculations

The results obtained from the harvesting trials was used for two purposes: (1) the data was used as input for the model and (2) the data was used for calculating the agronomic and efficiency indicators of the supply system. By measuring the material yield from each of the treatments, the juice yield, the total fermentable sugars recovery rate, the dry bagasse yield, it was possible to calculate the simple sugars yields. Finally, after calculating the total amount of sugars that could be recovered from both, the juice and the biomass, the *ethanol conversion rate* was used for estimating the ethanol yield that could be obtained from the total sugars yield for each of the scenarios (for the production of 1 liter of ethanol is required the total amount of 3.7 lb of sugars, reported by Day *et al.* 2012).

8.2 Simple sugars recovery sweet sorghum

Table 8.3 illustrates the yield of the simple sugars obtained from sweet sorghum. The results of the simple sugars indicate that the yield increased as the fan speed of the extractor system decreased, suggesting that by processing billets with a higher amount of fibers, the yield of the simple sugars increased, especially when the material is processed shortly after harvesting (t = 0 hours).

Table 8.3 Simple sugars yield – Sweet sorghum

	6 inches - % (ton/acre)		8 inches - % (ton/acre)	
fan (rpm)	T = 0 h	T = 24 h	T = 0 h	T = 24 h
0	100 (1.35)	60(0.81)	100 (0.87)	72 (0.62)
900	100 (0.86)	68 (0.59)	100 (0.66)	83(0.55)
1100	100 (0.77)	87 (0.67)	100 (0.71)	81 (0.56)

By not using the fan extractor of the harvester, the simple sugars yield increased by 19%+ more compared to the results obtained from using the fan extractor with a speed of 1100 rpm, for the case of the material harvested with a billet length of 8 inches. Figure 8.1 and Figure 8.2 illustrates the results obtained from Table 8.3.

"Simple sugars yield – sweet sorghum, 8 inches billet length"

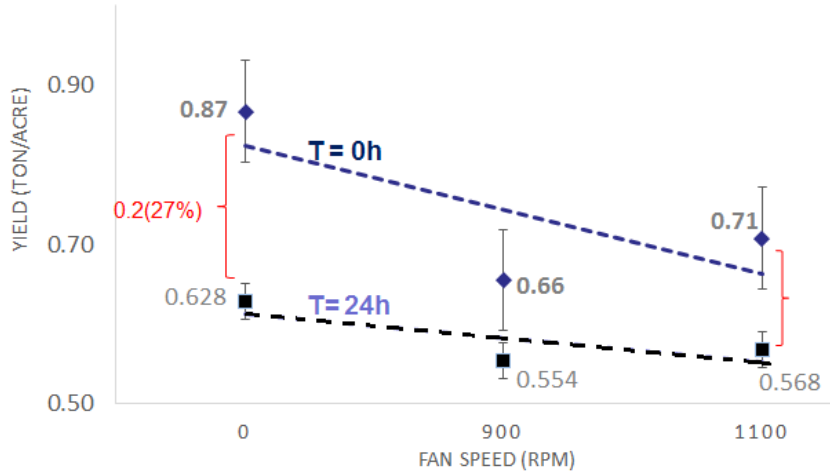


Figure 8.1 Simple sugars yield from billets of 8 inches from sweet sorghum

"Simple sugars yield – sweet sorghum, 6 inches billet length"

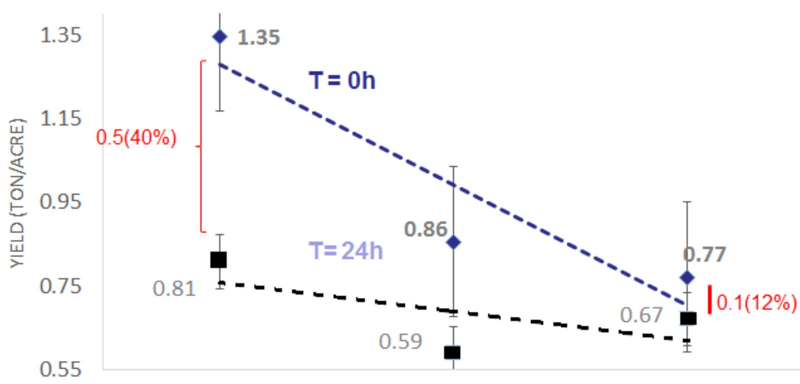


Figure 8.2 Simple sugars yield from billets of 8 inches from sweet sorghum

In the other hand, when the billets were harvested with a length of 6 inches and when the fan extractor was not used, an increment of approximately 42%+ of simple sugars was achieved compared to the results obtained from using a fan extractor speed of 1100 rpm.

The results suggested, that no matter the billet size in which the material is harvested, that simple sugars deteriorate faster as the storage time increase, especially when the fan is not used during harvesting.

It can be expected that by storing the material with some amount of leaf matter, bacteria, decomposition and weight loss can occur faster. It was reported by Pope that by an increase of 5% of leaf matter, a reduction of approximately 0.1-0.2 tones occurred (Pope *et al.* 1998). Similarly, it was reported by Saska that by storing the feedstock after harvesting, sucrose losses occurred, especially, when storage temperature are higher than 22C.

8.3 Simple sugars recovery from energycane

Table 8.4 illustrates the yield of the simple sugars yield obtained from the energycane.

Table 8.4 Energycane simple sugars yield

Fan speed -rpm (6 inches billet)	t = 0 h % (ton/acre)	t = 24 h % (ton/acre)	sugar losses % (ton/acre)
0	100 (1.13)	69 (0.78)	15 (0.16)
900	100 (1.07)	80 (0.80)	13 (0.17)
1100	100 (0.90)	80 (0.70)	7.5 (0.11)
Fan speed -rpm (8 inches billet)	t = 0 h % (ton/acre)	t = 24 h % (ton/acre)	sugar losses % (ton/acre)
0	100 (1.09)	85 (0.93)	30 (0.35)
900	100 (1.35)	80 (1.17)	25 (0.27)
1100	100 (1.33)	92 (1.23)	22 (0.20)

The results obtained suggest that during a period of storage of 24 hours, the sugar losses decreased as the fan speed of the fan extractor system tend to increase, suggesting that by harvesting the

billets with the minimum amount of leaf matter, the sugar losses during storage tend to decrease (24 hours).

This phenomena can be explained because when more leaf matter is attached to the billets after harvesting, and when the material is stored in high ambient temperatures, the presence of bacteria and fungi can appear in the stalks. Sucrose losses can occur as well as billet decomposition, as it was mentioned by Watt *et al.* 2009, in his report titled Post harvest biology of sugarcane.

8.4 Complex sugars recovery from sweet sorghum and energycane

As it was mentioned in Section7, the complex sugars recovery was calculated based on the yield of the dry bagasse and the total fermentable sugars recovery rate assumed in the model (60% of the sugars from the fiber can be recovered as complex sugars, Day, 2014).

The results indicated that the material that was processed shortly after harvesting contained a bagasse moisture of approximately 50%.

It was determined in the calculations of the harvesting trials, that the material that was processed after 24 hours, contained a moisture bagasse less than 50%. Table 8.5 and Table 8.6 illustrates the yield of the complex sugars.

Table 8.5 Complex sugars yield (ton/acre) – sweet sorghum

Fan speed rpm (6 inches billet)	T = 0 h	T = 24 h
0	100 (4.97)	99 (4.91)
900	100 (3.46)	94 (3.25)
1100	100 (3.43)	96 (3.28)
Fan speed rpm (8 inches billet)	T = 0 h	T = 24 h
0	100 (4.01)	100 (4.01)
900	100 (1.96)	98 (1.92)
1100	100 (1.95)	96 (1.88)

Table 8.6 Complex sugars yield (ton/acre) – energycane

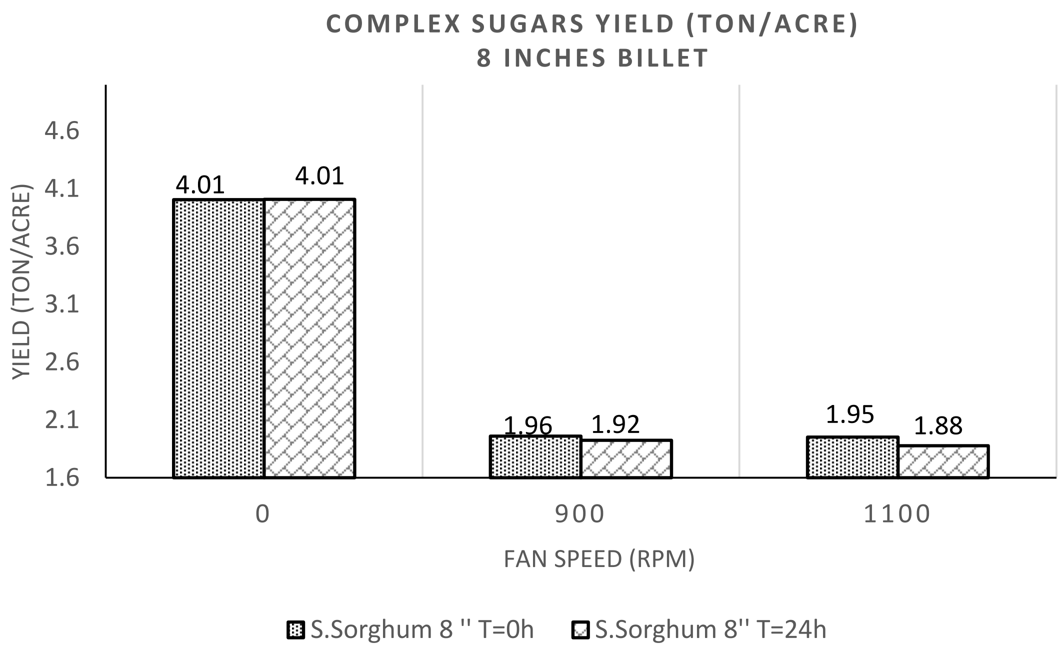
Fan speed rpm (6 inches billet)	T = 0 h	T = 24 h
0	100(4.60)	99(4.50)
900	100(2.68)	97(2.61)
1100	100(2.01)	99 (1.92)
Fan speed rpm (8 inches billet)	T = 0 h	T = 24 h
0	100(4.40)	93(4.20)
900	100(3.46)	94(3.28)
1100	100(3.42)	93(3.25)

Figure 8.3 and Figure 8.4 illustrates the behavior of the results obtained from Table 8.5 and Table 8.6.

The results presented in Figure 8.3, suggest that for both of the billet sizes measured, the yield of the complex sugars increased as the fan speed decreased, suggesting that by recovering most of the leaf matter while harvesting, the yield of the complex sugars can be higher compared if cleaner billets are processed. For both of the cases (6 and 8 inches billet length), the complex sugars tend to deteriorate slower over time compared to the deterioration of the simple sugars.

For the case of the billets that were harvested with a billet size of 8 inches and when the fan extractor was not used during the harvesting operation, there was approximately a 52%+ of complex sugars.

In the other hand, for the case of the billets that were harvested with a billet size of 6 inches and when the fan extractor was not used during the harvesting operation, there was approximately 33%+ of complex sugars. Finally, for the case of the energycane, the results showed a similar behavior to the results obtained from sweet sorghum.



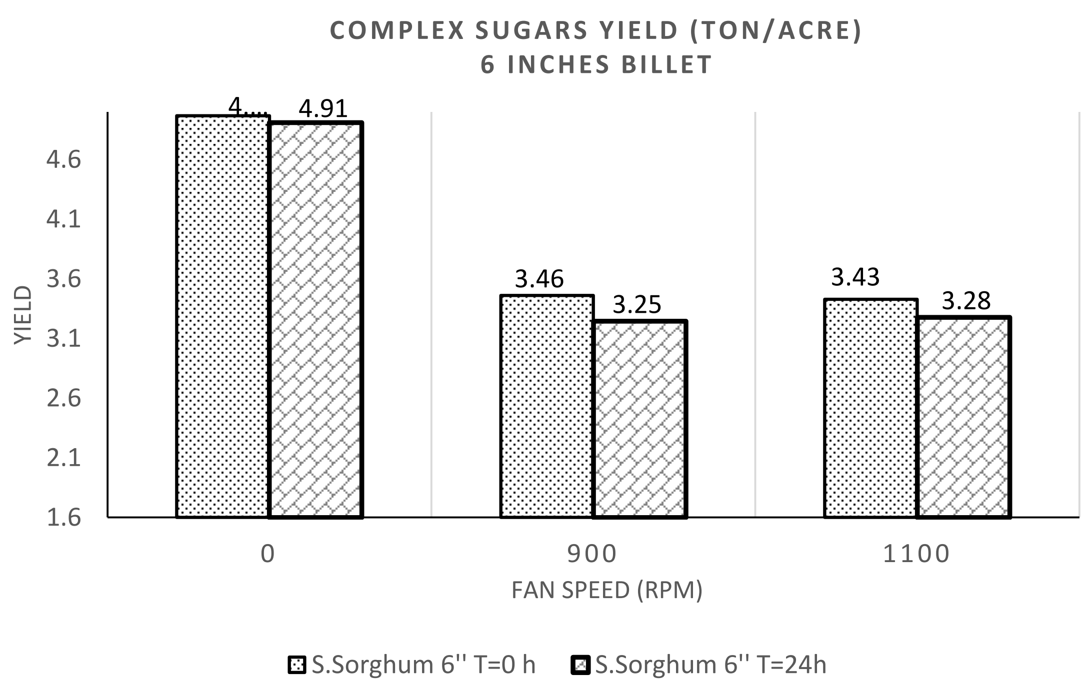
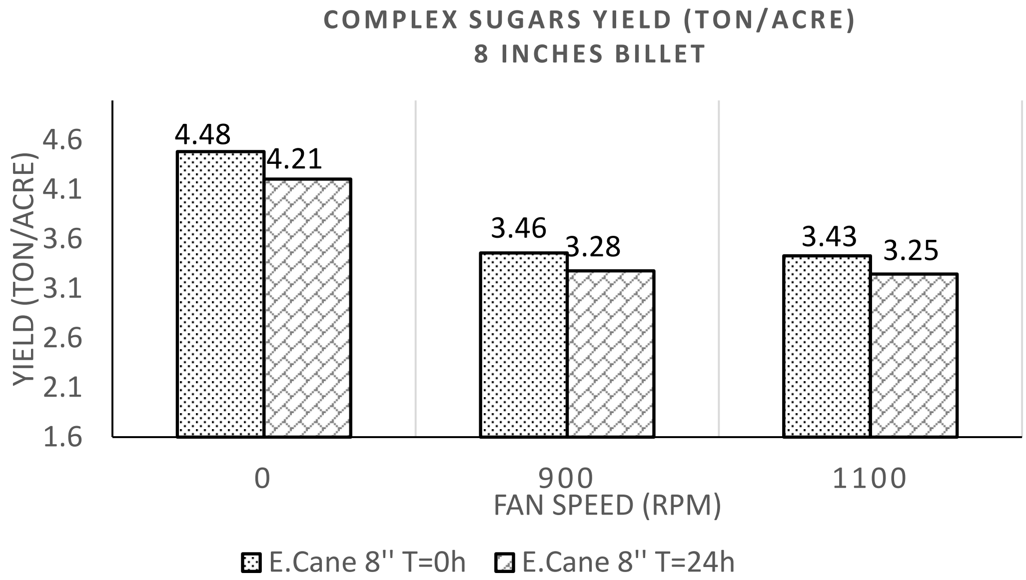


Figure 8.3 Complex sugars yield from energycane



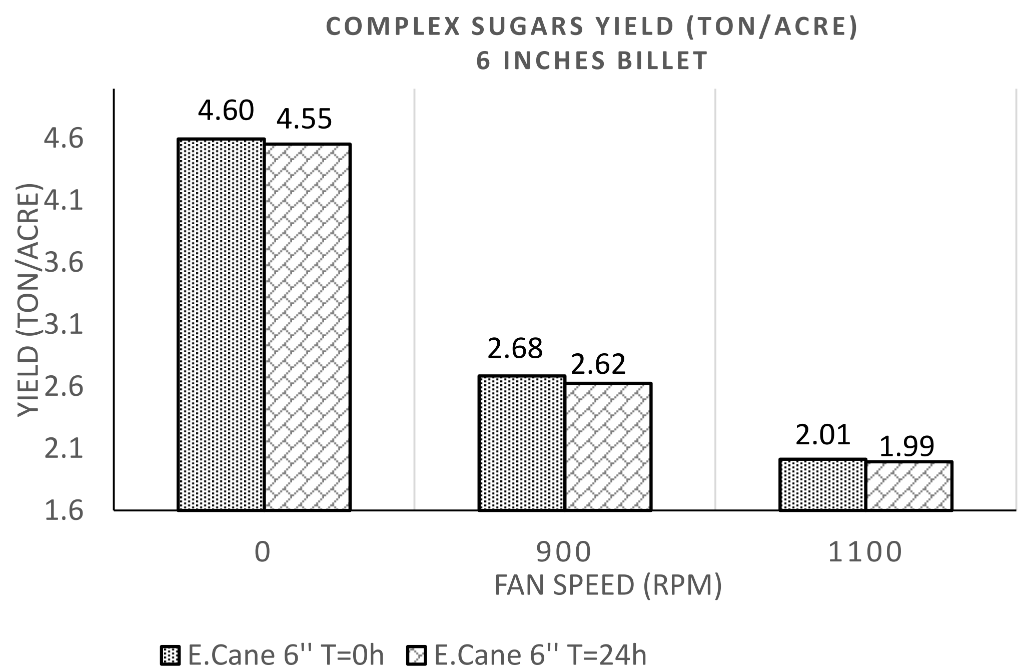


Figure 8.4 Complex sugars yield from energycane

For both billet lengths used for harvesting (6 and 8 inches), the complex sugars yield indicated that as the fan speed of the extractor system decreased (0 rpm), the yield of the complex sugars

increased. The complex sugars tend to deteriorate more slowly over time compared to the deterioration of the simple sugars.

For the case of the billets that were harvested with a length of 8 inches and when the fan extractor was not used during the harvesting operation, an increment of approximately 23%+ of complex sugars occurred. In the other hand, by harvesting billets, with a length of 6 inches, an increment of approximately 56%+ when using 0 rpm and processing the material shortly after harvesting.

8.5 Total sugars recovery from sweet sorghum and energycane

After calculating the simple and complex sugars recovery from both of the crops, the total sugars recovery indicator was calculated by adding the results of the simple and complex sugars according to the yields obtained from each of the scenarios. With this indicator, the potential ethanol yield was calculated by the implementation of the s*ugars – ethanol conversion rate*. Table 8.7 and Table 8.8 illustrates the results obtained from the "Total sugars recovery" indicator.

Table 8.7 Total Sugar recovery – Sweet sorghum

	(8 inches billet)		(6 inches billet)	
fan (rpm)	Time *t* = 0 hours	Time *t* = 24 hours	Time *t* = 0 hours	Time *t* = 24 hours
0	4.9	4.6	6.3	5.7
900	2.6	2.5	3.6	3.3
1100	2.7	2.4	2.7	2.3

Table 8.8 Total Sugar recovery – energycane

	(8 inches billet)		(6 inches billet)	
fan (rpm)	Time *t* = 0 hours	Time *t* = 24 hours	Time *t* = 0 hours	Time *t* = 24 hours
0	5.6	5.1	5.7	5.3
900	4.8	4.5	3.8	3.5
1100	4.8	4.5	2.9	2.7

As can be seen from the yield of the total sugars obtained from sweet sorghum, the results suggest that as the fan speed decrease, the yield of the total sugars recovery increases, especially when the material is processed shortly after harvesting. It also was evidenced that by storing the material for 24 hours, the yield of the t*otal sugars recovery* decreased. The following behavior of the results was evidenced for the case of the sweet sorghum:

1. When the material was harvested with a billet length of 8 inches and processed shortly after harvesting with a fan speed of 0 rpm, the yield of the Total fermentable sugars (TFS), increased by 6% compared to the results obtained 24 hours later.
2. When the material was harvested with a billet length of 8 inches and processed shortly after harvesting with a fan speed of 900 rpm, the yield of the Total fermentable sugars (TFS), increased by 4% compared to the results obtained 24 hours later.
3. When the material was harvested with a billet length of 8 inches and processed shortly after harvesting with a fan speed of 1100 rpm, the yield of the Total fermentable sugars (TFS), increased by 11% compared to the results obtained 24 hours later.
4. When the material was harvested with a billet length of 6 inches and processed shortly after harvesting with a fan speed of 0 rpm, the yield of the Total fermentable sugars (TFS), increased by 9% compared to the results obtained 24 hours later.
5. When the material was harvested with a billet length of 6 inches and processed shortly after harvesting with a fan speed of 900 rpm, the yield of the Total fermentable sugars (TFS), increased by 8% compared to the results obtained 24 hours later.
6. When the material was harvested with a billet length of 6 inches and processed shortly after harvesting with a fan speed of 1100 rpm, the yield of the Total fermentable sugars (TFS), increased by 14% compared to the results obtained 24 hours later.

From the results showed in Table 8.7 and Table 8.8, it can be evidenced that when the material was harvested with a billet length of 8 inches and processed shortly after harvesting with a fan speed of 0 rpm, the yield of the Total fermentable sugars (TFS), increased by 8% compared to the results obtained 24 hours later.

When a billet length of 8 inches and processed shortly after harvesting with a fan speed of 900 rpm, the yield of the Total fermentable sugars (TFS), increased by 6% compared to the results obtained 24 hours later.

8.6 Ethanol yield from the simple and complex sugars

After calculating the simple and complex sugars recovery from both of the crops and the total sugars recovery indicator, the potential ethanol yield was calculated based on the conversion rate of sugars into ethanol defined by Day, 2012.

It is assumed that for the production of 1 liter of ethanol, it is required 3.7 pounds (1.6 kilograms) of total fermentable sugars. By calculating the total amount of recoverable sugars after implementing different harvesting treatments, the ethanol yield was calculated for each of the scenarios.

Table 8.9 and Table 8.10 illustrates the results obtained from converting the total fermentable sugars recovered from both crops into ethanol according to the scenarios defined for the study.

Table 8.9 Ethanol yield from sweet sorghum

Fan (rpm)	8 inches, time = 0 hours	8 inches, time = 24 hours	6 inches, time = 0 hours	6 inches, time = 24 hours
0	2942.1	2798.6	3810.6	3451.9
900	1579.6	1495.5	2173.8	2016.3
1100	1606.1	1476.1	1640.8	1407.4

Table 8.10 Ethanol yield from energycane

Fan (rpm)	8 inches, time = 0 hours	8 inches, time = 24 hours	6 inches, time = 0 hours	6 inches, time = 24 hours
0	3364.2	3103.8	3453.22	3219.82
900	2893.9	2689.5	2264.10	2105.33
1100	2889.5	2702.3	1760.43	1636.43

Figure 8.5 and Figure 8.6 illustrates the behavior of the results obtained from the ethanol yield of sweet sorghum.

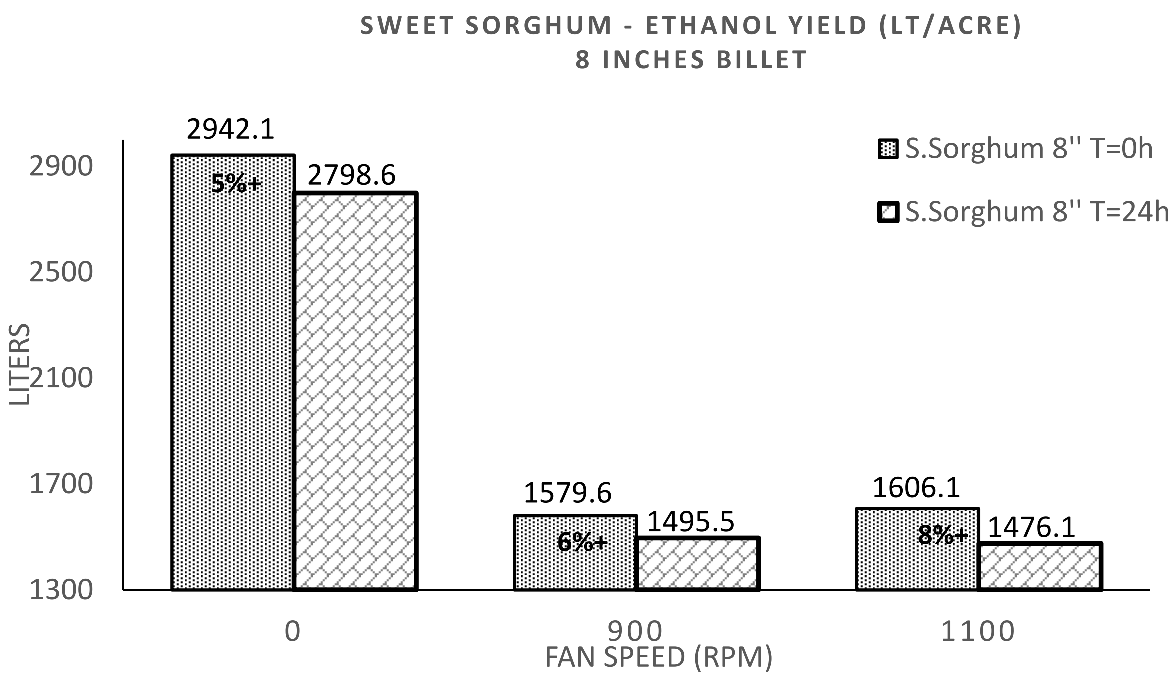


Figure 8.5 Ethanol yield from sweet sorghum, billets 8 inches

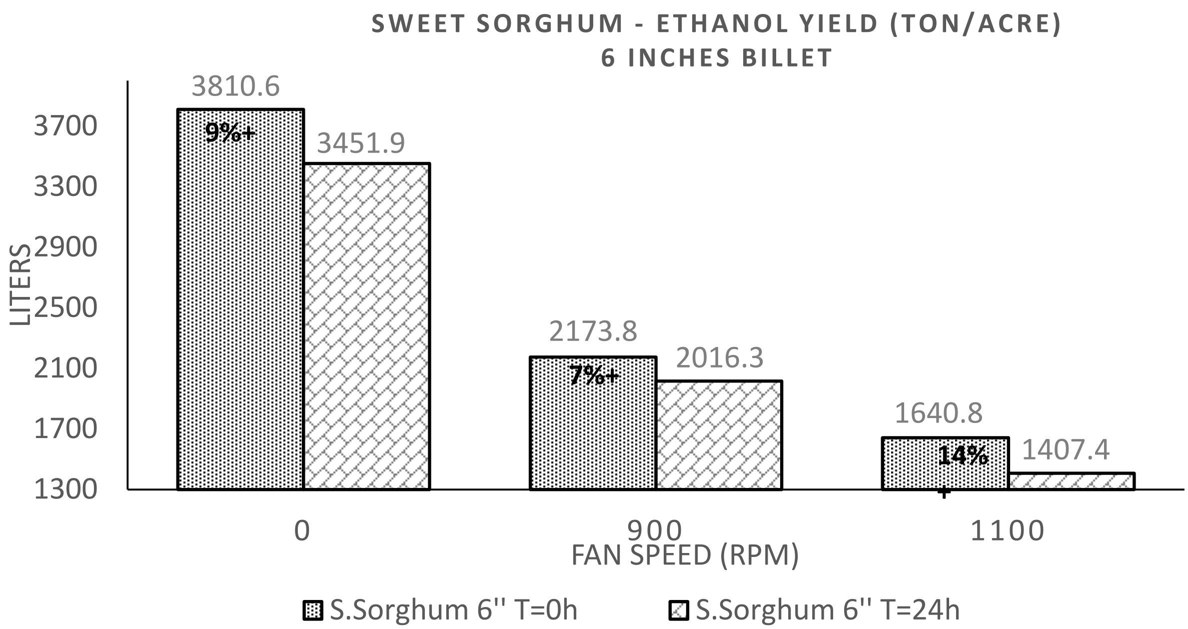


Figure 8.6. Ethanol yield from sweet sorghum, billets 6 inches

The results illustrated on Figure 8.7 and Figure 8.8 present similar behavior; it can be evidenced that as the fan speed of the extractor system is reduced (0 rpm), the yield of the ethanol tend to increase, especially, when the material is processed shortly after harvesting.

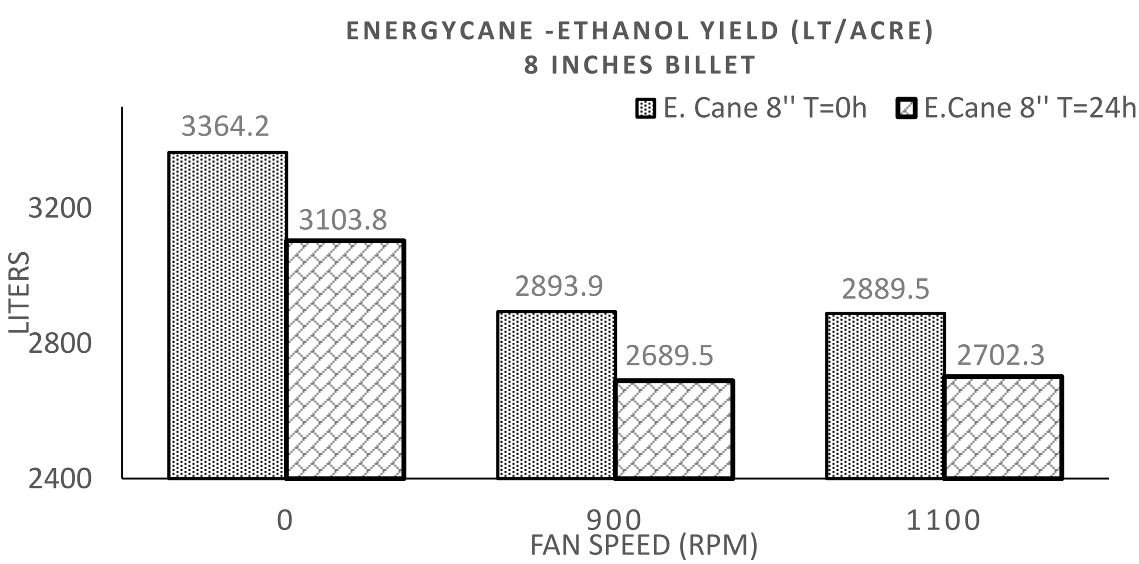


Figure 8.7 Ethanol yield from energycane, billets 8 inches

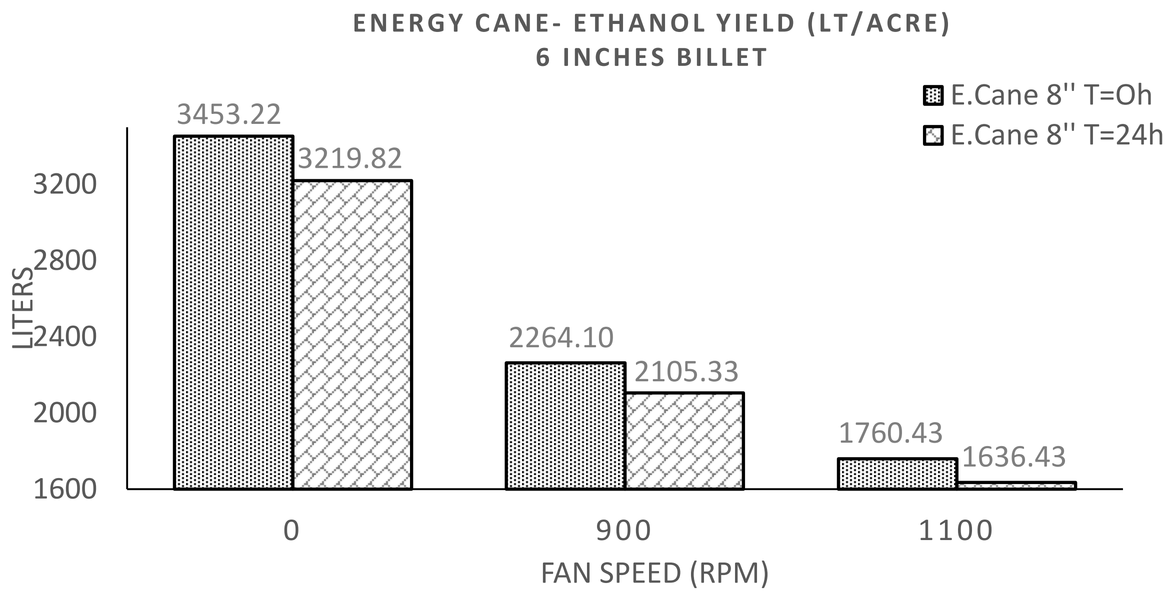


Figure 8.8 Ethanol yield from energycane, billets 6 inches

The yield of ethanol tend to increase when the material is not stored during a period of time before processing, hence, some losses between treatments can be evidenced when the material that was processed shortly after harvesting, is compared to the results of the material that was processed 24 hours later.

The following differences of the yields obtained between treatments were observed when processing the material shortly after harvesting and 24 hours later. When the material was processed with a billet length of 8 inches, the following differences were evidenced:

1. By using a fan speed of 0 rpm, the ethanol yield increased by 5%+ when processing the material short after harvesting in comparison if the material was processed 24 hours later using the same fan speed.
2. By using a fan speed of 900 rpm, the ethanol yield increased by 6%+ when processing the material short after harvesting in comparison if the material was processed 24 hours later using the same fan speed.

3. By using a fan speed of 1100 rpm, the ethanol yield increased by 8%+ when processing the material short after harvesting in comparison if the material was processed 24 hours later using the same fan speed.

The results illustrated on Figure 8.7 and Figure 8.8 present similar behavior. It can be seen that as the fan speed of the extractor system is reduced (0 rpm), the yield of the ethanol increases, especially, when the material is processed shortly after harvesting (t = 0 hours).

From all the treatments shown in Figure 8.7 and Figure 8.8, the yield of ethanol increased when the material is not stored during a period before processing, hence, some losses between treatments can be evidenced when the material that was processed shortly after harvesting is compared to the results of the material that was processed 24 hours later.

The following differences of the yields obtained between treatments were observed when processing the material shortly after harvesting and 24 hours later. When the material was processed with a billet length of 8 inches, the following differences were evidenced:

1. By using a fan speed of 0 rpm, the ethanol yield increased by 8%+ when processing the material short after harvesting in comparison if the material was processed 24 hours later using the same fan speed.
2. By using a fan speed of 900 rpm and 1100 rpm, the ethanol yield increased by 7%+ when processing the material short after harvesting in comparison if the material was processed 24 hours later using the same fan speed.
3. When the material was processed with a billet length of 6 inches, the following differences were evidenced. By using a fan speed of 0 rpm, 900 rpm and 1100 rpm, the ethanol yield increased by 7%+ when processing the material short after harvesting in comparison if the material was processed 24 hours later using the same fan speed.

8.7 Simulation Results "Profit Maximization"

The simulation of the model was performed using Microsoft Excel, version 2010. 24 scenarios were defined in the model and were simulated. A total of 240.000 iterations of the *ethanol profit function* were obtained after simulating all the scenarios.

In the simulation, the *total supply cost* function was defined, which considered the following costs: agronomic production of the crop ($/acre), the harvesting cost ($/acre) and the wagon cost ($/acre). Also, in the simulation was defined the processing cost ($/material obtained from an acre), all these costs were constant per treatment, and were calculated based on the mathematical definition developed on Section 7 and also were calculated based on the input data for the model (harvesting trials data).

The transportation cost was not defined as a fixed cost, because it varies according to the distance parameter defined from the simulation (range between 1 to 100 miles). Table 8.11, provide the results of the supply cost (cost/acre), the processing cost (cost$/acre) and the ethanol sale value ($/acre).

The ethanol sale value was calculated from the yield of the total sugars obtained from each of the treatments and was converted into the potential ethanol yield per acre (lt/acre). By using the selling price of the ethanol, the expected ethanol sale value was calculated ($/acre).

It can be evidenced from Table 8.11 that treatment number 1 illustrate the following results:

1. Treatment configuration: "sweet sorghum" harvested with a billet size of 8 inches, a fan speed of 1100 rpm, and a processing time of t = 0h.
2. The expected ethanol yield per acre was approximately 1605.89 liters
3. The supply cost per acre was estimated in 484.19 dollars.
4. The processing cost per acre was estimated in 573.39 dollars.

5. The expected ethanol sale value was estimated in 1,251.9.

The transportation cost cannot be calculated as a fix value because it changes based on the total transportation distance.

The simulation calculated the *final ethanol profit* by simulating the tentative *ethanol profit function* that at the moment has been defined. This function consist in subtracting from the *ethanol sale value* the processing cost and the supply cost.

Table 8.11 Supply costs, processing costs and ethanol sale value for energy crops per acre

CROP	Billet size (inch)	storage time t (h)	fan speed (rpm)	ethanol yield (lt/acre)	Ethanol sale value ($/acre)	Supply cost ($/acre)	Processing cost ($/acre)
S.SORGHUM	8	0	1100	1605	1,251	484	573
S.SORGHUM	8	24	1100	1475	1,150	484	550
S.SORGHUM	8	0	900	1579	1,231	482	575
S.SORGHUM	8	24	900	1495	1,165	482	563
S.SORGHUM	8	0	0	2941	2,293	477	1,172
S.SORGHUM	8	24	0	2798	2,181	477	1,171
S.SORGHUM	6	0	1100	1640	1,279	484	572
S.SORGHUM	6	24	1100	1407	1,097	484	488
S.SORGHUM	6	0	900	2173	1,694	482	805
S.SORGHUM	6	24	900	2015	1,571	482	805
S.SORGHUM	6	0	0	3810	2,970	477	1,455
S.SORGHUM	6	24	0	3451	2,690	477	1,436
ENERGY-CANE	8	0	1100	2893	2,255	687	1,062
ENERGY-CANE	8	24	1100	2701	2,106	687	996
ENERGY-CANE	8	0	900	2889	2,252	685	1,052
ENERGY-CANE	8	24	900	2689	2,096	685	1,005
ENERGY-CANE	8	0	0	3363	2,622	680	1,372
ENERGY-CANE	8	24	0	3103	2,419	680	1,286
ENERGY-CANE	6	0	1100	1760	1,372	687	618
ENERGY-CANE	6	24	1100	1636	1,275	687	611
ENERGY-CANE	6	0	900	2263	1,764	685	824
ENERGY-CANE	6	24	900	2105	1,641	685	804
ENERGY-CANE	6	0	0	3452	2,691	680	1,406
ENERGY-CANE	6	24	0	3219	2,509	680	1,392

In the simulation, this function was simulated considering the cost of transporting the material between a range of 1 to 100 miles.

8.8 Simulation: Objective function results

From the 24 matrixes that were defined for the simulation (1 matrix per treatment), two indicators were measured, the first one defined as *Maximum profit from the best case scenario,* which consisted on selecting from the 10.000 iterations developed per matrix (per scenario).

The maximum expected profit that was obtained after implementing different harvesting and storage practices and after varying different areas and distances for harvesting and transporting the material.

Each of the matrixes simulated represented each one of the treatments illustrated in Table 8.11, hence, after simulating and obtaining the 10.000 iterations per matrix, the solution that provided the maximum ethanol profit was identified and selected as the optimum.

The parameter configuration obtained with this specific iteration; as a result, the maximum ethanol profit was selected from all 24 treatments defined in the study.

The other indicator, was defined as *Maximum profit from the worst case scenario (least feasible solution),* which consisted in selecting from the results of the simulation, the solution that provided the highest ethanol profit with the maximum feasible distance and area to cover.

The results suggested that up to that range of distances and area for covering, the solution found is feasible, however, the solution will be the least feasible solution for operating the system, therefore, by passing the range of distances or area to cover suggested by the solution, the operation will not be feasible. After using all the data measured in the harvesting trials, the following results were obtained from the simulation.

Table 8.12 and Table 8.13 illustrates the results obtained from the *Maximum profit results from the best case scenario* and Table 8.13, illustrates the results of the *Maximum profit results from the worst case scenario*; these s provide the following information:

1. Maximum profit that can be achieved per treatment.
2. Optimum area for harvesting and transporting the material.
3. Profit per acre (/acre).
4. Supply costs: transportation cost, the total supply cost (agronomic production cost + harvesting cost + wagon cost + processing cost) and the potential ethanol sale value that can be obtained after recovering and converting all the sugars into ethanol.
5. Total amount of simple and complex sugars that are expected to be recovered from the crop.
6. Expected cost per pound of sugar recovered.

Table 8.12 Simulation results of ethanol profit maximization for the best case scenario

Tre.	Max profit ($)	Profit ($/acre)	D (m)	A acres	No. truck	Transp. cost ($)	Total supply Cost ($)	Ethanol sale value ($)	Simple sugars (ton)	Comp. sugars (ton)	Total sugars (ton)	Cost sugar $/lb sugar
T1	19,292	192	1	100	80	144	105,902	125,194	71	195	266	0.181
T2	11,432	114	1	100	80	144	103,623	115,055	57	188	245	0.193
T3	17,132	114	1	100	85	153	105,992	123,123	66	196	262	0.184
T4	11,749	117	1	100	85	153	104,823	116,572	55	192	248	0.192
T5	63,567	636	1	100	410	742	165,766	229,333	87	401	487	0.155
T6	52,482	525	1	100	410	742	165,664	218,146	63	401	464	0.162
T7	22,114	221	1	100	67	121	105,785	127,899	77	195	272	0.177
T8	12,336	123	1	100	67	121	97,364	109,700	67	166	233	0.190
T9	40,442	404	1	100	96	173	129,004	169,446	86	275	360	0.163
T10	28,126	281	1	100	96	173	129,040	157,165	59	275	334	0.176
T11	103,039	1,030	1	100	382	691	193,988	297,02	135	497	631	0.140
T12	77,038	770	1	100	382	691	192,030	269,068	81	491	572	0.153
T13	50,366	504	1	100	147	266	175,204	225,570	133	346	479	0.166
T14	42,053	421	1	100	147	266	168,587	210,640	123	325	448	0.171
T15	51,084	511	1	100	152	275	174,149	225,233	136	343	479	0.165
T16	40,227	402	1	100	152	275	169,414	209,641	118	328	446	0.173
T17	56,531	565	1	100	248	448	205,702	262,232	109	448	557	0.168
T18	44,797	448	1	100	248	448	197,140	241,936	94	421	514	0.174
T19	6,537	65	1	100	125	226	130,778	137,221	90	201	292	0.204
T20	-	-	-	-	-	-	-	-	-	-	-	-
T21	25,341	253	1	100	119	215	151,202	176,481	107	268	375	0.183
T22	14,897	149	1	100	119	215	149,270	164,105	86	262	349	0.195
T23	60,228	602	1	100	142	257	208,951	269,170	113	460	572	0.166
T24	43,505	435	1	100	142	257	207,481	250,977	78	455	533	0.177

Table 8.13 Results of simulating the Maximum profit from the worst case scenario

Treat.	Min Profit ($)	Profit ($/acre)	Max. D (miles)	Max. A (acre)	No. trucks	Transp. Cost ($)	Total Supply cost ($)	Ethanol sale value ($)	simple sugars (ton)	complex sugars (ton)	total sugars (ton)	Cost $ /lb sugar
T1	7,592	75.9	35	100	80	11,844	117,602	125,19	71	195	266	0.20
T2	71	0.7	34	100	80	11,505	114,984	115,05	57	188	245	0.21
T3	4,701	47.0	35	100	85	12,584	118,422	123,12	66	196	262	0.21
T4	83	0.9	33	91	77	10,748	105,998	106,08	50	175	225	0.21
T5	3,705	37.4	35	99	405	59,960	223,334	227,03	86	397	483	0.21
T6	82	82.2	30	1	5	635	2,283.73	2,181	1	4	5	0.22
T7	192	1.9	47	100	67	22,043	127,707	127,89	77	195	272	0.21
T8	2,537	25.4	35	100	67	9,919	107,162	109,70	67	166	233	0.21
T9	393	4.2	60	93	89	37,380	157,192	157,58	80	255	335	0.21
T10	153	1.6	42	93	89	26,166	46,011	146,16	55	256	311	0.21
T11	2,145	21.7	38	99	378	100,548	291,912	294,05	133	492	625	0.21
T12	21,17	211.7	35	100	382	56,555	247,894	269,06	81	491	572	0.20
T13	423	4.5	49	95	139	47,677	213,868	214,29	127	329	455	0.21
T14	311	3.3	41	95	139	39,893	199,798	200,10	117	308	425	0.21
T15	311	3.7	48	85	129	43,344	191,137	191,44	115	292	407	0.21
T16	113	1.3	38	85	129	34,314	178,082	178,19	100	279	379	0.21
T17	20,26	202.6	35	100	248	36,716	241,969	262,23	109	448	557	0.21
T18	8,529	85.3	35	100	248	36,716	233,407	241,93	94	421	514	0.21
T19	152	1.7	30	90	65	5,850	123,346	123,49	81	181	263	0.21
T20	-	-	-	-	-	-	-	-	-	-	-	-
T21	23	0.3	43	91	77	23,177	160,574	160,59	97	244	341	0.21
T22	2,467	24.7	35	100	85	12,58	161,638	164,10	86	262	349	0.21
T23	72	0.8	63	92	126	55,566	247,564	247,63	104	423	526	0.21
T24	598	6.0	45	100	137	43,155	250,379	250,97	78	455	533	0.21

8.9 Simulation results: best case scenario discussion – sweet sorghum

Figure 8.9 and Figure 8.10 illustrates the results obtained from simulating the objective function *ethanol profit* when sweet sorghum was used as input for the system; this section analyses the optimum results obtained for the best case scenario defined for the study (Section 8.1.2).

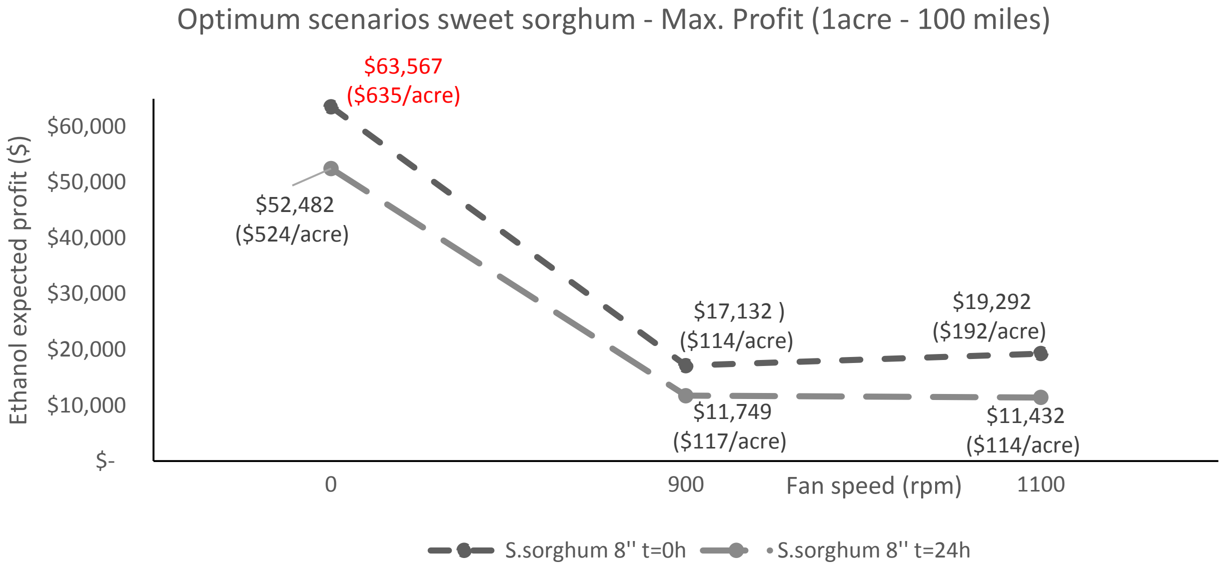


Figure 8.9 Simulation results of maximum profit for sweet sorghum – 8 inches billet

Figure 8.9 and Figure 8.10 illustrates the results of the maximum profit solution that was obtained during the simulation of the first 12 treatments defined in Table 8.10. The results suggested that the maximum ethanol profit that was obtained from the 10.000 iterations performed per treatment during the simulation, hence, each solution from each treatment, represent the optimum solution that maximizes the ethanol profit.

Figure 8.10 illustrates the optimum solutions for the first six treatments that maximizes the ethanol profit (sweet sorghum, harvested with a billet length of 8 inches).

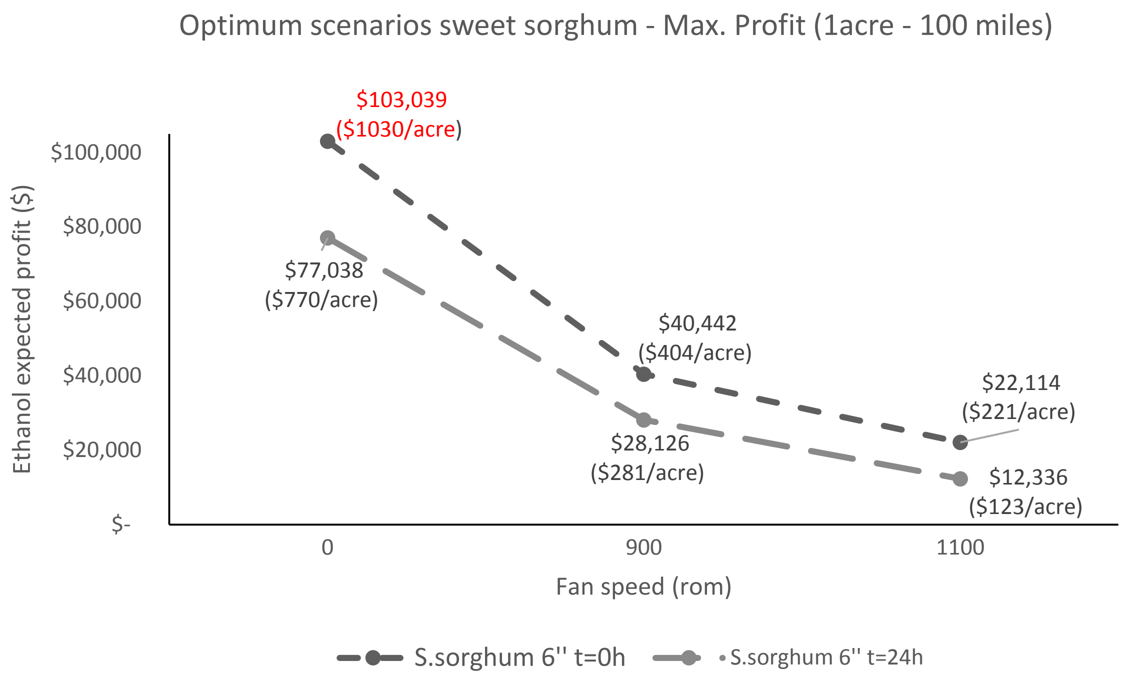


Figure 8.10 Simulation results of maximum profit for sweet sorghum – 6 inches billet

The optimum solution between these first six treatments corresponds to Treatment 5, because this treatment provides the maximum ethanol profit, hence, this solution is selected as the optimum solution for this first set of treatments. By harvesting sweet sorghum with a billet length of 8 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h) the optimum solution was defined by the following results (Figure 8.9 and Table 8.10):

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 1 mile; as a result, a total profit of $63,566.90 dollars can be expected to be obtained (Treatment 5).
2. For this specific scenario, the total transportation cost was of $742 dollars, covering a radius of 1 mile.

3. 410 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 1 mile, was $165,766.
5. The total ethanol sale value for this specific scenario was of $229,333 which was obtained from selling 294,214 liters of ethanol produced from 464 tons of sugars recovered.
6. 464 tons of sugars was recovered from this scenario (63 tons of simple sugars and 401 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of 0.15 cents.

This interpretation can be performed for all the results obtained from the simulation illustrated in Table 8.12:

1. The second set of treatments simulated in the model (Treatment 7 to 12) are illustrated on Figure 8.10 and described in Table 8.11; in this scenarios, the input was sweet sorghum and the billet length used was 6 inches. In the results presented in Figure 8.10, it can be evidenced the optimum solutions for this second set of treatments that maximizes the ethanol profit (sweet sorghum, harvested with a billet length of 8 inches).
2. The optimum solution between these six treatments corresponds to Treatment 11, which provides the maximum ethanol profit, hence, this solution is selected as the optimum solution for this set of treatments.
3. Also, it can be evidenced that from the treatments that corresponds to sweet sorghum (treatments 1 to 12), Treatment 11, provides the maximum ethanol profit solution, hence, it can be assumed that the optimum solution is obtained with the configuration of the parameters defined in Treatment 11.

When the sweet sorghum with a billet length of 6 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h), the optimum solution was defined by the following results (Figure 8.10 and Table 8.11):

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 1 mile; as a result, an expected total profit of $103,039.43 can be obtained (Treatment 11).
2. For this specific scenario, the total transportation cost was of $691 dollars (covering a radio of 1 mile).
3. 382 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 1 mile, was 193,988.84.
5. The total ethanol sale value for this specific scenario was of $297,028, which was obtained from 381,060 liters of ethanol produced from 631 tons of sugars recovered.
6. 631 tons of sugars was recovered from this scenario (135 tons of simple sugars and 497 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of 0.14 cents.

8.10 Simulation results: best case scenario discussion - energycane

Figure 8.11 and Figure 8.12 illustrates the results obtained from simulating the objective function *ethanol profit* when energycane was used as input for the system; this section analyses the optimum results obtained for the best case scenario defined for the study.

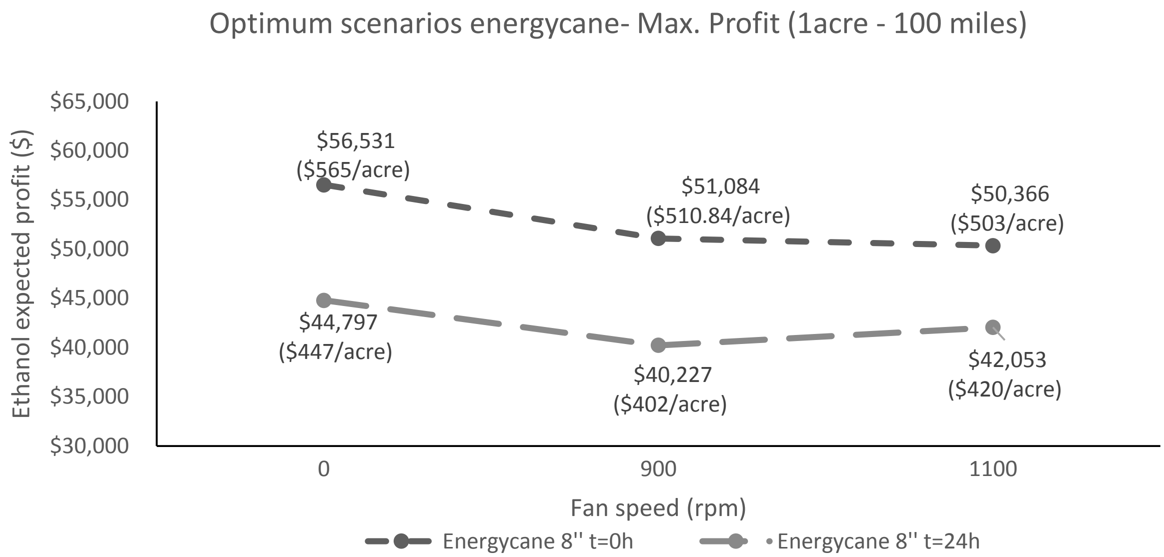


Figure 8.11 Simulation results of maximum profit for energycane – 8 inches billet

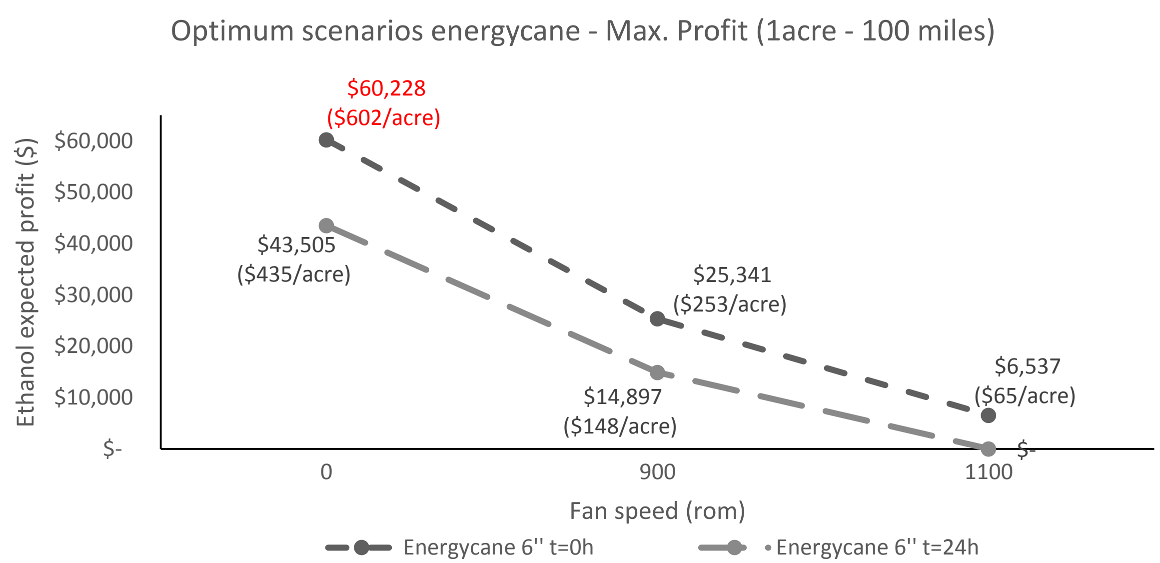


Figure 8.12 Simulation results of maximum profit for energycane – 6 inches billet

Figure 8.11 and Figure 8.12 illustrates the results of the maximum profit solution that was obtained during the simulation of treatments 13 to 24 defined in Table 8.11. These results represents the maximum ethanol profit that was obtained from the 10.000 iterations performed per treatment

during the simulation, hence, each solution from each treatment, represents the optimum solution that maximizes the ethanol profit. Figure 8.11 illustrates the optimum solutions obtained from treatments 13 to 18 that maximizes the ethanol profit (energycane, harvested with a billet length of 8 inches).

The optimum solution between these six treatments corresponds to Treatment 17, because this treatment provides the maximum ethanol profit from all treatments, hence, this solution is selected as the optimum solution for this set of treatments.

The description of the parameters used in Treatment 17 and the optimum results from this solution are interpreted as follow.

By harvesting energycane with a billet length of 8 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h), the optimum solution was defined by the following results (Figure 8.11 and Table 8.11):

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 1 mile; as a result, a total profit of $56,530.5 dollars was obtained from Treatment 17.
2. For this specific scenario, the total transportation cost was of $448 dollars (covering a radios of 1 mile).
3. 248 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 1 mile, was 205,702.39 dollars.

5. The total ethanol sale value obtained for this specific scenario was of $262,232.92 dollars, which was obtained from selling 336,421 liters of ethanol produced from 557 tons of sugars recovered.
6. 557 tons of sugars was recovered from this scenario (109 tons of simple sugars and 448 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of 0.16 cents.

The second set of treatments simulated in the model for the case of the energycane (Treatments 19 to 24) are illustrated on Figure 8.12 and described in Table 8.11; these scenarios used as input energycane with a billet length of 6 inches.

The information presented in Figure 8.11, illustrates the optimum results that maximizes the ethanol profit obtained from the 10.000 iterations simulated in each of the treatments. The optimum solution between these six treatments corresponds to Treatment 23, which provides the maximum ethanol profit, hence, this solution is selected as the optimum solution for this set of treatments.

The description of the parameters used in Treatment 23 and the optimum results are interpreted as follow. By harvesting energycane with a billet length of 6 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h), the optimum solution was defined by the following results:

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 1 mile; as a result, an expected total profit of $60,228.27 dollars can be obtained (Treatment 23).
2. For this specific scenario, the total transportation cost was of 257 dollars for covering a radial distance of 1 mile.

3. 142 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 1 mile, was $208,951.29 dollars.
5. The total ethanol sale value for this specific scenario was of $269,170.51 dollars which was obtained from 345,321 liters of ethanol produced from 572 tons of sugars recovered.
6. 572 tons of sugars were recovered from this solution (113 tons of simple sugars and 460 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of $0.17 cents.

8.11 Simulation results (sweet sorghum): worst case scenario discussion

The results presented in the *worst case scenario* represents the least feasible solution obtained from each of the 24 treatments after varying the objection function based on a combination of different distances and area to cover.

Based on the parameter configuration suggested by the solution selected as the *worst case scenario*, it is not feasible to over pass the distances for transporting the material or the area for harvesting the material. In the model was defined that up to the specific range of the solution, the system can operate and be feasible, however, these solutions are the least feasible alternatives for the system.

Figure 8.13 and Figure 8.14 illustrates the results (treatment 1 to 12) obtained from simulating the objective function *ethanol profit* when sweet sorghum was used as input for the system.

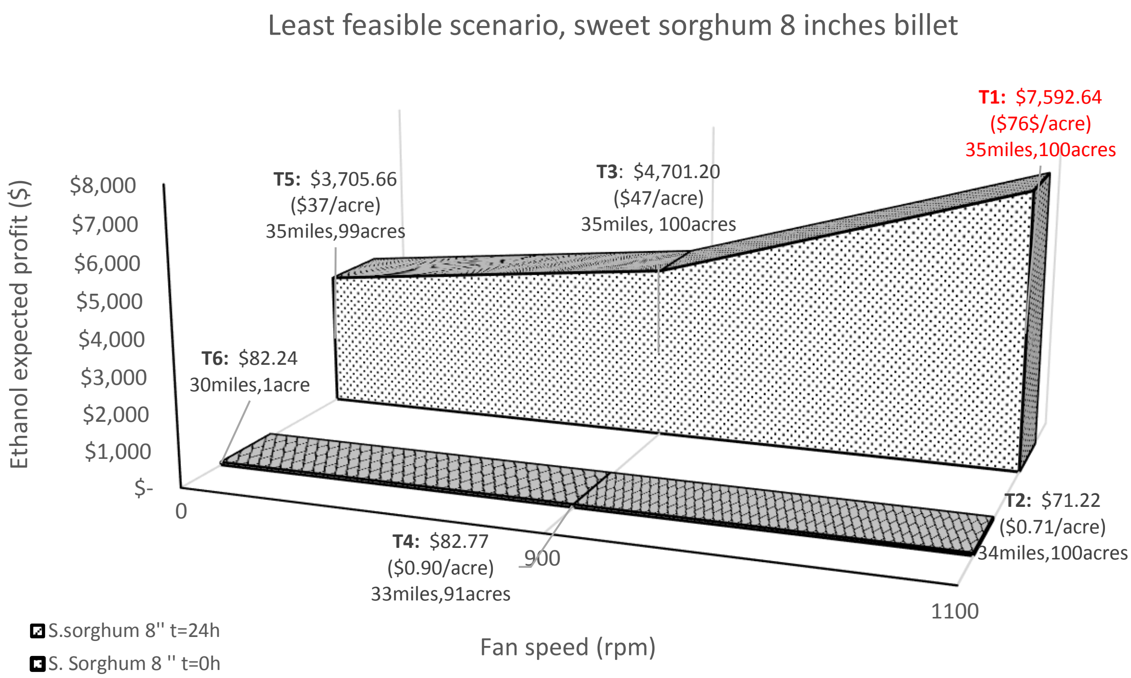


Figure 8.13 Least feasible solution sweet sorghum – 8 inches billet

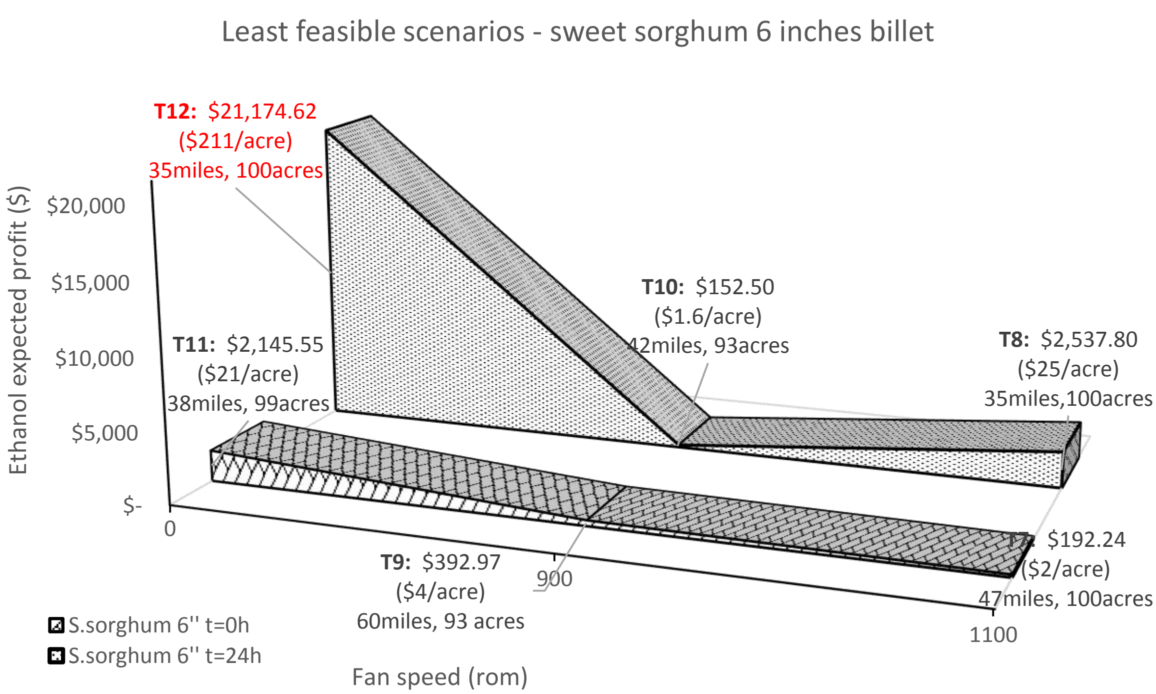


Figure 8.14 Least feasible solution sweet sorghum – 6 inches billet

Figure 8.13 illustrates the *optimum least feasible solutions* obtained from treatments 1 to 6; these solutions maximizes the ethanol profit in the worst case scenario. The optimum solution between these six treatments corresponds to Treatment 1 (T1), because this treatment provides the maximum ethanol profit, hence, this solution is selected as the optimum solution for this set of treatments.

The description of the parameters used in Treatment 1 and the optimum results from this solution are interpreted as follow. Treatment 1: By harvesting sweet sorghum with a billet length of 8 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h), the optimum solution was defined by the following results:

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 35 miles; as a result, a total profit of $7,592.64 was obtained from Treatment 1.
2. For this specific scenario, the total transportation cost was of $11,844.0 dollars (covering a maximum distance of 35 miles).
3. 80 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 35 miles, was $117,602.13 dollars.
5. The total ethanol sale value obtained for this specific scenario was of $125,194.64 dollars, which was obtained from selling 160,613 liters of ethanol produced from 266 tons of sugars recovered.
6. 266 tons of sugars was recovered from this scenario (71 tons of simple sugars and 195 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of 0.20 cents.

The second set of treatments simulated in the model for the case of the sweet sorghum (Treatments 7 to 12) are illustrated on Figure 8.15; these scenarios used as input sweet sorghum with a billet length of 6 inches.

The information presented illustrates the *optimum least feasible solutions* obtained from treatments 7 to 12; these solutions maximizes the ethanol profit in the worst case scenario.

From the treatments illustrated on Figure 8.14, the optimum solution corresponds to Treatment 12, which provides the maximum ethanol profit, hence, this solution is selected as the optimum solution for this set of treatments.

When the sweet sorghum with a billet length of 6 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h), the optimum solution was defined by the following results:

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 1 mile; as a result, an expected total profit of $21,174.6 dollars can be obtained (Treatment 12).
2. For this specific scenario, the total transportation cost was of $56,555.1 dollars for covering a radial distance of 35 miles.
3. 382 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 1 mile, was $208,951.29 dollars.
5. The total ethanol sale value for this specific scenario was of $269,068.67 dollars which was obtained from 345,191 liters of ethanol produced from 572 tons of sugars recovered.

6. 572 tons of sugars were recovered from this solution (81 tons of simple sugars and 491 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of 0.20 cents.

8.12 Simulation results (energycane): worst case scenario discussion

Figure 8.15 illustrates the results (treatment 13 to 24) obtained from simulating the objective function *ethanol profit* when energycane was used as input for the system. Figure 8.15 illustrates the *optimum least feasible solutions* obtained from treatments 13 to 24; these solutions maximizes the ethanol profit in the worst case scenario.

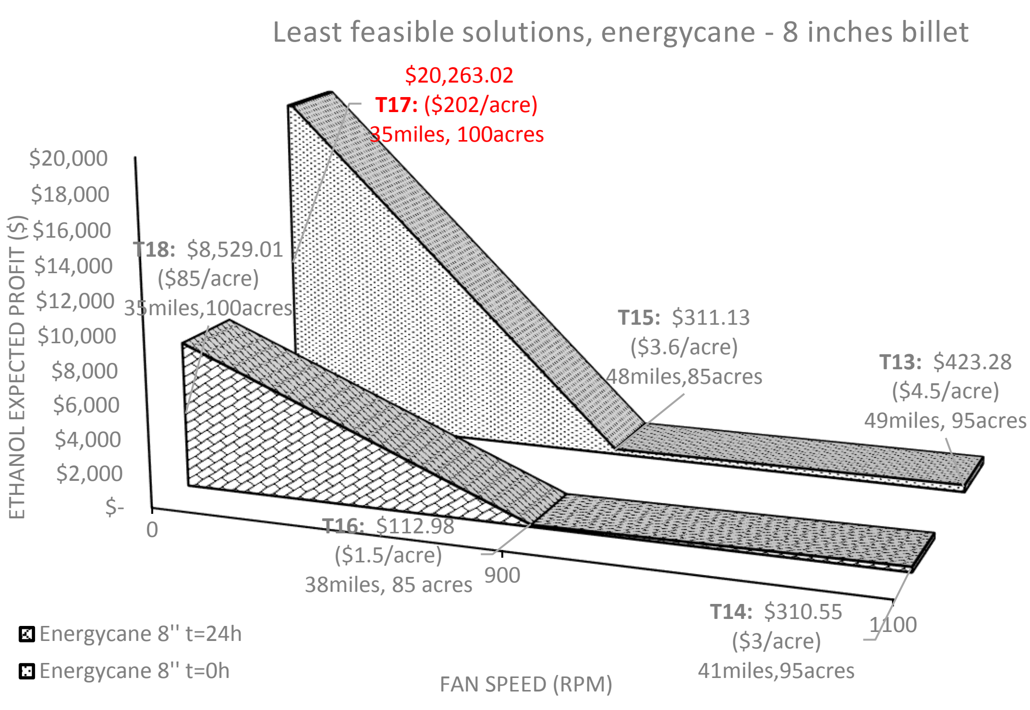


Figure 8.15 Least feasible solution energycane – 8 inches billet

From Figure 8.15 it can be evidenced that the optimum solution between these six treatments corresponds to Treatment 17 (T7), because this treatment provides the maximum ethanol profit

from all treatments, hence, this solution is selected as the optimum solution for this set of treatments.

The description of the parameters used in Treatment 17 and the optimum results from this solution are interpreted as follow:

Treatment17: By harvesting energycane with a billet length of 8 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h), the optimum solution was defined by the following results (Figure 8.16):

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 35 miles; as a result, a total profit of $20,263.02 was obtained from Treatment 17.
2. For this specific scenario, the total transportation cost was of $36,716.5 dollars (covering a maximum distance of 35 miles).
3. 248 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 35 miles, was $241,969.92 dollars.
5. The total ethanol sale value obtained for this specific scenario was of $262,232.92 dollars, which was obtained from selling 336,421 liters of ethanol produced from 557 tons of sugars recovered.
6. 577 tons of sugars was recovered from this scenario (109 tons of simple sugars and 448 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of 0.20 cents.

The second set of treatments simulated in the model for the case of the energycane (Treatments 19 to 24) are illustrated on Figure 8.16.

The information presented in Figure 8.16, illustrates the *optimum least feasible solutions* obtained from treatments 19 to 24; these solutions maximizes the ethanol profit in the worst case scenario. From the treatments illustrated on Figure 8.16, the optimum solution corresponds to Treatment 22, which provides the maximum ethanol profit, hence, this solution is selected as the optimum solution for this set of treatments.

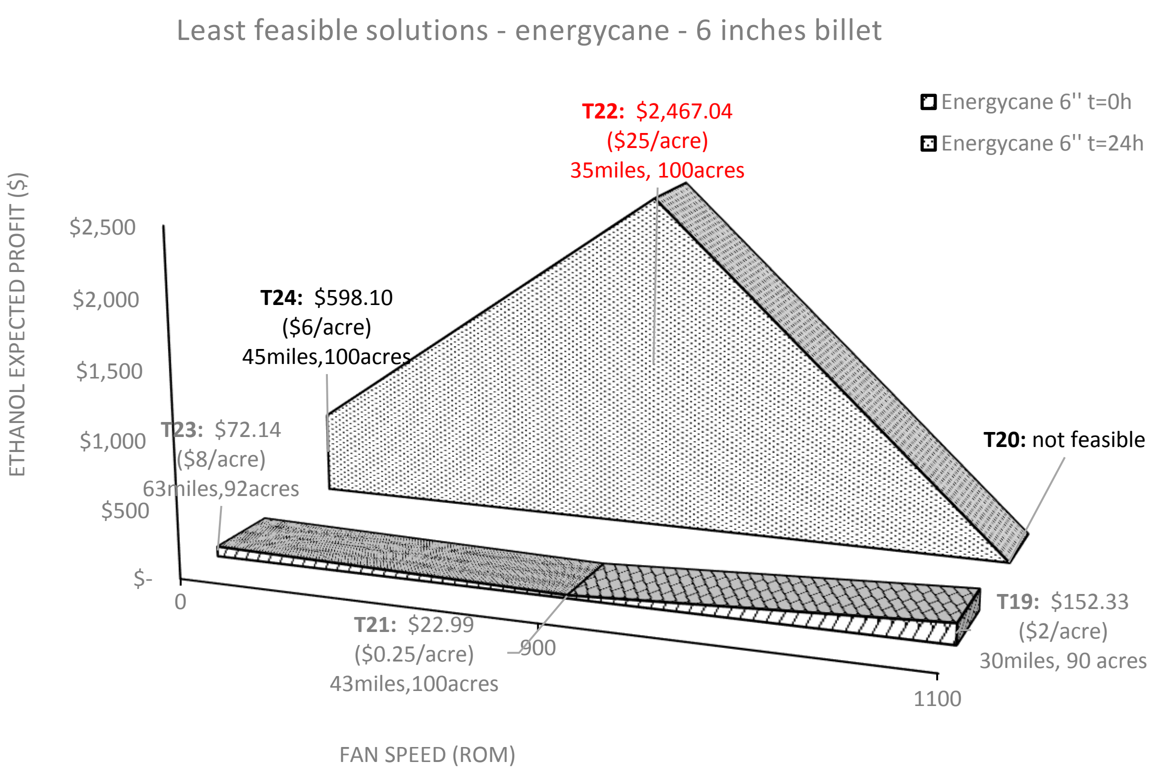


Figure 8.16 Least feasible solution energycane – 6 inches billet

By harvesting sweet sorghum with a billet length of 6 inches, by not using the fan extractor (0 rpm) and by processing the material shortly after harvesting (t = 0h), the optimum solution was defined by the following results (Figure 8.16):

1. The profit maximization took place when the area for harvesting was 100 acres and the travel distance for transporting the material was 35 miles; as a result, an expected total profit of $2,467.04 dollars can be obtained (Treatment 22).
2. For this specific scenario, the total transportation cost was of $12,584.25 dollars for covering a radial distance of 35 miles.
3. 85 trucks are needed for collecting the material from the 100 acres planned to be harvested.
4. The total supply cost of harvesting 100 acres and covering a distance of 35 miles, was 161,638.93 dollars.
5. The total ethanol sale value for this specific scenario was of $164,105.9 dollars which was obtained from 210,533 liters of ethanol produced from 349 tons of sugars recovered.
6. 349 tons of sugars were recovered from this solution (86 tons of simple sugars and 263 tons of complex sugars).
7. The production cost of a pound of sugar for this specific scenario was of 0.21 cents.

8.13 Simulation results – Discussion

The simulation of the model consisted on simulating the *ethanol profit function* obtained after implementing different harvesting and storages practices. The objective function was calculated and simulated based on an area range for harvesting that ranged between 1 to 100 acres and a distance range for transporting the material of 1 to 100 miles. Finally, the objective function was calculated after subtracting all the costs involved in the system (agronomic production cost of the crop, the harvesting cost, transportation cost and conversion of simple and complex sugars cost). From the 24 treatments that were defined in the model, the following categories were defined (Table 8.11):

- Treatment 1 to 6, implemented sweet sorghum as input for the system. In these treatments, the material was harvested with a billet length of 8 inches.

  In treatment 1, 3, 5, the material was processed shortly after harvesting, hence, the processing time was defined as *t* = 0 hours.

  In the other hand, the material from treatments 2, 4 and 6 was also collected by using a billet size of 8 inches, but the processing was performed 24 hours later (material stored 24 hours).

- Treatment 7 to 12, implemented sweet sorghum as input for the system. In these treatments, the material was harvested with a billet length of 6 inches.

  In treatment 7, 9, 11, the material was processed shortly after harvesting, hence, the processing time was defined as *t* = 0 hours. In the other hand, the material from treatments 8, 10 and 12 was also collected by using a billet size of 8 inches, but the processing was performed 24 hours later (material stored 24 hours).

- Treatment 13 to 18, implemented energycane as input for the system. In these treatments, the material was harvested with a billet length of 8 inches.

  In treatment 13, 15, 17, the material was processed shortly after harvesting, hence, the processing time was defined as *t* = 0 hours. In the other hand, the material from treatments 14, 16 and 18 was also collected by using a billet size of 8 inches, but the processing was performed 24 hours later (material stored 24 hours).

- Treatment 19 to 24, implemented energycane as input for the system. In these treatments, the material was harvested with a billet length of 6 inches.

  In treatment 19, 21, 23, the material was processed shortly after harvesting, hence, the processing time was defined as *t* = 0 hours. In the other hand, the material from treatments

20, 22 and 24 was also collected by using a billet size of 6 inches, but the processing was performed 24 hours later (material stored 24 hours).

This classification was performed because for each set of treatments, an optimum solution was found; the practices and parameters defined for each of the scenarios are different, hence, selecting only one optimum solution from all the treatments defined in the study will skew all the potential solutions that can be implemented for the system.

All 24 treatments defined for the model were simulated, treatments 1 to 12 were assigned for sweet sorghum and treatments 13 to 24 were assigned for energycane. After simulating the objective function of the model according to the characteristics of each of the 24 scenarios, 10.000 iterations per treatments were obtained and a total of 240.000 iterations were developed for the model.

Two different indicators were evaluated in the simulation, the first one called *Maximum profit from the best case scenario* which basically consisted on selecting the solution which allow the maximum ethanol expected profit after implementing different harvesting and storage practices. After identifying the solution that maximizes the profit function, the parameters of the solutions were defined as the optimum configuration of the system.

The second indicator was called *Maximum profit from the worst case scenario (least feasible solution)* which basically consisted on selecting the solution that allowed the highest ethanol profit as a result of covering the maximum feasible distance and area to cover for collecting and transporting the feedstock.

The main objective of the mathematical formulation for the supply system defined in the study, was to characterize the component costs of the supply system required for the production of ethanol from energy crops. With the mathematical definition of the component costs, it was possible to define the objective function, which consisted on the maximization of the ethanol profit obtained

from the ethanol produced from energy crop after implementing different harvesting and storage practices.

The simulation was developed by simulating the ethanol profit function obtained from each of the 24 treatments and by the variation of different distances for harvesting and transporting the material.

Table 8.14 and Table 8.15 shows the results obtained in the simulation for both cases, the *Maximum ethanol profit from the best case scenario* and the *Maximum ethanol profit from the least feasible scenario*.

The tables describe the optimum parameters and solutions obtained from the set of treatments described on the previous sections.

Table 8.14 Simulation summary results of Maximum profit from best case scenario

Tr.	Crop*	billet size inch	t (h)	Max. ethanol profit	Profit $/acre	Dist. mile	Area acre	ethanol yield (lt)	Ethanol cost ($/lt)	yield tons	$/lb
5	S.S	8	0	63,566	635	1	100	294,21	0.44	487	0.15
11	S.S	6	0	103,039	1,030	1	100	381,06	0.51	631	0.14
17	E.C.	8	0	56,530	565	1	100	336,42	0.61	557	0.16
23	E.C.	6	0	60,228	602	1	100	345,32	0.61	572	0.16

*S.S: Sweet sorghum, E.C: energycane.

Table 8.15 Simulation summary results of Maximum profit from least feasible scenario

Tr.	Crop*	billet size inch	t (h)	Max. ethanol profit	Profit $/acre	Dist. mile	Area acre	ethanol yield (lt)	Ethanol cost ($/lt)	yield tons	$/lb
1	S.S.	8	0	7,592	75	35	100	160,6	0.81	266	0.20
12	S.S.	6	24	21,174	211	35	100	345,1	0.88	572	0.20
17	E.C.	8	0	20,263	202	35	100	336,4	0.83	557	0.20
22	E.C.	6	0	2,467	24	35	100	210,5	0.83	349	0.21

8.14 Optimum solutions from best case scenario

From Table 8.14, the optimum solution from the best case scenario from the set of treatments assigned to sweet sorghum (Treatment 1 to 6), was Treatment 5, which provided a solution that maximized the ethanol profit 63,566.90 by harvesting 100 acres and traveling a distance of 1mile. The results obtained were: 294,214 liters of ethanol can be produced with a cost of 0.44/lt and 487 tons of sugars can be recovered with at a cost per pound of 0.15/lb.

It also can be evidenced from Table 8.14, that the optimum solution from the best case scenario from the set of treatments assigned to sweet sorghum (Treatment 7 to 12), was Treatment 11, which obtained a maximum ethanol profit of 103,039.4 by harvesting 100 acres and traveling a distance of 1mile.

The results obtained in this treatment were: 381,060 liters of ethanol can be produced at a cost per liter of 0.51/lt and 631 tons of sugars can be recovered at a cost per pound of 0.14/lb**.**

As a result of the selection of the optimum solutions in the best case scenario, it can be concluded the following:

1. Treatment 5 provided the optimum solution which maximized the ethanol profit and minimized the production per liter of ethanol and the production per pound of sugars. From all the treatments that included the crop of sweet sorghum and billet size configuration of 8 inches, Treatment 5 was the optimum.
2. Treatment 11 provided the optimum solution which maximized the ethanol profit and minimized the production per liter of ethanol and the production per pound of sugars. From all the treatments that included the crop of sweet sorghum and billet size configuration of 6 inches, Treatment 11 was the optimum.

In the other hand, for the case of the energycane, it can be evidenced from 63, that the optimum solution from the set of treatments 13 to 18 (8 inches billet), was Treatment 17, which allowed to obtained a maximum ethanol profit of 56,530.54 by harvesting 100 acres and traveling a distance of 1mile.

The result of the treatment were: 336,421 liters of ethanol can be produced at a cost per liter of 0.61/lt and 557 tons of sugars can be recovered with at a cost per pound of 0.16$/lb. It also can be evidenced from Table 8.14, that the optimum solution from the best case scenario from the set of treatments 19 to 24, was Treatment 23. With this treatment, a maximum ethanol profit of $60,228.27 by harvesting 100 acres and traveling a distance of 1mile; as a result, 345,321 liters of ethanol can be produced at a cost per liter of 0.61$/lt and 572 tons of sugars can be recovered at a cost per pound of 0.16$/lb.

From the results it was defined the following conclusions:

1. Treatment 17 provided the optimum solution which maximized the ethanol profit and minimized the production per liter of ethanol and the production per pound of sugars.

   From all the treatments that included the crop of energycane and billet size configuration of 8 inches, Treatment 17 was the optimum.

2. Treatment 23 provided the optimum solution which maximized the ethanol profit and minimized the production per liter of ethanol and the production per pound of sugars.

   From all the treatments that included the crop of energycane and billet size configuration of 6 inches, Treatment 17 was the optimum.

8.15 Optimum solutions from worst case scenario (least feasible solutions)

From Table 8.15, the optimum solution simulated on the *least feasible scenario* from the set of treatments that implemented sweet sorghum as input for the system (8 inches billet, Treatment 1 to 6), was Treatment 1.The results obtained from the treatment were: maximum ethanol profit of $7,592.64 by harvesting 100 acres and traveling a distance of 35 miles. As a result, 160,613 liters of ethanol can be produced with a cost of 0.81$/lt and 266 tons of sugars can be recovered with at a cost per pound of 0.20/lb.

The optimum solution simulated on the *least feasible scenario* from the set of treatments characterized with sweet sorghum (6 inches billet, Treatment 7 to 12), was Treatment 12. With this treatment a maximum ethanol profit of $21,174.6 by harvesting 100 acres and traveling a distance of 35 miles; as a result, 345,191 liters of ethanol can be produced at a cost per liter of 0.88$/lt and 572 tons of sugars can be recovered at a cost per pound of 0.20$/lb.

In the other hand, for the case of the energycane, the optimum solution from the *least feasible scenario* from the set of treatments characterized with energycane (8 inches billet, Treatment 13 to 18), was Treatment 17.

A maximum ethanol profit of $20,263 by harvesting 100 acres and traveling a distance of 35 miles; as a result, 336,421 liters of ethanol can be produced at a cost per liter of 0.83$/lt and 557 tons of sugars can be recovered with at a cost per pound of 0.20$/lb.

The optimum solution from the *least feasible scenario* from the set of treatments characterized with energycane (6 inches billet size, Treatment 19 to 24), was Treatment 22, which obtained a maximum ethanol profit of $2,467 by harvesting 100 acres and traveling a distance of 35mile. 210,533 liters of ethanol can be produced at a cost per liter of 0.83$/lt and 349 tons of sugars can

be recovered at a cost per pound of 0.20$/lb. The optimum solutions found in the simulation are described below:

1. Treatment 17 provided the optimum solution which maximized the ethanol profit and minimized the production per liter of ethanol and the production per pound of sugars. From all the treatments that included the crop of energycane and billet size configuration of 8 inches, Treatment 17 was the optimum.
2. Treatment 22 provided the optimum solution which maximized the ethanol profit and minimized the production per liter of ethanol and the production per pound of sugars. From all the treatments that included the crop of energycane and billet size configuration of 6 inches, Treatment 17 was the optimum.

CHAPTER 9: CONCLUSIONS AND FUTURE WORK

In this study a set of harvesting and storage trials with energycane and sweet sorghum were conducted in order to evaluate the effect of the variation of harvesting practices on the sugars yield, ethanol yield and the economics of the system. With the development of the harvesting trials, a characterization of the supply system was developed for the case of sweet sorghum and energycane; in the same way, different agronomic and efficiency indicators were calculated.

Finally, the development of a mathematical model integrated by the main component costs of the supply system was defined and tested; 24 treatments were simulated on the model based on the objective function defined for the study.

The optimum configuration of parameters for the system were defined, allowing to obtain the maximum ethanol profit and the minimum production cost of ethanol and sugars.

9.1 Harvesting trials and agronomic/efficiency indicators

Planning and execution of harvesting trials with energycane and sweet sorghum for the calculation of the following indicators:

1. Quality indicators (%Sugars, %Brix, Material yield, %juice yield, material composition before and after harvesting, %weight losses due to storage and internal temperature and RH% of the material stored).
2. Efficiency indicators of the supply processes (harvesting efficiency, cutting system accuracy of the harvester, transportation bulk density, potential ethanol profit).

The harvesting trials were developed based on the variation of several parameters from the supply processes, such as billet size (6 and 8 inches), level of leaf matter (fan speed, 0 rpm, 900 rpm, and 1100 rpm), and storage time before processing the feedstock (24 hour). According to the variation

of parameters, a set of scenarios were defined and evaluated for both of the crops; the results of the indicators measured were different between treatments and crops.

9.2 Simple sugars indicator

One of the main indicators measured and calculated from the harvesting trials was the *simple sugars yield indicator*. The results of the simple sugars yield obtained when sweet sorghum was used as input, suggested that an increment of approximately 27% of simple sugars can be recovered when a billet size of 8 inches is used, when the fan speed of the extractor system decrease to 0 rpm and when the material is processed shortly after harvesting (t = 0h). The increment evidenced occurred by comparing the treatments that presented the same conditions but had different processing time (storage time = 24 hours). By processing the material shortly after harvesting, it can be obtained a simple sugars yield of approximately 0.87 ton/acre (sweet sorghum, 8 inches billet, processing time t = 0h), but when the material is stored during 24 hours, the yield tend to decrease to 0.62 tons/acre.

For the case when the sweet sorghum was harvested with a billet length of 6 inches, the yield of the simple sugars tend to increase by reducing the fan speed of the extractor system; under these conditions it was obtained a simple sugars yield of approximately 1.35 ton/acre (sweet sorghum, 6 inches billet, processing time t = 0h). When the material was stored during 24 hours, the yield tend to decrease up to 0.8 tons/acre, indicating a reduction of approximately 40%.

For the case of the energycane, the results of the simple sugars yield suggested that by storing the material during 24 hours before processing, the sugar losses tend to decrease when the billets were harvested cleaner. Finally, it can be concluded that the yield of the simple sugars is highly affected by two factors, the amount of leaf matter obtained while harvesting and the storage time of the

feedstock. By increasing the amount of leaf matter, it was evidenced that the yield of the simple sugars tend to increase, however, this extra amount of leaf matter can produce some problems in the processing facilities. Finally, it was evidenced that the storage time significantly impact the yield of the simple sugars, suggesting that the greater the storage time is, the lower the yield of simple sugars will be.

9.3 Complex sugars indicator

Another important indicator measured and calculate in the study was the *Yield of the complex sugars*. The complex sugars were assumed to be recovered from the fiber of the feedstock. In this case, it was assumed that the Total fermentable sugars that were able to be recovered from the dry fiber was approximately 60%.

In the case of the complex sugars, it was evidenced that the time the material was stored before processing did not significantly affect the yield. It was concluded that the deterioration of the complex sugars over time was slower compared to the deterioration occurred to the simple sugars. Also, it was evidenced that by reducing the fan speed of the extractor system, the yield of the complex sugars tend to increase.

When sweet sorghum was harvested with a billet length of 8 inches and when the fan extractor was of 0 rpm, a yield of approximately 4.97 ton/acre was achieved. When the material was harvested with a fan speed of 1100 rpm, the yield tend to decrease to 2 tons/acre, a reduction of approximately 59% of the potential material that can be delivered in the factory.

This same behavior occurred when the material was harvested with a billet length of 6 inches. In the other hand, for the case of the energycane, when the harvester used a billet length of 8 inches and when the fan speed of the extractor was 0 rpm, a yield of approximately 4.4 ton/acre was

obtained. When the material was harvested with a fan speed of 1100 rpm, the yield tend to decrease to 3.42 tons/acre, representing a reduction of approximately 22%.

9.4 Total fermentable sugars yield

As a result of the behavior of the simple and complex sugars indicators, the total fermentable sugars yield presented the same pattern; as then fan speed of the extractor system tend to decrease (0 rpm), the yield of the sugars tend to increase. The results suggested that by recovering leaf matter and fiber while harvesting, the % of sugars (simple and complex) that can be recovered from the field can be higher. This pattern especially occurs when the material was processed shortly after harvesting (t = 0 hours).

For the case of the sweet sorghum when the fan extractor was not used (8 inches billet, 0 rpm fan speed and t = 0 h) a yield of 4.9ton/acre was recovered; in the other hand when the highest fan speed was used (1100 rpm) the yield decreased to 2.7 tons/acre, a reduction of approximately 44%. Finally, when the energycane was as input and by not using the fan extractor while harvesting (8 inches billet, t = 0h) a yield of 5.6ton/acre was achieved. When the highest fan speed was used (1100 rpm), the yield decreased to 4.8 tons/acre, representing a reduction of approximately15%.

9.5 Ethanol yield produced from simple and complex sugars

By using the conversion rate of sugars into ethanol, the results indicated that the ethanol yield (lt/acre) tend to increase when the feedstock was processed shortly after harvesting (t = 0h) and when the fan speed used while harvesting was reduced to 0 rpm.

The results suggest that the fiber and the leaf matter that can be recovered from the crop while harvesting, provide sugars that can be recovered from both, the simple sugars (juice) and the complex sugars (fiber) for ethanol production.

In the case of the sweet sorghum (8 inches billet, 0 rpm fan speed and t = 0h) an ethanol yield of 2942lt/acre was able to be produced from the sugars recovered; however, by using a higher fan speed 1100 rpm while harvesting, the yield decreased to 1606 liters/acre, representing a reduction of approximately 45%.In the other hand, when the sweet sorghum was harvested with a billet size of 6 inches and a fan speed of 0 rpm, the ethanol yield obtained was 3810lt/acre. By using a higher fan speed (1100 rpm), the yield decreased to 1640liters/acre, suggesting a reduction of approximately 56%.

For the case of the energycane (8 inches billet, 0 rpm fan speed and t = 0h) a yield of 3364liters/acre can be produced when the fan extractor is not used; in the other hand, when the highest fan speed was used (1100 rpm), the yield tend to decrease to 2889 tons/acre. Finally, when the energycane was harvested with a billet size of 6 inches and a fan speed of 0 rpm, a yield of 3453lt/acre was achieved; however, by using a higher fan speed (1100 rpm), the yield decreased to 1760 liters/acre, representing a reduction of approximately 49%.

9.6 Economic model formulation

In the mathematical formulation of the model, the objective function was defined as the maximization of the ethanol profit; the objective function was calculated after subtracting all the component costs defined for the supply system.

The costs defined for the system were:

1. Agronomic production cost of the crop

2. Harvesting cost (based on fuel consumption)
3. Wagon cost
4. Transportation cost
5. Processing cost

All the component costs consider the main activities and costs required for the supply of energy crops for the production of ethanol; all the consideration and assumption used in the model, were described and explained on Section8. According to the calculations of the costs of each of the supply stages defined in the model, the following insights were defined:

1. Agronomic production cost per acre: for sweet sorghum: 208/acre; this value was calculated as an average cost per acre from the literature defined by Hallam and Ribera (Hallam *et al.* 2001), (Ribera *et al.* 2013).
2. Agronomic production cost per acre for energycane: 411/acre. This value was calculated as an average cost per acre from the literature defined by Tyler, Salassi and Tyler (tyler *et al.* 2009), (Ribera *et al.* 2013) and (Salassi *et al.* 2014).
3. Harvesting cost per acre: The harvester cost was defined based on the fuel consumption. By using different rpm's in the extractor system of the harvester, the consumption of fuel changed. By using a fan speed of 1100 rpm, 900 rpm and 0 rpm, the cost per acre is $120.5, $119.3 and $113 respectively. These costs were calculated considering the cost of the fuel consumption, the cost of labor, maintenance cost, and fixed expenses.
4. Wagon cost: For the harvesting operations was assumed the utilization of 3 wagon trucks for collecting the material obtained per acre. The component cost included were: labor cost, fixed expenses costs and fuel consumption. As a result, a fixed cost per acre was calculated 154.8 per truck used in an acre.

5. Transportation cost: This cost varied in function of the total distance needed to cover for transporting the material, hence, in the simulation model a distance from 1 to 100 miles were simulated. The cost per mile for transporting was assumed with similar costs that the current sugar industry in Louisiana charged (Legendre, 2014).

   This cost also varied in function of the total trucks needed to transport the material; for calculating this indicator, the data from the harvesting trials was used according to each of the treatments defined for the study (material yield, bulk density, truck volume).

6. Processing cost: The processing cost considered the costs of recovering and converting simple and complex sugars from the energy crops into ethanol. The milling cost was also considered (6.02/ton) and the conversion cost of complex sugars by using the lime treatment reported by Day (Day, 2012).

   However, because the cost of recovering complex sugars was significantly high, the cost assumed for the model were reduced to a cost of 48/ton for the case of the sweet sorghum and a cost of 50.6/ton for the case of the energycane.

9.7 Model simulation

The main components required in the simulation were: material yield (ton/acre); simple and complex sugars yield (ton/acre), ethanol yield (lt/acre); expected ethanol sale value (/acre), supply and conversion costs (/acre) and ethanol profit (/acre). From the treatments defined for the study, 24 matrixes of dimension 100 x 100 were calculated using as variable parameters the *distance* for transporting the feedstock and the *area* for harvesting (100miles and 100acre). 10.000 iterations of the *ethanol profit function* were obtained per treatment, obtaining a total of 24.000 iterations.

From the results obtained from the simulation, two different indicators were defined for selecting the optimum solutions for the system.

The first indicator was called *Maximum profit from the best case scenario*, which consisted on selecting the solutions which allowed to obtain the maximum ethanol expected profit after implementing different harvesting and storage practices.

The second indicator was called *least feasible solution,* which consisted on selecting the solution that allowed the highest ethanol profit from the worst case scenarios obtained after covering the maximum feasible distance and area for collecting and transporting the feedstock. This indicator found the solution that allowed covering the “maximum feasible distance and area” for operating the system, guaranteeing a feasible solution (least feasible solution), therefore, after the area and distance defined, the operation of the system was not feasible.

9.8 Best case scenario simulation

Based on the classification of the treatments defined in the study, 4 different solutions for the *best case scenario* and another 4 different solutions for the *least feasible scenario* were obtained from the simulation; these solution are the optimum solutions from each set of treatments defined.

The optimum configuration of the system according to the optimum solutions selected from the *best case scenario* consist on:

- Harvesting sweet sorghum (6 inches billet, processing time t = 0 hours) covering an area of 100 acres and radial distance of 1 mile allowed to obtain a maximum profit of 103,039 dollars (1030/acre). A yield of 381,060 liters of ethanol (production cost per liter of 0.51 cents), 631 ton of sugars (production cost per pound of 0.14 cents).

- Harvesting energycane (6 inches billet, processing time t = 0 hours) covering an area of 100 acres and radial distance of 1 mile allowed to obtain a maximum profit of 60,228 dollars (602/acre). A yield of 345,321 liters of ethanol was obtained (production cost per liter of 0.61 cents), 572 ton of sugars (production cost per pound of 0.16 cents).

9.9 Least feasible solution simulation

In the other hand, the optimum configuration of the system according to the optimum solutions selected from the "least feasible solution – worst case scenario" consist on:

1. Harvesting sweet sorghum (6 inches billet, processing time t = 0 hours) covering an area of 100 acres and radial distance of 35 miles allowed to obtain a maximum profit of $21,174 dollars (2110/acre). A yield of 345, 19 liters of ethanol (production cost per liter of $0.88 cents), 572 ton of sugars (production cost per pound of $0.20 cents).
2. Harvesting energycane (8 inches billet, processing time t = 0 hours) covering an area of 100 acres and radial distance of 35 mile allowed to obtain a maximum profit of $20,263 dollars (202/acre). A yield of 336,42 liters of ethanol was obtained (production cost per liter of $0.83 cents), 557 ton of sugars (production cost per pound of $0.20 cents).

9.10 Feasible solutions

According to the optimum solutions defined from both scenarios *best and worst scenario*, it was defined a distance and area range that can be implemented in the operation of the system guaranteeing a feasible solution; these are:

1. Profit maximization under best case scenario solutions:

All four solutions selected as optimum solutions for these scenarios consisted on harvesting an area of 100acres and covering a radial distance of 1 mile for transporting the material, hence, the range of area and distance for covering that will guarantee the maximum profit can be defined as:

- Transporting distance: 0.1miles ≤ distance < 1mile.
- Area for harvesting: 0.1≤ area ≤ 100 acres; as the area for harvesting increase in this range, the ethanol expected profit tend to increase.

Because all four solutions obtained from the *best case scenario* provided the same configuration of distances and areas to cover, the range defined previously can be applied for any of the optimum solution obtained for this scenario. Based on the range given, any combination of the area or distance for harvesting and transporting the material, will guarantee a feasible operation.

2. Profit maximization under least feasible options solutions: In contrast of what occurred with the solutions found in the *best case scenario*, the optimum solution under the conditions of the worst case scenario, suggested different distances and area to cover.

The configuration between the optimum solutions that were selected between treatments is the same, which indicates that, for all four solutions, the least feasible distance to cover for transporting the material from the field to the factory is 35 miles and an area for harvesting of 100acres.

By overpassing 25 miles and 100 acres the operation will not be feasible, hence, the limit for transporting the material is covering a radial distance of 35 miles and the limit for harvesting is 100 acres. As a result, the following ranges are suggested to be incorporated while running the operation of the system in order to guarantee a feasible operation:

- Transporting distance: 0.1miles ≤ distance ≤ 35 miles
- Area for harvesting: 0.1≤ area ≤ 100 acres.

  Any combination of distance for harvesting and transporting the material according to the treatments defined in the study, will guarantee a feasible operation, however, under the considerations of the worst case scenario, the solutions suggested previously are feasible but are not the optimum solutions for the system, mainly because the solution do not guarantee the maximization of the objective function, nevertheless, the solutions guarantees that a profit can be obtained from the operation.

9.11 Considerations for future research

It was evidenced that was possible to simulated the supply stages of a system that implements energy crops as inputs for it conversion into ethanol (harvesting, transporting, processing – juice extraction and storage). It was viable to implement the practices of the supply system used by the sugar industry in Louisiana with alternative energy crops such as energycane and sweet sorghum; the same equipment used with sugar cane during the supply activities, was used for handling and processing (samples) the feedstock (harvester, wagons, hydraulic press for juice extraction).

It is important to continue developing more harvesting trials in order to understand better the conditions of the system and the parameters that should be used for maximizing the yields of the material and the quality of the final products; by the implementation of the indicators illustrated in the current study, an approach for this goal can be performed. It important to continue evaluating mechanisms to increase the yield of these energy crops, so the yields of the sugars can increase as well as the profit of the operation.

The cost of recovering and converting simple and complex sugars into ethanol is significantly high, hence, these costs affects the feasibility of the system and constraint the conditions of operations. Also, it is important to reduce the agronomic production cost of the crops, the harvesting and the transportation costs; these components represents a cost in the supply system of 12%, 16% and 2% respectively from the total cost of the system.

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