Development and Test of a Sweet Sorghum Feedstock Separation Technology and the Effect of Trash on Fermentable Sugar Yield in Juice and Syrup

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DEVELOPMENT AND TEST OF A SWEET SORGHUM FEEDSTOCK SEPARATION TECHNOLOGY AND THE EFFECT OF TRASH ON FERMENTABLE SUGAR YIELD IN JUICE AND SYRUP

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science

in

The Department of Biological & Agricultural Engineering

by

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B.S., Kun Shan University of Technology, 2012
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Dedicated to God, Cris & my son Edgar Jr.
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ABSTRACT

In recent years, processing sweet sorghum feedstock to obtain syrup for biofuels production is an option that has gained attention, especially where sugar cane milling infrastructure is already available; however, the leafy matter and panicles (trash) in the feedstock could negatively impact the process. Therefore, it seems sensible to reduce the trash level in the feedstock prior to milling and expand the current knowledge on the effect of trash in the juice and syrup. In this project, a pneumatic system to separate the leaves from sweet sorghum harvested with a sugar cane billet harvester was tested and a panicles separator was developed, since the panicles separation with air has been proven to be ineffective. In addition, the effect of the trash on the fermentable sugars, starch, ash and organic acids content in juice was investigated by milling four different treatments of feedstock and four different levels of trash % feedstock. Also, a computer simulation of a sugar cane mill and a basic economic analysis was conducted to assess the effect of the trash in the sweet sorghum syrup. The results on the pneumatic separator showed that the highest leaves separation efficiency of $56 \pm 3\%$ (no billets lost) is obtained at an air stream angle of $45^\circ$ in between $0.6$ m below the conveyor and with the splitter located at a horizontal distance of $2.06 \pm 0.06$ m from the conveyor. The panicles separator prototype achieved a selectivity of $9.5 \pm 1$ at $30^\circ$ when operated at $43$ rpm. Finally, it was demonstrated that by reducing the trash level in the feedstock, there was a decrease in the bagasse and a decrease in the starch and ash in the juice but an increase in the amount of fermentable sugars per tonne of feedstock in the syrup. Also, the brix extraction in the milling tandem was improved and the energy consumption to produce syrup was reduced. Furthermore, in terms of revenue, even though the cogeneration decreased as the trash was removed, the overall estimated revenue increased because the gains from the fermentable sugars proved to be greater.
CHAPTER 1. INTRODUCTION

The growing demand for renewable energy has led to a rising interest in processing sweet sorghum into fermentable sugars syrup for biofuels, especially where sugar cane milling infrastructure is already available. This interest is partly because the sweet sorghum offers many advantages. For instance, it has a high content of fermentable sugars that can be used for biofuels production (Aragon, Suhr, & Kochergin, 2013) (Cifuentes, Bressani, & Rolz, 2014). It is a low input crop that can be planted in marginal land (Viator et al., 2009), and it contains some non-sugar components that can be converted into value-added products including the bagasse for electric power generation (Manea et al., 2010) (Grooms, 2008). Previous studies have demonstrated that sweet sorghum can be processed in sugar cane mills (Smith & Lime, 1975) (Audubon, 1983) (Webster, Hoare, Sutherland, & Keating, 2004). However, a very important issue related to milling sweet sorghum in a factory is the effect that the leaves and panicles or trash in the feedstock could have in the process. This effect has been studied extensively in the sugar cane industry but for sweet sorghum, there are still some gaps in the current knowledge that need to be filled. Furthermore, previous studies with sugar cane (Legendre & Irvine, 1974) and sweet sorghum (Viator, Lu, & Aragon, 2015) suggest that the trash causes a negative impact on the process of syrup production. Therefore, separating the trash seems to be a practice that has to be conducted in order to process sweet sorghum feedstock with the efficiencies expected in a commercial facility. The aim of this project is to test a pneumatic separation system to separate the leaves and to design and develop a panicles separator. In addition, this work also aims to expand the state-of-the-art information available about the effects of milling sweet sorghum feedstock with trash on the juice production as well as to assess some technical and economic effects on the syrup production.
1.1 Justification

Sweet sorghum is one of the most sustainable ecological units for renewable fuel production because it has proven to be a very efficient crop in terms of use of land, water and other resources (De Vries et al., 2010) and it can also be processed in sugar cane mills where the juice is extracted and evaporated into syrup; however, the leafy matter and panicles in the feedstock could negatively impact the process. For instance, it is known that the fermentable sugars extraction from trashy sweet sorghum feedstock could be 62% of the fermentable sugars extraction from clean samples (Viator et al., 2015). It is also known that the trash decreases the efficiency of the sugar cane mills and increases the wear of the processing equipment, causing a negative economic impact in the companies (Rein, 2007).

For the commercial adoption of sweet sorghum, yields of the fermentable sugars have to be maximized. Removing the trash from the feedstock could be a key contributor to reach those higher standards. Further, it seems important to investigate and find better and more efficient ways of separating the trash from the feedstock. Preliminary studies have pointed out that removing the trash in the factory prior to milling is preferable to removing the trash on the field due to economic challenges and disadvantages caused to the agronomic operations (Smithers, 2014). In this thesis, the trash separation system tested is in the factory. To separate the leaves, the technology tested was the pneumatic separation. To separate the panicles, a mechanical device was developed and tested. Due to the small amount of recent literature that can be found about sweet sorghum crop characterization and the effect of trash on the syrup production process, this research aims to add recent information to the current knowledge by showing experimental results as well as results from a software-simulated sweet sorghum processing facility.
1.2 Problem Statement

Processing sweet sorghum in a sugar mill is challenged by the high content of leafy matter and the grain-holding panicles. For this reason, it seems sensible to reduce the trash level in the feedstock prior to milling. The separation of leaves and panicles could therefore increase the fermentable sugar yield and facilitate their production process.

1.3 General Objective

1. Design and test a trash separation equipment to improve fermentable sugar yield and processing efficiency of sweet sorghum.

1.4 Specific Objectives

1. Test a leaves separation system to determine its efficiency.

2. Design, develop and test a mechanical device to separate the sweet sorghum panicles from the feedstock.

3. Determine the amount of fermentable sugars, starch, organic acids and ash in the extracted juice when milling sweet sorghum feedstock with different amounts of trash.

4. Develop a simulated sweet sorghum processing facility using the software Sugars to assess the effect on syrup when milling feedstock with trash.
CHAPTER 2. LITERATURE REVIEW

2.1 Crop Characterization

The amount of leafy matter in sweet sorghum delivered to the mill and consequently the crop characterization depends on the efficiency of the trash removal and stalks collection during harvesting. Some of the harvesting methods include hand-harvesting, harvesting with a mechanical equipment without chopping the stalks and harvesting with a billet combine that can use a topper to leave the panicles or tops in the field and that use a fan also to remove the leaves. Smith et al., conducted sweet sorghum crop characterizations in many regions of the United States, finding that the net stalk percentage by weight (% always means in this thesis mass/mass unless otherwise noted) of the standing sweet sorghum ranged from 69.9% to 84.4%. Specifically, he showed an average of 79% stalks in Mississippi, which was the closest region to Louisiana where he conducted experiments. The other 21% were leaves and panicles, which are commonly known as trash (Smith et al., 1987). In Louisiana, Amaya reported a crop characterization of 73.2% billets, 23.6% leaves and 3.2% panicles (Amaya, 2014). Aragon et al. reported that for the experimental medium maturity hybrid variety of Ceres, the crop characterization on a dry basis was 74.9% stalks, 20.7% leaves and 4.2% panicles when the crop was hand harvested and when it was mechanically harvested with a billet combine with fans off, she reported 71.3% billets, 24.6% leaves and 4.1% panicles (Aragon, Viator, & Ehrenhauser, 2017). This thesis presents also different crop characterizations in order to expand the current information found and because it was necessary also to have a fully characterized crop for the other experiments conducted.

2.2 Feedstock Separation in the Field

The feedstock separation or feedstock cleaning can be conducted in the field by harvesting and then separating by hand or harvesting and separating with a combine. Equipment has been
designed specifically to harvest sweet sorghum (Ghahrae, Khoshtaghaza, & Bid Ahmad, 2008) (Rains & Cundiff, 1993) (Lamb, Von Bargen, & Bashford, 1982) and to separate the panicles in the field, there are some technologies developed by Benner et al. (Benner, Oakley, & Tomaszewski, 2012) and John Deere Company (Hinds & Hickman, 2010a) (Hinds & Hickman, 2010b). Sweet sorghum has also been harvested with sugar cane combines since morphologically both crops are similar and farmers have sugar cane combines already available. These combines usually have toppers to remove the tops or panicles, and air fans to remove the leaves or trash in general. In Louisiana, a study of the harvested sugar cane feedstock with the combines John Deere 3500 and 3510, at fan speeds of 1050 rpm, 850 rpm and 650 rpm, showed that the trash levels were 12.1%, 18.9% and 22.7% respectively, indicating a decrease in the trash percentage as the fan speed increased (Eggleston et al., 2012). A study conducted by Hurney et al. showed a topper efficiency of 65% and a leaves separation of up to 75% but with cane losses in the order of 3% to 11% (Hurney, Ridge, & Dick, 1984). A high loss of cane would be detrimental to the sugar yield per planted area. In this sense, other authors have studied the cane losses and sugar losses associated with the combine harvesting. Sichter et al. showed that the sugar losses in the harvesting operation were commonly in the range of 5% to 15% (Sichter, Whiteing, & Bonaventur, 2006) and Hockings et al. reported a cane loss in the range of 2% to 8% (Hockings, Norris, & Davis, 2000). Whiteing et al. concluded in their study with combines that the harvester designs are limited in their ability to effectively clean cane while minimizing cane loss at high harvesting rates. They pointed out that it cost 4.2 metric tons/hectare of cane loss to reduce the extraneous matter by 1%. They also concluded that under certain field conditions, the extraneous matter is predominantly controlled by harvester pour rate, showing that as the pour rate increased, fan speed became ineffective reducing extraneous matter and showed that a raise in fan speed leads to a large increase
in cane loss with minimal reduction in trash levels (Whiteing, Norris, Paton, & Hogarth, 2001). From the previous information it can be concluded that although the sweet sorghum feedstock and the sugar cane feedstock could be separated in the field, there are still some challenges associated with the billet losses in the field that cannot be recuperated and the additional costs required for the collection and transportation of the leaves and panicles to the process facility.

2.3 Feedstock Separation in the Processing Facility

Some advantages of separating the feedstock or cleaning the feedstock in the mill that have been reported in the sugar cane industry are that the factory throughput is increased due to less low-sugars material processed, there are lower sugar losses in filter cake, bagasse and molasses in addition to a lower viscosity in syrups and molasses, and the trash also increases the supply of large quantities of biomass that can be used for other industrial operations (Bernhardt, 1994). The development of technologies for sweet sorghum feedstock separation in the milling plant is scarce. Consequently, to develop a new technology it is imperative to do a review on previous studies on sweet sorghum feedstock separation technologies, but it is also important to review the advances in the separation technologies for the long-researched sugar cane industry since morphologically, the sugar cane and sweet sorghum are similar.

Figure 1 shows a separator proposed by Herkes (Herkes, 1974). The device includes a first rotary screen to loosen the mat, then an inclined conveyor, an air blower (7) and a second rotary screen that removes the rocks, soil and other wastes that come with the mechanically harvested material. Figure 2 shows the type of rotary rolls that the above mentioned device uses. The roller on the left is to loosen the feedstock making the leaves and panicles easier to separate and the roller in the right is to separate the extraneous matter which fall through the gaps that are between the discs (Herkes, 1974).
In addition, Herkes proposed a “Mechanical screening device for machine-harvested sugar cane” that works like a rotary screen for loosening extraneous material from the mat or feedstock of dirty machine-harvested sugar cane. The main objective is to break up the mat of machine-harvested sugar cane, thinning the mat and loosening extraneous material adhered to the cane stalk so that other devices and apparatus can separate the extraneous material (Herkes, 1975). The second objective is to remove large rocks from the mat of cane without the use of water.

Duncan patented a technology for dry separation that is a transportable apparatus that could be used in sugar cane fields or at a specific location in the mill. It is composed of a blower and a set of conveyors mounted in a transportable frame. The idea is to dump the feedstock in the conveyor,
pass it through the blower, and the billets fall directly into the truck or conveyor that goes to the mill (Duncan, 1967). Wykeham also proposed a “Dry cane cleaning and spreading process” that in the first step of the process, a low velocity air jet intercepts a falling curtain of cane, which separates the unwanted matters such as leaves or small rocks. In a second step, being this a high velocity air jet, it separates other higher density unwanted matter (Wykeham, 1972).

The leaves separation with air is a principle that has been broadly used to separate the feedstock. In the case of sugar cane and sweet sorghum, this principle takes advantage of the difference in the drag coefficient and weight between the billets and leaves (Gan-Mor, Wiseblum, & Regev, 1986). Figure 3 shows basic schematics of these technologies. Figure 3A and 3B have the disadvantage that if the feedstock is not well spread over the drum, they do not work well and very large surface area would be needed because the rotating speed that can be reached is limited (Gan-Mor et al., 1986). Figure 3C has the disadvantage that particle collision reduced its efficiency and caused jams. Figure 3D seems to be the most feasible and efficient from results in preliminary studies (Hobson, Joyce, & Edwards) (Hobson, 1995) (Schembri & Hobson, 2000).

![Figure 3: Schematics of four different pneumatic leaves separation technologies already developed.](image-url)
Using a design similar in principle to Figure 3D, Wright et al. designed a sweet sorghum leaves separation system by using essentially an air stream and an open flat wire belting mesh to separate the loose seeds. He reported that he was able to separate all the leaves yet loosing up to 23% of the billets. Also, his results showed that the billets lost % was proportional to the panicles separation efficiency %, meaning that it was difficult to separate the billets and the panicles with the air stream (Wright, Rea, Massey, & Clark, 1977).

Another approach that has been taken to increase the overall separation efficiency, is to develop systems that allow for feedstock separation in multiple phases. For instance, Bernhardt et al. proposed a dry cleaning system shown in Figure 4 (Bernhardt, 1994), with a tyned drum similar to the already developed and tested by other authors (Anon, 1993) (Du Plooy, 1994) (Olwage, 2000), a pipe slat conveyor or in other words a rotary screen, two adjacent drums or billetters, and an air fan. Simisa, a Brasilian company, offers a system that can reach a trash separation of 57% to 78%, (Teixeira, 2013). In the sugar research institute in Australia, Schembri et al. reported that they reached a level of 3%-13% trash in feedstock with less than 1% cane loss with their commercial trash separation prototype. They also reported that in Brazil, the copersucar technology centre constructed a trash separation plant in 1994 at Quata mill that reached a 70% efficiency of trash and dirt removal (Schembri, Hobson, & Paddock, 2002). In Louisiana, some sugar mills have tested and are currently testing dry cleaning systems. For instance, Enterprise sugar mill has used a cane cleaning system consisting of a blower with its output connected to a nozzle and in 2001, it reached an efficiency of 83% extraneous matter removal but there was no data about billets lost (Rein, 2005). Cora Texas factory is currently testing a system composed of radial air fans, cyclones and rotary drums. In the 2017 ASSCT conference, Eggleston et al.
presented that the system had reached a trash separation of up to 53% (Eggleston et al., 2017). This research is still ongoing and more improvements are being made to the equipment.

Figure 4: Sugar cane dry cleaning system proposed by Bernhardt (Bernhardt, 1994).

The insufficient information found about processes to separate the sweet sorghum feedstock prior to be milled at a sugar cane mill factory and the need to reduce the trash level in the feedstock led this investigation to test a pneumatic separator and to design a panicles separator. The process proposed in this work and shown in Figure 5 includes an equipment to separate the leaves that blows an air stream across the feedstock as it falls from one conveyor to another and a panicles separator or rotary screen featuring rotary grabbers that can selectively hook only the panicles of the sweet sorghum feedstock.

Figure 5: Proposed sweet sorghum feedstock separation process in this thesis.
2.4 Feedstock Separation in the Field vs. Separation in the Processing Facility

Smithers conducted a study analyzing different sugar cane trash recovery routes (Smithers, 2014). The same routes and analysis would be expected for sweet sorghum since in both crops, the majority of the trash are the leaves and the same combine harvesters would be used. The recovering route of separating the trash in the field was associated with baling problems that included the time loss due to trash drying to less than 20% moisture content, high ash content in the trash due to picking up soil and excessive wear on the machine causing mechanical problems. In addition, he pointed out other disadvantages on the agronomic operations that included losses in crop yield per planted area due to soil compaction caused by the recovery machines, loss of recycled nutrients and increase in herbicides costs due to elimination of the trash blanket that works as a weed suppressant. Smithers concluded that from the different trash recovery routes, the one involving mechanically harvesting using a combine with trash separation fans operating at reduced speeds to leave some trash in the field and further trash separation at the mill station, is the most economically viable method of collection of the trash, transportation and separation for additional use at the processing facility (Smithers, 2014).

2.5 Effect of the Trash Content in the Feedstock

It is important to take into account in this section the effect of the trash content in the sugar cane feedstock, because of some similarities that are present between sweet sorghum and sugar cane and since the interest in processing sweet sorghum is in the already available sugar cane milling infrastructure. Previous studies in the sugar cane industry have shown that the trash decreases the efficiency of the sugar mills and affects the processing equipment (Rein, 2007). In 1948 an investigation committee in South Africa reported that when milling trashy sugar cane there was a decrease in sucrose content of total cane, an increase in fiber content, more chokes in the juice extraction section, a reduction in the factory throughput and a decrease in the purity of
the mixed juice (Carter, 1948). Studies in Colombia mentioned that the recoverable sugar in the juice and the sugar yield per tonne of milled cane depended in characteristics like low percentage of trash in the feedstock, low content of non-sucrose brix and low fiber percentages (Cenicaña, 1995). Results presented by Larrahondo et al. specified that for each unit percentage increase of trash, the recoverable sugar was generally reduced by 0.18 to 0.23 pol % cane (Larrahondo, Briceño, Rojas, & Palma, 2006) and that a decrease of pol % cane of 2.5% is not uncommon when milling cane with about 10%-14% of trash (Larrahondo et al., 2009). Likewise, Legendre et al. in Louisiana showed that an increase of 10% trash in the feedstock caused a 1.8% increase of fiber % cane and a 30 lbs decrease in 96-pol sugar per tonne of cane (Legendre & Irvine, 1974). In addition, Eggleston et al reported that most quality and processing parameters like Brix, sucrose, fiber, ash, starch and color became progressively worse when milling sugar cane with higher levels of trash and for every 1% increase in trash, there is an approximate 0.13%-0.21% decrease in mixed juice purity (Eggleston et al., 2012).

In the case of sweet sorghum, some studies have shown that the juice extraction is significantly higher when the leaves and panicles are removed from the feedstock. For instance Guigou et al. found out that there was 12% more extraction in clean feedstock compared with feedstock with trash (Guigou et al., 2011). O’Hara et al. reported also a higher juice extraction and higher amount of sugars obtained when milling stalks than when milling the whole plant (O'Hara et al., 2013). Sipos et al. showed that the samples processed without the leaves produced approximately 20% higher sugar content than the samples with leaves and panicles (Sipos et al., 2009) and Lamb et al. concluded that stripping the leaves and tops increased the juice yield and reduced the stalk slip in the rollers. He also observed that milling the trashy crop affected the juice drainage in the rollers (Lamb et al., 1982). In contrast, Rao et al. did not find any significant
difference in juice extraction and sugar quality except for the brix and they recommended that even with bulk harvested stalks, there is no need for removing the leaf and sheath at the biofuel processing facility (Rao et al., 2013). In Louisiana, Viator et al. found that the sweet sorghum trashy samples produced sugars at an average of 62% of the total sugars in the juice of the clean samples and that the trash presence in the feedstock increased the fiber content in the feedstock (Viator et al., 2015).

The chemical composition of the whole sweet sorghum plant and specifically of the leaves and panicles has been already investigated by some authors and in this work is important in order to understand what would be the possible effect on the juice after crushing the feedstock and the impact of these components on the process. For instance, Aragon et al. found in sweet sorghum feedstock, 61.31% water, 7.51% sucrose, 1.22% glucose, 0.68% fructose, 2.7% ash and 26.58% fiber (Aragon, Lu, & Kochergin, 2015). Wall et al. pointed out that the sucrose in the stalk juice ranges from 6% to 15%, the glucose from 0.5% to 5% and the fructose from 0% to 1.5% (Wall & Blessin, 1970). Hence, when comparing the amounts of sugar obtained from the entire plant and the amounts obtained from only the stalks, it can be speculated that most of the sugar content is in the stalks. In the case of the seed heads or panicles, the composition is comparable to that of other grains grown for animal feed and human food. The ash content ranges from 1.6% to 2.2%, the protein from 11% to 15% and the sugar is at most 2% whereas the starch constitute a 68% to 76% depending on the variety (Wall & Blessin, 1970). For the leaves, it is known that they have less sugars than the stalks and add more ash, organic acids and polysaccharides like starch to the sweet sorghum juice (Lingle, 2010). In sugar cane for instance, Scott found that the leaves have 7.8 °Brix and 1.5% pol or apparent sucrose (Scott, 1977). Gil found 4.2 °Brix and 0.1% in pol (Gil, 2007) and Larrahondo et al. found in leaves less than 0.5% of sucrose and 8% of non-sucrose (Larrahondo
et al., 2009). Lingle pointed out that the starch, cellulose, gums, cell wall poly-saccharides and dextran that are present in the leaves increase the viscosity of the material processed in the plant. She also mentioned that the organic acids present in the sweet sorghum affect the process by decreasing the pH of the juice (Lingle, 2010). Moreover, the major organic acid found in the juice of the sweet sorghum is the aconitic acid at a concentration of about 12,000 ppm, followed by other acids at lower concentrations like the tartaric (succinic) at 11,000 ppm, malic at 5,000 ppm, citric at 2,000 ppm, and at even lower concentrations the oxalic, fumaric and acetic (Wall & Blessin, 1970). Regarding the ash, Singh et al. found that the stem tissue had an ash amount of 14.9 g/kg, the leaf tissue has 49.7 g/kg and the grain head has 29.5 g/kg, concluding that the leaves and grain heads represent approximately 33% of the biomass, but over half of the ash content (Singh et al., 2012). The ash affects all the equipment, affects the clarification process and increase also the level of incrustation in the evaporators. In some places like South Africa, the ash content in juice plays such an important role that there is a categorization of the quality of the cane according to the ash content. In this categorization, cane with an ash content of around 0.6% is a good quality cane, and cane with ash content of more than 4% is unacceptable by the mills (Rein, 2007). It can be concluded that the chemical composition of the panicles and leaves is different than the composition of the stalks and it can be speculated that to process this leafy matter and seed-heads or panicles along with the stalks would consequently add more non-sucrose materials to the juice, which would not be beneficial to the process, and would reduce the percentage by weight of the fermentable sugars in the juice by a dilution effect.

2.6 Processing Sweet Sorghum Feedstock

Some pilot plant trials as well as some factory trials, especially in sugar cane mills, have shown the feasibility of processing sweet sorghum. The trials showed that processing sweet sorghum in a sugar cane mill is possible with very-little-to-no changes in the infrastructure and
process; nonetheless, two main issues were noted: The first one was that the high fiber / sugar ratio of sweet sorghum affected negatively the brix extraction (Webster et al., 2004) and the second one was that producing crystalized sugar from sweet sorghum was challenged by the lower sucrose and higher reducing sugars content. The higher amount of starch in sweet sorghum juice also reduced the crystallization efficiency and the aconitic acid in the juice formed aconitate crystals that made the centrifugation of the sucrose crystals more difficult (Lingle, 2010). In Texas, Smith et al. conducted studies to process sweet sorghum in a sugar cane mill factory without any modifications. The starch content was reduced successfully by 87.5% in the clarification process and the aconitic acid content was reduced to 0.16% on syrup. The mixed juice presented a low purity of 62% but overall the milling process and the production of syrup was satisfactory (Smith & Lime, 1975). In Louisiana, at the Audubon Sugar Institute, trials of processing sweet sorghum were carried out in 1982 and 1983 at the ASI sugar mill and at the Breaux Bridge Sugar Cooperative. The process was carried out like a sugar cane syrup production process. Moreover, during these trials it was found that the sweet sorghum caused chokes in the knives but other than that, the process was successful. In the bagasse, it was found that the heat of combustion of the bagasse from stalks only was about the same as sugar cane; however, the bagasse from the whole plant had only 70-85% of the heating value of sugar cane bagasse. It was concluded that the reason for this was the high ash content, from the silica in the leaves and trash and mainly from the soil, because it was difficult to wash the sweet sorghum feedstock with water like it was used to be washed the sugar cane at that time (Audubon, 1982) (Audubon, 1983). Separating the trash from the feedstock, which is high in fiber, starch and organic acids suggest that these previous issues could be improved. If the idea of crystallization is dropped, then the extracted juice from sweet sorghum would rather be produced for direct fermentation or for syrup production. Even though
the production of biofuels can be directly performed with the extracted juice by adding yeast (Bridgers, Chinn, Veal, & Stikeleather, 2011), producing sweet sorghum syrup is the best pathway in order to increase the fermentation capacity of the processing plant, increase the feasibility of an efficient transportation and to have a better long-term storage, for year-round supply of syrup (Eggleston, Cole, & Andrzejewski, 2013). To investigate the effect of the trash in the fermentable sugars yield in the syrup, processing sweet sorghum during the sugar cane grinding season or during the sugar cane factory maintenance season is not feasible because it would require to plant several hectares of sweet sorghum, a high economic investment and a system to make the different feedstock treatments and different feedstock trash levels at large scale. Therefore, a model approach of a sugar mill producing sweet sorghum syrup is proposed in this work.
CHAPTER 3. MATERIALS AND METHODS

3.1 Crop Characterization

As part of the main juice extraction experiments, crop characterizations were conducted in both harvest seasons of 2015 and 2016. In the first harvest season, the sweet sorghum experimental variety Durasweet 120-day-hybrid from Ceres, Inc. (Thousand Oak, CA, USA) was evaluated. A plot (three rows, 121 meters long) was planted on May 7th, 2015. Eight samples of 20 kg each were hand harvested at dough stage. The stalks, panicles and leaves in each sample were separated by hand and weighted in order to calculate the percentage by weight of each one of them in the crop. In the 2016 harvest season, two plots (three rows each, 121 meters long) were planted on April 5th. The first plot was of the experimental variety Durasweet 90-day-hybrid from Ceres, Inc. (Thousand Oak, CA, USA) and the second plot was of Durasweet 120-day-hybrid. Each plot was harvested at dough stage with a sugar cane billet combine with fans off and three samples of 34 kg each were taken for further separation by hand and weighing of the billets, leaves and panicles.

3.2 Test of a Pneumatic Separation System

A leaves separation unit (Figure 6) was built and assembled using a wood frame. A 30° inclined belt conveyor was installed to transport the feedstock toward the separation unit. The pneumatic system consisted of 316 stainless steel pipes, two pressure gages, one Jamesbury ball valve, one Boston Gear air regulator for 2070 kPa, one Hedland flow meter, five air hoses and air-hose connectors for 2070 kPa. An EXAIR super air knife model 110024 was used to produce the high velocity air stream because when comparing it to a flat air nozzle that is usually employed for these applications, the super air knife consumes less power, emits a lower sound level, has a uniform airflow across its entire length and allows for manipulation to improve performance. In order to be able to change the angle of the air stream, the system had a rotational mounting frame...
fabricated in steel. A compressor powered by a diesel engine was connected to the system and regulated at 620 kPa and 1.84 m$^3$/min. With these conditions and from the air knife’s manufacturer’s specifications (EXAIR corporation, Cincinnati, Ohio, USA) the air stream had a velocity of 64 m/s and a thickness of 80 mm at the point of contact with the falling feedstock. The system is scalable since larger air knives could be used or many of them could be installed next to each other.

Figure 6: Pneumatic separation system and the schematic of the variables tested.
The variables tested with the pneumatic separator were $x$, $y$ and $\beta$. The variable $x$ is the splitter position and would represent the width of the receiving conveyor that takes the material to process. “$y$” is the distance from the end of the feeding belt conveyor and $\beta$ is the angle of the air knife. The separation system was tested with 90-day-hybrid sweet sorghum feedstock, mechanically harvested at its maturity stage. A crop characterization was conducted by separating the feedstock by hand and weighing the billets, leaves and panicles. The percentage by weight was calculated and then the feedstock was mixed up again. Three samples of 23 kg each were evaluated at air stream angles of $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, $45^\circ$ with $y = 0.30$ m and $x = 1.37$ m. Then using 30 kg samples, the separation system was tested at $y = 0.61$ m and $30^\circ$, $45^\circ$, $60^\circ$ angles with the splitter at a position to assure only the leaves separation with no billet losses. The distance of the splitter from the air knife (variable $x$) was measured at each configuration. Keeping constant $\beta = 45^\circ$, the system was tested at $y = 0.30$ m, $y = 0.61$ m and $y = 0.91$ m. The leaves separation efficiency was calculated as the weight of leaves that fell after the splitter over the total amount of leaves in the sample. In lieu of sweet sorghum feedstock, the pneumatic system was also tested with sugar cane feedstock due to constraints in sweet sorghum feedstock availability. The air knife was set at the best configuration found in the sweet sorghum tests, which was at $45^\circ$ and $y = 0.61$ m. The variable $x$ was not fixed and was measured at each trial because it was expected to be different since the billets of the sugar cane are thicker in average. Six samples of HoCP 96-540 variety, 23 kg each, mechanically harvested at maturity were used. Each sample was separated by hand and characterized by weight in terms of billets, leaves and tops and then, they were mixed again. Further, the samples were passed through the air stream to assess the leaves separation efficiency and to assess also how many air streams in line were necessary to have a close to 100% leaves separation.
3.3 Panicles Separator

Information obtained in preliminary investigations, analysis and tests were used to design the prototype of the equipment to separate the panicles from the feedstock. The basic design concept of the panicles separator was to build a rotary screen with a device (grabber) that could selectively grab down the panicles and let the billets remain moving on top of the screen. Figure 7 shows a schematic of this design concept and how the grabber works. The discs as well as the grabber rotate at a constant angular velocity. The imaginary axis that passes through the centers of the discs and the grabber is tilted an angle $\theta$. The nitinol wires attached to the grabber box serve to hook down the panicles, whereas the billets get kicked out by the grabber box. The width of the discs and grabber was based on the common diameter found in the panicles used for this thesis. The diameter of the discs and grabber were based on the analysis performed with a smaller scale separator previously built. The final prototype and a 3D drawing of a roller is shown in Figure 8.

Figure 7: Schematic of the design concept (courtesy of Dr. Franz Ehrenhauser)
Figure 8: The panicles separator prototype (A and B) and a 3D drawing of a roller (C).

The prototype was designed with the computer aided design software Solidworks 2014 (Waltham, Massachusetts, USA). The discs were made from wood and had a diameter of 254 mm and a thickness of 76 mm. They had a hole in the center of 31.7 mm diameter and a key way of 3.5 mm × 3.5 mm. The shafts were steel tubes with a diameter of 31.7 mm, having a welded key stock of 3.5 mm × 3.5 mm. Each one of the shafts were mounted on two self-lube steel base-mount bronze bearings. The traction system was composed of roller chains ANSI No. 40, finished bore sprockets for ANSI No. 40 roller chain, a right-angle speed reducer NEMA 56C input, 20:1 ratio, 52.3 mm center, left output and a NEMA 56C output electric motor of 560 watts at 1720 rpm. The
grabbers were made of 1 mm diameter and 90 mm length nitinol wires and wood profiles of 38 mm × 89 mm and 57 mm × 89 mm, fixed to the shaft by two flat head steel screws. The feeding chute was fabricated with ASTM-B 209 aluminum sheets of 3.2 mm thickness. The rest of the frame of the panicles separator was made of wood, reinforced with steel at the connections.

To test the panicles separator and obtain the best configuration, sweet sorghum samples of 43 kg containing only billets and panicles of the 90-days-hybrid variety were evaluated since it was assumed that the leaves would be completely separated in the leaves separator. The weight of the billets and panicles of each sample was recorded before and after passing them through the panicles separator. Different configurations of the panicles separator were tested. Three samples were passed at each configuration. The configurations tested were; \( \theta = 20^\circ \) at 21.5 rpm, 43 rpm and 86 rpm and \( \theta = 30^\circ \) at 21.5 rpm, 43 rpm and 86 rpm. The device was not tested at \( \theta = 10^\circ \) or more than \( \theta = 30^\circ \) angle because, from preliminary experiments and analysis, the separation performance was less. Then, the panicles separator was tested in the same way at the best configuration with 34 kg sample of the sweet sorghum 90-days-hybrid variety with 1\% leaves, 2.4\% panicles and 96.6\% billets to simulate a feedstock with an almost complete leaves separation in the pneumatic separator and to evaluate the effect of this 1\% leaves in feedstock in the panicles separator efficiency. After, the panicles separator was tested again at the best configuration by using 43 kg sample of the sweet sorghum 90-days-hybrid variety with 7.6\% leaves, 1.8\% panicles and 90.6\% billets, which was feedstock after one pass through the pneumatic separator. This test was to evaluate how the panicles separator performed in line with the pneumatic separator and to evaluate the effect of this amount of leaves in the panicles separation efficiency and consequently in the panicles selectivity. The panicles separator was evaluated in terms of the panicles selectivity. The selectivity was calculated as the panicles separation efficiency over the billets lost, where the
panicles separation efficiency is the weight of the separated panicles over the weight of all the panicles in the sample times 100% and the billets lost % is the weight of the billets lost over the weight of all the billets in the sample times 100%.

3.4 Juice Extraction

The juice extraction experiments aimed to simulate the actual juice extraction of the first mill in a sugar cane milling tandem. Each feedstock sample was passed three times through a three roll mill (Farrel-Birmingham Company Inc., USA) shown in Figure 9, driven by an electric motor with its reducer. The sugar cane mill was configured to have 10,342 kPa of hydraulic pressure in the two pistons, delivering 249,990 Newtons in the top roll. In the 2015 harvest season, the juice extraction experiment consisted in fabricating nine samples of 20 kg each divided in three different treatments. Three samples of regular feedstock (RF) with an average of 19% trash, which is feedstock as it came from the field. Three samples of billets and panicles (BP) and three samples of only billets (B). The juice and bagasse was weighed and samples were taken for the lab analysis.

Figure 9: Three roll mill driven by an electric motor (Farrel-Birmingham Company Inc., USA)

In the 2016 harvest season, the first experiment consisted in evaluating five different treatments of a mechanically harvested 120-days-hybrid sweet sorghum feedstock. 15 samples of 20 kg each were prepared by hand in the following way: Three samples of regular feedstock (RF)
with 18% trash, three samples of feedstock with 0% of trash, three samples with 10% of trash, three samples with 20% of trash and three samples with 30% of trash. The weight of the leaves and panicles needed for the samples with different trash levels was calculated using the ratio leaves/panicles found in the crop characterization. The second experiment consisted in evaluating the mechanically harvested 120-days-hybrid sweet sorghum by sorting 12 samples of 20 kg each, to evaluate four different treatments as follows: Three samples of regular feedstock (RF) as it came from the field with 17% trash, three samples of billets and leaves (BL) with 14% leaves, three samples type of billets + panicles (BP) with 2% panicles and three samples of only billets (B). The trash percentage in the RF samples was obtained by conducting a crop characterization. To fabricate each sample, the leaves and panicles were separated and weighed by hand. In both experiments the total extracted juice and total bagasse was weighed in each feedstock sample. The juice was passed through a mesh of 355 microns (ASTM E-11, No. 45 mesh) to remove some big solids. The brix extraction was calculated as the brix in the juice times the weight of the juice extracted after the three millings over the brix in the feedstock times the weight of the feedstock. The fermentable sugars yield was derived from the fermentable sugars in the juice. The fiber percentage in the feedstock was determined by subtracting the mass of the dissolved solids left in the bagasse after the three millings assuming that this juice had the same composition as the squeezed juice.

3.5 Laboratory Analyses

To obtain the moisture of the bagasse, the procedure was based on the international commission for uniform methods of sugar analysis ICUMSA method GS7-5 (1994), with the difference that instead of drying samples of 1000 grams, samples of 100 grams were evaluated. The size of the samples was changed because there was not enough oven space; yet the main criteria of drying the samples until there was a mass loss of less than 0.2%, as stated in the method,
was followed. The temperature of the oven was 43 °C. Triplicates of each bagasse sample of each treatment were evaluated. Then, the fiber was calculated by subtracting dissolved solids of the juice left in the bagasse, assuming that this juice had the same composition as the pressed juice. All the juice samples from the previous experiments were analyzed in triplicates. The brix was measured on a Bellingham + Stanley RFM 340+ lab refractometer (Xylem, Kent, UK) calibrated to measure brix as total soluble solids. The sucrose, glucose and fructose analysis were conducted with an Agilent 1200 high performance liquid chromatography equipment (Santa Clara, CA, USA) using a 7.8 X 300-mm BioRad Aminex HPX-87K column (Hercules, CA, USA) following a method developed at the Audubon Sugar Institute. Samples of 20 µL were injected into the mobile phase at 5 °C. The pump flow rate was 0.6 mL/min with the column temperature at 85 °C. The time of analysis was 15 minutes. Each juice sample was diluted in deionized water with a conductivity of 17.4 MOhm and filtered through a VWR International (Radnor, PA, USA) 25 mm syringe filter with 45 µm nylon membrane. The concentrations were determined with the Agilent OpenLab software (Santa Clara, CA, USA) by manually integrating the peak areas under the curve nRIU (Refractive index) vs. minutes (time) of each sugar in each sample calibrated against seven standards, with each of the three sugars nominal concentrations at 100, 200, 300, 600, 1000, 2000 and 3000 mg/L, that were ran every six juice samples. The concentration of 14 acids in the juice (TAA or trans-aconitate, cis-aconitate, lactate, acetate, propionate, formate, butyrate, chloride, succinic, sulfate, oxalate, phosphate, citrate, iso-citrate) were determined as their corresponding anions with a Dionex Thermo Scientific ICS5000+ high performance ion chromatography equipment (Waltham, Massachusetts, USA) using an IonPac AS11 capillary column and suppressed-conductivity detector following a method developed at the Audubon Sugar Institute. Samples of 0.4 µL were injected into the mobile phase with a Dionex AS-AP auto sampler. The
mobile phase was integrated by an eluent and a generator cartridge of potassium hydroxide at 1 mM and 60 mM, changing its composition according to a gradient program. The time of analysis was 30 minutes. Each juice sample was diluted in deionized water with a conductivity of 17.4 MΩm and filtered through a VWR International (Radnor, PA, USA) 25 mm syringe filter with 45 μm nylon membrane. The concentrations were determined with the Dionex Chromelcron7 software from the peak areas calibrated against three standards ran before and after the samples. To determine the starch content in the juice, the analysis procedure was the ICUMSA method GS1-17. Lastly, the conductivity ash analyses were based on the ICUMSA method GS1/3/4/7/8-13 (1994) without temperature measurement; however the samples used were at room temperature and the equipment was calibrated with three solutions at room temperature as well.

3.6 Modeling of the Sweet Sorghum Syrup Production Facility

To estimate the fermentable sugars yield and other parameters in the syrup production, simulations of various case scenarios were conducted by modeling a sweet sorghum syrup production facility with the software Sugars™ (Denver, Colorado, USA). The software Sugars™ is a flowsheeting software dedicated to the sugar industry that offers a user-friendly interface that allows the operation of all the unitary processes involved in the production of sugar and power generation in order to conduct mass balances and energy balances. The proposed conceptual approach of this work assumes that the sweet sorghum syrup can be produced in a sugar cane mill. The model replicates the process and equipment currently used by a sugar factory in Louisiana and was validated by running a simulation using the same input parameters of a common day operation in the 2015 harvest season. The difference in the evaluated parameters, which were the mixed juice pol and brix, bagasse pol and moisture, clarified juice pol and brix and syrup pol and brix, between the real sugar cane mill factory and the model was less than 5%.
The process began with the juice extraction section (Figure 10). First, the sweet sorghum feedstock is prepared by one set of leveling knives driven by a steam turbine followed by two swing back knives sets driven also by steam turbines. The juice was extracted in a tandem of six mills driven all by steam turbines. The juice extracted from the first and second mill was the juice that was pumped to the juice clarification section. The juice extracted from the third to sixth mill served as maceration for the previous mill’s entering feedstock. Imbibition water was applied to the feedstock entering the sixth mill at a rate of 213% fiber, as it was the rate used by the sugar cane mill in Louisiana from which this model was based on. In this section the settings of the mills were adjusted in order to obtain a brix extraction close to 95.5% with the completely clean sweet sorghum feedstock B (0% trash). After the juice extraction, a portion of the bagasse was sent to the boilers, other portion was passed through a mesh and the obtained bagacillo was sent to the mud filters and the rest of the bagasse or excess exited the model to be stored. In the cogeneration case, this excess bagasse was used as the fuel.

Figure 10: Flowsheet diagram of the simulated juice extraction section.
The clarification process (Figure 11) began with adding milk of lime and then heating the juice. First the juice was passed through a liquid-to-liquid plate heater that reduced the condensates temperature by pre-heating the juice through heat exchange. Further, the condensates that come out from the pre-heater were used as the imbibition water for the sixth mill in the juice extraction section (Figure 10). The juice continued to the gas-to-liquid plate heaters that used the vapor 1 coming from the pre-evaporators in the evaporation section to increase the juice temperature above 100 °C. Then, the juice passed through a flash tank and entered into the clarifier. This model simulated a Dorr clarifier with a total capacity of 263,000 gal. The clarifier removed the impurities from the juice through sedimentation and then the clarified juice went to the evaporation station. The mud from the clarifier flowed to a mixer where bagacillo was added and then a portion of the juice in the mud was recovered in the rotary mud filters. This filter juice went back to the mixed juice tank. The filter cake was dumped.

![Flowsheet diagram of the simulated juice clarification section.](image_url)
For the production of biofuels from sweet sorghum juice, the clarification step may not be necessary; however, for this simulation the juice clarification system was modeled because clarifying the sweet sorghum juice helps to reduce the viscosity, color and amount of the foam layer that is formed during the juice evaporation (Eggleston et al., 2013) and reduces the losses of the fermentable sugars in the evaporation without affecting the downstream fermentation yield (Andrzejewski, Eggleston, & Powell, 2013).

The evaporation section of this work, as shown in Figure 12, was modeled with multiple-effect evaporators since the sugar cane mills use this kind of equipment because is more energy efficient and the lower boiling temperature at high vacuum prevents the formation of color and sugar losses associated with the thermal degradation reactions. (Clarke, Edye, & Eggleston, 1997). Two pre-evaporator not under vacuum of 30,000 sq. ft. and 25,000 sq. ft. worked as the first effect. The vapor obtained from evaporating the water in the juice at these two evaporators, was used to increase the temperature of the limed juice at the clarification station with the gas-to-liquid plate heaters. This vapor is commonly known vapor 1. After the pre-evaporators, two triple effect evaporators and one quadruple effect were used with total heating surfaces each of 15,000 sq. ft., 60,000 sq. ft. and 50,000 sq. ft. respectively. All of the pre-evaporators and evaporators included a condenser and a vacuum pump to condensate the steam from the last effect and create the vacuum in the evaporator. The condensates of all the pre-evaporators and evaporators that used exhaust steam were used to feed the boiler. For the design of the facility in this model specifically, the condensates of the other effects were combined and passed through flash tanks and then were used to increase the temperature of the limed juice at the liquid-to-liquid plate heater and as imbibition of the sixth mill in the juice extraction section. Lastly, from the last effect of the evaporators, the syrup was obtained and the quality parameters were recorded.
Figure 12: Flowsheet diagram of the simulated evaporation section.

Figure 13 shows the simulated plant for producing the steam and power required to produce the syrup and to co-generate. The boiler consumed the required bagasse, from the juice extraction station, to produce enough live steam at 1620 kPa and 202 °C to power all the turbines installed in the mills, juice pumps and boiler pumps. The turbo-generator had a producing capacity of 1.5 MW for internal electric consumption. The exhaust steam at 207 kPa and 125 °C was used in the evaporators and the condensates from this steam, were pumped again into the boiler. Figure 14 shows the connections between the condensates and the cooling tower used to decrease the temperature of the injection water that was pumped to the condensers to condensate the vapors and create vacuum in the evaporators.
Figure 13: Flowsheet diagram of the simulated steam/power plant.

Figure 14: Flowsheet diagram of the condensates connections and the cooling tower of the injection water.
3.7 Simulations and Basic Economic Analysis

The same nine different feedstock treatments evaluated in the juice extraction experiment of the 2016 harvest season were considered for these simulations: RF with 18% trash, 0% trash, 10% trash, 20% trash, 30% trash, RF with 17% trash, BL with 14% trash, BP with 2% trash and B with 0% trash. The throughput of the plant was simulated to be 17,000 tonnes of feedstock per day during a harvest season of 60 days. The difference in the syrup production for each treatment was recorded. The energy consumption was obtained from all the turbines and the generator in the model and recorded as kWh. Also, to evaluate the potential of energy cogeneration and the differences between the treatments in this sense, another set of simulations were performed by adding a more efficient boiler with a bagasse consumption of 2.3 kg steam/kg bagasse and a turbo-generator working at 6,500 kPa and 500 °C producing exhaust steam at 207 kPa and 125 °C (Aragon et al., 2015). The excess bagasse was used to feed this cogeneration system. In order to evaluate the possible use and revenue of the starch in the juice, it was supposed that the starch could be converted to glucose through enzyme hydrolysis (Ratnavathi, Chakravarthy, Komala, Chavan, & Patil, 2011) (Eggleston et al., 2013). The glucose yield from the starch hydrolysis in syrup was assumed to be the theoretical yield of 1.1 gram of glucose per gram of starch (Borglum, 1980).

The economic analysis was conducted to obtain the differences in revenue between the different treatments and different cases of cogeneration and starch removal. The estimated prices to calculate the revenue were intended to represent wholesale industrial prices and not to represent special retail opportunities. The price of the fermentable sugars assumed for these analyses was based on the U.S. price of blackstrap molasses and adjusted for the average brix and average fermentable sugars content of the blackstrap molasses according to the following equation:
\[ FS \text{ price} = \frac{PBM}{907.19 \times BM^\circ \text{Brix}/100} \div BMFS \text{ purity} \]

Where PBM (US$150/short ton) is the price of the blackstrap molasses (USDA Economic Research Service, 2017a), BM\(^{\circ}\)Brix is the 2016 average Brix in the blackstrap molasses in Louisiana of 81.8 (Verret, 2017), BMFS is the average blackstrap molasses fermentable sugars purity (56.5%) in Louisiana for the 2016 season (Verret, 2017) and the constant of 907.19 is the conversion factor from short tons to kilograms. With these information, the calculated price was US$0.358 per kilogram of fermentable sugars.

When calculating the possible revenue of the starch, if the starch was completely separated, then the average selling price utilized for these calculations was the cost of producing corn starch, which is US$0.12 per kilogram (USDA Economic Research Service, 2017b). On the other hand, if the starch is hypothetically hydrolyzed in the syrup, the resulting weight of glucose from the projected starch hydrolysis, could be added to the amount of fermentable sugars in the syrup, resulting in a price per kilogram of glucose equal to the FS price of US$0.358. For the cogeneration, the price of electricity was considered the average industrial price by January 2017 in Louisiana of US$0.0407 per kWh (U.S. Energy Information Administration, 2017). The possible revenue from selling the panicles was also calculated. The amount of panicles in the feedstock assumed was 2% (mass/mass) and was based on the crop characterization presented in this work in section 4.1 for the Durasweet 120-days-hybrid variety. The average grains % panicles assumed was 75.6%, which was obtained from preliminary characterization work conducted at the Audubon Sugar Institute. The estimated price of the sorghum grain as for April 2017 in the U.S. was US$ 4.9 / CWT (USDA National Agricultural Statistics Service, 2017). The unit CWT is a hundredweight or 100 lbs in the U.S.
CHAPTER 4. RESULTS AND DISCUSSION

4.1 Crop Characterization

In order to conduct the tests of the pneumatic separator and the panicles separator and to assess the effect of the trash in the juice and syrup quality parameters, it was necessary to characterize the feedstock. Table 1 shows the results on the sweet sorghum crop characterization for the harvest seasons 2015 and 2016. These results coincide with the results obtained by Smith et al. who conducted sweet sorghum crop characterizations in many regions of the United States, finding that the net stalk percentage by weight raged from 69.9% to 84.4% being 79% the closest region to Louisiana from the places where he conducted his experiments (Smith et al., 1987). Also, in the case of the Durasweet 120-days-variey, even though it was hand-harvested in the 2015 season and in the 2016 season it was harvested with a combine with fans off, there was not a notable difference in the crop composition between these two years in terms of weight percentage of billets, leaves and panicles and their standard deviations. This suggest that a sugar cane combine harvester with fans off can recover most of the crop from the field. Aragon et al. also reported that there was no significant difference in the crop characterization of the hand-harvested sweet sorghum and the combine harvested sweet sorghum with fans off (Aragon et al., 2017).

<table>
<thead>
<tr>
<th>Year</th>
<th>Sweet sorghum hybrid-variet</th>
<th>Harvesting method</th>
<th>Billets</th>
<th>Leaves</th>
<th>Panicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Durasweet 120-day</td>
<td>Hand</td>
<td>81.0 ± 1.5%</td>
<td>17.0 ± 1.3%</td>
<td>2.0 ± 0.6%</td>
</tr>
<tr>
<td>2016</td>
<td>Durasweet 90-day</td>
<td>Combine fans off</td>
<td>83.2 ± 0.8%</td>
<td>13.6 ± 0.4%</td>
<td>3.1 ± 0.2%</td>
</tr>
<tr>
<td>2016</td>
<td>Durasweet 120-day</td>
<td>Combine fans off</td>
<td>82.31 ± 2.2%</td>
<td>16.0 ± 0.7%</td>
<td>1.7 ± 0.4%</td>
</tr>
</tbody>
</table>
4.2 Pneumatic Separation

Figure 15 shows the results of the pneumatic separation at different air streams angles. The vertical axis shows the leaves separation efficiency percentage and each bar represents different air stream angles. The results indicates that the leaves separation efficiency increases as the angle of the air stream increases to 45°, showing a separation efficiency at 45° of 77 ± 16% and at 0° of 42 ± 12%.

![Figure 15: Leaves separation efficiency for different air stream angles at x = 1.37 m and y = 0.30 m.](image)

Although the leaves separation efficiency at 45° was acceptably good, there were still many billets and panicles lost to the leaves side of the splitter. This observation was also made by Wright et al. when they developed a sweet sorghum leaves separation system with a centrifugal blower with an outlet of 0.91 m × 1.22 m. In their system, they reported that they were able to separate 100% of the leaves with up to 23% billets lost. With the panicles, they found that it was more difficult to separate them (Wright et al., 1977). A loss of up to 23% of the billets in the feedstock
would be a disadvantage for the fermentable sugars yield and to the option of using a feedstock separation system to improve the efficiency of a mill.

Table 2 shows the results from the test of the pneumatic separator in terms of the separation efficiency obtained with no billets lost by placing the splitter at $x = 2.06 \pm 0.06$ m. The results indicate that when testing the air knife for different angles, keeping constant the distance between the air knife and the end of the feeding conveyor at $y = 0.61$ m, the highest leaves separation efficiency of $56 \pm 3\%$ was found at an angle of $45^\circ$. After passing the feedstock one time through the pneumatic separator at this highest separation efficiency, the feedstock had a new crop characterization of $90.6 \pm 1.3\%$ billets, $7.6 \pm 0.8\%$ leaves and $1.8 \pm 0.4\%$ panicles. If the angle of the air knife was less ($30^\circ$) or more ($60^\circ$) than $45^\circ$, the efficiency notably decreased to $37 \pm 4\%$ and $35 \pm 3\%$ respectively as shown in Table 2. It is very important to point out that by moving the splitter to different positions for each configuration of angle and $y$ distance, no billets were lost to the trash. For instance, the splitter positions “$x$” at $y = 0.61$ m for $30^\circ$, $45^\circ$ and $60^\circ$ were $1.93 \pm 0.03$ m, $2.06 \pm 0.06$ m and $1.98 \pm 0.03$ m respectively. The trash separation percentage was reduced from the results shown in Figure 15 at $x = 1.37$ m, by increasing the $x$ distance to two meters. This principle suggest that for any pneumatic separation system installed, it is extremely important to assess the $x$ variable or in other words, to assess where should the splitter be positioned to achieve the highest leaves separation while losing few to none billets. When evaluating the change in variable $x$ at a fixed $y = 0.61$ m, from the results mentioned above, the variable $x$ was larger when the angle $\beta$ was $45^\circ$ or more. As expected from the principle of the parabolic motion of projectiles, the particles reach the longest horizontal distances at $45^\circ$. Furthermore, Table 2 shows that when keeping the angle constant at $45^\circ$, there was no perceptible difference in the leaves separation efficiency when placing the air stream at less than $y = 0.61$ m (2 feet) below the conveyor; however,
when this distance was increased beyond these 0.61 m, the leaves separation efficiency decreased significantly from $56 \pm 3\%$ to $25 \pm 8\%$ meaning that the air stream should be placed at no more than 0.61 meters or 2 feet below the conveyor. In conclusion, the results indicate that for this system the air knife should be placed at no more than 0.61 m below the conveyor, at an angle of $45^\circ$ and with the splitter at two meters in order to obtain the highest leaves separation efficiency with no billets loss to the trash. Also, measuring the variable $x$ is a good indicative of where the splitter or the receiving conveyor should be placed in order to obtain the highest leaves separation efficiency at a minimum billets lost percentage. In any application of this pneumatic separator, it is highly recommended to install a movable system for the splitter in order to change it whenever is necessary in the case that more billets are lost, or in the case that more trash needs to be separated.

Table 2: Leaves separation efficiency for different angles and different distances below the conveyor.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>$y=0.61$ m</th>
<th>$\beta=45^\circ$</th>
<th>$\beta=60^\circ$</th>
<th>$y=0.30$ m</th>
<th>$y=0.61$ m</th>
<th>$y=0.91$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaves Separation Efficiency %</td>
<td>$37 \pm 4$</td>
<td>$51 \pm 3$</td>
<td>$35 \pm 3$</td>
<td>$53 \pm 7$</td>
<td>$56 \pm 3$</td>
<td>$25 \pm 8$</td>
</tr>
</tbody>
</table>

The pneumatic separator was evaluated with the sugar cane variety HoCP 96-540 harvested with a combine with fans off. Even though the tops are usually considered trash, in this study as the study presented by Schembri et al. (Schembri et al., 2002), the separation of the leaves was the main objective and the tops remained with the billets. This allowed to compare the results of the sugar cane leaves separation to the sweet sorghum leaves separation. The percentage by weight obtained from the crop characterization was $80.9 \pm 1.0\%$ billets, $17.5 \pm 1.0\%$ leaves and $1.5 \pm 0.2\%$ tops. The leaves were separated by passing the feedstock multiple times through the
pneumatic separator. The results from the assessment of the pneumatic separator performance at $\beta = 45^\circ$ and $y = 0.61$ m (best configurations from previous experiments) is presented in Figure 16. The leaves separation efficiency % is the weight of the separated leaves at each pass over the weight of the leaves in the feedstock before that specific pass. The cumulative leaves separation % is the weight of the leaves separated until that pass over the original weight of the leaves in the feedstock as came from the field before the first pass. These results indicate that as the feedstock passed through the subsequent air streams, the leaves separation efficiency increased at each pass showing that it is possible to completely separate just the leaves from the feedstock. This effect suggests that in this system, to reach a leaves separation close to 100%, it is required to pass the feedstock through a minimum of four air streams. The results also indicate that the device performed with a higher efficiency when the feedstock had a lower level of leaves.

![Figure 16: Leaves separation efficiency for different number of subsequent air streams. The air knife was kept constant at $y = 0.61$ m and $\beta = 45^\circ$.](image_url)
The following distances of the splitter from the air knife were obtained for each subsequent pass respectively: \( x = 1.69 \pm 0.05 \text{ m} \), \( x = 1.64 \pm 0.02 \text{ m} \), \( x = 0.62 \pm 0.01 \text{ m} \) and \( x = 0.59 \pm 0.01 \text{ m} \).

There was a large drop in this \( x \) value after the second pass, which would suggest that at certain level of leaves in the feedstock, the billets are less prone to change their trajectory due to being collided and dragged by the leaves that are being blown. Moreover, when comparing the efficiency results of sweet sorghum leaves separation shown in Table 2 at \( \beta = 45^\circ \) and \( y = 0.61 \text{ m} \) and the efficiency results at the very first pass with sugar cane feedstock shown in Figure 16, the pneumatic system performed 19\% less efficient with sugar cane (37 \pm 8\%) than with sweet sorghum feedstock (56 \pm 3\%). The difference in efficiency was probably because it was more difficult to separate the leaves from the tops than to separate the leaves from the panicles, causing more leaves to stay with the billets and tops in the “unseparated” area. The smaller distance \( x \) in the case of sugar cane (1.69 \pm 0.05 \text{ m}) when compared to sweet sorghum (2.06 \pm 0.06 \text{ m}) was expected since the sugar cane billets are on average thicker and weigh more than the sweet sorghum billets.

### 4.3 Panicles Separation Efficiency

The results are presented in terms of selectivity in order to relate the variables of the angles and the rotational speed, as well as the panicles separation efficiency percentage and the billets lost percentage, since the selectivity was calculated as the panicles separation efficiency \% over the billets lost \%. From this equation, as the panicles separation efficiency \% is higher and the billets lost \% is lower, the selectivity number is higher. Further, it was determined that the best configuration of the panicles separator would be when the selectivity was the highest or at its best, infinite i.e. no billets lost. It is important to notice that an infinite panicles selectivity, would not necessarily mean a high panicles separation efficiency \%.

Figure 17 shows the performance of the panicles separator with the selectivity in the vertical axis and the rotational speed in the horizontal axis. These results demonstrate that it is
possible to separate the panicles from the billets. With our prototype, the highest selectivity obtained was $9.5 \pm 1$ at $30^\circ$ and 43 rpm. The graph of the results shows that the optimum rotational speed to operate this device is at 43 rpm. With this highest selectivity, the panicles separation percentage was $13 \pm 1\%$ and the separated billets percentage was $1.4 \pm 0.1\%$. This prototype had six rollers from which basically only four worked as separators since the first one and last one function only as receivers and handlers of the feedstock. It is expected that if an equipment with more effective rollers is built, the panicles separation percentage will increase proportionally, whereas the billets separation percentage would not increase proportionally since from observation, only the shorter and thinner billets where separated along with the panicles, and the amount of shorter and thinner billets in the feedstock is limited. The effect on the panicles separation due to the rotational speed was that as the rotational speed increased, the grabbers had less time to hook down the panicles, reducing the amount of separated panicles. For instance, at $\theta = 20^\circ$ and 21.5 rpm, 43 rpm and 86 rpm, the separated panicles percentage were 29%, 21% and 7% respectively. In the case of the billets, the effect was the contrary and as the rotational speed increased, the billets lost decreased ($6\%, 3\%, 3\%$) since the billets had more impulse and consequently they fell through the grabber with less frequency. At low rotational speeds of the device, the billets had less impulse to pass on top of the grabber and they fell through the separator with the grabbed panicles. Furthermore, the best balance between the grabbed panicles and the billets lost was found at the highest selectivity at 43 rpm with $13\% \pm 1\%$ panicles separation and $1.4 \pm 0.1\%$ billets lost. Figure 17 illustrates also that the device performed better at an angle of $30^\circ$. The effect due to the angle was that as the angle increased, the position of the panicles approaching to the grabber changed, making more difficult for the grabber hook down the panicles. In addition, the increase in the angle increased also the velocity at which the feedstock advanced.
on the prototype because of the gravity force component that was added in the direction tangential to the discs. This rise in the feedstock velocity, reduced the time for hooking down the panicles, reducing in this way the panicles separation efficiency which was negative; however, it reduced also the billets lost percentage. The best ratio between the highest amount of grabbed panicles and the less billets lost percentage was found at the angle of 30°.

![Selectivity obtained in the panicles separator test for different angles and different rotational speeds. ▲ is at θ = 30°, ● is at θ = 20°.](image)

Figure 17: Selectivity obtained in the panicles separator test for different angles and different rotational speeds. ▲ is at θ = 30°, ● is at θ = 20°.

When the panicles separator prototype was tested at θ = 30° and 43 rpm with feedstock having 1% leaves, the selectivity obtained was 8.9 ± 1.5. This result suggested that 1% of leaves in the feedstock did not have much effect on the performance of the panicles separator since the selectivity obtained with this amount of leaves was the same as the selectivity obtained with no leaves in the sample (9.5 ± 1) at θ = 30° and 43 rpm (Figure 17), because it falls between the standard error bars. Further, when the prototype was tested at θ = 30° and 43 rpm with sweet sorghum feedstock having 7.4% leaves after one pass through the pneumatic separator, the
selectivity decreased to $6 \pm 1.2$. The leaves clearly affected the performance of the device. This was because the leaves kept the feedstock attached as a mat, preventing the panicles to even get in contact with the rotating grabbers. The leaves also got stuck in the nitinol wires and ended up wrapping the grabber, covering up eventually all nitinol wires and affecting in this way the selectivity. These results showed that in order to obtain the highest selectivity possible with the current panicles separator design, the leaves have to be completely removed from the feedstock prior to the panicles separation. Further work is required to improve the panicle selectivity when leaves are still present.

4.4 Effect of the Feedstock Trash Content

4.4.1 Fiber

Figure 18 and 19 present the results of the fiber percentage feedstock for different levels of trash in the milled feedstock as well as the different feedstock treatments. Figure 18 indicates that as the amount of trash in the feedstock increases, the fiber in the feedstock also increases. Moreover, the results show that for every 10% of the trash level that is removed from the feedstock, there is a decrease of fiber percentage feedstock in the range of 1.8 to 2.8%. The results from the experiment with different feedstock treatments and presented in Figure 19 also show the same trend as for instance between the treatment BP and treatment BL, there is a 12% trash difference, and the difference in fiber percentage feedstock is 1.8%. When comparing the BP treatment with the RF treatment, the trash % feedstock difference is 15% and the fiber percentage feedstock difference is 2.9%, which falls within the previously mentioned range of fiber decrease with feedstock trash decrease ($1.8 - 2.8\% \times 1.5 = 2.7 - 4.2\%$). If the BP treatment is compared with the B treatment, the averages fall within each other’s standard deviations, suggesting that the panicles in the feedstock at 2%, do not affect the amount of fiber percentage feedstock obtained.
Figure 18: Fiber % Feedstock obtained from milling the feedstock with different levels of trash in kilograms per tonne of feedstock.

Figure 19: Fiber % Feedstock obtained from milling different feedstock treatments. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock as came from the field.
4.4.2 Juice extraction

Figure 20 shows the results of the experiment conducted in the 2015 harvest season for the juice extraction in the first, second and third milling as well as the total extracted juice from the three millings. In the line of the total juice extracted and the line of the juice extracted at the third milling, there was less juice extraction percentage when the feedstock with 19% trash was milled compared to the cleaned feedstock or treatment B. Two possible explanations for this effect are that the trash had less juice and sugars than the stalks and that the fiber of the trash and rind could have eventually absorbed some of the extracted juice and affect the non-structural carbohydrates extraction as found before by other authors (Cundiff & Worley, 1992; Weitzel, Cundiff, & Vaughan, 1987). Since maceration or imbibition was not used in this experiment, the effect of the trash in the juice extraction percentage was more accentuated at the last milling or third milling where the fiber percentage in the input feedstock is higher since a good amount of the juice was extracted already in the previous millings. Moreover, the average extraction obtained in the first milling of 37% for regular feedstock and 46% for cleaned feedstock is comparable to the extraction obtained by Rao et al. (Rao et al., 2013) and Monroe et al., (Monroe, Nichols, Bryan, & Sumner, 1984) that reported a 40.4% to 44.4% and a 40% to 47% extraction respectively using a sugar cane three roll mill to extract the sweet sorghum juice without imbibition as well. The results in this thesis are consistent also with the results presented by Guigou et al., who found a 47 ± 1% of juice extraction when milling stalks only, which was significantly higher compared to the samples with stalks and leaves at a 43 ± 2% juice extraction and the samples with stalks, leaves and panicles at 35 ± 3% extraction (Guigou et al., 2011). O’Hara et al. reported also a higher extraction of 70% for stalks only and a 45% for the whole plant samples (O’Hara et al., 2013). It is important to point out that in the results presented in this experiment, the total juice extraction was in average between 64% and 75% depending on the treatment, which was a higher amount of juice extraction.
compared with the previous authors because we passed the same feedstock three times through the three roll mill, leading to a higher difference.

![Graph showing juice extraction at each of the millings and total juice extraction for different feedstock treatments. B = only billets; BP = billets + panicles; RF = regular feedstock as came from the field.]

**4.4.3 Dissolved solids yield**

Figure 21 shows the results in the juice extraction of the dissolved solids yield for different levels of trash in the feedstock. The vertical axis indicate the dissolved solids yield or the amount of extracted dissolved solids in kilograms per tonne of feedstock, which was calculated by multiplying the brix by the weight of the extracted juice over the weight of the milled feedstock. The horizontal axis has the different types of feedstock milled with their respective trash percentage. These results showed that the lower the trash % feedstock, the more extracted dissolved solids. The dissolved solids are mainly composed of fermentable sugars. If the sweet sorghum trash separation system presented in this work is used to lower the trash level by 20%, the dissolved solids in juice could be increased by 20 kilograms per tonne of milled feedstock, as
it can be seen in Figure 21 when comparing the extracted dissolved solids from 0% trash and 20% trash in feedstock. An observation from these results was that if the difference in the trash % feedstock is more than 10%, then the difference in the milling quality including the dissolved solids extraction becomes more perceptible as concluded also by Legendre et al. (Legendre & Irvine, 1974) in their study of the effect of sugar cane trash.

![Graph showing extracted dissolved solids for different levels of trash in feedstock. RF = regular feedstock as came from the field.](image)

Figure 21: Extracted dissolved solids for different levels of trash in feedstock. RF = regular feedstock as came from the field.

The results of the juice extraction experiment conducted for different feedstock treatments in the harvest season of 2016 can be seen in Figure 22. As the trash percentage in the feedstock increased, there was a significant decrease in the extracted dissolved solids. The BP treatment with a 2% trash of only panicles trash as well as the BL treatment with 14% trash of only leaves showed on average, a higher amount in dissolved solids in the juice when comparing both of them with the RF treatment with 17% trash. This means that by percentage weight, the panicles have a higher effect on the dissolved solids yield since from the RF treatment to the BL treatment, only the
panicles were removed and caused an increase in the dissolved solids yield. From the RF treatment to the BP treatment, only the leaves were removed but in a higher weight and it also increased the dissolved solids yield.

Figure 22: Extracted dissolved solids for different treatments and levels of trash in feedstock. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock as comes from the field.

4.4.4 Fermentable sugars yield

In the experiment conducted in 2015, the extracted fermentable sugars (fermentable sugars in the juice) in kg per tonne of feedstock were 79 ± 22 for the only billets or treatment B, 57 ± 12 for the BP treatment and 45 ± 9 for the RF treatment or feedstock as came from the field. These results indicated that there was a difference in the amount of extracted fermentable sugars between milling feedstock with only billets and feedstock with billets, leaves and panicles or regular feedstock. Although, there was no difference in the fermentable sugars purity in the extracted juice between the three sample types, the difference in the total fermentable sugars yield was due to a higher amount by weight of juice extracted when milling cleaned feedstock than when milling the
other two types of feedstock with trash. This constant fermentable sugars purity suggested that the behavior of the fermentable sugars with respect to the different feedstock treatments and different levels of trash in the feedstock was the same as the behavior of the extracted dissolved solids. Figure 23 shows the results of the evaluation conducted with feedstock at different levels of trash on the fermentable sugar yield or sucrose + glucose + fructose yield. The vertical axis indicate the fermentable sugars yield in kilograms per tonne of feedstock and the horizontal axis shows the different levels of trash in the feedstock. These results confirmed the information obtained in 2015 because again there was a decrease of the extracted fermentable sugars as the trash percentage in the feedstock increased. The results from this experiment showed also that the amount of total sugars extracted from the RF treatment or regular feedstock with 18% trash was in average a 75.6% of the total extraction of sugars of the only billets feedstock with 0% trash.

![Figure 23: Fermentable sugars yield in juice for different levels of trash in the feedstock.](image)

The assessment on the effect of different feedstock treatments on the fermentable sugars yield conducted in the 2016 harvest season is shown in Figure 24. The vertical axis shows the
fermentable sugars yield in kilograms per tonne of feedstock and the horizontal axis shows the four different treatments evaluated. The results indicate that although the percentage by weight of the panicles was less than the leaves percentage in the feedstock, they had similar effect in the extraction of the fermentable sugars. In other words, if compared by same weight, the results suggest that the panicles had a higher negative effect than the leaves. O’Hara et al. concluded as well that the inclusion of grain heads has a significant negative effect on milling performance (O’Hara et al., 2013). The RF treatment with 17% trash presented a fermentable sugars yield that was 77.9% of the fermentable sugar yield of the B treatment or only billets feedstock with 0% trash. This 77.9% and the 75.6% obtained in the previous experiment, are a little bit higher than the results presented by Viator et al. who obtained that the sweet sorghum trashy samples produced an average of 62% of the total sugars in juice of the clean samples (Viator et al., 2015). This difference might be due to the extraction with a Honiron hydraulic press. Conversely, my results are more congruent with the results presented by Sipos et al. who showed that the samples processed without the leaves produced approximately 20% higher sugar content, which would mean in other words that the total extracted sugar from the trashy samples were between 77% and 88% of the total extracted sugar from the cleaned samples (Sipos et al., 2009). O’Hara et al. reported also a larger percentage of extracted glucose and fructose in juice when milling the stalks only (3.38 - 4.32% / juice) than when milling the whole plant (1.66 – 2.8% / juice) since he reported a larger concentration of these sugars in the juice and a larger extraction of juice in the talks only samples (73 – 75%) than in the whole plant (43 – 46%) (O’Hara et al., 2013). In conclusion, the higher the amount of trash in the feedstock, the less kilograms of extracted fermentable sugars per tonne of feedstock for the first mill. Further, the panicles have a higher negative impact by weight on the extraction of fermentable sugars.
Figure 24: Fermentable sugars yield in juice for different treatments and levels of trash in feedstock. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock as came from the field.

Tables 3 and 4 show the results of the amount of sucrose, glucose and fructose independently in the extracted juice. Table 3 presents the difference in the amount of extracted sucrose between the feedstock treatment B and the regular feedstock with 17% trash or treatment RF. These results coincide with the results obtained by Viator et al. who showed that for the sweet sorghum in the medium maturity group, which is the 120-days-hybrid variety that was also used for the experiment presented in Table 3, there was a significant higher amount of sucrose in juice of clean stalks (0.507 g / g dry weight) compared to trashy stalks (0.316 g / g dry weight) (Viator et al., 2015). Table 3 illustrates as well that BP feedstock has less sucrose than the only billets feedstock (treatment B). This suggest that the panicles have a higher effect on the amount of sucrose that can be extracted from the feedstock. A reason for this effect could be that those 2% trash in the feedstock of only panicles have little to no sucrose, causing less sucrose yield in the extracted juice at the end. In the case of the leaves, they contain some sucrose that can add up to
the total sucrose yield, causing less apparent difference when milling them with the feedstock at small amounts like the 14% in this case. In the same way, Table 4 shows that the less amount of trash, the higher the amount of extracted sucrose per weight of feedstock. In the case of the glucose, the results in both tables indicate that there was no difference. In contrast, for the fructose there was a more perceptible difference when there was 30% trash in the feedstock. One observation that can be made is that the glucose was higher than the fructose in all cases.

Table 3: Amount of sucrose, glucose and fructose in the juice for different feedstock treatments. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock as came from the field.

<table>
<thead>
<tr>
<th>Yield (kg/tonne of feedstock)</th>
<th>Feedstock treatments (Trash % Feedstock)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B (0%)</td>
</tr>
<tr>
<td>Sucrose</td>
<td>53.2±3.7</td>
</tr>
<tr>
<td>Glucose</td>
<td>12±1.8</td>
</tr>
<tr>
<td>Fructose</td>
<td>5.8±1.2</td>
</tr>
</tbody>
</table>

Table 4: Amount of sucrose, glucose and fructose in the juice at different levels of trash in the feedstock.

<table>
<thead>
<tr>
<th>Yield (kg/tonne of feedstock)</th>
<th>Trash % Feedstock level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF (18%)</td>
</tr>
<tr>
<td>Sucrose</td>
<td>42.8±7.1</td>
</tr>
<tr>
<td>Glucose</td>
<td>10.8±0.5</td>
</tr>
<tr>
<td>Fructose</td>
<td>5.8±0.4</td>
</tr>
</tbody>
</table>

4.4.5 Organic acids in juice

Tables 5 present the results of the acids in parts per million of dry mass in the juice extracted from feedstock with different levels of trash. The results are presented as the average of the triplicates of the feedstock samples and the triplicates of the juice analysis of each extracted juice with their respective standard deviations. There was no presence of acetate, propionate,
butyrate, oxalate and *iso*-citrate in the juice. The results showed also that for the lactate, formate, sulfate, citrate and trans-aconitate or TAA, there was no perceptible difference of their concentration for the different levels of trash. In the case of the chloride, succinic, phosphate and *cis*-aconitate acids, their concentration increased as the trash level in the feedstock increased. When summing up the concentration of all these acids, the results showed that the total concentration of organic acids in the juice increased as the trash level in the feedstock increased. The results of the analysis of the experiment with different feedstock treatments showed also that in average the total concentration of acids was higher in the regular feedstock with 17% trash (59,709 ± 9,537 ppm/°Brix) than in the cleaned feedstock (55,425 ± 1,635 ppm/°Brix). Furthermore, the results from the experiment with the different feedstock treatments were congruent with the results of the different trash levels in the feedstock experiment in the order of the concentrations of the different organic acids in the juice from the highest that was the *trans*-aconitate to the lowest that was the Lactate and the trends found for each one of them discussed above and shown in the Table 5. The TAA is the main non-volatile organic acid found also in the sugar cane juice by having a reported concentration in the order of 1 and 1.54%  °Brix in juice or 10,000 and 15,400 ppm/°Brix (Mane, Kumbhar, Barge, & Phadnis, 2002) (Martin et al., 1960). If compared with the results presented in Table 5, the concentration of the TAA almost doubled the reported concentration of TAA in sugar cane juice. Ventre reported that the sugar cane varieties in Louisiana had only 25 to 40% of the aconitic acid present in the sweet sorghum (Ventre, 1949) (Ventre, 1955). The aconitic acid exists in two stereo isomers, the *trans*- isomer TAA, and the *cis*-isomer. The results in Table 5 show that the *cis*-aconitate concentration increases as the trash level increases, resulting in an overall increase of the aconitic acid. The problem with the aconitic acid and the organic acids is that they have a buffer capacity, which is the ability to absorb large
quantities of lime or other base with a small change in pH, leading to a higher requirement of milk of lime to control the pH in the process of syrup production (Honig, 1963).

Table 5: Concentration of acids in the juice for different trash levels in the feedstock.

<table>
<thead>
<tr>
<th>Acids</th>
<th>Lactate (ppm/°Brix)</th>
<th>Acetate</th>
<th>Propionate</th>
<th>Formate (ppm/°Brix)</th>
<th>Butyrate</th>
<th>Chloride (ppm/°Brix)</th>
<th>Succinic</th>
<th>Sulfate</th>
<th>Oxalate</th>
<th>Phosphate (ppm/°Brix)</th>
<th>Citrate</th>
<th>Iso-citrate</th>
<th>cis-aconitate</th>
<th>trans-aconitate</th>
<th>TOTAL (ppm/°Brix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF (18%) 0%</td>
<td>471±471</td>
<td>400±373</td>
<td>0</td>
<td>470±66</td>
<td>0</td>
<td>7100±19</td>
<td>2,387±43</td>
<td>2,514±412</td>
<td>0</td>
<td>1,295±393</td>
<td>1,926±107</td>
<td>0</td>
<td>7,119±896</td>
<td>27,593±670</td>
<td>53,785±835</td>
</tr>
<tr>
<td>10%</td>
<td>77±77</td>
<td>0</td>
<td>0</td>
<td>370±17</td>
<td>0</td>
<td>6850±362</td>
<td>2,192±52</td>
<td>2,527±228</td>
<td>0</td>
<td>2,061±107</td>
<td>2,061±107</td>
<td>0</td>
<td>5,817±418</td>
<td>26,783±1184</td>
<td>51,290±2600</td>
</tr>
<tr>
<td>20%</td>
<td>787±149</td>
<td>0</td>
<td>0</td>
<td>383±21</td>
<td>0</td>
<td>7132±79</td>
<td>2,120±296</td>
<td>2,483±75</td>
<td>0</td>
<td>2,378±298</td>
<td>2,378±298</td>
<td>0</td>
<td>7,260±601</td>
<td>27,360±1305</td>
<td>54,043±2802</td>
</tr>
<tr>
<td>30%</td>
<td>659±212</td>
<td>0</td>
<td>0</td>
<td>442±37</td>
<td>0</td>
<td>7364±286</td>
<td>2,653±152</td>
<td>2,527±232</td>
<td>0</td>
<td>1,878±260</td>
<td>1,878±260</td>
<td>0</td>
<td>8,587±586</td>
<td>28,475±555</td>
<td>58,296±187</td>
</tr>
</tbody>
</table>

4.4.6 Starch in juice

Tables 6 and 7 illustrate the results of the starch concentration in parts per million of dry mass in the extracted juice for different feedstock treatments and for different levels of trash in the feedstock. The results are presented as the average of the triplicates of the feedstock samples and the triplicates of the juice analysis of each extracted juice with their respective standard deviations. The level of the starch in the juice obtained in these experiments is in the lower range limit of the level of the starch in juice reported by Smith who mentioned that the starch in the sweet sorghum juice varies from 0.4 to 3.0%/°Brix (Smith, 1969). However, the starch concentration obtained in
this work for the sweet sorghum juice is higher (almost double) when compared to the starch concentration reported for sugar cane juice in the sugar mills that is in average 1546, 1745 and 2105 ppm/°Brix for 12.1, 18.8 and 22.7% of trash in the feedstock (Eggleston et al., 2012). Table 6 shows that the starch was not higher in the BP treatment as it would be expected since the panicles have about 60% of starch (Wall & Blessin, 1970). In contrast, when comparing the BL treatment with the B treatment, the leaves added more starch to the juice. Furthermore, the results in Table 7 indicate that there was an increase in the average starch concentration as the trash percentage increased. This trend coincides with the findings on the starch concentration in sugar cane juice from feedstock with different trash levels mentioned above (Eggleston et al., 2012).

Table 6: Concentration of starch in the juice for different feedstock treatments and trash levels. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock as came from the field.

<table>
<thead>
<tr>
<th>Concentration in Juice (ppm/°Brix)</th>
<th>Feedstock treatments (Trash % Feedstock)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B (0%)</td>
</tr>
<tr>
<td>Starch</td>
<td>3484±470</td>
</tr>
</tbody>
</table>

Table 7: Concentration of starch in the juice for different levels of trash in the feedstock.

<table>
<thead>
<tr>
<th>Concentration in Juice (ppm/°Brix)</th>
<th>Trash % Feedstock level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF (18%)</td>
</tr>
<tr>
<td>Starch</td>
<td>3472±417</td>
</tr>
</tbody>
</table>

4.4.7 Ash in juice

Figure 25 shows the results of the conductivity ash analysis to the extracted juice. The vertical axis has the percentage of the ash over the dissolved solids in the juice. The horizontal axis has the type of treatment with the amount in weight percentage of trash in the feedstock. There was no difference in the ash %/°Brix between the cleaned feedstock with 0% trash, the feedstock
with billets and panicles BP, and the feedstock with billets and leaves BL. However, at 17% trash in the RF treatment, there was a more apparent difference with respect to the treatment B of completely cleaned feedstock. One reason that there was no difference found in the ash content of the extracted juice at lower levels of trash could be that it might be more difficult to extract some amount of the ash out of the leaves. The ash content in the juice can change with the weather conditions and the type of soil; however, the results presented in this work compared material harvested at the same time and from the same plot, eliminating this influence. From a mass balance point of view, it is unknown why the treatments of BP and BL do have a similar ash content as the RF treatment. A reason could be that in this experiment the RF treatment was milled directly as came from the field harvested with the billet combine and the BP and BL treatments were hand made from the feedstock that came from the field. This could have removed some soil that the leaves could have naturally brought when harvested with a combine.

![Figure 25: Conductivity ash percentage brix in juice for different feedstock treatments and levels of trash. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock as came from the field.](image)
Figure 26 shows the results of the conductivity ash analysis performed to the extracted juice from the feedstock with different levels of trash. The horizontal axis has the RF treatment and the treatments with different levels of trash in the feedstock in increments of 10% from 0% to 30%. The results are presented in the percentage of ash in the dry mass of the extracted juice. The results indicate that the ash concentration in the extracted juice from the feedstock containing more than 20% trash was higher compared with the cleaned feedstock with 0% trash. The results showing the less concentration of ash in the juice obtained when less amount of trash in the feedstock was milled, reaffirms that cleaning the feedstock prior to milling is a good practice to increase the performance of the processing plant since it reduces the amount of ash that gets into the factory.

![Figure 26: Conductivity ash percentage brix in juice for different levels of trash in the feedstock.](image)

4.4.8 Simulation of the production of sweet sorghum syrup

The fermentable sugar data from section 4.4.4 was used as input in the simulation and is shown in Tables 8 and 9.
Table 8: Input parameters and estimated fermentable sugars content on feedstock for the syrup production with the computer simulation for different levels of trash in the feedstock.

<table>
<thead>
<tr>
<th>Input</th>
<th>Trash % Feedstock level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF (18%)</td>
</tr>
<tr>
<td>Brix % Juice</td>
<td>11.8</td>
</tr>
<tr>
<td>Sucrose % Juice</td>
<td>7.1</td>
</tr>
<tr>
<td>Invert (glucose, fructose) % Juice</td>
<td>2.8</td>
</tr>
<tr>
<td>Estimated F.S. % Feedstock</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Table 9 Input parameters and estimated fermentable sugars content on feedstock for the syrup production with the computer simulation for different feedstock treatments.

<table>
<thead>
<tr>
<th>Input</th>
<th>Feedstock Treatment (Trash % Feedstock)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RF (17%)</td>
</tr>
<tr>
<td>Brix % Juice</td>
<td>14.7</td>
</tr>
<tr>
<td>Sucrose % Juice</td>
<td>6.1</td>
</tr>
<tr>
<td>Invert (glucose, fructose) % Juice</td>
<td>3.7</td>
</tr>
<tr>
<td>Estimated F.S. % Feedstock</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Tables 10 and 11 present the results from the simulation of syrup production with sweet sorghum feedstock. The results showed that as the trash percentage in the feedstock increases, there was a decrease in the brix extraction (kg of dissolved solids in extracted juice / kg of dissolved solids in the feedstock) and in the fermentable sugars yield. In contrast, there was an increase in ash content in the syrup, the starch yield and in the energy consumption for the syrup production as the trash level in the feedstock increased. The fermentable sugars yields (level) in these results were higher than in the results presented in Figures 23 and 24 (Section 4.4.4) because the model had a tandem of six mills whereas the results presented in section 4.4.4, were calculated from the
experimental simulation of the juice extraction of one mill (three-times millings in the Farrel mill shown in Figure 9).

The results in Tables 10 and 11 suggested that an increase of at least 0.6% in brix extraction can be obtained by removing 10% of the trash level in the feedstock. The fermentable sugars yield on syrup from these simulations suggested that an increase of 20 kg/tonne of feedstock can be obtained by completely cleaning the feedstock. Moreover, the results indicate also that an increase in fermentable sugars yield of 0.2 to 13.4 kg/tonne of feedstock can be achieved for every 10% of the trash level in the feedstock removed. When comparing the RF vs. BP treatments and the BL vs. B treatments in Table 11, an increase of 0.8 to 0.9% of brix extraction and an increase in fermentable sugars yield of 1.9 to 8.6 kg/tonne of feedstock can be obtained by removing the leaves. Furthermore, by removing the panicles from the feedstock (RF vs. BL and BP vs. B), these results indicate that an increase of 0.1% of brix extraction and an increase in fermentable sugars yield of 1.4 to 8.1 kg/tonne of feedstock can be reached. In like manner, the previous ranges suggest that removing the leaves from the feedstock leads to a higher range of increase in brix extraction and in fermentable sugars yield than removing the panicles.

Table 10: Results from the simulations of a sweet sorghum syrup production factory for different levels of trash in the feedstock.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Trash % Feedstock level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RF (18%)</td>
</tr>
<tr>
<td>Brix extraction</td>
<td>%</td>
<td>95.0</td>
</tr>
<tr>
<td>Fermentable Sugars Yield</td>
<td>kg/tonne of feedstock</td>
<td>79.0</td>
</tr>
<tr>
<td>Ash % Syrup</td>
<td>%</td>
<td>4.5</td>
</tr>
<tr>
<td>Starch Yield</td>
<td>kg/day</td>
<td>5,781</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>kW</td>
<td>5,311</td>
</tr>
</tbody>
</table>
Table 11: Results from the simulations of a sweet sorghum syrup production factory for different feedstock treatments. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock as came from the field.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Feedstock Treatment (Trash % Feedstock)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RF (17%)</td>
</tr>
<tr>
<td>Brix Extraction</td>
<td>%</td>
<td>95.7</td>
</tr>
<tr>
<td>Fermentable Sugars Yield</td>
<td>kg/tonne of feedstock</td>
<td>78.4</td>
</tr>
<tr>
<td>Ash % Syrup</td>
<td>%</td>
<td>4.0</td>
</tr>
<tr>
<td>Starch Yield</td>
<td>kg/day</td>
<td>7,253</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>kW</td>
<td>5,346</td>
</tr>
</tbody>
</table>

The results on energy consumption on Tables 10 and 11 show the amount of energy required to produce the syrup for each different amount of trash in feedstock and for each different feedstock treatment. In general, there was an increase in energy consumption as the trash percentage in the feedstock increased. This was because as there was more trash in the feedstock, the fiber increased and the mills required more power in the turbines to process the feedstock and more imbibition water since the amount of imbibition water is a function of the fiber percentage in the feedstock. Further, as the trash increases and consequently the imbibition water, there is more juice in the process with lower purity, increasing in this way the amount of steam needed to heat up and evaporate the water to produce the syrup.

4.4.9 Basic economic analysis

Figure 27 illustrates the revenue obtained in the 60-days-harvest season of sweet sorghum from the fermentable sugars and the cogeneration. It also shows the total sum of both of these activities for the different amounts of trash in feedstock. The vertical axis presents the revenue in million dollars and the bars represent the different amount of trash in the feedstock. The results indicate that as the trash % feedstock increases, the revenue in fermentable sugars decreases but
the revenue in cogeneration increases. However, up to a level of 20% trash in the feedstock, the gains in cogeneration are not enough to cover the losses in the fermentable sugars in the entire harvest season and overall, the total revenue decreases from these two economic activities as the trash % feedstock increases. At the 30% trash percentage feedstock level, the revenue from cogeneration covers already the losses from the fermentable sugars revenue and the overall revenue start to increase.

![Figure 27: Estimated revenue from the fermentable sugars in sweet sorghum syrup and the cogeneration with the bagasse for different levels of trash in the feedstock. Also, the total revenue from these two economic activities.](image)

To put the revenue level of US$ 27.9 million from producing sweet sorghum syrup with the regular feedstock (RF 18%) in context with the revenue obtained by a sugar cane mill; if the facility process 17,000 tonnes/day of sugar cane during a 60 days harvest season producing raw sugar and blackstrap molasses. Assuming 3.75 tonnes of molasses produced per 100 tonnes of cane milled, a raw sugar yield of 105 kg per tonne of feedstock (Rein, 2007), a molasses price of US$ 150 / short ton (USDA Economic Research Service, 2017) and a raw sugar price of US$0.50 /kg. The revenue from the molasses would be US$ 5.7 million and the revenue from the raw sugar
would be US$ 53.5 million. The revenue of the sweet sorghum syrup is much higher than the revenue from the blackstrap molasses; however, it falls short when compared to the raw sugar revenue.

Figure 28 shows the revenue from the fermentable sugars and the cogeneration of the entire harvest season for different feedstock treatments in the same way as Figure 27. The Figure 28 indicates that the total revenue decreases when the feedstock is milled with any type of trash in any amount in between 2% to 17% when compared with the cleaned feedstock or B treatment with 0% trash. Although, the revenue losses are less perceptible than in Figure 27 because the difference in the amount of trash is less, it is clear the loss in revenue between the B treatment and the rest of the treatments. When analyzing the BP treatment or feedstock with billets and panicles, it presents a loss of revenue in fermentable sugars and in cogeneration from the B treatment. This was the only case where there was a loss in both of this products from all the different treatments and amounts of trash. This suggests that the panicles have the largest impact on revenue and their separation prior to milling should be strongly considered. In general, the results from the calculations suggest that separating the trash from the feedstock would cause an advantage by yielding higher economic gains. If the trash level in the feedstock is decreased from 20% to 0%, perhaps with the equipment proposed in this thesis, higher revenue gains would be obtained in the order of two million dollars in the entire season from selling the fermentable sugars and cogenerating electricity. In addition, if the panicles could be sold and the leaves could be used for cogeneration or to produce another value added product, then this difference in revenue would be even larger because all the separated trash from the 20% trash level to the completely cleaned feedstock would also generate a revenue.
Figure 28: Estimated revenue from the fermentable sugars in sweet sorghum syrup and the cogeneration with the bagasse for different feedstock treatments and different levels of trash. Also, the total revenue from these two economic activities. B = only billets; BP = billets + panicles; BL = billets + leaves; RF = regular feedstock.

The results from the simulations and revenue analysis indicated also that the revenue from the starch in the juice was very small compared to the revenue from the fermentable sugars and the cogeneration. For instance, the total starch yield in the harvest season obtained from the simulation ranged between 295,000 to 460,500 kilograms. If this starch is converted into glucose through hydrolysis with selected \( \alpha \)-amylases and glucoamylases (Eggleston et al., 2013), then the glucose would add to the fermentable sugars yield and consequently it would increase the total revenue from the entire harvest season in a range of between US\$ 106,000 to US\$ 166,000. This revenue from the starch in the syrup is small compared to the revenue from the fermentable sugars in the entire harvesting season that is in the order of low-double-digit millions, and the revenue from the cogeneration that is in the order of low-single-digit millions. It is important to mention that although the concentration of starch in the juice extracted for this work was in the low range of the concentration found by Smith (0.4 to 3.0%/°Brix) (Smith, 1969), the high range of starch
concentration would still lead to a comparably low revenue. On the other hand, an opportunity arises to obtain a higher revenue by separating the high-starch-content panicles. The revenue for an entire 60-days-harvest season from selling the grains of the panicles could reach US$ 1.7 million. In the case that an equipment like the prototype proposed in this work is built at an industrial scale to separate the panicles prior to milling with a selectivity of 10 and having 12 rollers to reach a panicles separation efficiency of 39% with 3.9% of billets lost, the revenue increase from using the panicles separator could reach US$ 396,500 in the entire harvest season. Table 12 shows the considerations for this revenue calculation.

Table 12: Estimated revenue from using a panicles separator with a selectivity of 10 for a 17,000 tonnes/day processing facility and a 60 days harvest season.

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue from selling the panicles</td>
<td>$ 649,480</td>
<td>*2% panicles in feedstock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*39% separation efficiency</td>
</tr>
<tr>
<td>Increase in revenue from removing 39% of the panicles in the feedstock</td>
<td>$ 1,163,755</td>
<td>*Calculated from the difference in fermentable sugars revenue between the BP and B treatments. (Figure 28)</td>
</tr>
<tr>
<td>Revenue loss from billets lost to the panicles</td>
<td>- $ 1,416,735</td>
<td>*3.9% billets lost.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Calculated from the fermentable sugars revenue of feedstock with 0% trash.</td>
</tr>
<tr>
<td>Total estimated economic advantage of the panicles separator in revenue</td>
<td>$ 396,500</td>
<td>*Revenue in the harvest season</td>
</tr>
</tbody>
</table>

This estimated economic advantage of the panicles separator could improve to US$ 1.02 million if all the panicles were separated. More importantly, the grain price is currently very low (4.9 US$/CWT) compared to the average price of 8.1 US$/CWT from 2007 to 2015 (USDA National Agricultural Statistics Service, 2017). This means that the grain price could double, leading to a much higher revenue by separating them from the feedstock.
CHAPTER 5. CONCLUSIONS

The results of the tests conducted with the pneumatic separator showed that the highest leaves separation efficiency is obtained at an air stream angle of 45° and that the air stream should be placed in the first 0.6 meters (2 feet) below the conveyor. The position of the splitter was of great importance to increase the leaves separation efficiency and minimize the billets lost to the trash. In any application of this pneumatic separator, it is highly recommended to install a movable system for the splitter in order to change it whenever is necessary. Further, it was also found that the leaves separation efficiency increased as the feedstock was passed through subsequent air streams and a leaves separation of close to 100% was possible with four air knifes in line. The panicles separator reached a selectivity of 9.5 ± 1 at 30° angle and 43 rpm with a panicles separation efficiency per six rolls of 13 ± 1%, demonstrating that it was possible to selectively separate the panicles.

The results from the milling experiments showed that the effect of the trash in the juice was less apparent when the difference in trash level was less than 10%. Furthermore, for every 10% of the trash level that was removed from the feedstock, the fiber % feedstock level decreased in a range of 1.8-2.8%. However, the amount of fermentable sugars in juice from feedstock with 18% trash was on average 75.6% of the total amount of fermentable sugars in the juice of the cleaned feedstock with 0% trash. The starch and the ash in the juice was higher when the trash level in the feedstock was more than 14% and 17% respectively, when compared to the starch and ash in the juice from cleaned feedstock. The concentration of the total amount of organic acids in the juice increased as the level of trash in the feedstock increased. The results obtained from the computer simulation indicated that by removing 10% of the level of trash in the feedstock, the brix extraction could increase by at least 0.6% and the fermentable sugars yield on syrup could increase
between 0.2 to 13.4 kg per tonne of feedstock. The results on the energy consumption necessary to produce the syrup showed that as the trash percentage in feedstock increased, the energy consumption increased as well, due to more fiber in the feedstock and more juice in the system to evaporate. The basic economic analysis showed that the revenue from the starch in the juice was small compared to the revenue from the syrup production and cogeneration. In addition, the analysis indicated that as the trash level in the feedstock increased, the revenue in fermentable sugars decreased but the revenue in cogeneration increased. However, the gains in cogeneration were not enough to cover the losses in the fermentable sugars in the entire harvest season and overall, the total revenue decreased from these two economic activities as the trash in the feedstock increased. By separating and selling 39% of the panicles in the feedstock, a revenue of 0.65 million dollars could be obtained. If perhaps, the trash is removed from a regular feedstock with 20% trash to an almost cleaned feedstock with close to 0% trash, a higher revenue from the syrup and cogeneration would be obtained in the order of six million dollars per harvest season for a company with a 60-days harvest season, milling 17,000 tonnes/day.
CHAPTER 6. FUTURE WORK

Further studies are needed to assess the efficiency of the air knife using exhaust steam instead of compressed air. The air knife could also be tested even with live steam at 220 psi or with a flow and pressure regulator. If the operation of the system and the efficiencies are positive, then the cost of operating the equipment would be decreased in the case where there is an excess of steam in the factories and separating the trash would become even more attractive. In order to increase the performance of the panicles separator, it would be interesting to simulate or to build a longer panicles separator with more rollers. Another idea would be to assess the performance of the panicles separator after increasing the width of the grabbers from the current 3.5 inches, which is based on the diameter of the big panicles, to 7 inches width, which is a width that would be based on the common length of the panicles harvested with a billets sugar cane combine. More studies are also needed on the chemical composition of the sweet sorghum leaves since there is scarce information in this sense. As presented in this work, the trash affects the juice extraction and one reason could be that the fiber especially on the trash, absorb the juice in a “sponge effect” that as a consequence, impacts negatively the milling quality, so it would be of good significance to develop a method to assess directly if the leaves and panicles in fact absorb juice or their impact in the juice extraction is just by dilution effect.
REFERENCES


VITA

Edgar J. Tobias was born in Guatemala City, Guatemala. In 2012 he was awarded a B.S. in Mechanical Engineering with a Business minor at Kun Shan University of Technology in the Republic of China, Taiwan. Later, he was awarded a B.S. in Mechanical Engineering at Universidad San Carlos de Guatemala, becoming a member of the national association of engineers of Guatemala. He began his professional career as assistant to the chief engineer at a sugar mill factory and thermoelectric plant. His interest in the sugar industry led him to aim for a specialization at the Audubon Sugar Institute. In April 2015, he was accepted into the Louisiana State University department of Biological and Agricultural Engineering with a position as a graduate assistant at the Audubon Sugar Institute. He anticipates graduating with his Master of Science degree in August 2017. He plans to continue in the sugar industry for many years to come.