

The costs of sugar production from different feedstocks and processing technologies

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Received July 19, 2018; revised December 21, 2018; accepted January 07, 2019

View online February 16, 2019 at Wiley Online Library (wileyonlinelibrary.com);

DOI: 10.1002/bbb.1976; *Biofuels, Bioprod. Bioref.* 13:723–739 (2019)

Abstract: Sugar production is essential for the production of foods, biochemicals, and biofuels via biochemical or catalytic routes. Sugar-containing crops, and starch-based and cellulosic feedstocks are resources for sugar production via juice extraction, starch saccharification, and pretreatment and hydrolysis, respectively. Technologies have been developed to attain a high sugar yield; however, production costs are a major consideration in commercializing newly developed approaches to the production of sugars. In this review, the fixed capital and production costs of sugar produced from first- and second-generation crops are summarized. As expected, first-generation crops provide the lowest fixed capital costs, ranging from 0.01 to 0.13 \$ kg⁻¹ feedstock, and have production costs ranging from 0.22 to 0.55 \$ kg⁻¹ sugar. For cellulosic crops, because of their recalcitrant structure and complex processing, the fixed capital and production costs are higher, ranging from 0.02 to 1.10 \$ kg⁻¹ feedstock and 0.10 to 3.37 \$ kg⁻¹ sugar, respectively. © 2019 Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: sugar production; sugar-containing crops; starch-based feedstocks; cellulosic feedstocks; fixed capital cost; production cost

Introduction

Sugar is one of the most important components for broadening the bioeconomy through new biorefineries. The biorefinery concept has been broadly defined to represent conversion of biomass to an extensive

portfolio of products analogous to that of oil refineries.¹ Feedstocks, processes, platforms, and products are the four elements of the biorefinery concept. Carbohydrates (or sugars) are among the most common biorefinery platforms and are used for the production of food, pharmaceuticals, biofuels and other value-added chemicals.^{1–3}

Chemicals produced from sugars meet a wide variety of industrial applications. Sugars can be converted into various products via fermentation, hydrogenation, dehydrogenation, oxidation, and other processes. For example, ethanol and propanediol (PDO) can be produced by fermenting hexose with microorganisms; xylitol is obtained from pentose hydrogenation, and furfural is formed by xylose dehydration. In addition, furandicarboxylic acid (FDCA) can be produced from the oxidation of 5-hydroxymethylfurfural (5-HMF), which is the product of the dehydration of glucose or fructose.⁴ Many chemicals, such as ethanol, xylitol, PDO, furfural, and levulinic acid, can be produced entirely by biobased carbohydrates.⁴

Carbohydrates used for sugar production can be obtained from sugar-containing, starch-based, and cellulose-based crops and biomass. An extraction process is used for sugar-containing crops such as sugarcane and sugar beet to produce a sugar stream directly. For starch-based crops and cellulosic biomass, additional processing is required to convert storage and structural carbohydrates into sugars. Liquefaction followed by saccharification is used to produce sugars from starch-based crops.⁵ When processing cellulosic biomass, harsher pretreatment is needed to disrupt the recalcitrant structure of the plant cell walls to enable enzymatic extraction of structural carbohydrates as sugars (Fig. 1).

Sugars produced from sugarcane and sugar beets in the USA are mainly used for syrup and sweetener production.⁶ Corn is another primary resource for the production of sugar, and syrup, ethanol, starch, protein, and oil via corn refining processes. Cellulosic biomass has been proposed as an alternative feedstock for production of biofuels and biochemicals because of the ability to convert its high car-

bohydrate content (~75%) to sugar via thermo-chemical pretreatment and hydrolysis.⁷

The efficient pretreatment and hydrolysis (saccharification) of cellulosic biomass are critical to reduce capital and operating costs and to ensure a profitable and sustainable biorefining industry. Pretreatment and hydrolysis expenditure accounts for 20% of the total capital and operating costs of biorefining and is only eclipsed by material and feedstock costs.^{8–10} Low-cost sugar production is regarded as the primary driver for the use of biomass feedstocks to produce biofuels and other biobased chemicals, such as furfural, 5-HMF, and levulinic acid, in the biorefining industry.¹¹

In recent biorefinery developments, new techniques and integrated processes have been proposed to increase product yields and broaden the applications of coproducts. However technical feasibility is not sufficient; sustainable commercial development also requires the technology to be economical. Computer simulation models have been used to determine and understand the economic implications of biorefinery processes based upon laboratory and pilot results for industrial and commercial cost estimations. The fixed capital investment and the operating costs related to raw materials, utilities, and various process schemes (e.g. inclusion of recycling or heat regeneration loops) are the basic parameters used to estimate the profitability of a biorefinery process.^{5,12,13} This has led to the marketing of new technologies to increase process efficiency. However, the economic analysis of sugar production in biorefinery processing is generally considered within the context of biofuel production and only lists the final costs of producing the biofuel and co-products. Hence, the lack of sugar production cost profiles derived

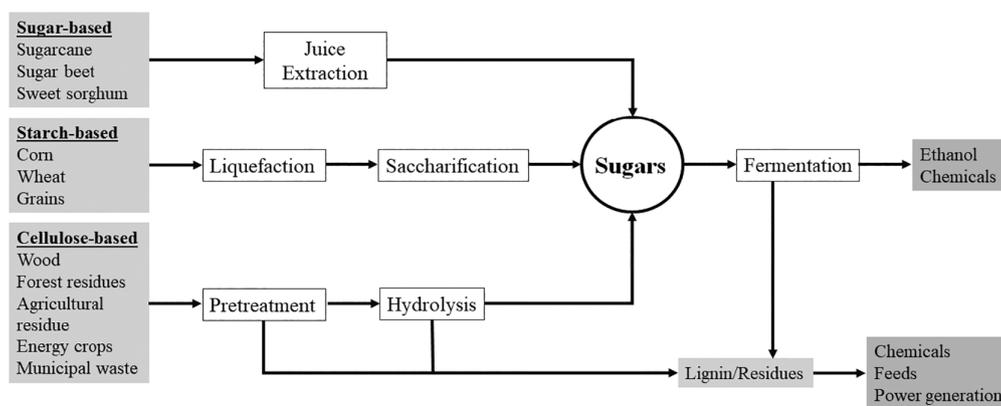


Figure 1. Biorefinery system for producing fuels, chemicals, feeds, and power from different feedstocks and biomass.

from different feedstocks is a barrier to economic analysis considering the conversion of sugars to other products.

In this study, a review of techno-economic modeling reports and literature related to biofuel production from first-generation (G1) and second-generation (G2) feedstocks is conducted, and the cost of fermentable sugar production is evaluated. The goal is to summarize the estimated capital investment and production costs for producing sugars from biomass as a resource for the further development of industrial biotech applications.

Data collection, boundary definition, and cost estimations

Sugar production costs from starch-based, sugar-containing, and cellulosic biomass feedstocks were extracted from published literature focused on the production of biofuels and biochemicals. For starch-based sugar production, the techno-economic analyses of corn-based biorefineries, primarily dry-grind and wet milling, were used. For sugar production using sugar-containing crops, the literature on sugarcane and sugar beet milling processes was collected. In addition, the costs of sugar production from sweet sorghum, which has a high sugar content, were compared to those of the more conventional sugar-containing crops. The cost estimation of cellulosic sugar production was extracted from techno-economic models of cellulosic biofuel production by only considering unit operations associated with feedstock handling, pretreatment, and hydrolysis. The definition of sugar production is confined to feedstock handling, pretreatment, and sugar production, namely, saccharification or hydrolysis. Prices are presented here in 2017 US dollars, adjusted for inflation.

Sugar-production technologies are compared for fixed capital and production costs. The sugar yield is estimated to be 0.79 kg sugar produced per 1 kg corn.¹⁴ For starch-based sugar production, the production cost is estimated to be 83.28% of that for producing corn ethanol, which is based on the dry-grind process model by Kwiatowski *et al.*⁵ The capital cost associated with processing grain through liquefaction and those associated solely with saccharification are 72.45% and 10.83% of the total amount of capital to build a corn dry grind ethanol plant. The capital cost of liquefaction and saccharification was added to the wet milling process model (up to starch production). This additional capital cost is 12.84 million dollars and was extracted from the Kwiatowski *et al.*⁵ model. A 0.836 power relationship is also used to adjust the fixed cost according to the plant capacity.¹⁵ For the production cost, the unit cost of saccharification is estimated to be 0.02 \$ kg⁻¹ sugar with a 99%

saccharification efficiency;⁵ this value is added to the total sugar production cost from the wet milling process.

For the processing of sugar-containing crops, it is estimated that 90% of the sugar present is extracted from sugarcane.¹⁶ The fixed capital cost associated with only sugar production in a sugar to ethanol production facility is 21% of the total fixed capital cost.¹⁶ The production costs for crop handling and sugar extraction are estimated to represent 59% and 5.85% of the total sugar crop to ethanol production cost, respectively.¹⁶

In the case of cellulosic feedstocks, the fixed capital costs of cellulosic sugar production via dilute acid and steam pretreatments (commonly used technologies) are estimated as 79%, 74%, and 72% of the total capital costs for ethanol production from herbaceous or agricultural residues, hardwood, and softwood, respectively.^{17,18} Similarly, the sugar production cost represents 85%, 83.9%, and 86.4% of the total ethanol production costs for agricultural and herbaceous residues, hardwood, and softwood, respectively.¹⁸

Starch-based sugar production

Feedstocks

Saccharification describes the step where starch is end hydrolyzed to sugars and is a necessary step for producing potable and fuel ethanol. Starch-based crops, including corn, wheat, rice, sweet sorghum, barley, and cassava, are considered first-generation renewable feedstocks.¹⁹

Starch-based sugar production process

In the USA, corn is the primary feedstock for starch, sweeteners, and ethanol production, especially in the Midwest corn-belt USA.²⁰ Corn dry-grind and wet milling are the dominant commercial processes used for the production of syrup, ethanol, and other products such as corn gluten meal, corn gluten feed, and distiller's dried grains and solubles (DDGS).^{19,21} The dry-grind process is primarily used for ethanol production, and accounts for approximately 90% of the ethanol produced in the USA.²² The conventional dry-grind process includes the following steps: corn grinding, slurry formation, starch liquefaction, simultaneous saccharification and fermentation, distillation and dehydration, and coproduct recovery. Sugar production in the dry-grind process will only include the following steps: corn grinding, slurry formation, starch liquefaction, dextrin saccharification, sugar refining and coproduct recovery (Fig. 2).

Corn is ground using a hammer mill to pass through a 1/'' to 3/16'' sized screen to increase the accessibility of the cornstarch matrix by amylases. Corn is mixed with water

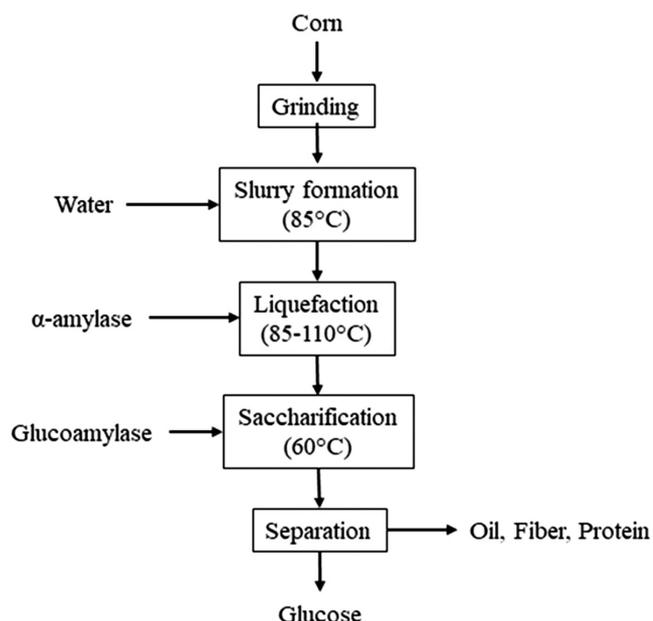


Figure 2. Flow diagram of the corn dry-grind process for sugar production.

and cooked at 110 °C to pasteurize the slurry, solubilize the starch and form a mash. The mash is liquefied at 85 °C, and α -amylase is added to break down the starch into small dextrins and reduce the corn mash viscosity. After liquefaction, the mash is cooled to 60 °C, and glucoamylase is added to hydrolyze dextrins to glucose.^{5,21,23}

The unrefined sugar stream produced from the dry-grind process also contains fiber, oil, and protein, which limits its application.²⁴ New separation techniques, including the use of dewatering equipment (i.e., paddle screens) to separate soluble glucose from non-soluble impurities post liquefaction, have been marketed by technology providers.²⁵ In addition, the fiber, oil and protein obtained from the separation steps can be marketed as coproducts. Wang *et al.*²⁶ demonstrated that a thermal treatment (105 °C, 30 min) followed by a series of hydrolysis refining steps, including centrifugation, active charcoal treatment, and cation and anion exchange chromatography, could produce a refined sugar stream, and that thermal treatment does not lower the final sugar yield.²⁶ This effort was undertaken to show the feasibility of producing refined glucose syrup from a modified dry-grind process.²⁶

The corn wet-milling process separates and recovers the different parts of the kernel using water, which affords production of many more co-products than dry milling-based processes. Only 11% of US ethanol is produced from wet-milled corn.^{22,23,27} The major unit operations of the corn wet mill sugar production process are steeping, grind-

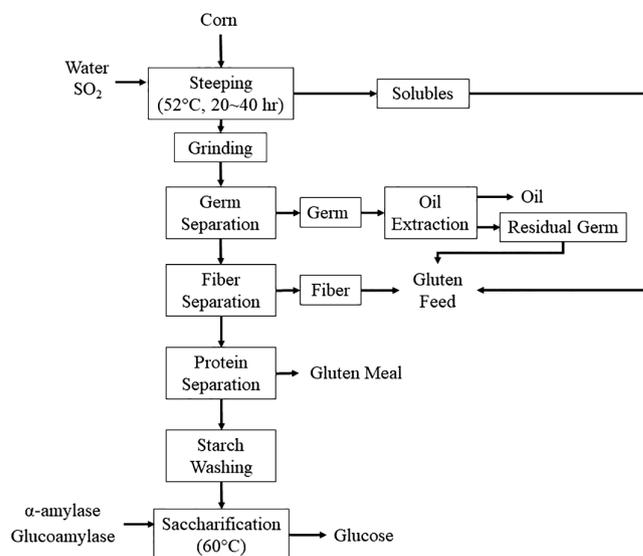


Figure 3. Diagram of corn wet-milling process for sugar production.

ing, germ separation, protein and starch separation, starch cleaning, starch saccharification, and sugar refining (Fig. 3).

In the corn wet-milling process, intact kernel is steeped in a dilute SO_2 solution at 52 °C for 25–40 h using a counter-current continuous process. Steeping disrupts the protein matrix of the kernel by cleaving the disulfide bonds present and softens the kernel. The softened kernel is passed through a germ-mill set to extract the oil-laden germ intact. A series of hydrocyclones are used for germ separation based on density differences. After germ separation, fiber is separated by screening. Fiber retained on the screens is washed free of starch, recovered and mixed with steep water and fermentation stillage to produce corn gluten feed. The protein (gluten) is separated from the starch in disk stack nozzle centrifuges based on density differences. The recovered gluten is dewatered, dried, and sold as a high-value protein enriched animal feed marketed as gluten meal. The recovered starch is washed to remove residual protein in a series of small hydrocyclones. Finally, the cleaned starch slurry is hydrolyzed into glucose.^{23,28}

Costs of starch-based sugar production

Fixed capital costs

Fixed capital costs include the facilities, equipment, and construction costs for the plant and are estimated based on the costs of the major equipment. Table 1 shows the fixed capital costs of sugar production from the corn dry-grind and wet milling processes.

Table 1. Fixed capital cost and production cost of the corn milling process for fermentable sugar production (in 2017 prices).

	Milling process	Capacity (1000 tonne corn year ⁻¹)	Fixed cost (million \$)	Unit fixed cost (¢ kg ⁻¹ corn)	Lang factor	Sugar yield (1000 tonne year ⁻¹)	Production cost (million \$)	Unit production cost (\$ kg ⁻¹ sugar)
Dale and Tyner (2006) ¹⁴	Dry grind	315	2.84	0.90	3.02	248.85	65.02	0.26
Kwiatkowski <i>et al.</i> (2006) ⁵	Dry grind	367	10.61	2.89	n/a	239.76	53.90	0.22
Ou <i>et al.</i> (2014) ²⁹	Dry grind	955	18.65	1.95	5.03	624.42	207.22	0.33
Ramirez <i>et al.</i> (2008) ²⁸	Wet milling	841	106.41	12.65	n/a	508.96	115.84	0.23
Ramirez <i>et al.</i> (2009) ³⁰	E. wet milling ^a	840	101.34	12.06	n/a	512.78	116.66	0.23

^aE. wet milling: enzymatic wet milling.

The fixed capital costs of the dry-grind process analyzed by Dale and Tyner¹⁴ and Kwiatkowski *et al.*⁵ are based on similar plants with similar capacities (315 000 tonne corn year⁻¹ and 367 000 tonne corn year⁻¹, respectively); however, differences in location and equipment vendors can lead to variations as large as four times the presented costs.^{5,14} Ou *et al.*²⁹ conducted a techno-economic analysis of a corn dry-grind process with a larger grind size (955 tonne corn year⁻¹) and reported a fixed sugar production cost of 18.65 million dollars.²⁹ Normally, fixed costs increase with plant size. Gallagher *et al.*¹⁵ reported a power rule of 0.836 between the capital cost and plant capacity for the dry-grind process.¹⁵ In the studies of Ou *et al.*,²⁹ Kwiatkowski *et al.*,⁵ and Dale and Tyner,¹⁴ the fixed capital costs adjusted for just sugar production (only liquefaction and saccharification) at a corn dry-grind facility are 15.5%, 18.63%, and 7.18%, respectively.^{5,14,29}

In the wet-milling process, the fixed capital costs reported by Ramirez^{28,30} for a plant with a capacity of 840 000 tonne year⁻¹ are 88–94 million dollars.^{28,30} When saccharification and sugar refining processes are added, the fixed costs are 101–106 million dollars. Enzymatic wet milling is an experimental technology that uses select enzymes to substitute for traditional steeping with SO₂. In addition to eliminating use of SO₂, a source of volatile organic emissions, it is expected to lower total fixed costs because the use of enzymes reduces the steeping time and size of the steeping tanks. Enzymatic wet milling reduces the fixed costs compared to conventional wet milling by approximately 5.5%. However, when compared to the dry-grind process, the wet-milling process requires higher fixed capital costs due to the greater number of unit

operations required to recover the individual corn components. As for the unit fixed capital costs, the dry-grind process is 1–3 ¢ kg⁻¹ corn and the wet-milling process is 12.06–12.65 ¢ kg⁻¹ corn.

Production costs

Production costs include materials, labor, utilities, facility maintenance fees, and capital depreciation. Sugar product costs estimated in the literature for starch-based crops are summarized in Table 1.

As listed in Table 1, the production costs of the corn dry-grind process range from 0.22 to 0.33 \$ kg⁻¹ sugar. The biggest portion of the production costs (> 80%) comprises the material costs (mostly feedstock) followed by the utility costs. Grain-processing activities such as grinding are therefore critical in maximizing sugar yields for starch-based sugar production.

Refined starch production costs are compared for conventional and enzymatic wet mills sized to process 2.54 million kg of corn per day (100 000 bu day⁻¹).³⁰ When adjusted to include saccharification and sugar separation steps, the production costs of the conventional and enzymatic wet-milling processes are both estimated to be 0.23 \$ kg⁻¹ sugar. Robert³¹ reported that the sugar production cost of a corn-grind process modified to produce glucose, as developed by Jakel *et al.*,²⁵ is approximately \$0.3/kg sugar; this process has been implemented in a Midwestern dry grind ethanol plant with 635 tonne of corn/day capacity.^{25,31}

In addition to extracting the fermentable sugar production cost from ethanol production techno-economic studies, Solomon *et al.*³² proposed a simple mathematical

model (Eqn (1)) to estimate corn ethanol production costs; this model is derived from a previous model developed by Solomon.³³ The mathematical model considers the capital investment, material costs, and revenues from coproducts. In this equation (Eqn (1)), C_e represents the production cost of ethanol; C_c is the corn cost; C_k indicates the total capital investment; and C_E , C_M , C_L , and C_O represent the energy, raw material, labor, and other costs, respectively. P_{cp} indicates the credits and revenues earned from the coproducts.

$$C_e = C_c + C_k + C_L + C_E + C_M + C_O - P_{cp} \quad (1)$$

A similar concept can be applied to estimate the sugar production cost of corn biorefineries. The coproducts from milling processes are also considered as sources of net revenue, which can be marketed as ingredients in animal diets.

Sugar production from sugar-based crops

Feedstocks

Sugar crops are the other source of glucose for the production of first-generation biofuel. Sugarcane refineries for food and fuel production are well established in Brazil, India, and Thailand.^{34–36} In the USA, sugarcane and sugar beet are the two major feedstocks for sugar production. Since the mid-1990s, sugarcane and sugar beet have accounted for 45% and 55%, respectively, of the total sugar production in the USA.³⁷ Sugarcane is mainly planted in southern states, including Florida, Louisiana, Texas, and Hawaii.³⁷ Sugar beet is grown predominantly in the northern and parts of the central plains and the west, but mainly North Dakota and Minnesota.^{38,39}

Generally, the sugar contents of sugarcane and sugar beet raw juices are 11–15% and 11–18%, respectively.^{36,39,40} Sweet sorghum is attracting increased interest as a sugar crop. When sweet sorghum is harvested, raw juice can be squeezed from the stems, which have a sugar content of 11–17%.^{41,42} Moreover, sweet sorghum can grow in temperate and tropical climate regions as a perennial crop. Sweet sorghum potentially resists drought and requires less fertilizer and water than other sugar crops.

Sugar production

The sugar crop refining process is used for granulated sugar and ethanol production (Fig. 4). Harvested crops are cleaned and size reduced by passing through a shredder. Mechanical pressing is used to extract sugar juice. The juice can be either refined to granulated sugar and / or can be used for ethanol fermentation.⁴¹

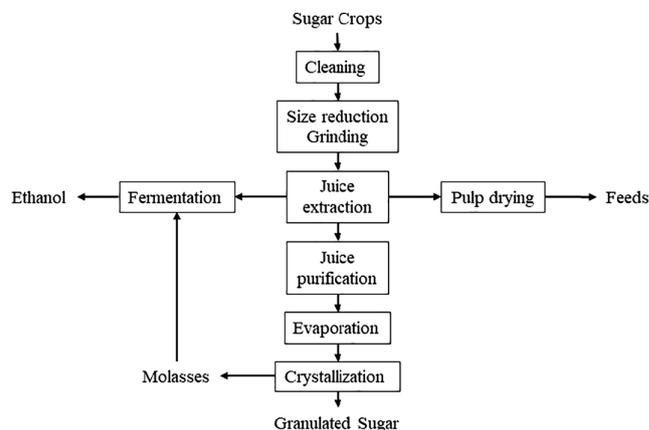


Figure 4. Sugar milling for granulated sugar and ethanol fuel production.

For granulated sugar production, lime is added to the juice to remove impurities; this process is followed by carbonation using CO_2 to precipitate the lime milk and remove impurities from the raw juice to obtain thin sugar juice. A series of evaporators, fed with high-pressure steam, are used to concentrate the sugar juice from 15% to 70% sugar content. Sugar is crystallized from the concentrated syrup under vacuum and at a lower temperature. After crystallization, the slurry is fed through a centrifuge to recover the sugar crystals. The liquid from the centrifugation, which is known as green syrup or molasses, has a sugar content of approximately 50% and can be used for ethanol production. Finally, the crystallized sugar is dried with a drum dryer to produce granulated table sugar.⁴¹

Alternatively, the raw juice obtained from mechanical pressing can be directly fermented to ethanol using distillers' yeast. This ethanol operation is much simpler than when starch or cellulosic feedstocks are used because pretreatment and saccharification steps are unnecessary.^{38,43} The pulp obtained from the extraction process, such as sugarcane bagasse, sweet sorghum bagasse, and sugar beet pulp, can also be used for cellulosic ethanol production, feed applications, or as solid boiler fuel to generate process steam and electricity.

Costs of sugar production

Fixed capital costs

Capital expenditures for sugarcane, sugar beet, and sweet sorghum operations are listed in Table 2. The fixed costs include equipment for crop handling, juice extraction, juice clarification, other plant hardware, and storage facilities. The fixed costs vary with different plant capacities

Table 2. Fixed capital cost and production cost of sugar-containing crops for sugar production (in 2017 prices).

	Feedstock	Capacity (1000 tonne year ⁻¹)	Sugar yield (1000 tonne year ⁻¹)	Fixed cost (million \$)	Unit fixed capital cost (¢ kg ⁻¹ feedstock)	Production cost (million \$)	Unit production cost (\$ kg ⁻¹ sugar)
Řezbová <i>et al.</i> (2013) ⁴⁴	Sugarcane	n/a	8.7 tonne ha ⁻¹	n/a	9.56 ^a	n/a	0.40 ^a
Huang <i>et al.</i> (2016) ¹⁶	Sugarcane	1600	111.25	27.92	1.75	51.54	0.46
Řezbová <i>et al.</i> (2013) ⁴⁴	Sugar beet	n/a	6.7 tonne ha ⁻¹	n/a	8.30 ^a	n/a	0.39 ^a
Bowen <i>et al.</i> (2010) ⁴⁵	Sugar beet	1400	234.7	63.09	4.50	n/a	n/a
Shapouri and Salassi (2006) ⁴⁶	Sugar beet	n/a	n/a	n/a	n/a	n/a	0.21
Maung and Gustafson (2011) ³⁸	Sugar beet	n/a	117.32	n/a	n/a	25.17	0.21
Gnansounou <i>et al.</i> (2005) ⁴¹	Sweet sorghum	2000	172.4	38.18	1.90	95.63	0.55

^aTotal operation capacity and time were not reported in the study.

to a power of 0.7.⁴⁷ Řezbová *et al.*⁴⁴ compared the costs of sugar production from sugarcane in the USA to those in other countries, including Brazil, Thailand, and India.⁴⁴ Of these countries, Brazil has the highest fixed capital cost of sugar production (23 ¢ kg⁻¹ sugar), followed by the USA (9.1 ¢ kg⁻¹ sugar), Thailand (1.4 ¢ kg⁻¹ sugars), and India (1.1 ¢ kg⁻¹ sugar). According to a study by Nguyen and Prince⁴⁷, the fixed cost of sugarcane plants in Australia is an estimated 3.07 \$ kg⁻¹ sugar. This high cost in Australia results from a low 70% sugar extraction efficiency.⁴⁷ The unit fixed capital cost of 1.75 ¢ kg⁻¹ sugarcane (for Brazil) was estimated by Huang *et al.*,¹⁶ who reported that 1.6 million tonne year⁻¹ of processed sugarcane produces approximately 111 250 tonne year⁻¹ of sugar.¹⁶

In the study by Bowen *et al.*,⁴⁵ fixed costs were estimated from a sugar beet-derived ethanol production model; based on this model, sugar production comprises approximately 60% of the entire ethanol production facility cost.⁴⁵ Haankuku *et al.*³⁹ applied a power of 0.73 to estimate the capital costs of a sugar beet ethanol production plant.³⁹ For the sugar produced from sweet sorghum, the base capacity reported by Gnansounou *et al.*⁴¹ is 2 million tonne year⁻¹ of processed straw.⁴¹ Furthermore, after the juice is extracted for sugar production, the residual bagasse is used to generate approximately 189.1 GWh year⁻¹ of electricity; the molasses obtained from sugar crystallization (approximately 87.8 million kg year⁻¹) is also sold as a coproduct. However, the

Lang factor used for sugar crop refining plants was not reported in these studies.

Production costs

The material cost is still the most substantial portion of the total production cost. This study focused on processing and, therefore, the costs of crop production are not considered. The costs of sugar production from sugarcane, sugar beet, and sweet sorghum are summarized in Table 2.

For sugarcane milling, Řezbová *et al.*⁴⁴ compared the sugar production cost in the USA to the cost in Brazil, Thailand, and India.⁴⁴ Of these countries, the USA has the highest production cost (40 ¢ kg⁻¹ sugar), followed by Thailand (21 ¢ kg⁻¹ sugar), India (17 ¢ kg⁻¹ sugar), and Brazil (14 ¢ kg⁻¹ sugar).⁴⁵ Production of refined granulated sugar in the USA is protected from the international market because of the higher domestic production costs.⁴⁸

Cane sugar production costs have also been estimated from models of ethanol production operations. In a study by Nguyen and Prince⁴⁷, the total cost of producing 108 680 tonne of sugar was estimated at 204.63 million dollars, with a unit production cost of 1.88 \$ kg⁻¹.⁴⁷ Huang *et al.*¹⁶ reported that the sugar extraction accounts for approximately 65% of the cost of producing ethanol from sugarcane because a large amount of energy is consumed by crop handling and mechanical pressing.¹⁶

The USA has a higher production cost for sugar beet milling (\$0.39/kg) than Germany (\$0.36/kg sugar), Poland (\$0.24/kg sugar), and Ukraine (\$0.17/kg sugar).⁴⁴ However, Shapouri and Salassi⁴⁶ report that the sugar production cost of sugar beet is approximately \$0.21/kg sugar (North Dakota, USA), as estimated from commercial ethanol production from sugar beets.⁴⁶ In a study by Maung and Gustafson,³⁸ the sugar production cost was also an estimated 0.21 \$ kg⁻¹ sugar (North Dakota, USA).³⁸

For sweet sorghum processing, in addition to sugar revenues, added revenue is generated from molasses and bagasse; for a plant processing two million tonnes of sweet sorghum annually, electricity generation from bagasse combustion yields 8.57 million dollars per year, and molasses sold for other applications yields 16 million dollars per year.⁴¹ Sweet sorghum straw is therefore a potentially profitable feedstock compared to other sugar crops. A 0.7 power relationship could also be used to estimate the sugar production costs for different capacities of sugar-crop processing plants.⁴⁷

Cellulosic sugar production

Feedstocks

Cellulosic biomass has become an attractive feedstock for producing biofuel because of its abundant availability and high carbohydrate content. Cellulosic biomass is a second-generation feedstock for biofuel and biochemical production. The US Renewable Fuel Standard 2 (RFS2) has led to an increased annual production of cellulosic biofuel from 33 million to 230 million gallons from 2014 to 2016.¹⁷ Accordingly, an estimated 98.8 and 94.7 million dry tonne of herbaceous and wood-based biomass, respectively, are consumed for biorefining applications; furthermore, the consumption of herbaceous- and wood-based biomass is expected to increase to 366.8 and 100.7 million dry tonne, respectively.⁴⁹

Cellulosic biomass is contained within the plant cell wall, which contains approximately 75% polysaccharides made up of cellulose and hemicellulose fibers.⁵⁰ Cellulosic

biomass includes agricultural residues, forest residues, and herbaceous biomass; forest residue can also be classified into softwood and hardwood biomass. In the USA, herbaceous biomass, especially corn stover, is a common feedstock being developed for biorefining process. Currently, only one plant uses corn stover to produce ethanol in Iowa and it has a maximum capacity of 30 million gallons per year.⁵¹ While generally enriched in carbohydrate contents, various sources of cellulosic biomass do vary in chemical composition and this needs to be taken into account when designing a process for sugar or ethanol production (Table 3).

Cellulosic biomass is seen as a sustainable feedstock with minimal impact on food production. It provides the use of agricultural residues and non-commercial production fields. Furthermore, there is evidence that partial removal of agricultural residues is beneficial for pest and disease control, increasing soil temperature in the spring, and facilitating seed germination.^{57,58} Cellulosic feedstocks are therefore not only potential alternative resources for biorefining processes but also provide a good way to support sustainable agriculture.

Sugar production from cellulosic biomass

Pretreatment and hydrolysis are the major unit operations for sugar production from cellulosic feedstocks. Figure 5 illustrates the sugar production in cellulosic biorefineries. After harvest, cellulosic biomass is first cleaned to remove

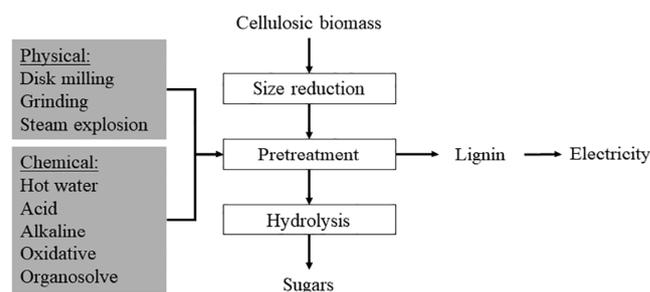


Figure 5. Diagram of fermentable sugar production from cellulosic feedstocks.

Table 3. Composition of cellulosic feedstocks.

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Hardwood	38–50	25–35	15–25	Taylor (2009) ⁵²
Softwood	40–50	25–30	25–35	Dwivedi <i>et al.</i> (2009) ⁵³
Corn stover	31–38	19–44	13–21	Schnepf (2010) ⁵⁴
Miscanthus	64	49	22	Boakye-Boaten <i>et al.</i> (2016) ⁵⁵
Herbaceous crop	45	30	15	Bull (1991) ⁵⁶

impurities; this is followed by size reduction to increase the surface area and improve the efficiency of pretreatment and hydrolysis. After the size-reduction step, inclusion of a pretreatment step is critical to obtain high yields of fermentable sugar because pretreatment disrupts the recalcitrant plant cell wall, especially lignin and hemicellulose, which surrounds the cellulose fibers.⁵³ Biomass pretreatment costs are estimated to be 17–22% of the total capital investment.^{10,32}

Biomass pretreatment are categorized as physical and chemical based. Physical pretreatment increases the feedstock surface area and loosens the feedstock structure. It is conducted by size reduction via grinding and milling. Physical pretreatment retains the hemicellulose and lignin fractions in the feedstock. Chemical pretreatment is used to solubilize lignin and hemicellulose and improve the sugar released from the cellulose in the hydrolysis step. Physiochemical approaches include thermal, acid, alkaline, oxidative process, organosolv, and biological pretreatments. Table 4 lists the main effects of each chemical pretreatment. Another common pretreatment is hot-water pretreatment (150–180 °C) or steam explosion.⁵³ Thermal treatments mainly break down the hemicellulose and lignin linkages in biomass structures.

Dilute sulfuric acid pretreatment mainly hydrolyzes hemicellulose. It is the most common acid treatment used in the industry and is considered a developed technology. In pilot plant operations using dilute acid, approximately 63% of the hemicellulose is hydrolyzed.⁹ Although this

well-characterized technology is being considered by the cellulosic ethanol industry, its high energy consumption, extra neutralization costs, and corrosion of equipment are major disadvantages.⁵⁹ Sodium hydroxide and calcium hydroxide are two common chemicals used for alkaline-based pretreatment. Alternatively, ammonia can be used, for example, as ammonia fiber expansion (AFEX), which combines explosive decompression with the ammonia treatment of biomass.^{60,61} Another alternative is that chemistries can be combined. Alkaline hydrogen peroxide (AHP) combined oxidative and alkaline chemistries to solubilize ester-linked xylan and lignin.^{62,63} Organosolv and ionic liquid treatments are somewhat unique in that they convert crystalline to amorphous cellulose and solubilize lignin, which greatly lowers the required loadings of cellulases.^{53,64,65} Fungi, including white, brown, and soft-rot fungi, which naturally degrade lignin, have also been proposed for biological pretreatment. However, fungal pretreatment is not favored for industrial applications because treatment lasts for 10–14 days.^{53,54} Another disadvantage of this pretreatment method is the high loss of hemicellulose and cellulose via fungi metabolism during pretreatment.⁶⁶ In summary, an ideal pretreatment for sugar production loosens the recalcitrant structure of the biomass while generating a minimum amount of toxic compounds and retaining most of the hemicellulose and cellulose.^{7,67}

After pretreatment, acid- or enzyme-based hydrolysis converts carbohydrates into sugars. Acid hydrolysis has

Table 4. Effects of pretreatment on cellulosic biomass processing

Pretreatment	Main characteristics and effects
Hot water	No chemical addition. Minimal inhibitor formation. Dissolves the majority of hemicellulose and removes some lignin.
Dilute acid (0.5–5%, H ₂ SO ₄ , HCl)	Simple technique. Hydrolyzes hemicellulose. High sugar yield. Toxic inhibitor formation. Requires a recovery process.
Alkaline (Ammonia, sulfite, lime)	Removes lignin. Retains pentose during the pretreatment. Forms fewer toxic inhibitors than acid pretreatment. Lowers sugar conversion rate.
Oxidative	Reduces toxic inhibitor formation. Removes ester-linked xylan and lignin.
Organosolve/ionic liquid	Sugar yield improved by acid addition. Removes lignin. Toxic inhibitor formation. Solvent recovery required.

a high efficiency and a short reaction time but requires intense energy consumption, special facilities to prevent acid corrosion, and proper strategies for neutralization, detoxification, and acid waste management. Sugars can also be degraded under the extreme acid and high-temperature conditions. Enzymatic hydrolysis is favored by the industry because it can be performed under mild reaction conditions and it produces high sugar yields. The major enzymes used are endoglucanase (EC 3.2.1.4), exoglucanase (EC 3.2.1.91), and β -glucosidase (EC 3.2.1.21), which are the minimum suite required for converting cellulose fibers to glucose.⁶⁸ Enzyme loadings / costs can be high; it is estimated that enzyme costs can account for over 70% of the total material cost.⁶⁹ On-site enzyme production has been proposed as one solution to reduce the total operating cost of the cellulosic biorefinery process.^{69–71}

Costs of sugar production from lignocellulosic biomass

Fixed capital costs

Techno-economic estimates in the process industry uses the Lang factor to estimate total plant cost based upon total equipment costs. For cellulosic sugar production, the Lang factor used for estimating the total capital investment is generally 1.5–3.5.⁶⁹ In Table 5, the production of cellulosic sugar from corn stover, switchgrass, miscanthus, sugarcane bagasse, sweet sorghum, softwood, and hardwood by using different pretreatment strategies with enzymatic hydrolysis are summarized and compared. For processing corn stover, the dilute acid pretreatment requires the highest fixed capital costs, followed by AFEX and hot-water pretreatments. The high cost of dilute-acid is due to the use of special metal alloys for pretreatment equipment to prevent acid corrosion.⁷⁰ If the enzyme used for hydrolysis is produced on site, the fixed cost increases by approximately 12–13 million dollars (a 6% increase). In the study by Davis *et al.*,⁶⁹ hydrolyzed sugar is used to produce hydrocarbons such as alcohols, ketones, and ethers, and includes hydrolysate conditioning and purification; therefore, the fixed costs are higher than those of an ethanol biorefinery plant.⁶⁹

Humbird *et al.*⁷² performed a techno-economic analysis of ethanol and sugar production from corn stover by dilute acid pretreatment and enzymatic hydrolysis.⁷² The fixed cost was estimated to be 180.42 million dollars for processing 2000 tonne of dry biomass per day and is similar to the capacity used in the study by Kazi *et al.*⁷⁰ and Davis *et al.*⁶⁹ Chen *et al.*⁷³ replaced the dilute acid pretreat-

ment with deacetylation by sodium hydroxide followed by disk refining (DDR).⁷³ The DDR process achieved high glucose recovery (87%) and resulted in a 29% lower total fixed cost compared to dilute acid pretreatment.^{72,73} To improve the ethanol yield from corn stover-derived sugars, Aghazadeh and Engelberth⁷⁴ proposed liquid-liquid extraction by ethyl acetate following hydrolysis to remove acetic acid based on the plant modeled by Humbird *et al.*⁷² The additional extraction column and solvent recovery facilities resulted in a < 1% increase in the total fixed cost of the biorefinery but improved sugar recovery by 10%.⁷⁴ The lower fixed capital costs reported by Yang and Rosentrater⁷⁵ might result from the Lang factor and estimations of other indirect capital investments.⁷⁵ The ionic liquid pretreatment has higher fixed capital costs than other pretreatments because of the special storage requirements for ionic liquids.⁷⁶

The assumptions for miscanthus-derived sugar production are similar to those reported in Davis *et al.*⁶⁹ Enzymes are produced in the plant, so the fixed capital costs increase by approximately 14%.⁷¹ In the study by Boakye-Boaten *et al.*,⁷¹ the capital investment in hydrolysis, 40.83 million dollars, was also included in fermentation.⁷¹ Hence, the capital investment for hydrolysis was estimated to be 60% of the total 'hydrolysis and fermentation' capital investment,⁷⁰ resulting in a value of approximately 24.54 million dollars.⁷⁰ For switchgrass-derived sugar production, ionic liquid pretreatment has higher fixed costs than dilute acid plus steam explosion pretreatment. The cost of dilute acid plus steam explosion pretreatment was estimated to be 63.72 million dollars in the study by Gnansounou *et al.*⁷⁷ Similarly, the fixed cost of sugar production from sugarcane bagasse was estimated to be 193.33 million dollars.⁷⁸ Lower fixed costs were estimated by Rijn *et al.*⁷⁹ using sweet sorghum as feedstock and with a process similar to that outlined by Gubicza *et al.*⁷⁸ For the base-case scenario, a fixed cost of 19.38 million dollars was estimated for a plant capacity of 300 thousand tonne per year, and the fixed cost increased to 22.86 million dollars for a larger plant capacity of processing 600 thousand tonne of sweet sorghum per year.⁷⁹ In another study, the fixed capital cost of a straw-based sugar production plant with a capacity of 1960 tonne of feedstock per day was estimated to be 54.04 million dollars.⁷⁷

Wood-based sugar production costs are summarized for hard and soft woods (Table 5). In the study by Gnansounou *et al.*,⁷⁷ the fixed capital costs of the hardwood refining for poplar and eucalyptus were similar, approximately 45.67 million dollars.⁷⁷ The pretreatment and hydrolysis stages accounted for approximately 39.4% and 13.8% of the

Table 5. Estimated fixed capital cost and production cost of cellulosic sugar production via enzymatic hydrolysis (in 2017 prices).

	Feedstock	Pretreatment	Capacity (1000 tonne year ⁻¹)	Fixed cost (million \$)	Lang factor	Cellulose to glucose (%)	Xylan to xylose (%)	Total sugar yield (1000 tonne year ⁻¹)	Production cost (\$ kg ⁻¹ sugar)
Kazi et al. (2010) ⁷⁰	Corn stover	Dilute acid	700.8	269.28	3.44	91.09	92.50 ^c	409.42	0.33
Kazi et al. (2010) ⁷⁰	Corn stover	Hot water	700.8	238.71	3.44	89.97	56.61	328.81	0.45
Kazi et al. (2010) ⁷⁰	Corn stover	AFEX	700.8	265.15	3.44	95.90	77.70	380.15	0.32
Kazi et al. (2010) ⁷⁰	Corn stover	Dilute acid ^a	700.8	303.97	3.44	91.09	92.50 ^c	409.42	0.28
Humbird et al. (2011) ⁷²	Corn stover	Dilute acid ^a	700.8	180.42	3.44	90.00	92.40 ^c	412.95	0.17
Chen et al. (2015) ⁷³	Corn stover	DDR ^{#a}	700.8	127.96	3.44	87.00	81.00	337.14	0.28
Aghazadeh and Engelberth (2016) ⁷⁴	Corn stover	Dilute acid	700.8	163.32	3.44	90.00	92.40 ^c	361.64	0.18
Davis et al. (2011) ⁶⁹	Corn stover	Dilute acid	656.7	465.10	3.44	90.00	90.00 ^d	397.70	0.19
Davis et al. (2011) ⁶⁹	Corn stover	Dilute acid ^a	656.7	491.84	3.44	90.00	90.00 ^d	397.70	0.11
Yang and Rosentrater (2015) ⁷⁵	Corn stover	LMAA	660	9.99	n/a	90.00	89.00	301.58	0.54
Baral and Shah (2016) ⁷⁶	Corn stover	IL	349.5	165.05	1.2	96.47	54.98	188.97	2.84
Boakye-Boaten et al. (2017) ⁷¹	Miscanthus	Dilute acid	701	343.73	1.8	90.00	90.00 ^d	521.68	0.18
Baral and Shah (2016) ⁷⁶	Switchgrass	IL	398.4	189.38	1.2	90.95	42.19	188.97	3.37
Gnansounou et al. (2010) ⁷⁷	Switchgrass	Dilute acid + Steam	181 tonne day ^{-1b}	50.39	n/a	90.00	90.00 ^d	365.09	0.32
Baral and Shah (2016) ⁷⁶	Poplar	IL	354.4	177.84	1.2	90.90	58.99	188.97	3.14
Gnansounou et al. (2010) ⁷⁷	Poplar	Dilute acid + Steam	1636 tonne day ^{-1b}	45.67	n/a	90.00	90.00 ^d	365.09	0.32
Gnansounou et al. (2010) ⁷⁷	Eucalyptus	Dilute acid + Steam	1680 tonne day ^{-1b}	45.67	n/a	90.00	90.00 ^d	365.09	0.19
Moncada et al. (2018) ³	Spruce	Organosolv	1000	264.26	n/a	90.00	91.00 ^d	669.76	0.67
Gnansounou et al. (2010) ⁷⁷	Straw	Dilute acid + Steam	1960 tonne day ^{-1b}	54.04	n/a	90.00	90.00 ^d	365.09	0.28
Gubicza et al. (2016) ⁷⁸	Sugarcane baggase	Dilute acid + Steam	272.2	152.80	n/a	68.00	86.35 ^c	166.81	0.34
Rijn et al. (2018) ⁷⁹	Sweet sorghum	Dilute acid + Steam	300	19.38	3.2	68.00	90.00 ^c	92.99	0.49
Rijn et al. (2018) ⁷⁹	Sweet sorghum	Dilute acid + Steam	600	22.86	3.2	90.00	90.00 ^c	220.20	0.38
Biddy et al. (2016) ⁸⁰	Lignocellulosic	Dilute acid	724	793.07	n/a	90.00	98.46 ^c	316.85	0.29

^aIncludes enzyme production in the plant;^bTotal operation time is not provided by the study; LMAA: low-moisture anhydrous ammonia pretreatment;^cXylan converted into xylose during dilute acid pretreatment and enzymatic hydrolysis;^dXylan converted into xylose during pretreatment; #: deacetylation and disk refining (milling).

total capital investment for sugar production, respectively.¹⁸ For softwood-based sugar production, the pretreatment and enzymatic hydrolysis stages accounted for approximately 42.5% and 12.95% of the total sugar production fixed capital costs, respectively.¹⁸ Moncada *et al.*³ reported an estimated fixed capital cost for organosolv pretreatment with enzymatic hydrolysis of approximately 264.26 million dollars scaled to process 1000 tonne of spruce annually.³

Biddy *et al.*⁸⁰ reported that the fixed capital cost of a lignocellulosic sugar production plant with an annual capacity of 724 000 tonne of biomass was approximately 793.07 million dollars.⁸⁰ Moreover, the total carbohydrates (structural sugars) and lignin accounted for approximately 59.76% (db) and 15.76% (db), respectively, similar to that which is observed for hardwoods.

Production costs

Material costs, including feedstock and chemicals, account for over 60% of the total production cost.³ But utility, labor, and other operating costs vary with different pretreatments and operating conditions. Sugar production from lignocellulosic biomass accounts for approximately 85% of the total cellulosic biochemical production cost, including feedstock handling, pretreatment, lignin separation, and hydrolysis.¹⁸ Table 5 summarizes the operation costs for various feedstocks for sugar production by enzymatic hydrolysis.

For corn stover sugar production, the production cost varies from 0.11 to 0.54 \$ kg⁻¹ sugar; the hot water pretreatment has the highest production cost, followed by the dilute acid and AFEX pretreatments, due to the high energy consumption and low sugar yields of the hot water process. When cellulase is produced on site and not purchased, the operation costs decrease from \$0.33/kg sugar to \$0.28/kg sugar.⁷⁰ Based on the study of Davis *et al.*,⁶⁹ the sugar production cost also decreases from \$0.19/kg sugar to \$0.11/kg sugar when the enzyme is produced on site.⁶⁹ The sugar production cost with the LMAA (low-moisture anhydrous ammonia) pretreatment was estimated to be \$0.54/kg by Yang and Rosentrater.⁷⁵ Baral and Shah⁷⁶ reported a high sugar production cost using a ionic liquid based process (\$2.84/kg) due to the high costs of the ionic liquid and anti-solvent, despite recycling of the solvent.⁷⁶

The sugar production cost by Humbird *et al.*⁷² was estimated to be \$0.17/kg sugar with minimum sugar selling price (MSSP) of \$0.30/kg.⁷² The sugar production cost (\$0.28/kg sugar) of the DDR process is higher than that of the dilute acid pretreatment evaluated by Humbird *et al.*⁷³

A higher sugar production cost for the DDR process is due to the higher electricity cost required for milling and onsite enzyme production. The effects of refining (milling) energy (128–468 kWh/oven-dried metric tonne (ODMT)) and different enzyme loadings (11.6–28.4 mg protein g⁻¹ cellulose for CTec3; 0–5 mg protein g⁻¹ cellulose for HTec3) for DDR process on the sugar production cost were investigated by Chen *et al.*⁷³ If the refining energy is more than 317 kWh ODMT⁻¹, the importation of electricity from the grid is necessary, irrespective of enzyme loadings. However, with a refining energy consumption between 128 and 317 kWh ODMT⁻¹, the energy requirement for the DDR process depends on enzyme loadings because higher power is needed for air compressors used in aerobic enzyme production.⁷³ At the optimal sugar yield shown in Table 5, the refining energy requirement is 317 kWh/ODMT and the enzyme loading is 28.4 mg protein g⁻¹ cellulose and 2.5 mg protein g⁻¹ cellulose of CTec3 and HTec3, individually. At this optimal setting, the DDR process requires a higher energy cost compared to a dilute acid pretreatment process and thus a higher sugar production cost and MSSP of \$0.47/kg sugar.⁷³ If deacetylation by liquid-liquid extraction is added to the dilute acid pretreatment, the sugar production cost increases by 5.9% due to solvent recycling.⁷⁴

In herbaceous feedstock processing, the sugar production costs from miscanthus and switchgrass are estimated to be \$0.18/kg and \$0.32/kg, respectively.^{71,77} In addition to the feedstock costs, operation capacity is a factor affecting sugar production costs. In terms of plant capacities, the switchgrass processing capacity in the study by Gnansounou and Dauriat⁷⁷ is smaller than the processing capacity reported by Boakye-Boaten *et al.*⁷¹ for miscanthus.^{71,77} The highest production cost, which is approximately \$3.37/kg, is associated with the ionic liquid pretreatment.⁷⁶

For sugar production from wood-based materials, the cost of hydrolysis for hardwood and softwood accounts for approximately 4.3% and 4.2% of the total cost, respectively.¹⁸ In hardwood-derived sugar production, the production cost is estimated to be \$0.19–0.32/kg; however, the ionic liquid pretreatment results in the highest production cost of \$3.14/kg, for a similar capacity processing facility. For softwood processing, the sugar production cost from spruce using the organosolv pretreatment is estimated to be 0.67 \$ kg⁻¹ sugar.³ The high costs of ionic liquid and organosolv pretreatments compared to other pretreatments are due to high material costs (90% of the total material cost). Furthermore, plants using ionic liquid and organosolv would require solvent recycling processes.

For the use of straw and sugarcane bagasse in sugar production, the production cost is estimated to be \$0.28–\$0.34/kg sugar.^{77,78} For the sugarcane bagasse process, sugar yields also include hemicellulosic sugars produced during pretreatment and they account for approximately 40% of the total sugar production. The sugar production cost from sweet sorghum bagasse is estimated to be \$0.38–\$0.49/kg sugar, based on a similar process with sugarcane bagasse, as investigated by Gubicza *et al.*⁷⁸ The material costs account for over 90% of the total production cost.⁷⁹ Bidy *et al.*⁸⁰ reported an estimated sugar production cost of \$0.29/kg for an industrial-scale operation.⁸⁰

Comparisons of sugar production from different feedstocks and processing technologies

Sugar, starch, and cellulosic enriched feedstocks are what is available for producing sugar-based biofuels and biobased products. Sugars produced from these feedstocks are important intermediate products. In this study, we compare the capital investments and production costs among different feedstocks and processes based on the unit fixed costs and production costs.

In fixed capital investment (Fig. 6(a)), cellulosic (second-generation) refining processes have higher fixed costs than first-generation feedstock processing, including starch-based and sugar-containing crops. The unit fixed capital cost for processing cellulosic feedstocks for sugar production is 23–44 ¢ kg⁻¹ feedstock. The acid-based pretreatment has the highest fixed cost because of the extra costs required to guard against equipment corrosion. The ionic liquid and organosolv pretreatments have the second highest fixed costs because of the additional equipment needed for recycling and facilities for storing the solvents. On the other hand, the least expensive sugar production operation used sugar crops (approximately, 5 ¢ kg⁻¹ feedstock) because it required a relatively simple process for juice extraction. For starch-based sugar production, the fixed costs varied from 1.9–12.4 ¢ kg⁻¹ feedstock. The fixed cost of the wet-milling process is higher than that of the dry-grind process because of unit operations associated with fractionation of the corn kernel.

In terms of feedstocks, the fixed capital costs for herbaceous and wood-based feedstocks are 9–56 ¢ kg⁻¹ and 9–51 ¢ kg⁻¹, respectively, which are higher than the fixed costs of the first-generation feedstocks (5–6 ¢ kg⁻¹). The facilities used for feedstock handling, pretreatment, and lignin separation are the major contributors to the higher fixed capital investments for cellulosic feedstocks.

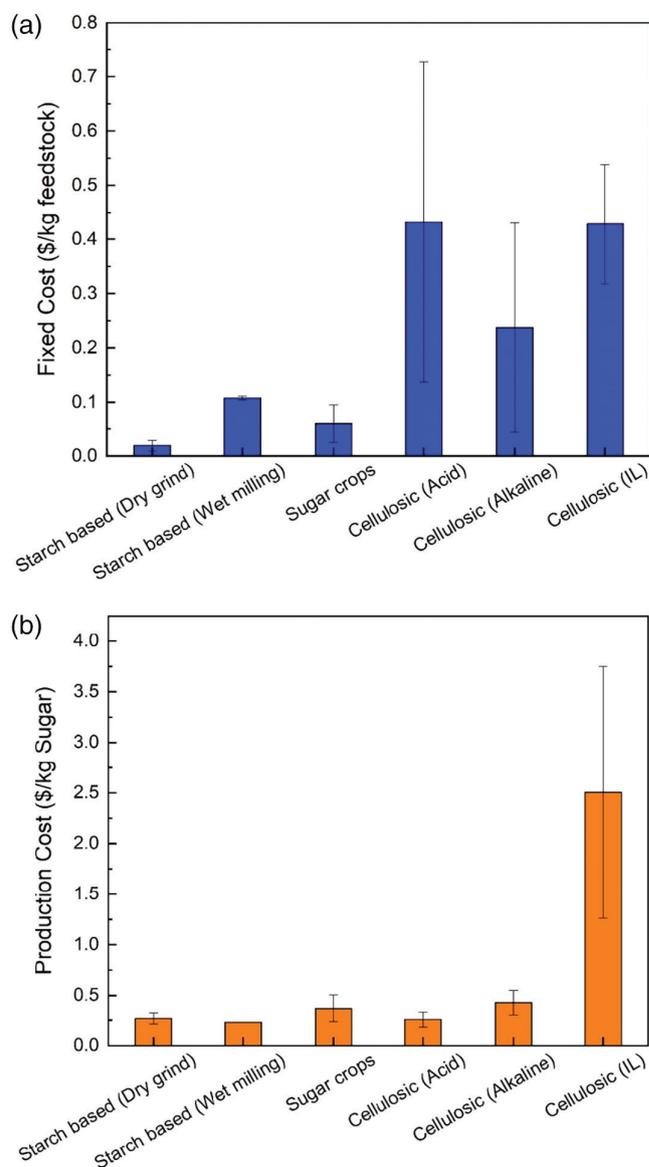


Figure 6. Costs of sugar production from different feedstocks. (a) Fixed capital cost; (b) Production cost.

For first-generation sugar production using well-established technologies, sugar production costs are 22–55 ¢ kg⁻¹ sugar (Fig. 6(b)). The production cost of sugar crop refining (37 ¢ kg⁻¹ sugar) is higher than that of the corn dry-grind process (25 ¢ kg⁻¹ sugar) because of the higher energy consumption required for mechanical juice extraction and sugar purification. The sugar production cost is also lower from a corn wet mill versus corn dry grind mill.

For the second-generation biorefining process, the production costs range from \$0.10 to \$3.37/kg sugar production. The different pretreatment approaches, including energy consumption, enzyme production, and enzyme loadings,

Table 6. Profile of saccharide sources and processes

	Process complexity	Sugar yield (purity)	Feedstock storage	Product
Starch-based	Moderate	Low to high	Long	Hexose
Sugar crops	Simple	High	Short	Hexose
Cellulose-based	High	Low	Long	Hexose/ Pentose

critically affect sugar yields and costs. Additionally, the variation in the sugar production costs is caused by differences in geographical location, processing capacity, major equipment needs, and vendors. As shown in Fig. 6(b), the acid pretreatment-based operation has the lowest sugar production cost because it has high efficiency and sugar productivity. The low sugar productivity of the alkaline pretreatment leads to high sugar production cost. The high solvent costs of the ionic liquid and organosolv pretreatments lead to the highest reported sugar production costs. These results might explain why acid pretreatment is popular with industry.

According to the capital investments and production costs presented above, the feedstock type and the process (technology) complexity play important roles in determining the total sugar production costs. The profile of saccharide sources is summarized in Table 6. Streamlining processes directly lowers production costs. Furthermore, storage fees associated with storage of feedstocks and products are also influential in determining costs.

Reasonable capital investments and operating costs are essential considerations to develop profitable and sustainable processes. The economic and cost analyses of sugar production are generally included in bioethanol production models. More detailed knowledge regarding sugar production is essential for the industrial biotech industry. This would not only help in estimating the feasibility of sugar production from different types of feedstocks but also in providing a sugar cost baseline for chemical processes beginning with sugar feeds for production of sustainable fuels and chemicals.

Conclusions and future outlook

Sustainable and low-cost sugar production is necessary for continued growth of the industrial biotech sector. Large quantities of low-cost industrial sugar production can be realized by retrofitting existing dry-grind ethanol facilities. Lignocellulosic biomass is considered a potential resource in addition to first-generation feedstocks for sugar

production; however, the high cost of cellulosic sugar is at present a barrier to commercialization. A lack of industrial process data and varying processing assumptions make it difficult to determine an accurate sugar production cost profile from past studied feedstocks and processing technologies. A normalization study is warranted to provide a comprehensive reference for biorefinery ventures.

Acknowledgement

This work was funded by the DOE Center for Advanced Bioenergy and Bioproducts Innovation (US Department of Energy, Office of Science, Office of Biological and Environmental Research under Award Number DE-SC0018420). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the US Department of Energy.

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