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Review

Sorghum as a renewable feedstock for production of fuels and industrial chemicals

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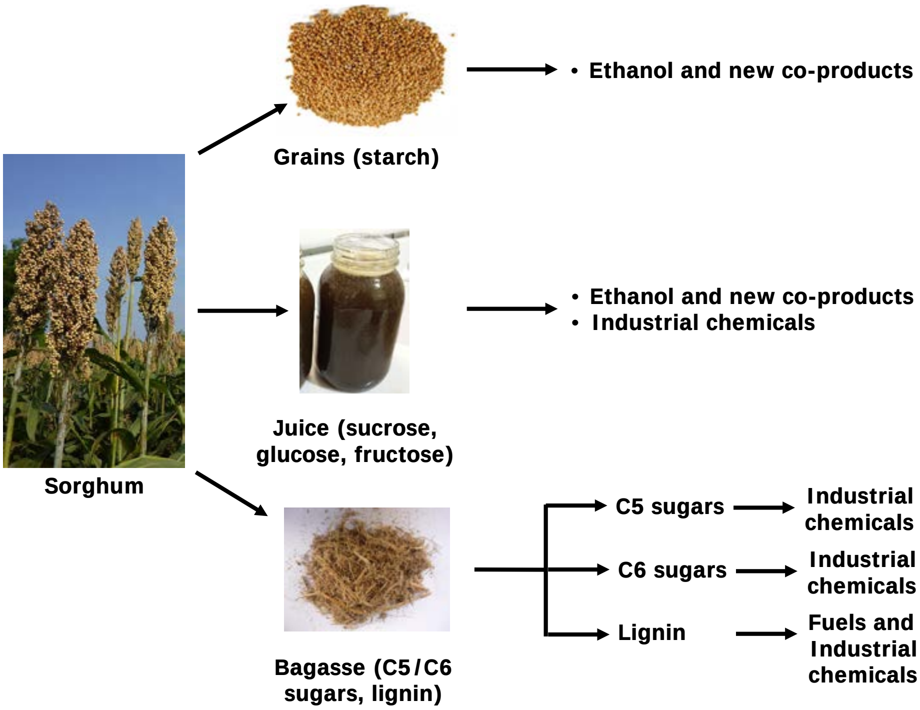
Abstract: Considerable efforts have been made in the USA and other countries to develop renewable feedstocks for production of fuels and chemicals. Among these, sorghum has attracted strong interest because of its many good characteristics such as rapid growth and high sugar accumulation, high biomass production potential, excellent nitrogen usage efficiency, wide adaptability, drought resistance, and water lodging tolerance and salinity resistance. The ability to withstand severe drought conditions and its high water usage efficiency make sorghum a good renewable feedstock suitable for cultivation in arid regions, such as the southern US and many areas in Africa and Asia. Sorghum varieties include grain sorghum, sweet sorghum, and biomass sorghum. Grain sorghum, having starch content equivalent to corn, has been considered as a feedstock for ethanol production. Its tannin content, however, may cause problems during enzyme hydrolysis. Sweet sorghum juice contains sucrose, glucose and fructose, which are readily fermentable by *Saccharomyces cerevisiae* and hence is a good substrate for ethanol fermentation. The enzyme invertase, however, needs to be added to convert sucrose to glucose and fructose if the juice is used for production of industrial chemicals in fermentation processes that employ microorganisms incapable of metabolizing sucrose. Biomass sorghum requires pretreatment prior to enzymatic hydrolysis to generate fermentable sugars to be used in the subsequent fermentation process. This report reviews the current knowledge on bioconversion of sorghum to fuels and chemicals and identifies areas that deserve further studies.

Keywords: Sorghum; renewable feedstocks; ethanol; industrial chemicals; biorefinery.

Graphical abstract:



1. Introduction

Millions of years were needed by nature to create gas, oil, and coal, but as soon as they were discovered, we have burned them at alarming rates. Now there is no doubt that fossil fuels are not sustainable [1]. Since the 1970's, there has been considerable interest in the development of technology for production of fuels and industrial chemicals using renewable feedstocks. The liquid fuel that has received the most attention was ethanol. The two countries with the largest fuel ethanol production are the USA and Brazil. The annual ethanol outputs in the USA and Brazil in 2014 were 99.1 billion liters (14.3 billion gallons) and 23.4 billion liters (6.2 billion gallons), which accounted for 58.2% and 25.2% of the total world production, respectively [2]. In addition to ethanol, higher alcohols that potentially can be produced from renewable resources also have attracted significant interest [3–6]. A recent report by the U.S. Department of Energy [7] identified and ranked compounds that can be produced from renewable feedstocks and used as precursors for production of important industrial chemicals and consumer products. Many attempts have been made on the development of microbial strains and commercially feasible fermentation processes for production of the compounds identified in this report. One example is the joined effort by several U.S. Department of Energy's laboratories on the development of the technology for production of succinic acid [8–10], which finally has reached commercialization [11]. It is anticipated that other compounds will follow succinic acid on the path toward commercialization in the not-so-distant future.

Whereas corn is the major feedstock for ethanol production in the USA, sugarcane is used for that purpose in Brazil. In industrial fermentations for production of chemicals such as amino acids and organic acids the main substrate is glucose, which is derived from corn. Considerable efforts have been made in the USA and other countries to develop feedstocks other than corn and sugar cane for production of fuels and chemicals. Among these, sorghum has attracted strong interest because of its many good characteristics such as rapid growth and high sugar accumulation [12], high biomass production potential [13], excellent nitrogen usage efficiency [14], wide adaptability [15], drought resistance [16], and water lodging tolerance and salinity resistance [17]. The ability to withstand severe drought conditions and its high water usage efficiency make sorghum a good renewable feedstock suitable for cultivation in arid regions, such as the southern US and many areas in Africa and Asia. Sorghum varieties include grain sorghum, sweet sorghum, forage sorghum and high-tonnage (energy) sorghum [18]. There have been several reviews written on the use of sorghum as a potential renewable feedstock. Most of these reviews focused almost exclusively on production of ethanol [19–23] and did not cover works on the use of sorghum-derived sugars for production of industrial chemicals in sufficient detail. In this report, we review the studies that have been reported in the literature and at conferences on the use of sorghum as feedstocks for production of fuels and industrial chemicals in biochemical conversion processes. Grain sorghum and sweet sorghum juice are considered separately whereas sweet sorghum bagasse, forage sorghum and high-tonnage sorghum are considered together under the topic of sorghum biomass since they all contain cellulosic materials (cellulose and hemicellulose) as the major sources of fermentable sugars for conversion to useful products. Finally, a biorefinery concept for production of fuels and chemicals using sorghum feedstocks in an integrated process is discussed and areas where additional research is needed are identified.

2. Grain Sorghum

The range of chemical composition of grain sorghum kernels of 70 genotypes and hybrids is shown in Table 1 [24].

Table 1. Range of chemical composition of grain sorghum kernels.

Composition	(%, dry basis)
Starch	64.3-73.8
Fiber	1.41-2.55
Protein	8.19-14.02
Oil	2.28-4.98
Ash (minerals)	1.46-2.32

The high starch and protein contents, which are equivalent to those of corn, have attracted attention to grain sorghum as a feedstock for ethanol production. In 2014, 433 million bushels of grain sorghum were produced in the USA, of which 16% was used in 12 commercial plants to produce 168 million gallons (636 million liters) of ethanol [25]. This quantity, however, was still a rather modest fraction (4.5%) of the total ethanol production of 14.3 billion gallons in the USA in that year [26]. The details of the commercial fermentation process are not publicly known. However, it is believed that in these ethanol plants, grain sorghum is used as an adjunct and blended with corn rather than being used as the sole feedstock. The potential of grain sorghum for use as a feedstock in commercial ethanol production also has attracted interest from several research groups. Wu et al. [24] and Wang et al. [27] used 70 grain sorghum genotypes and elite hybrids to study the factors that affected ethanol production in a dry-grind fermentation process employing 23 wt% dry solid (based on total mass of the mash) and commercial starch hydrolytic enzymes. It was found that the two factors that positively affected the final ethanol yield were starch content and protein digestibility. Higher protein digestibility led to higher levels of free amino nitrogen (FAN) available to the yeast. According to Wang et al. [27], the final ethanol yield and fermentation efficiency could be related to starch content (from 64.3 wt% to 73.8 wt% on dry basis) and protein digestibility by the following linear relationships:

$$\text{Ethanol (\% by volume)} = 0.22 \times \text{Starch content (\% dry basis)} - 2.03 \ (R^2 = 0.82)$$

$$\text{Fermentation efficiency (\%)} = 0.16 \times \text{Protein digestibility (\%)} + 82.51 \ (R^2 = 0.91)$$

In a more recent study, it was found that the amount of completely hydrolyzed starch was a better indicator for predicting ethanol yield than the total starch content [28]. Wu et al. [24] also found that increase of the tannin content had a strong negative effect on the process efficiency. Since sorghum tannin has the ability to interact with proteins [29], high tannin contents could significantly reduce the efficiency of the starch hydrolytic enzymes. High tannin contents also caused increase in viscosity of the mash [24], which could adversely affect enzyme efficiency during starch liquefaction and nutrient availability during fermentation. Since tannins are located mostly in the pericarp and testa layers of the sorghum grains, decortication could reduce the tannin contents and improve fermentation efficiency [30]. Decortication also allowed higher starch loading resulting in higher final ethanol concentrations [30] and concentration of high-value phytochemicals with antioxidant activities in the collected bran fractions [31]. In the dry-grind ethanol process, distillers dried grains with solubles (DDGS) is the most important co-product. In their decortication study, Corredor et al. [30] also observed that increase in degree of decortication significantly increased the protein content of the DDGS, which would give it a higher value. On the other hand, decortication resulted in lower total amount of DDGS produced per unit mass of the initial grain sorghum feedstock. In addition to decortication, other methods for tannin deactivation using either acids or bases [32, 33] potentially can also be used to improve grain sorghum fermentation efficiency. The effects of these tannin deactivation methods on ethanol yield and fermentation efficiency, however, have not been investigated. Published research results on grain sorghum ethanol production to date have only focused on the use of grain sorghum as the sole feedstock. Future research efforts should be directed toward the effect of using grain sorghum and corn mix at various ratios on the fermentation process performance, the quality of the DDGS co-product, and the overall commercial plant economics.

Most of the research on the use of grain sorghum as a feedstock for production of fuels and chemicals has been focused on ethanol fermentation. There have been only a small number of published reports on the use of grain sorghum for production of chemicals. Zhan et al. [34] investigated the production of lactic acid from extrusion-cooked grain sorghum using *Rhizopus oryzae*. In a 5-liter bioreactor with pH and temperature control using a simple salt medium and grain sorghum substrate at 15 wt%, the final lactic acid concentration obtained at 72 hours was 42.3 g/L. Fang and Hanna [35] studied the production of levulinic acid using whole kernel sorghum grains blended with 2%, 5% and 8% aqueous solutions of sulfuric acid. The maximum yield of levulinic acid was achieved at 200^{o}C, 8% sulfuric acid and 10% substrate loading. Valuable products can also be obtained from the DDGS co-product of grain ethanol fermentation, for example, extraction of kafirin (main storage proteins in sorghum) with acetic acid, HCl-ethanol and NaOH-ethanol mixtures under reducing conditions [36].

3. Sweet Sorghum Juice

The stalks of sweet sorghum contain a sugar-rich juice, which can be used in various fermentation processes. Brix is a crude measure of sugar content in sweet sorghum juice based on total dissolved solids. Since sugar contributes the majority of dissolved solids in sweet sorghum juice [37], the actual total sugar content can be related to the Brix measurement (^{o}Brix) by a linear relationship such as the one determined by Guigou et al. for the range of 12.2 to 18.6 ^{o}Brix [38]

$$\text{Total sugar (g/L)} = 12.6 \times {}^{o}\text{Brix} - 43.1\ (R^2 = 0.96)$$

The total sugar content of the juice varies widely with growing conditions and locations. Although the sugar content of sweet sorghum juice is highly variable based on factors such as variety, climatic conditions, and maturity, it is typically in the range of 60–250 g/L with an average of 185 ± 40 g/L (Figure 1).

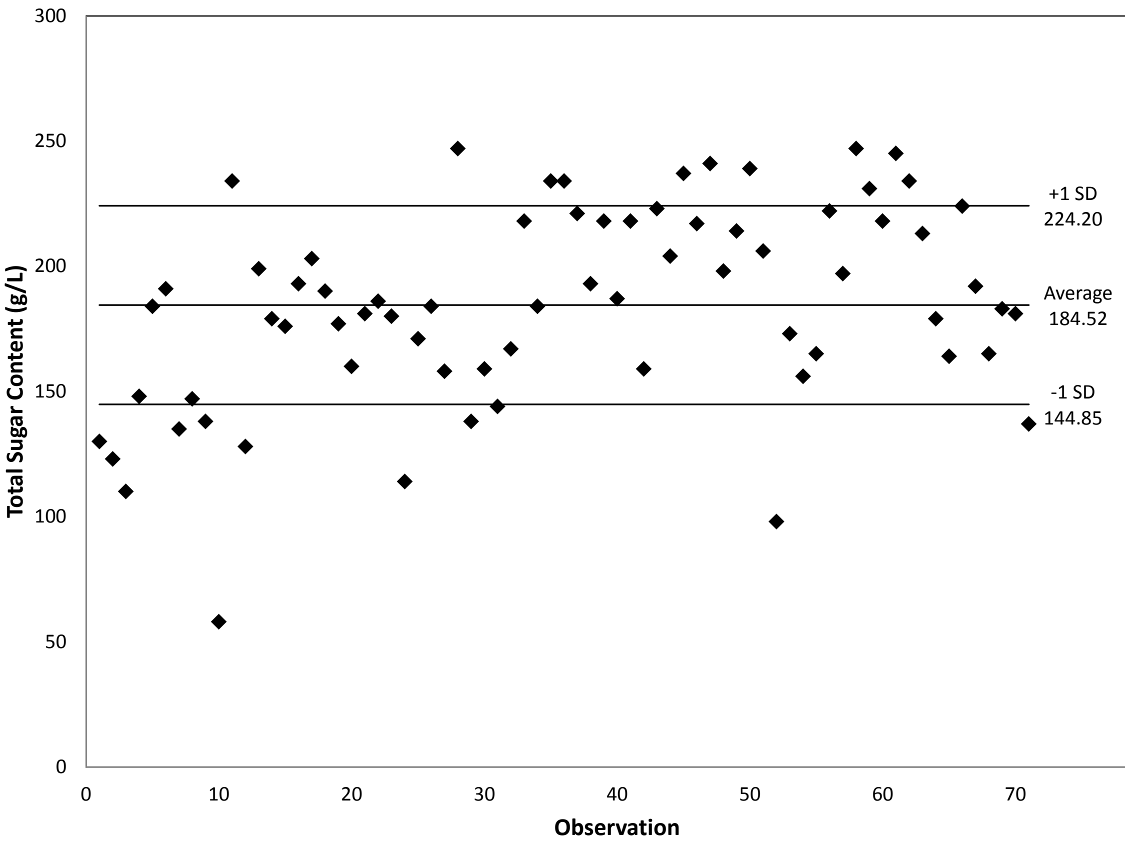


Figure 1. Total sugar content of sweet sorghum juice from a variety of sources [19, 38, 39, 40, 41*, 42*, 43, 44*, 45, 46, 47*, 48, 49*]. *Data was presented as °Brix and converted to% using the formula developed by Guigou et al. [38].

The major sugar in the juice is sucrose with glucose and fructose making up the rest. All of these sugars are readily fermentable by the yeast *Saccharomyces cerevisiae* for ethanol production.

Sucrose is not metabolizable by some microorganisms of industrial interest, e.g. the succinic acid-producing *Escherichia coli* strain AFP184 [50]. Upon treatment with heat and the enzyme invertase, sucrose is converted to glucose and fructose, which can be used by virtually all industrial microorganisms. Sweet sorghum juice also contains several elements, many of which are required for microbial activities. An example of concentrations of the individual sugars, mineral contents, and other characteristics are listed in Table 2 and Table 3 [43]. The juice can be squeezed out of the stalks using equipment similar to those used for extracting sugarcane juice. Because of the relatively high fiber contents in sweet sorghum, the sugar extraction efficiency is expected to be lower than that for sugarcane [47]. Using a laboratory-scale mill it was shown that the efficiency of sweet sorghum juice extraction and total sugar recovery depend on whether the whole plant, plant without panicle, or just stalk (i.e. plant without panicle and leaves) is processed (Table 4) [38]. The results of other studies on sweet sorghum juice extraction have been reviewed by Eggleston et al. [23].

Table 2. Characteristics of sweet sorghum juice (KKU 40 from Mitr Phu Viang Sugar Mill, Thailand) [43].

Constituents	Contents
pH	4.9
Total soluble solids (°Brix)	18
Total sugars (g/L)	173.02
Glucose	20.85
Fructose	16.8
Sucrose	124.05

Table 3. Mineral contents of sweet sorghum juice (KKU 40 from Mitr Phu Viang Sugar Mill, Thailand) [43].

Constituents	Contents (ppm)
NH^{4+}-N	21.4
NO^{3-} -N	4.4
Total P	20
Total K	1790
Total Na	170
Total S	120
Total Ca	166
Total Mg	194
Total Fe	2
Total Mn	3
Total Cu	0.3
Total Zn	1.4

Many investigators have studied ethanol production from sweet sorghum juice. Both suspended cultures and immobilized yeast cells have been investigated for ethanol production from sweet sorghum juice [39,42–45,51]. In commercial practice, because the sugars in sweet sorghum juice are readily fermentable, the juice cannot be stored in its native state without losses of sugar, and subsequently ethanol. Thus, it must be fermented immediately upon harvest, or stabilized in such a way that allows for medium to long-term storage for later fermentation. In the first case, juice will only be available for a short period of time during harvesting, forcing a sweet sorghum fuel ethanol plant to seek alternative feedstocks such as sugarcane juice or be idle for much of the year. To alleviate this, juice may be concentrated to very high sugar concentrations, such that natural fermentation will be largely prevented due to osmotic stress, and then stored for year-round use. The additional processing required to achieve this will impose significant costs, both in terms of capital cost and process energy and water usage, to a fuel ethanol plant. The effects of these additional costs on the overall economics should be carefully considered in the process design and plant operation.

Table 4. Juice extractability and total sugars from sweet sorghum varieties using different post-harvest treatments [38].

Variety	Post treatment [1]	Juice extractability (%)[2]	Total sugars in Juice (g/L)
M81-E	W	35 ± 2	130 ± 21
	WP	43 ± 2	123 ± 10
	S	48 ± 2	110 ± 7
Topper	W	40 ± 1	148 ± 17
	WP	37 ± 2	184 ± 4
	S	39 ± 2	191 ± 13
Theis	W	35 ± 3	135 ± 5
	WP	43 ± 2	147 ± 18
	S	47 ± 1	138 ± 7

(1) Notes: W: the whole plant; WP: the plant without panicle; S: the stalk (plant without panicle and leaves).

(2) Grams of juice recovered per 100 g material milled.

In the case where fresh juice is utilized without concentration, ethanol levels in some cases may be too low for recovery by distillation. To avoid excessive use of energy in distillation, the ethanol concentration in the fermentation broth should be at least 50 g/L [52]. Since the theoretical yield of ethanol from sweet sorghum juice sugars is 0.51 g ethanol/g sugar, and assuming 90% fermentation process efficiency, the sugar content in the juice should be at least about 110 g/L. Therefore, juices having sugar content below that level must be supplemented, for example, with addition of syrup, to raise the sugar content to the desired level. An alternate solution to overcome the aforementioned challenges is a hybrid process wherein fresh sweet sorghum juice and corn are co-fermented, eliminating the need for concentration and storage of the juice. During the period of time in which juice is not available, corn may be utilized as the primary feedstock for the plant. Because sweet sorghum juice is readily fermented, only minor changes to an existing corn ethanol facility should be required to implement such a process. Nghiem et al. [53] used sweet sorghum juice to prepare a corn mash at 19 wt% solids and achieved the same ethanol yield as should be obtained with 30 wt% corn mash using water for mashing, which is the typical process condition employed in a commercial dry-grind corn ethanol plant. In other words, by using sweet sorghum and corn co-fermentation a 37% reduction in the quantity of corn needed was achieved. Recently reported economic modeling results indicated that a conventional corn dry-grind ethanol facility that switches entirely (i.e. *without* co-fermentation) to freshly harvested juice fermentation during time of juice availability will operate at an economic advantage over year-round corn fermentation [54]. Because co-fermentation of corn and juice will result in a higher ethanol concentration, costs associated with distillation should be reduced, improving this advantage. As an added benefit, it is likely that fuel ethanol produced from sweet sorghum juice will be classified as an advanced biofuel under the Renewable Fuels Standard, allowing it to be sold at an advantage over conventional biofuels such as purely corn-derived ethanol. In addition to studies that focused solely on the fermentation process, several investigators also conducted techno-economic studies on the use of sweet sorghum as a feedstock for ethanol production. Linton et al. [55] examined the potential use of sweet sorghum as feedstock for ethanol production in the southeastern US. Similar studies have been conducted to address the technical, economic, social, and environmental issues related to the use of sweet sorghum for ethanol production in Africa, China and India [47,49,56–58].

Sweet sorghum juice has also been investigated as a potential feedstock for production of industrial chemicals such as lactic acid [59], docosahexaenoic acid (DHA) [60], poly-β-hydroxybutyrate [61], butanol [62,63], hydrogen [64] and succinic acid [65]. As discussed previously, unlike the yeast *Saccharomyces cerevisiae*, which is used in commercial corn and sugarcane ethanol production, many industrial microorganisms cannot metabolize sucrose. Thus, invertase must be added to convert sucrose to glucose and fructose, which are readily fermented by all industrial microorganisms via glycolysis. For example, Hetényi et al. [59] observed significant increases of lactic acid production when invertase was added to the fermentation medium. A similar observation was made by Nghiem et al. [65] with succinic acid fermentation.

Sweet sorghum juice has not been used widely in commercial production of ethanol or industrial chemicals. Large-scale use of this feedstock still is in the developmental stage. There have been plans for development and construction of ethanol plants using sweet sorghum juice in many places in the world, for example, Thailand, the Philippines, Nigeria, the USA and China. Only in China that commercial ethanol production from sweet sorghum juice has actually been realized. The sweet sorghum ethanol plant in China employed a solid-state fermentation process which used the whole stalks rather than extracting the juice out and fermenting it. In 2015, ethanol production from sweet sorghum juice in the stalks accounted for less than 5% of the total ethanol production in the country [66]. In the USA, sweet sorghum juice produced in a commercial plant was successfully tested in a dry-grind corn ethanol plant for ethanol production and plans for construction of several ethanol plants using sweet sorghum juice and sugarcane juice as seasonal feedstocks were announced but there has been no report on actual operations for commercial ethanol production.

4. Sorghum Biomass

In addition to grain sorghum and sweet sorghum juice, sorghum biomass, which contains large quantities of lignocellulosic materials, also is a potential feedstock for production of fuels and chemicals. Extraction of juice from the sweet sorghum stalks leaves a solid residue, which is normally referred to as bagasse. Forage sorghum is fast growing grass that is used for animal feed. Thus, the major focus in breeding of forage sorghum is high biomass yield and not sugars in the stalks [18]. High-tonnage sorghum, which also is referred to as energy sorghum or photoperiod-sensitive sorghum, can produce high levels of cellulosic materials. This type of sorghum delays the flowering, which in turn will delay the decline in forage quality and allow high accumulation of biomass dry matter for longer periods during the growing season [18]. The composition of sweet sorghum bagasse, forage sorghum and high-tonnage sorghum are summarized in Table 5 [67]. Other potential lignocellulosic feedstocks, sugarcane bagasse, corn stover and switchgrass are also included for comparison [68].

Table 5. Composition of sweet sorghum bagasse, forage sorghum, high-tonnage sorghum [67], sugarcane bagasse, corn stover and switchgrass [68] and theoretical ethanol yields.

Components	SSB	FS	HTS	SCB	CS	SG
Structural carbohydrates	46.3	50	55.6	63.2	55.4	54.2
Celluose (%)	20.0	20.5	26.3	39.0	34.6	31.0
Hemicellulose (%)	26.3	29.5	29.3	23.1	20.8	23.2
Lignin (%)	7.1	8.6	7.6	23.1	17.7	17.6
Non-structural carbohydrates (%)	36.4	27.7	22.2	N/A	N/A	N/A
Theoretical ethanol yield (L/MT)	336	363	403	449	401	393

Note: 1. The theoretical ethanol yields are calculated by the authors using the following values: a. 1.11 g glucose produced per g cellulose; b. 1.14 g xylose produced per g hemicellulose; c. 0.51 g ethanol produced per g sugar. 2. SSB: sweet sorghum bagasse, FS: forage sorghum, HTS: high-tonnage sorghum, SCB: sugarcane bagasse, CS: corn stover, SG: switchgrass, MT: metric ton.

Whereas fermentation of sweet sorghum juice and grain sorghum for ethanol production is straightforward, bioconversion of lignocellulosic materials in sorghum biomass is much more difficult since it requires a pretreatment step prior to enzymatic hydrolysis for production of fermentable sugars and subsequent ethanol fermentation. The key steps in a biochemical process for ethanol production from cellulosic biomass are shown schematically in Figure 2.

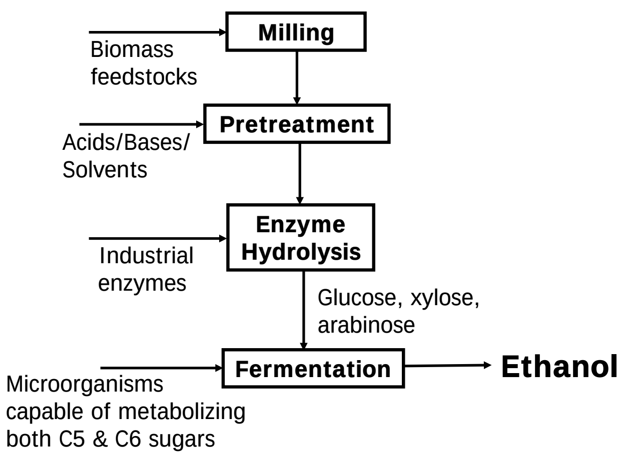


Figure 2. Process flow diagram of biochemical ethanol production from lignocellulosic biomass feedstocks.

Several processes for pretreatment of lignocellulosic feedstocks have been developed. Dilute sulfuric acid hydrolysis is the pretreatment process that has been most extensively studied. One of the serious drawbacks of dilute sulfuric acid pretreatment is formation of several by-products such as acetic acid and hydroxymethyl furfural (HMF), which strongly inhibit biological activities of microorganisms used in the subsequent fermentation stage. Detoxification of the sugar stream is difficult and expensive. Formation of inhibitors and the high corrosiveness of sulfuric acid are the two main factors preventing commercialization of dilute acid pretreatment. Other pretreatment processes thus were developed to alleviate the problems encountered in the dilute acid hydrolysis process. These pretreatment processes have been reviewed by Drapcho et al. [69].

The residual bagasse obtained after juice extraction has been used as feedstocks for ethanol production in several studies. Various pretreatment methods were employed to enhance enzymatic hydrolysis of the bagasse to produce fermentable sugars for subsequent ethanol fermentation, for examples, steam [70], ammonia fiber expansion (AFEX) [71], soaking in aqueous ammonia (SAA) [53] and phosphoric acid hydrolysis [72]. In a recent study, Cao et al. [73] compared five pretreatment methods for enhancement of enzymatic hydrolysis of sweet sorghum bagasse for subsequent ethanol production. These methods included autoclaving, dilute NaOH solution and autoclaving, high concentration NaOH solution immersing, dilute NaOH autoclaving and H_2O_2 immersing, and NaOH/H_2O_2 treatment. Ethanol production from forage sorghum also has been studied, for example, by Li et al. [71] and Dien et al. [74].

Conversion of a lignocellulosic biomass feedstock such as sweet sorghum bagasse to ethanol has two major problems: 1. Ethanol-producing microorganisms developed for utilization of both glucose and xylose are not as efficient as the yeast *Saccharomyces cerevisiae* and also have significantly lower ethanol tolerance; and 2. Low final ethanol concentrations result in high distillation costs, which make the process economically unattractive. In attempt to alleviate these problems, Nghiem et al. [75] developed a process using barley straw as a feedstock. In this process, barley straw was pretreated by the SAA method, and then was hydrolyzed with a commercial xylanase to produce a xylose-rich sugar solution, which came mostly from the hemicellulosic fraction, and a cellulose-enriched solid residue. The xylose-rich solution was used for production of value-added co-products and the cellulose-enriched residue was converted to ethanol by the yeast *Saccharomyces cerevisiae* in a fed-batch simultaneous saccharification and fermentation (SSF) process. The final ethanol concentration obtained was >70 g/L, which was above the normally accepted limit (50 g/L) for commercially viable ethanol production from cellulosic biomass [52]. Although the process was developed using barley straw, it should be applicable to other similar biomass feedstocks such as sweet sorghum bagasse and sorghum biomass.

Theoretical yield normally is used to assess the feasibility of a feedstock for use in ethanol production. The actual ethanol yield in reality is lower than the theoretical yield because of several factors such as formation of other products (e.g. glycerol and organic acids), utilization of the carbon source for growth and maintenance of the microbial cells, and fermentation process efficiency. To put this in perspective, Table 6 is set up, in which the potential ethanol production from sorghum grain, sweet sorghum juice, sweet sorghum bagasse, forage sorghum and high-tonnage sorghum is calculated using actual experimental data. For sorghum grain and sweet sorghum juice, the data obtained from direct fermentation of these two substrates are used [76,77]. For sorghum biomass, it is more complicated since there is no single universal process for ethanol production. In other words, the potential ethanol yield depends strongly on the pretreatment process and the configurations of the subsequent enzymatic hydrolysis and fermentation process. Thus, the conversion factors that are deemed having the highest probability of being achieved in practice are assumed. These assumptions are: a. Hydrolysis of glucan by cellulase produces glucose at 90% theoretical yield; b. Hydorlysis of xylan by xylanase produces xylose at 75% theoretical yield; and c. Ethanol is produced from all sugars at 0.45 g ethanol/g sugars.

Table 6. Potential ethanol yield from sorghum grain, sweet sorghum juice, sweet sorghum bagasse, forage sorghum and high-tonnage sorghum. (See text for the assumptions used in the calculations of the values in this table.)

Components	Available substrate for bioconversion	Potential ethanol yield	Potential ethanol production (L/MT)
Sorghum grain	69.1 wt% starch	0.48 g ethanol/g starch	466
Sweet sorghum juice	184.5 g/L sugar	0.45 g ethanol/g sugar	105
Sweet sorghum bagasse	20.0 wt% cellulose + 26.3 wt% xylan	0.45 g ethanol/g cellulose 0.38 g ethanol/g xylan	271
Forage sorghum	20.5 wt% cellulose + 29.5 wt% xylan	0.45 g ethanol/g cellulose 0.38 g ethanol/g xylan	291
High-tonnage sorghum	26.3 wt% cellulose + 29.3 wt% xylan	0.45 g ethanol/g cellulose 0.38 g ethanol/g xylan	327

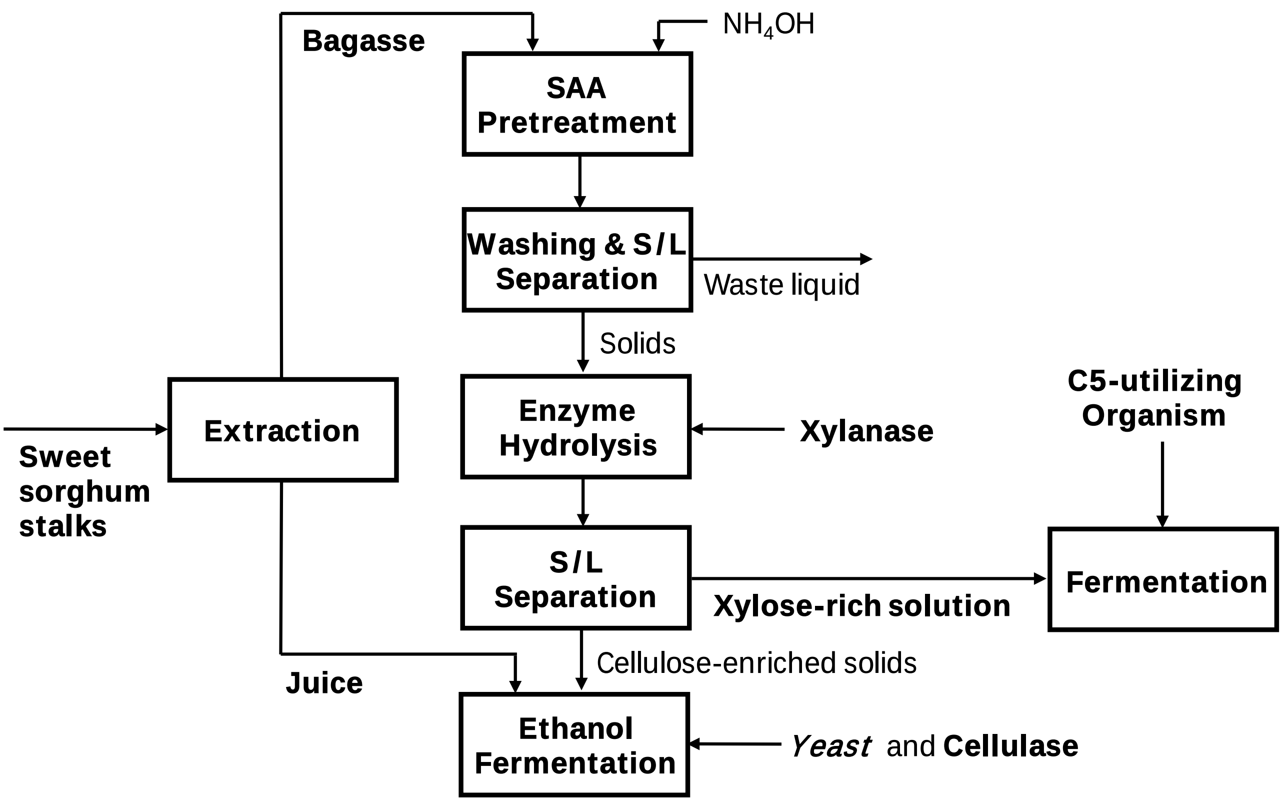


Figure 3. The sweet sorghum biorefinery for production of ethanol and chemicals from sweet sorghum juice and bagasse.

There have been only few studies on production of chemicals from sorghum biomass. Camargo et al. [78] investigated production of xylitol by the yeast *Candida guilliermondii* in hemicellulosic hydrolysate obtained by dilute acid hydrolysis of forage sorghum biomass. Nghiem et al. [79] introduced the concept of a sweet sorghum biorefinery in which both fuel (ethanol) and chemicals (astaxanthin, D-ribose) are produced from sweet sorghum juice and the residual bagasse. In this process, the bagasse was first pretreated by the SAA method then hydrolyzed with a commercial xylanase to generate a xylose-rich hydrolysate and a cellulose-enriched residue. The xylose-rich hydrolysate was used for production of astaxanthin by *Phaffia rhodozyma* and production of D-ribose by *Bacillus subtilis*. The cellulose-enriched residue was added to the extracted juice at 7 wt% solid loading together with a commercial cellulase and inoculated with *Saccharomyces cerevisiae*. Addition of the cellulose-enriched residue resulted in an increase in final ethanol concentration, which was equivalent to an 80% theoretical yield based on the glucan content of the cellulose-enriched residue. The concept of this sweet sorghum biorefinery is shown in Figure 3.

5. Conclusion

Sorghum is a renewable resource suitable for use as a feedstock for production of fuels and chemicals. The majority of the research on sorghum bioconversion has focused on fuel ethanol but there also have been studies on production of industrial chemicals. To realize the full potential of sorghum as a renewable feedstock in the upcoming bio-based economy, future studies are needed in the following areas:

Carbon dioxide utilization: Large quantities of CO_2 are generated in ethanol production and also in aerobic fermentation processes. This important co-product can be used in many applications, for example, for growth of phototrophic microalgae for production of chemicals of industrial significance [80] or for use as a co-substrate in succinic acid fermentation [81]. Other applications of fermentation- derived CO_2 should be investigated.

Lignin conversion: One area of biomass bioconversion that has not been given much attention is processing and conversion of the residual lignin to useful products. Thus far the option for lignin utilization following carbohydrate conversion is to burn it. New processes have been developed for conversion of lignin to bio-oil and specialty chemicals [82]. This is one of the areas that deserve to be further explored.

Integrated biorefinery: Development of integrated biorefineries where various types of sorghum are used together as feedstocks or where sorghum is co-utilized with other feedstocks such as corn for production of fuels and chemicals is an area that needs to be investigated. In these studies, the major thrusts should be focused on integrated conversion processes, water and energy balances, and overall process economics.

Conflict of Interest

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S.

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