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Assessment of Sweet Sorghum as a Feedstock for a Dual Fuel Biorefinery Concept

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In the field of sustainable biorefinery concepts, sorghum receives increasing attention as a raw material. Main advantages of various sorghum types are fast growth as well as efficient nutrient and water utilization. When considering the competition between food and energy crop production, sorghum could be part of a sustainable solution. Through a convenient integration in a crop rotation system, sorghum could be grown as an alternative crop with good harvest results within a short vegetation period. In cooperation with a biogas plant in lower Austria, the potential of sorghum as a resource for fuel and energy production was evaluated. Field tests were carried out, and for a certain period of time, a sweet sorghum variant was incorporated into the substrate mixture of a biogas plant to monitor the process. Three concepts for grain and sweet sorghum variants were simulated in ASPEN Plus® to assess the coproduction of bioethanol and biogas in one facility and compared to the crops ethanol potential and conventional biofuel processes. The future growing conditions for this crop were evaluated on a climatologic basis for the Lower Austrian region in question. The highest harvest yields were achieved in the first year of testing, highlighting the dependency on cultivar and weather conditions. The sorghum processes could compete against the established processes, reaching up to 92 % ethanol, 107 % DDGS, 80 % methane and up to 202 % of their total energy output. Climatologic evaluation shows, that more regions in Austria will become available for sorghum cultivation due to climate change.

1. Introduction

Sorghum is a C4 plant, therefore its water use efficiency is very good compared to other field crops (Geng 1989). An additional advantage is that sorghum roots grow very deep and therefore are able to take up water from deeper soil levels (Zegada-Lizarazu, 2012). As only 1st generation ethanol production is investigated in the course of this study, sugar or starch is needed as the main source for fermentation. In the case of sorghum both can be produced. There are variants that form free sugars that can be fermented directly to ethanol. Other variants build up grain with a high starch content which can also be fermented after a saccharification step (Rooney, 2007). Concerning the technology required for the cultivation of sorghum, existing machinery from maize cultivation can be used. The presented work was carried out in the framework of the “BiSunFuel” project, which is aimed to assess the potential for sorghum as an energy crop in Austria.

2. Materials and Methods

2.1 Field Tests

In the course of this project, planting experiments with different sorghum varieties were carried out. A special focus was laid on the opportunity of growing sorghum as a side crop. Therefore, the seeding dates were varied between May in the first year, at the beginning of June in the second year and at the end of June and beginning of July in the third year of the experiment. In the first year (2011) two sugar producing

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(Sugargraze I, SG I & Sugargraze II, SG II) and one starch producing (Chopper, C) varieties, in the second year (2012) two sugar producing varieties (Sugargraze I & Nectar, N) and in the third year (2013) two starch producing varieties (Supersol, SU & GK Emese, GKE) were examined.

2.2 Climatological Evaluation

Since the project behind this study focuses on energy and fuel production for a community in lower Austria, the harvest yield security when using sorghum as a raw material had to be assured. The following minimum climatic requirements were defined using literature research (EURALIS, 2013 and FNR, 2007) and crop modelling: soil temperature in June > 12 °C, minimum air temperature (June - September) > 4 °C and sum of degree days (June – October) > 2,500 °C. Since sorghum bicolour originates from arid subtropical climates, temperature is the limiting factor. For evaluation of potential cultivation regions the INCA dataset was used for current climate and bias corrected and localized Regional Climate Models - RCMs (Aladin, RegCM3, REMO) for future climate conditions. Eventually maps for current and future potential cultivation regions in Austria were drawn.

2.3 Biogas plant Monitoring

A local biogas plant (400 m³ biogas/h, 630 kWel) in Margarethen am Moos, Lower Austria, was monitored from early May to late July 2013. A simple flowsheet of the plant is shown in Figure 1.
Substrate feed and composition, electric consumers' power demand and operating time, the produced biomethane, biogas, and electricity were monitored in order to establish mass and energy balances.

2.4 Simulation of Sorghum Process Concepts

Process variants were developed and presented previously (Weinwurm, 2013). Different concepts were designed to accommodate the specific properties of grain and sweet sorghum cultivars. Two benchmark variants were also considered, which were considered completely independent biogas and bioethanol plants with corn silage and corn grain as feedstock, . The process variants are pictured in Figure 2. While the data for the benchmark scenario were taken from literature, the sorghum process variants were simulated with the software ASPEN Plus® V7.3.2 (Aspen Technology Inc., 2012) incorporating experimental date or, when not available, literature values. To meet project requirements, the available field area and plant scale had to be matched to the existing biogas plant. The benchmark biogas case (a) consists of the harvesting of silage maize, which is ensiled on site and used to continuously produce biogas throughout the year. The benchmark bioethanol case (b) is a conventional first generation corn ethanol process with a production capacity of 100,000 tons ethanol per year. The grain sorghum process variant (c), utilizes the "Chopper" variety, which exhibits a rather high starch content of the grains. The ensiled straw is used for biogas production, which was in all cases calculated according to VDI 4630 (2009), and the grains are dried and transported to a central ethanol plant (100,000 t/y capacity) for ethanol production. As a by-product, DDGS, which is a valuable fodder for livestock, is obtained. The concepts d) and e) were designed for use with the Sugargraze I cultivar. Sweet sorghum plants form a glucose-rich juice that can be used directly for ethanol fermentation. To prevent sugar loss through microorganisms after exposition of the juice to the environment after harvesting, the plants are stabilized by addition of formic acid to a concentration of 1 % (Schmidt et al., 1997).

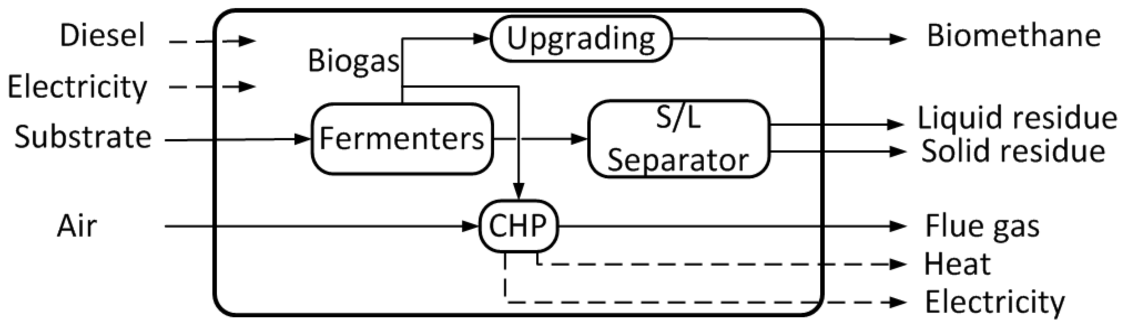

Figure 1: Flow sheet of the monitored biogas plant

In process variant d), the whole plant is fed into a solid state fermenter after stabilization and size reduction. A yeast load of 4 g/kg fresh material (Rohowsky et al., 2011) and a sugar to ethanol conversion of 90.5 % is assumed (Li et al., 2013). A mainly lignocellulosic solid fraction will remain which is separated by pressing to a dry matter content of 50 %. The liquid at this stage contains about 2.8 % (by weight) of ethanol. The separated solids are washed, and the liquid fractions combined for distillation. For the last concept, the parameters of concept d) were reused, if applicable. The sugar juice is obtained in a milling process described by Dias et al. (2009) under the addition of fresh water where 96 % of the sugar is recovered. The sugar juice is fermented to ethanol (90.5 % conversion rate), distilled and purified further. The washed press cake is again used for biogas production.

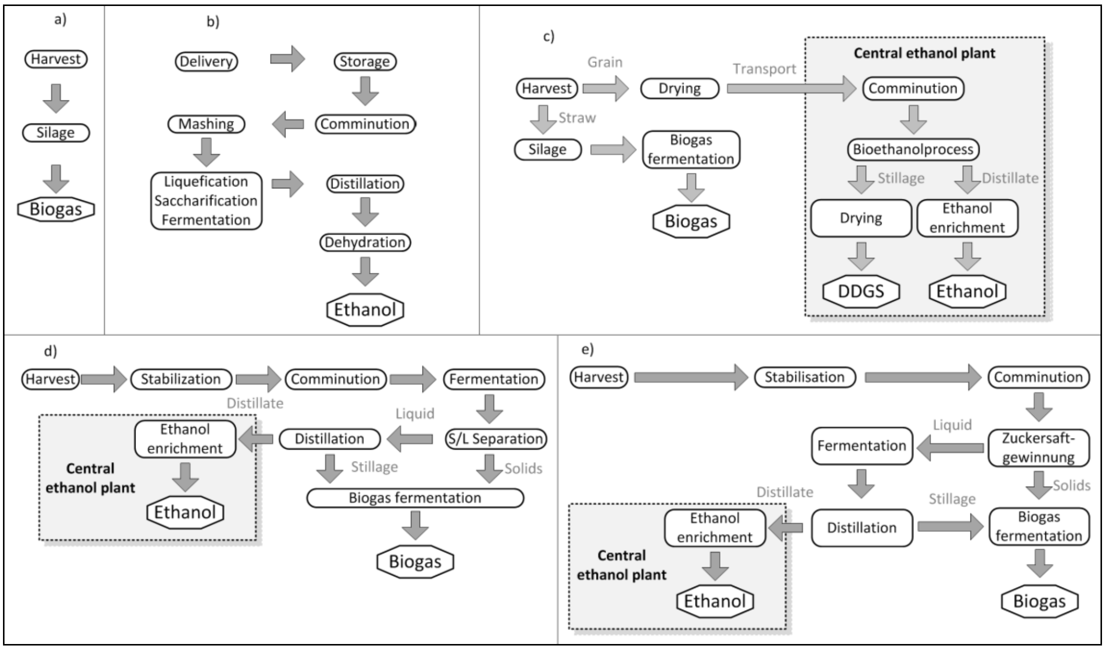

Figure 2: Evaluated process concepts: a) Benchmark Biogas variant, b) Benchmark Ethanol variant, c) Grain sorghum variant with separate grain and straw utilization, d) Sweet sorghum variant with whole plant fermentation, e) Sweet sorghum variant with separate juice fermentation

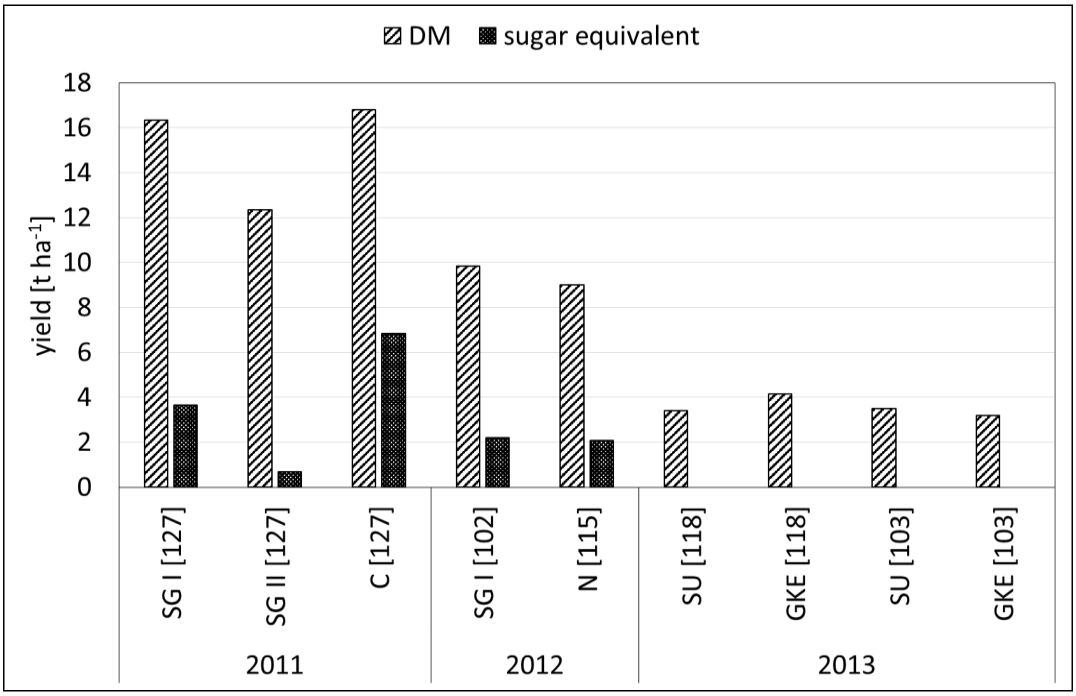

Figure 3: Dry matter (DM) and sugar yields for the sugar forming sorghum varieties Sugargraze I (SG I), Sugargraze II (SGII), and Nectar (N), and the starch forming varieties Chopper (C), Supersol (SU) and GK Emese (GKE). Vegetation days are indicated in brackets

3. Results

3.1 Field Tests

The experiment in the first year showed that the sorghum variety “Chopper”, which is a grain variant, would be the most promising option for ethanol production. The sugar forming varieties showed similar biomass yields but the lower sugar content leads to a lower ethanol yield. In the second year of the experiment, the seeding date was moved to the 15th of June. Due to slow growth at the beginning of the vegetation period, the maximum yields were about 60 % of those from the first year. As the starch variety showed the highest potential in the first year, it was decided to investigate two starch varieties with two seeding dates in the third year of the experiment. The first seeding date was the 25th of June and the second was the 6th of July. As the summer in 2013 was extraordinary dry and hot, yields remained very low. The analysis of the grain showed that there was no yield that would have been relevant for ethanol production. The harvest yields are shown in Figure 3.

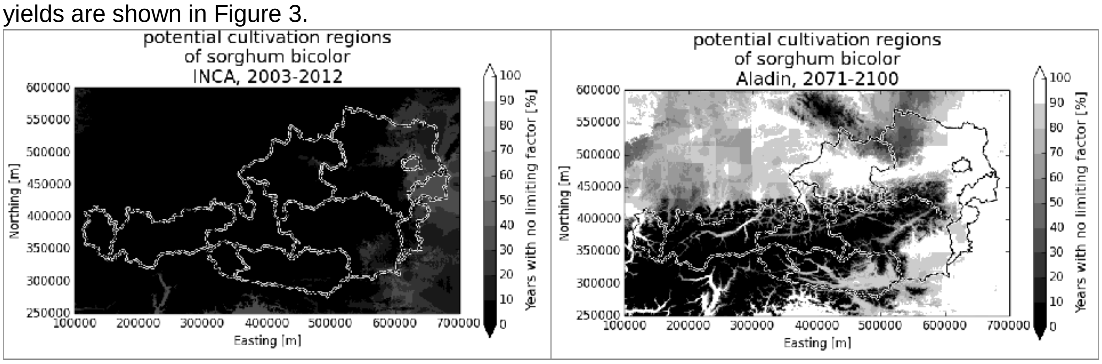

Figure 4: Potential cultivation regions (light shading) under current climatic conditions (INCA-dataset, 2003 – 2012) (left) and by end of the century (Aladin RCM, 2071 – 2100) (right)

3.2 Potential cultivation regions

Under current climatic conditions, only the flatlands in east most Austria and around Lake Constance are suitable for cultivation of sorghum bicolor in most years. The most critical factor is the high vulnerability to temperatures below 4 °C. However, due to climate change, more low regions become potential sites for cultivating sorghum bicolor as can be seen in Figure 4.

Table 1: Biogas plant mass balance

	Substrate	Biogas to CHP	Biomethane	Residue	Sum	Difference
Input (kg/h)	2,425.5				2,425.5	
Output (kg/h)		353.5	1.2	2,014.3	2,369.0	56.5

Table 2: Process yields and gains

	Benchmark processes		Sorghum processes		
	Bioethanol	Biogas	GS	SS-WPF	SS-SJF
Specific yields					
Ethanol (kg/t TS)	377.91		317.07	97.22	93.83
CH4 (kg/t TS)		240.93	206.32	168.88	172.66
DDGS (kg/t TS)	373.26		362.97		
Total Energy (kWh/kg TS)	2.82	3.35	2.57	3.07	3.10
Total annual yields					
Ethanol (t/y)	702.00		648.72	332.64	321.04
CH4 (t/y)		959.17	297.92	577.85	590.78
DDGS (t/y)	693.36		742.64		
Total Energy (GWh/y)	5.24	13.32	8.98	10.51	10.60

GS: Grain Sorghum process, SS-WPF: Sweet Sorghum – Whole plant fermentation, SS-SJF: Sweet Sorghum – Separate Juice Fermentation

3.3 Biogas plant Monitoring

The mass balance was based on the data for substrate input, biomethane output and biogas flow to the CHP unit. No measurement of the flue gas could be established, so the CHP unit was taken out of the mass balance. Lacking a flow measurement of the fermentation residue, we estimated the residue via the experimentally determined biogas potential, and therefore the consumed volatile solids (data not shown) to close the balance. All streams were averaged and considered constant over the monitoring period. The substrate consisted of grass (4.3 % of the total VS (volatile solids)) input, sorghum (30.7 %), beet greens (5.3 %), green rye (7.1 %), alfalfa (5.5 %), corn straw (36.6 %), horse manure (6.1 %), and liquid manure (4.6 %). Measurements and estimates resulted in the Balance in Table 1. The difference between Input and Output of 56.6 kg/h equals 2.3 % of the biomass input. It includes gas losses, moisture in the flue gas, all other losses, as well as measuring and rounding errors.

3.4 Simulation of Sorghum Process Concepts

Preliminary simulation results have been previously presented (Weinwurm, 2013). Since then, the simulation the concepts has been completed, and a number of assumptions had to be adjusted. The specific product yields (kg product per ton dry input) of methane, pure ethanol and dry DDGS and total annual yields were calculated. Energy yields were also calculated based on the lower heating value of the produced ethanol and methane. All calculated yields are shown in Table 2.

For the benchmark bioethanol plant, average harvest yields for Lower Austria were assumed (Bader and Kriesel, 2012). Ethanol and DDGS yields were taken from Friedl (2012). The biomethane yield was assumed to be 240.9 kg/t TS, in the middle of the range reported by Englert et al. (2009). As can be seen in Table 2, the specific ethanol yield with GS is lower than with the benchmark process (84 % of the benchmark value) and the methane yield is also somewhat lower (86 %), while the specific DDGS yield in GS was calculated to be 97 % of the benchmark yield.GS is quite competitive due to the coproduction of bioethanol and biogas which combined yield roughly 77 % of the specific energy output of the benchmark biogas process. The specific ethanol, methane and energy yields from the sweet sorghum variants only reach up to 26 %, 72 % and 93 % with the SS-SJF process. In terms of total annual production, the GS process can partially compete with the classic processes. Ethanol production reaches about 92 % and DDGS production reaches 107 % of the benchmark maximum, but is still outperformed by the benchmark biogas process with a combined energy output of 67 % of the benchmark value. The sweet sorghum processes reach up to 80 % of the benchmark biogas, and 202 % of the benchmark ethanol process' energy output. Theuretzbacher et al. (2012) presented the ethanol potential for several crops which was compared to the simulated yearly production from the available field area (Figure 5). Utilizing the sweet sorghum variety SG I, the simulated sweet sorghum processes yielded 80 % of the plants ethanol potential (410.4 t/y). The GS process seems to be highly efficient, reaching 97 % of the potential ethanol production.

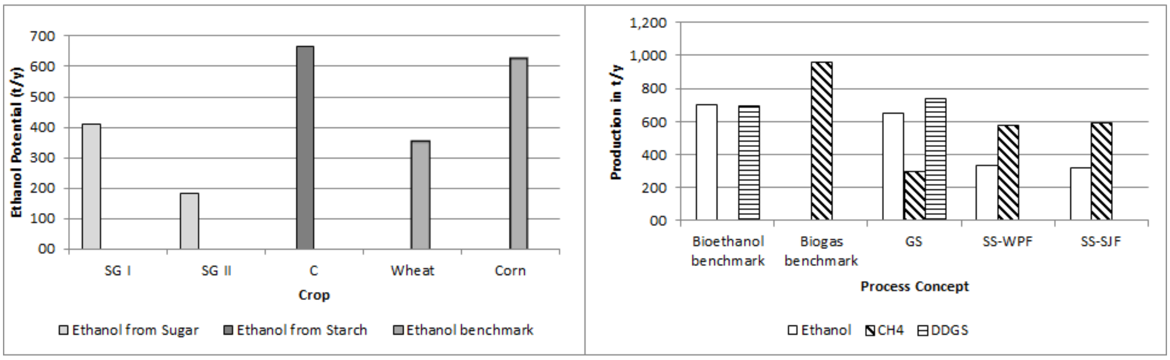

Figure 5: Annual ethanol potential of different crops (left) and simulated product gains (right)

4. Conclusions

The results show that sweet sorghum could be utilized in small scale, decentralized plants to provide fuel and energy in an ethanol and biogas coproduction plant. Grain sorghum straw could be a viable option to produce some biogas locally, and use the efficiency of a central bioethanol production site for the sorghum grains. It is interesting, that all proposed concepts yield a higher combined Energy than the established benchmark ethanol process which may be a result of omitted data in the sources. It was shown that both cultivar and climate strongly affect sorghum as a viable future option for decentralized energy supply.

Acknowledgement

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