

BIOLOGICAL HYDROGEN PRODUCTION FROM SWEET SORGHUM BY THERMOPHILIC BACTERIA

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ABSTRACT: Sweet sorghum cultivation was carried out in South-west Greece. The fresh biomass yield was about 126 t/ha. Stalks weight accounts for 82% of total crop weight while leaves and panicle account for 17% and 1%, respectively. The major components in variety 'Keller' stalks were, based on dry weight, sugars (45%), (hemi)cellulose (35%), lignin (9%) and ash (3%). This means that per hectare, 14.5 ton sugars is produced for hydrogen fermentation. Hydrogen fermentations by the extreme thermophilic bacterium, *Caldicellulosiruptor saccharolyticus*, using sweet sorghum juice as carbon and energy substrate showed that it is an excellent substrate with a H₂ yield of 58% of the theoretical maximum at a maximal production rate of 21 mmol/L.h. Besides the sugary juice, 15 ton/ha bagasse (dry weight) is obtained from the sweet sorghum crop. The pre-treatment of bagasse for increasing biomass fermentability was optimised. After hydrolysis with commercial enzymes, 37 g glucose and 26 g xylose from 100 g bagasse could be obtained which corresponded to conversion efficiencies of 60% for cellulose and 100% for xylan. Defined media with glucose, xylose or a mixture corresponding to the sugars in the sweet sorghum bagasse hydrolysate supported growth and hydrogen production by *Caldicellulosiruptor saccharolyticus*. The theoretical production in the complete bioprocess under consideration from the 14.5 t sugars/ha could amount to 1.3 ton hydrogen/ha and to 2.1 ton when the bagasse is also converted to hydrogen.

Keywords: Sweet sorghum, biological hydrogen production, de-centralized energy generation

1 INTRODUCTION

The application of fuel cells is gaining an increasing interest in the world of energy production. The advantages of fuel cells are clear: the energy conversion is more efficient as compared to traditional energy conversion systems and emission is zero. However, when the feedstock for fuel cells, hydrogen, is derived from fossil fuels the process as such is not regarded as sustainable because of its contribution to the increase in carbon dioxide.

Biomass is one of the renewable resources that enable a sustainable hydrogen production. The focus of this study is on the biological conversion of biomass to hydrogen. The best-known, but often not recognized, site of biological hydrogen production is in the production of biogas [1]. Here bacteria convert organic matter to lower metabolites like organic acids, carbon dioxide and hydrogen. This hydrogen is immediately consumed by methanogenic bacteria, and methane is the final end-product which becomes available. By decoupling hydrogen production from methane production, a complete conversion of the organic matter to hydrogen can be realised. The first step in this process is the fermentation of organic matter to hydrogen and acetic acid. This is done using thermophilic bacteria which are highly efficient and prevent growth of methanogenic bacteria. The second step is the conversion of acetic acid in the effluent of the thermophilic reactor to hydrogen (Fig. 1) [2]. Because of unfavourable thermodynamics of this reaction, extra energy must be provided. By using photo-heterotrophic bacteria which obtain energy from light and organic matter, this drawback is overcome. The distinctive merit of the biological conversion is the

efficient production of very pure hydrogen from wet biomass.

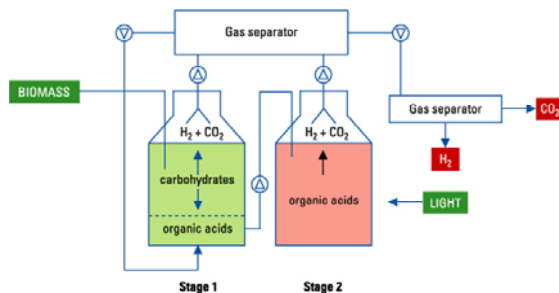


Figure 1: Two-stage bioprocess for hydrogen production from biomass

The raw material studied here is sweet sorghum which is under serious examination as a potential European energy crop. It is a C₄ crop, with a fibrous root system that branches profusely. Under favorable conditions, the above ground nodes may produce strong adventitious roots that may help to anchor the plant and reduce lodging; the roots can be extended to a distance of up to 1 m and a depth of 1.8 m. Sweet sorghum plants attain a height of up to 4 m. It is well adapted to the warm southern regions of Europe and moderately well adapted to several central European regions with mild climates. It is a cold sensitive plant, so its adaptation in northern, cooler climates is poor. Historically, syrup production was the main use of sweet sorghum, but nowadays this crop is gaining attention as a potential alternative feedstock for energy and industry, because of its high yield in biomass and, particularly, fermentable

sugars. Sweet sorghum can be converted into energy carriers through either one of two pathways: biochemical and thermo-chemical. Through biochemical processes the crop sugars can be converted to biofuels (ethanol, hydrogen). Thermo-chemical processes such as combustion and gasification can be used for the conversion of the sweet sorghum bagasse (the residual cake from crop pressing) to heat and electricity [3]. Pulp for paper, compost, and composites materials are some other products that can also be derived from sweet sorghum bagasse.

In this paper experimental data on the crop and the conversion to hydrogen by thermophilic bacteria are presented. These data are the basis for determining the potential of sweet sorghum for hydrogen production in a two-stage bioprocess since here the intrinsic properties of the biomass feedstock are most important. The second stage of the bioprocess is mainly affected by light penetration which determines the photochemical efficiency. This fermentation is much less dependent on the biomass parameters and will be addressed elsewhere.

2 RESULTS AND DISCUSSION

2.1 Feedstock

As Figure 2 indicates, biomass yields in the EU are significantly affected by the latitude.

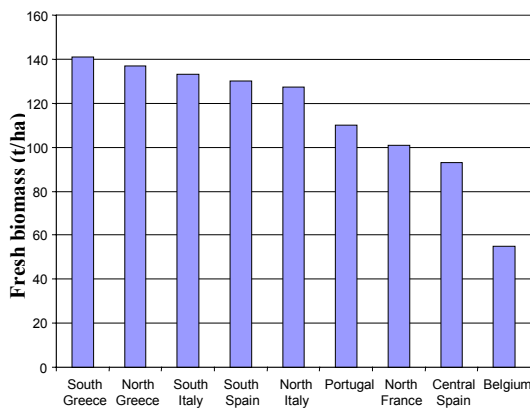


Figure 2: Total fresh biomass yields of sweet sorghum in various EU regions.

During the first 50 days after planting in May, sweet sorghum grows really slowly. After this period the crop height increases exponentially. At the end of August stalks were 4.20 m and total fresh matter was 126 t/ha. Table I shows the composition of sweet sorghum variety 'Keller' and Table II the cost for growing this crop.

2.2 Sweet sorghum juice

Stalks were cut to 5-10 cm pieces and then milled. Three different procedures were tested in order to produce the juice which was used as substrate for hydrogen production: 1) pressing; 2) pretreatment and pressing; 3) water extraction and pressing the residue. For the pretreatment a central composite design was applied with four design factors, namely the temperature and the duration of the pretreatment, the pressure and the amount of water added to the sample before pressing.

Table I: Composition of sweet sorghum variety 'Keller' in ton/ha.

Component	Weight (t/ha)
Sugars	14.5
(Hemi)cellulose	11.1
Lignin	2.8
Others	2.9
Ash	0.9
Total	32.1

Table II: Sweet sorghum cultivation cost in Greece.

	Cost (Euro/ha)
Land	208
Seeds	22
Fertilizers	230
Harvesting	150
Water	150
Tillage	88
Labour costs	60
Total	908

The quantity and the quality of the substrate depended on the sugar extraction procedure that has been used. With the first procedure the resulting juice had a sugar concentration of 108 g/l, but 25-30% of sweet sorghum total sugars remained in the bagasse. With the second procedure the quantity of sugars remaining in the bagasse was reduced, but the sugar concentration of the juice was maximally 89 g/l. With the third procedure up to 98% of total sugar present in sweet sorghum stalks could be extracted. The sugar concentration of the resulting juice was 9,8 g/l. Fermentability tests showed that the juice produced in all these procedures is suitable for hydrogen production.

2.3 Sweet sorghum bagasse

The sweet sorghum bagasse contained approximately 55% glucan (cellulose), a relatively large amount of xylan (20%), and a small portion of arabinan, about 2%. The lignin content of the bagasse, 17% of dry matter, was considerably high. The ash content was found to be 1.5%.

For the pretreatment of the bagasse two alternative solutions were evaluated based on the hot water cooking treatment. In the first case alkaline (sodium-hydroxide), and in the second case acidic (sulfuric acid) catalyst was applied. Prior to pretreatment the bagasse was fractionated and the fractions having a particle size between 0.32 – 0.64 mm were used in the experiments. In a 1-litre flask 55 g (50 g dry matter) sweet sorghum bagasse was treated at 110°C in a pressure cooker for 2 hours together with 445 g aqueous solution of either 2 wt-% NaOH or 2 wt-% sulfuric acid. The washed fiber was enzymatically hydrolyzed with Celluclast 1.5L and Novozym 188 (Novozymes, Denmark). The results of the enzymatic hydrolysis are shown in Table III. The best results were obtained after the alkaline pretreatment where 37.1 g glucose, corresponding to a 60% cellulose conversion, was obtained from 100 g of original bagasse. Xylan conversion was 100% in both cases where pretreatment was applied.

Table III: Enzymatic hydrolysis of pretreated sweet sorghum bagasse obtained from stalks.

	Pretreatment		
	none	alkaline	acidic
Glucose (g/100 g)	15	37	24
Cellulose conversion (%)	27	60	37
Xylose (g/100 g)	2	26	26
Xylan conversion (%)	7	100	100

2.4 Fermentation of sweet sorghum juice

The average production rate of hydrogen in cultures of *C. saccharolyticus* growing on sweet sorghum juice was approximately 10 mmol/L.h during the first 16 hours with a maximum production rate of 21 mmol/L.h at 10 hours after the start of the fermentation (Fig. 3).

Caldicellulosiruptor saccharolyticus preferred the utilisation of sucrose and fructose above glucose. After 16 hours growth had stopped, but hydrogen production continued although at a much lower rate (2 mmol/L.h). This may have been caused by limitation of one of the medium components or by-product inhibition. In the first part of the fermentation lactate was also formed, probably caused by the high pH₂ in the culture fluid due to the fast production of hydrogen in the first 16 hours. The production of lactate stopped when the production of hydrogen decreased. The production of biomass was 3 g/L. The final yield of H₂ per consumed C₆ sugar was 58% of the theoretical maximal obtainable in this thermophilic fermentation (4 mol H₂/mol C₆).

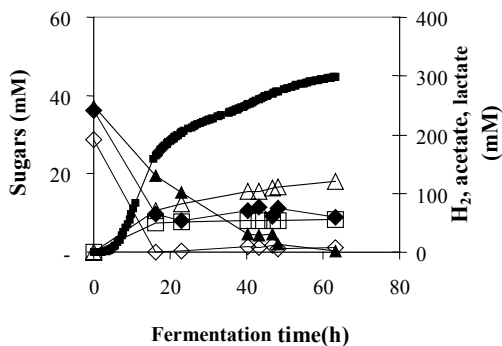


Figure 3: Growth and H₂ production by *C. saccharolyticus* on sweet sorghum juice. Hydrogen: ■; acetate: △; lactate: □; sucrose: ▲; glucose: ◆; fructose: ◇

2.5 Fermentation of (hemi)cellulose derived sugars

Caldicellulosiruptor saccharolyticus was grown on glucose, xylose or a mixture of these substrates to test its ability to ferment a hexose and pentose sugar representative of sugars in bagasse hydrolysate. All cultures showed vigorous growth and hydrogen production to high efficiencies (Table IV). The utilisation of glucose and xylose was virtually simultaneous. Without correction for lactate or biomass production, the obtained hydrogen yields were 63, 67 and 61% of the maximum theoretical yield on glucose, xylose and the mixture of glucose and xylose, respectively.

Table IV: Utilisation of hexose and pentose as model substrates by *Caldicellulosiruptor saccharolyticus* for hydrogen production.

	Glucose	Xylose	Glc+Xyl
Consumed	54 mM	62 mM	34+14 mM
Produced			
H ₂ (mmol/L)	143	138	113
Acetate (mM)	81	73	63
CO ₂ (mmol/L)	81	80	65
Lactate (mM)	2	6	15
Biomass (g/L)	2	2	1

2.6 Potential of sweet sorghum for hydrogen production in a 2 stage bioprocess

The potential production of hydrogen from sweet sorghum was calculated assuming efficiencies that seem presently within reach for the thermophilic fermentation as well as the consecutive fermentation by photoheterotrophic bacteria. This meant that for the fermentative conversions, efficiencies of 80% of the theoretical maximum were used in the calculations. For the production of biomass, the data obtained with growing the crop in Greece were used. The efficiency of bagasse hydrolysis was kept at the achieved 70% for (hemi)cellulose. The results are shown in Figure 4. In terms of combustion enthalpies, the initial 32.1 ton sweet sorghum, represents 546 GJ, at 17 GJ/ton dry matter. On the other hand, the production of 2.1 ton hydrogen is worth 298 GJ, assuming the higher heating value of 142 GJ/ton H₂.

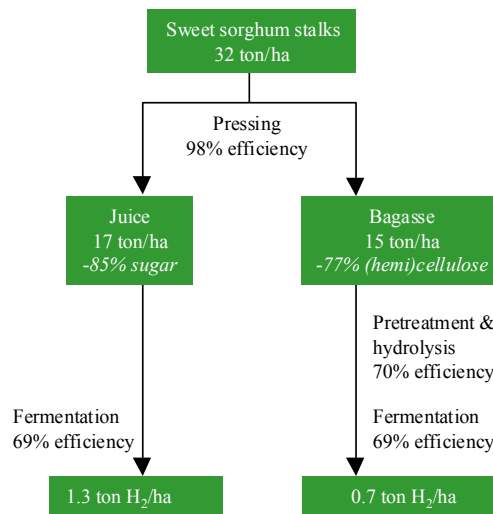


Figure 4: Flow sheet for hydrogen production from sweet sorghum with efficiencies which are realistic in the medium to long term.

This means that 55% efficiency is obtained in converting biomass to hydrogen. This figure is an initial estimate. Several contributing data have still to be established, as e.g. the energy consumption for crop production or during the pretreatment of the bagasse, or in the bio-process. These may reduce the final efficiency.

On the other hand, the calculation has been based on the combustion enthalpy of dry matter which obviously needs to be corrected for the energy consumption during the drying of sweet sorghum.

If 2.1 ton of hydrogen/ha is produced with one crop of sweet sorghum per year, the productivity would amount to 0.24 kg hydrogen/ha.h. The aim of a bioprocess for hydrogen production from biomass is hydrogen production at small, decentralised communities. Previously [2], the goal was set at production plants with a productivity of 40 kg hydrogen/h, which would enable the supply of electricity in approximately 2000 households. Such a plant would need to be supplied by the harvest of 166 ha of sweet sorghum in Greece, and proportionally more when this crop is grown at suboptimal latitudes.

3 CONCLUSION

The biological production of hydrogen in a 2-stage bioprocess shows great promise to convert biomass such as sweet sorghum to a pure hydrogen stream. Future optimisations should address, besides increased performance of the micro-organisms and system efficiency, research and development of process parameters such as bioreactors design. Furthermore, full integration of all process units from well-to-wheel, including e.g. logistics and location of the feedstock production, and the final implementation in society will need to be addressed.

4 REFERENCES

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