PRODUCTION OF ETHANOL FROM SWEETSTEM SORGHUM AND TROPICAL SUGAR BEET FOR A RURAL COMMUNITY

Sanette Marx, Daphne Mutepe, Janine Brandling, Percy van der Gryp
Focus Area Energy Systems, School of Chemical and Minerals Engineering, North-West University, Private Bag X6001, Potchefstroom, 2520, South Africa
Tel: +27 18 299 1995, Fax: + 27 18 299 1535, Email: sanette.marx@nwu.ac.za

ABSTRACT: Rural communities in the North West Province of South Africa are among the poorest in the world with an average income of less than ZAR 8.75 (EU 0.875) per day. The South African government has committed itself to upliftment of these communities through job creation and joining of the first and second economies of the country. The Thusanang community project concept was initiated to stimulate job creation and skills development in our local communities through biofuels production. Water is scares in the North West Province with less than 200 mm of rain annually. Crops that do not threaten food security and require little water for energy production is thus favored for use as ethanol feedstock in this area. Sugar beet had been used as a source for sugar production for some time, but its development as a large scale agricultural crop in South Africa has been limited by the large production of sugarcane in tropical areas. Recent trials on tropical sugar beet production in the Eastern Cape and North Western regions of South Africa has shown promise for large scale production of tropical sugar beet for ethanol production. Sweetstem sorghum has attracted the attention of the biofuels world because of the potential of producing both food and ethanol in a single crop. The picture is not that simple though, since the plants usually contain large amounts of fermentable sugar during the flowering period, when the grains for food have not yet been formed, and then the sugar content steadily declines towards the time for harvesting of the grain. A trade-off thus needs to be found between food and energy production. The influence of various process parameters such as pH, initial sugar concentration, yeast concentration and nutrient addition on the ethanol yield obtained from sweet stem sorghum juice and tropical sugar beet juice was studied and the results is reported in this paper. The initial Brix index of the tropical sugar beet used was 21.8 wt% and 40.1wt% for the tropical sugar beet juice and the sweetstem sorghum juice respectively. All juice was fermented without prior filtering or sterilization. The highest initial sugar content was observed for the USA1 sweetstem sorghum cultivar harvested at 3 months (only energy production) and for the Hunni green sweetstem sorghum cultivar harvested at 6 months (food and energy production).
Keywords: Bioethanol, sweet sorghum, sugar beet, fermentation, yield

1 INTRODUCTION

Fossil fuels provide 80% of the primary energy needed worldwide and the combustion of fossil fuels accounts for 73% of worldwide carbon dioxide emissions (Nigam and Singh, 2011, Balat et al., 2008). The progressive depletion of fossil fuel resources, increasing energy demand and concern over greenhouse gas emissions has increased the research and development of alternative and renewable energy resources.

Transport plays a major role in the economic activity of South Africa and transport costs constitute approximately 20% of the gross domestic product (Singh, 2006). South Africa has an estimated oil reserves of 16 million barrels (Wabiri and Amusa, 2010) and proven coal reserves of 30 408 billion tons (BP statistical energy survey, 2010). South Africa has a coal based economy with the largest part of industrial and domestic electricity supplied through coal-fired furnace power plants. Most of South Africa's energy is generated in-land where the coal deposits are, which poses problems for delivery of electricity to remote rural communities.

Most rural and informal settlements are currently using paraffin and gathered wood as primary energy source for cooking and heating, because these settlements are either in remote locations which makes electricity supply difficult and expensive or because the poor that mostly occupies such settlements simple cannot afford electricity. Paraffin has been proven to be a health hazard (Schwebel et al., 2009:700) and the cause of many fires in informal settlements where the close proximity of dwelling to each other compounds the problem. To alleviate this problem, the South African government has embarked on a campaign to replace the use of paraffin with that of ethanol gel. The production of ethanol gel from bioethanol has the potential to create alternative off set markets for small farmer produce while also lowering carbon emissions.

The Biofuels Industrial Strategy of South Africa proposes a 2% market penetration of biofuels by 2013.

The aim of the Biofuels Industrial Strategy is ultimately to uplift and empower rural impoverished communities through the production of biofuels in communal environments. The Thusanang community project concept was initiated by the North-West University as a means of transferring research into practice while also supporting the goals of the Industrial Biofuels Strategy. Maize is a staple food for a large part of the population and can thus not be used for energy production. Tropical sugar beet and Sweetstem sorghum however are currently not cultivated on a large scale in South Africa if implemented correctly could be used as a source of food and energy in a rural community context.

Tropical sugar beet has a higher tolerance to a wide range of climatic variations, requires 30-40% less water and fertilizer to sugar cane and has a similar sugar yield as sugar cane (Chukauya et al., 2009). Sweetstem sorghum has the potential to be a source of both food (grain) and energy (sugar juice in stalks), but the grain and sugar yield depends on the time of flowering of the plant and thus also the harvesting time. In this paper, the potential of tropical sugar beet and sweetstem sorghum as a feedstock for ethanol production on a community scale level was investigated.

2 EXPERIMENTAL

2.1 Materials

Tropical sugar beet was obtained from the Agricultural Research Council of South Africa and Sweetstem sorghum was obtained from a local farmer.

The tropical sugar beet was chopped and juiced using and industrial juicer. The tropical sugar beet juice was used without further purification, filtering or sterilization.

Sweetstem sorghum juice was pressed from the stalks and used without further purification, filtering or sterilization. The composition of fermentable sugars of each of the juices used in this study is presented in Table I.

Table I: Sugar analysis of tropical sugar beet and sweet sorghum juice

	Sugar content (g.L^{-1})		
Sweetstem sorghum	**Sucrose**	**Fructose**	**Glucose**
USA1 (3 months)	318	25.24	57.98
USA1 (6 months)	27.37	44.32	47.33
Tropical sugar beet	**Sucrose**	**Fructose**	**Glucose**
Cultivar 3	4	111	103

Saccharomyces cerevisiae was obtained in dried form from Anchor Yeasts South Africa and constituted with the fermentation broth prior to use.

Sulfuric acid (98%, Labchem) and sodium hydroxide (98%, Fluka) was used to adjust the pH of the fermentation broth during fermentation. Peptone (8% total nitrogen, Fluka), Ammonium sulfate (99%, Fluka), Urea (98%, Sigma) and Yeast Extract (9-12% total nitrogen, Sigma) was used as nitrogen source during the investigation into the effect of nitrogen addition on the ethanol and glycerol yield.

2.2 Experimental procedure

In all instances a working volume of 50 mL of juice was used during the experiments. Fermentations were carried out in Scott Duran bottles in an incubator at 30°C for 12 to 48 hours at an agitation rate of 120 rpm.

Samples were taken at regular intervals for analysis of sugar, ethanol and glycerol content by High Performance Liquid Chromatography (HPLC). All sugar uptake curves showed that the simple sugars were consumed after approximately 3 hours and the ethanol yield sharply decreased after 12 hours of fermentation.

The Figures shown in this paper will thus only show the data up to 12 hours of fermentation for sweet sorghum and 24 hours for tropical sugar beet. Glycerol was the only by-product of fermentation that was observed in this study

2.3 Analyses

All samples taken during fermentations were filtered through a 0.45 μm and a 0.2 μm microfilter to remove all solids prior to analysis. All analyses were done using an Agilent Model 1206 HPLC fitted with a Shodex sugar column and a refractive index detector. HPLC grade water was used as mobile phase (0.75 ml.min^{-1}) with a column temperature of 75°C, a detector temperature of 55°C and an injection volume of 5 μL.

3 RESULTS AND DISCUSSION

The influence of process parameters such as initial sugar concentration, pH of the broth, yeast concentration and the addition of different nitrogen sources on the ethanol yield (g ethanol per g sugar) as well as the glycerol yield (g glycerol per g sugar) is presented in this study.

3.1 Influence of initial sugar concentration

The influence of initial sugar concentration on ethanol and glycerol yield from tropical sugar beet and sweetstem sorghum was investigated by diluting the raw juice obtained from the different feedstock. The sweetstem sorghum juices used was that obtained from the USA1 cultivar at a harvesting time of 3 months. The pH was kept constant at 4.5 and a yeast concentration of 1 g.L^{-1} was used in all instances with no additional nitrogen added to the broth. The influence of initial sugar concentration on the ethanol and glycerol yields (based on sugar present in the broth) is shown in Figure 1. The experimental error calculated for a 95% confidence level was 6.37% for the tropical sugar beet data and 2.93% for the sweetstem sorghum data.

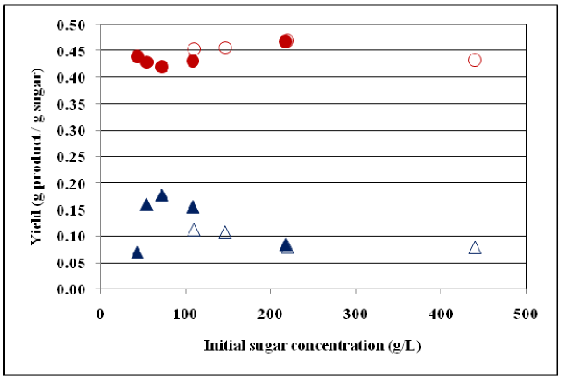

Figure 1: Influence of initial sugar concentration on ethanol and glycerol yield after 12 hours fermentation (● - ethanol (sugar beet), ▲ - glycerol (sugar beet), ○- ethanol (sorghum), Δ - glycerol (sorghum))

In each instance, the exact same amount of sugar juice with the same amount of initial sugar was used in the experiments. It has been shown (Munene et al., 2002, Dodic et al, 2009, Hinkova and Bubnik, 2001) that *Saccharomyces cerevisiae* experience significant osmotic effects when the sugar content is above 20%, which results in an increase in glycerol production at high initial sugar concentrations. This was observed for the sweetstem sorghum juice when the initial sugar concentration was lowered from 440 g.L^{-1} to 220 g.L^{-1}, but in all the other experiments the initial sugar concentrations were low enough that no osmotic pressure effects were observed. Lowering the initial sugar concentration by adding water really on had the effect of diluting the product concentration as shown in Figure 2.

Figure 2 show that product concentrations decreases linearly with a decrease in initial sugar concentration.

3.2 Influence of pH

The influence of pH during fermentation of tropical sugar beet juice and sweetstem sorghum juice was investigated without dilution of the raw juice with a yeast concentration of 1 $g.L^{-1}$ and no additional nitrogen added to the broth. The influence of pH on the ethanol and glycerol yields (g product per g sugar) obtained from tropical sugar beet and sweetstem sorghum is presented in Figure 3. The experimental error calculated for a 95% confidence level was 4.17% for the tropical sugar beet data and 3.7% for the sweetstem sorghum data.

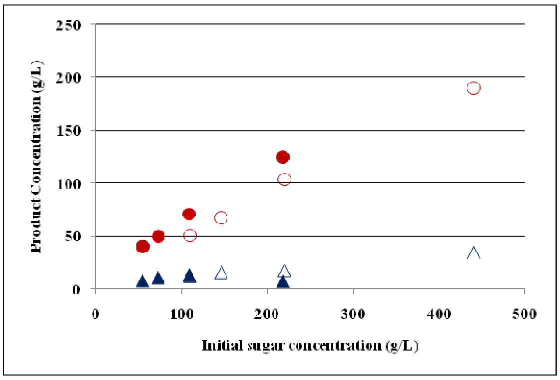

Figure 2: Effect of initial sugar concentration on ethanol and glycerol concentration in the fermentation broth after 12 hours of fermentation
(● - ethanol (sugar beet), ▲ - glycerol (sugar beet), ○- ethanol (sorghum), Δ - glycerol (sorghum))

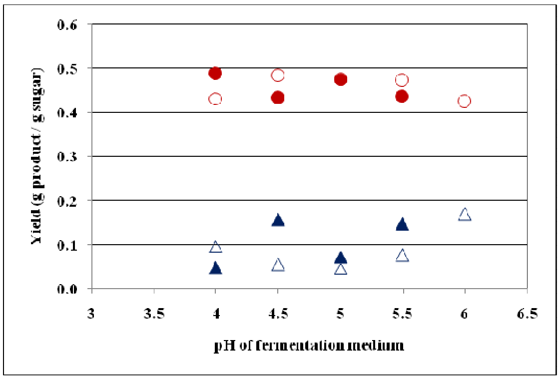

Figure 3: Influence of pH on ethanol and glycerol yield after 12 hours of fermentation
(● - ethanol (sugar beet), ▲ - glycerol (sugar beet), ○- ethanol (sorghum), Δ - glycerol (sorghum))

It would seem from Figure 3 that varying the pH of the fermentation broth between 4 and 6 had not significant effect on the ethanol yield, but a slight decrease in glycerol yield was seen at pH values of 5 and lower for the sweetstem sorghum data. The pH of the broth regulates the utilization of enzymes and nutrients by *S. cerevisiae*. From this data it is clear that a pH of approximately 4.5 gives a reasonable ethanol yield while producing the minimum amount of glycerol. When comparing the ethanol and glycerol yields of the two feedstock on a concentration bases (see Figure 4), the ethanol concentration obtained from sweetstem sorghum is much higher than that of tropical sugar beet, because the sweetstem sorghum juice contains more fermentable sugars (400 $g.L^{-1}$) than the tropical sugar beet juice (218 $g.L^{-1}$).

3.3 Influence of yeast concentration

The influence of yeast concentration during fermentation of tropical sugar beet juice and sweetstem sorghum juice was investigated without dilution of the raw juice at a pH of 4.5 and no additional nitrogen added to the broth. Yeast concentration should have an influence on the rate of ethanol production, but given enough time, all yeast concentrations should reach the same ethanol concentration. The juice sample used in these experiments was small (50 ml) and thus mass transfer limitations that is usually experienced in large unstirred fermentation tanks were not observed during experimentation. Sugar uptake curves (total sugar) for tropical sugar beet and sweetstem sorghum is shown in Figures 5 and 6 respectively. The experimental error calculated for a 95% confidence level was 2.6% for the tropical sugar beet data and 2.9% for the sweetstem sorghum data.

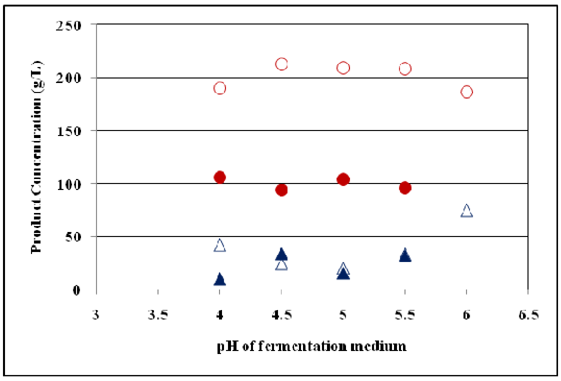

Figure 4: Influence of pH on ethanol and glycerol concentration after 12 hours of fermentation
(● - ethanol (sugar beet), ▲ - glycerol (sugar beet), ○- ethanol (sorghum), Δ - glycerol (sorghum))

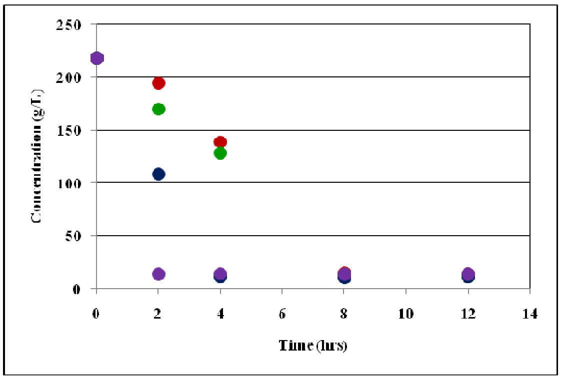

Figure 5: Sugar uptake curves for tropical sugar beet fermentation at different yeast loadings
(● - 1 $g.L^{-1}$, ● -3 $g.L^{-1}$, ● - 5 $g.L^{-1}$, ● - 10 $g.L^{-1}$)

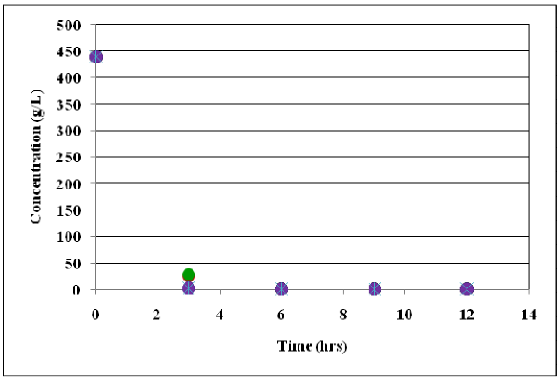

Figure 6: Sugar uptake curves for sweetstem sorghum fermentation at different yeast loadings
(• - 1 g.L^{-1}, • -2 g.L^{-1}, • -3 g.L^{-1}, • - 4 g.L^{-1}, • - 5 g.L^{-1})

The uptake of sugars was much faster for the sweetstem sorghum juice (3 hours) than for the tropical sugar beet juice (8 hours). All the sugars were utilized in the sweetstem sorghum fermentations, but during the tropical sugar beet fermentations the fructose present in the broth (approximately 10 g.L^{-1}) was not utilized by the yeast. There is no ready explanation for this phenomenon. Ethanol and glycerol production curves at a yeast loading of 3 g.L^{-1} for tropical sugar beet and sweetstem sorghum is compared in Figure 7.

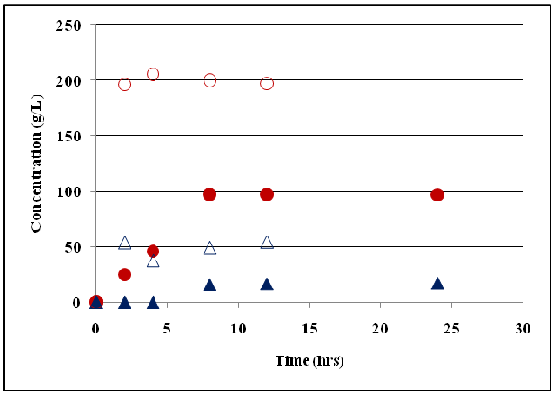

Figure 7: Ethanol and glycerol production curves at a yeast concentration of 3 g.L^{-1}
(• - ethanol (sugar beet), ▲ - glycerol (sugar beet), ○- ethanol (sorghum), Δ - glycerol (sorghum))

The fast production of ethanol from the sweetstem sorghum juice (within the first 3 hours of fermentation) seen in Figure 7 relates to the fast uptake of sugars in Figure 6. The higher ethanol concentration for the sweet stem sorghum compared to that of tropical sugar beet correlates with the higher initial sugar concentration of the sweetstem sorghum broth. The ethanol and glycerol yields of tropical sugar beet and sweetstem sorghum are compared in Figure 8.

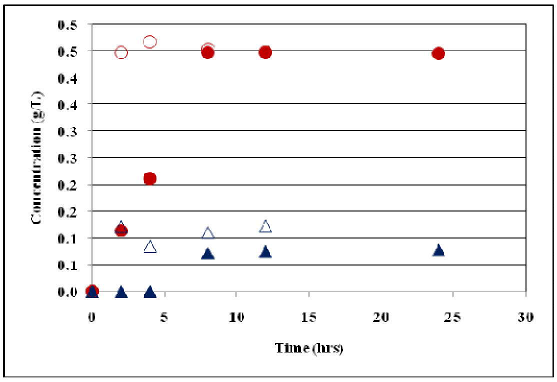

Figure 8: Ethanol and glycerol production curves at a yeast concentration of 3 g.L^{-1}
(• - ethanol (sugar beet), ▲ - glycerol (sugar beet), ○- ethanol (sorghum), Δ - glycerol (sorghum))

It is interesting to note that at the same yeast concentration, the two crops both give approximately the same ethanol yield after 12 hours of fermentation. The sweetstem sorghum have produced significantly more glycerol than the tropical sugar beet through. The explanation for this lies in the production of glycerol as a protection mechanism for the cells. Glycerol production takes place during fermentation to protect the cells from lyses and to help maintain the NAD^{+}/NADH balance (Aili and Xun, 2008). Sugar is utilized very quickly in the sweetstem sorghum fermentation and fast uptake of a large amount of sugar will place stress on the cells. The natural protection process will shift production towards glycerol instead of ethanol to ensure that enough energy is produced to maintain the cells as well as ethanol production during the rest of the fermentation time. In the case of tropical sugar beet, sugar uptake is much slower and the cells are not put under the same amount of stress when compared to sweetstem sorghum.

Mass transfer limitations did not play any role in these experiments since the sample sizes used were very small (50 ml) and the fermentation broths were continuously stirrer. Any changes in mass or concentration yields are thus changes that were effected by a change in one of the process parameters.

3.4 Influence of nitrogen supplementation

In influence of the addition of different sources of nitrogen as nutrient during fermentation was investigated by adding nitrogen sources such as ammonium sulfate, peptone, yeast extract and urea to the fermentation broth.

Yeast requires a constant supply of assimilable nitrogen as it plays a role in the structure and function of the cell (Junior et al., 2008). It has been shown that the addition of nitrogen to the fermentation broth can increase biomass production as well as increase sugar utilization (Beltran et al., 2005, Zayed and Foley, 1987, El-Refai et al, 1992). The ethanol and glycerol yields obtained for each of the different nitrogen sources added at a concentration of 750 mg.L^{-1} compared to a blank fermentation where no additions nitrogen was added is presented in Figure 9. The experimental error calculated for a 95% confidence level was 1.4% for the tropical sugar beet data and 3.7% for the sweetstem sorghum data.

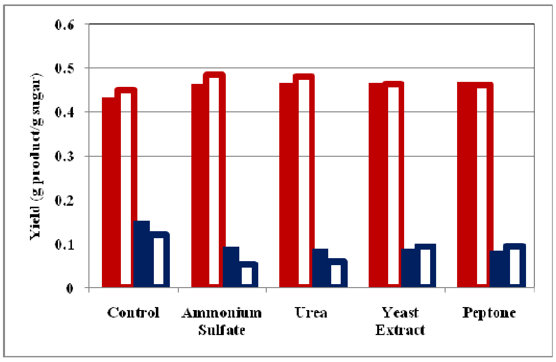

Figure 9: Influence of addition of different nitrogen sources on the ethanol and glycerol yield after 12 hours of fermentation
(■ - ethanol (sugar beet), ■ - glycerol (sugar beet), □- ethanol (sorghum), □ - glycerol (sorghum))

The ethanol yield was significantly increased with the addition of all the nitrogen sources used. The most significant effect of the addition of nitrogen to the fermentation broth was in the lower glycerol yields that were obtained with ammonium sulfate resulting in the lowers glycerol yield for both tropical sugar beet and sweetstem sorghum fermentation. The ethanol yield from sweetstem sorghum benefitted more than the ethanol yield from tropical sugar beet from the addition of a nitrogen source in the cases when ammonium sulfate and urea were used as nitrogen sources. Ammonium sulfate and urea contained more nitrogen per mass than yeast extract and peptone and the nitrogen within these chemicals are said to be more assimilable than the nitrogen in peptone and yeast extract (Mendes-Ferreira et al, 2004). The sugar uptake rate during tropical sugar beet fermentation was increased as all the sugars were utilized after 4 hours as compared to 8 hours when no addition nitrogen is added.

4 CONCLUSIONS

The results from this study show that both tropical sugar beet juice and sweestem sorghum juice from crops cultivated in the Northwest Province of South Africa can be used for the production of ethanol. Initial sugar concentration had little effect on ethanol and glycerol yield except for diluting the concentrations of the products. The pH value of the broth also did not significantly influence the ethanol yield obtained from both crops, but a pH of 4.5 is recommended because the lowers glycerol yield was observed at this pH value.

Yeast concentration has a significant effect on the time for completion of the fermentation as well as the amount of glycerol being formed. The addition of different nitrogen sources had a significant effect on the glycerol yield with the lowest glycerol yield obtained when ammonium sulfate was added to the fermentation broth for both crops. An average yield of 150 tons of sugar beet roots per hectare was reported in a trial in the Northwest Province, while an average yield of 6.3 tons of sweet sorghum stalks was reported at 3 months harvesting for the USA1 cultivar. An average of 500 kg of juice can be obtained per ton of biomass for both tropical sugar beet and sweetstem sorghum. A total sugar yield of 16.35 and 1.39 ton sugar /hectare can thus be obtained for tropical sugar beet and sweetstem sorghum respectively. The highest ethanol yield obtained for tropical sugar beet and sweetstem sorghum respectively was 0.46 g ethanol/g sugar and 0.48 g ethanol/g sugar. A total ethanol yield of 7.52 ton/ha and 0.67 ton/ha can thus be obtained in a single season. Tropical sugar beet can only be harvested once per year while two crops of sweetstem sorghum can be harvested. If the assumption is made the both crops will have the same sugar content, then the yield from sweetstem sorghum can be doubled to 1.2 ton ethanol/ha. From these results the conclusion can be made that tropical sugar beet is the better crop for ethanol production, but sweetstem sorghum has the advantage that food can also be produced together with the ethanol, making sweetstem sorghum a better choice for sustainable ethanol production without compromising food security.

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