Sugarcane as a renewable biofuel biology essay

Science, Biology

Bioprocess Engineering AssignmentJerome Levinson 326555

Executive Summary

With an ever-growing need to curb fossil fuel production and consumption, renewables have consistently been put in the spotlight to take over as a cleaner, modern form of energy. Bioethanol production from sugarcane biomass is one important focus for this area. Brazil has an economy reliant on ethanol fuels for vehicles, with ethanol being produced from the juices of sugarcane typically used for sucrose. However, an opportunity has been identified in converting the unused portions of the sugarcane, known as the cellulosic biomass. This has many advantages including using a much larger portion of the plant for ethanol from a plant that is semi-perennial and grows much faster than many other biomasses. However, the technology for this method still requires further development in research in enzymes for treatment and hydrolysis, which liberate the sugars from the cellulosic material, as well as microbes for converting pentose sugars and wider adoption for commercial viability.

Introduction

Renewable energy is, and continues to be, an important focus of the modern era in an effort to reduce the reliance on environmentally damaging fossil fuels, which are becoming scarce and harder to source, and to produce more carbon neutral friendly energy. Renewable energy is not only generally cleaner for the environment, but infinite, liberating society from the complex problem of non-renewables including natural gas and petroleum, which bring with them issues both political and economic. In conjunction with better known sources of renewables such as solar and wind energy, much research is taking place into new sources of energy from existing stocks, particularly plant matter, called biomass. Biomass is any matter that is a natural biological product from plants or animals. Presently, biomass can be used to produce biofuels and in particular, bioethanol, in addition to many chemical products. Common sources for bioethanol are corn in the US, sugar beet in the UK and sugar cane in Brazil and Australia. These sources were initially primarily for sucrose (or in the case of corn, vegetable) production, but with increasing societal demands have found a new life in the production of energy by fermentation of these sugars. Ethanol is being increasingly used as a fuel in car engines with many countries supplying E10 fuel which contains 10% ethanol in addition to the petroleum. Brazil has an economy with ethanol so deeply entrenched that their cars are unique and can run on much higher ethanol purities, breaking down the ‘ blend wall’ which states that current petroleum engines can only contain a certain amount (10-15%) ethanol and continue to operate to specification. Ethanol is also a precursor to many chemical products such as medical, and as a solvent. The advantages of using bioethanol as a fuel are: It burns cleaner due to fewer impurities such as sulphurIt requires a decreased reliance on fossil fuels and uses renewable biomassThe carbon dioxide released is the same amount as the plant ingests while it is growing, making the process near-carbon neutral (production may require external energy inputs)Aids complete combustion of fossil fuels in engines due to extra oxygenSome disadvantages are also recognised however: The energy content is lower than other fuels, meaning that a greater amount of bioethanol must be carried for the same energy inputThe world’s demand for energy cannot be met by this crop due to the extreme amount of arable land that would be neededPolitical and environmental problems exist in countries such as Brazil, where rainforests are demolished to make way for profitable sugarcane farming and labour is misusedHard to get past the ‘ blend wall’ in most countries where engines are not modified for ethanol useProduction from bioethanol from sugarcane has been recognised as one of the most important renewable energy focuses in the near future due to the opportunity to increase efficiency of production. It is one of the most promising sources for cellulosic ethanol production with only one third of the biomass being used for production currently. It is also semi-perennial, only needing to be replanted every 5 years or so, and can be harvested without uprooting the plant. This report analyses current technologies for bioethanol production from sugarcane, primarily the conversion of the easily accessible cane juice into ethanol, as well as developing technologies and future technology, such as the conversion of lignocellulosic material and second generation biofuels.

Results and Discussion

Currently sugarcane is harvested primarily in Australia and Brazil, though for different means. In Brazil it is used to produce high quantities of ethanol, while in Australia it is still used mostly for sugar production. The process through which Brazil produces its ethanol is discussed in Section 3. 2. Whilst this process is efficient in the conversion of cane juice to ethanol, it lacks attention to the possible conversion of waste products to ethanol. Section 3. 3 discusses the emerging technology of bagasse production to ethanol, a recommended pathway for the future, drastically increasing the efficiency of sugar cane to ethanol production. Furthermore, Section 3. 4 and 3. 5 identify future technologies that deserve attention involving second generation biofuels and process areas which require development to make production more efficient and commercially viable.

Structure of Sugar Cane

When harvested, often by machine or sometimes by hand, the sugar cane is separated into two components: the stem and the straw. The stem is the main part of the cane which is collected while the straw is often left in the field as trash. The stem itself produces two further components: cane juice and bagasse. The cane juice is comprised of carbohydrates, mostly sucrose, and can be processed to make sugar for human consumption or can be fermented to produce ethanol. A by-product of the juice processing is molasses which is the portion from which the sucrose cannot be separated and is generally used as an animal feedstock. The bagasse is the part of the cane that is the leftover fibrous waste after the juice is extracted. This is made up of three components; cellulose, hemicellulose and lignin, and is thus labelled a lignocellulosic biomass. Currently, the bagasse is typically used to produce power for the ethanol production plant by using it as a boiler feedstock. This makes enough power not only for the plant but often excess is produced and returned to the grid, making most sugarcane processing facilities self-sufficient. The straw can be combined with the bagasse for this use at it has a similar chemical composition. Figure 1 shows a breakdown of the different parts of the sugarcane down to a chemical basis.[1]Figure – The majority components of sugar cane down to a chemical basis

Processing Sugar Cane Juice into Ethanol

The overall process of converting cane juice into ethanol is quite a simple one that is represented in Figure 2 below. It essentially requires separating of the cane juice from the plant through a milling process, biological fermentation of the juice to produce ethanol, then distillation and drying to produce anhydrous ethanol. The milling stage is the first to be completed once the sugar cane is harvested and brought back to a processing facility as the juice must be extracted from the plant before fermentation. To do this, the sugar cane is reduced into smaller pieces through cutting and chopping techniques and is then crushed in rollers. The juice can be collected and the leftover bagasse goes to the boilers. Figure – Process flowsheet of cane juice conversion into ethanolThe fermentation stage converts the sugars in the juice into the required ethanol using biological processes due to the addition of yeast. These are microbes that convert glucose into ethanol and carbon dioxide in a manner much more efficient than a chemical process could provide. This process is classified anaerobic digestion by the microbes of the carbohydrates to produce ATP for energy along with ethanol and carbon dioxide. The glucose reacts with zymase, an enzyme that catalyses the fermentation process and is naturally occurring in yeasts. Though regarded as an anaerobic process this is not a strict requirement as the yeast strongly prefers reaction with the sugars than oxygen, and thus a sealed environment is not necessary. Glucose is fermented into ethanol using the following overall reaction: $C6H12O6 + Zymase \rightarrow 2C2H5OH + 2CO2$(1)To produce glucose, the sucrose dimer in the cane juice must be broken up into the glucose and fructose constituents. The first step cleaves the glycosidic linkage present using the enzyme invertase from the yeast in the following reaction: $C_{12}H_{22}O_{11} + H_2O + \text{Invertase} \rightarrow 2C_6H_{12}O_6$(2)Following the fermentation stage, the ethanol must be separated from the remaining components, such as water, through distillation and then drying. Figure 3 presents an example of a process flow diagram for the entire process described above. Full-size image (19 K)Figure – Process flow diagram of cane juice to ethanol production with bagasse used as energy

Bagasse into Ethanol

Current technology is now allowing for the production of the bagasse into ethanol whereas previously it was too difficult and expensive to achieve. This would allow approximately double the amount of ethanol to be produced from the same amount of land and is a very promising technology for the future. Since sugarcane also regenerates very quickly in comparison to other crops, approximately four times as fast as trees [1], this process would make it a very efficient form of biofuel energy production. However, it is currently much more expensive than production from cane juice due to the extra processing required. To produce ethanol the sugars must be extracted from the cellulose and hemicellulose fractions, with the lignin being separated because it is a barrier to ethanol production. It is a complex aromatic and limits the accessibility of enzyme, acting as glue within the cell wall by binding the other components together and providing rigidity to the structure of the plant. The successful removal of lignin improves the conversion by enzymatic hydrolysis. Lignin has many other applications such as a fuel, chelating agent or chemical precursor. Sugarcane bagasse in Brazil has a composition of about 38-45% cellulose, 22-27% hemicellulose, and 19-

32% lignin. Sugarcane from other regions, environments or species can have different compositions. The rest of the composition of the biomass is typically ash and extractives. The sugarcane straw is composed of the same components as the bagasse, only in slightly different (±5%) proportions.[1] The cellulose of the bagasse is a polymer of mostly glucose units, as mentioned previously, and is not susceptible to hydrolysis immediately. Hemicellulose, however, is a much less complex polysaccharide and is easily hydrolysable. It contains C5 and C6 sugars, with glucose, mannose and xylose being the most abundant. To be converted into ethanol, the lignocellulosic material must undertake additional steps than the cane juice. It first must be converted into simple sugars to then allow for fermentation. This is generally achieved by pre-treatment then hydrolysis, reactions due to the addition of water, to break the long chains of polymers. Usually acid hydrolysis and in the future, enzymatic hydrolysis, is used. The pre-treatment and hydrolysis steps in this process are the main differences than in the conversion of the cane juice because the sugars are more readily available in that instance. Pre-treatment is necessary because the lignocellulose has a rigid structure due to its role in the support of the plants cell wall and structure. The cellulose and hemicellulose components which contain the required carbohydrates need to be liberated from lignin, a complex molecule that typically contains alcohols. The process must effectively liberate the cellulose whilst minimize formation of degradation products which can inhibit further processing such as the hydrolysis and fermentation processes. In the pre-treatment process (also known as first stage hydrolysis) hemicellulose is hydrolysed into the basic sugars and a small amount of cellulose is also hydrolysed to glucose during the pre-treatment. The mixture obtained is separated into liquid and solid (containing lignin + unhydrolysed cellulose). The liquid is filtered and sent to a fermentation column for ethanol production while solids are sent for another round of hydrolysis. At this second stage of hydrolysis, cellulose is converted into glucose. Again, the mixture obtained at the end of hydrolysis is separated into liquid and solid (lignin only). After filtration, the liquid is sent to a fermentation column for ethanol production and combined with the previously fermented liquid for distillation to ethanol, and lignin is fed into a boiler for energy production. This entire process is shown in Figure 4.

Pre-treatment methods

Thermal pre-treatment: the bagasse is heated to about 150–180 °C to break down the lignin and hemicellulose. Higher temperatures can cause unwanted compounds to form which may inhibit the fermentation of the sugars. This treatment method can be completed by multiple processes such as steam heating, steam explosion, hot water, CO2 explosion and ammonia fibre explosion. Acid pre-treatment: dilute sulphuric acid (0. 5-1. 5%) is added which hydrolyses the hemicellulose at about 160°C. The acid is neutralized prior to fermentation, and this is currently the most preferred method of pre-treatment. Many other options exist for pre-treatment but these are often less preferred, more expensive, less refined or experimental. These include: alkaline, oxidative, Organosolve or biological pre-treatments.

Second stage hydrolysis technologies

Acid hydrolysis: following on only from dilute acid pre-treatment, this can be used for the hydrolysis stage. A higher temperature and more concentrated acid (215°C and 4% respectively) are used to convert the remaining cellulose to glucose, and then the solution is neutralized. This method is quite effective with a high yield, rapid (about 12 hours) with low degradation of products. Enzymatic hydrolysis: provides some advantages over the acidic method such as milder temperatures and pressures, achieving high yields, few inhibiting compounds and cheaper equipment. This uses enzymes called cellulases to break the cellulose into glucose in a similar manner as some animal digestive systems, and is sometimes used in conjunction with chemical hydrolysis for a high yield. Figure – Ethanol production from lignocellulosic feedstock using the cellulosic approach

Fermentation

Much like the fermentation of the cane juice, the monosaccharides are now fermented using yeast to produce ethanol. Currently, technology typically allows the conversion of C6 sugars only. Baker’s yeast (saccharomyces cerevisiae) is used for the C6 sugars, while combinations with others such as Escherichia coli for C5 sugars is being researched for optimal cost and yields. After fermentation is complete the mixture of ethanol and water is distilled to obtain ethanol, which is then dehydrated to produce anhydrous (fuel grade) ethanol. Water produced as a part of distillation is diverted towards a wastewater treatment facility.

Thermochemical Approach

Instead of the above described two-stage pre-treatment and hydrolysis, a thermochemical approach can also be used. Gasification transforms the lignocellulosic material into carbon monoxide and hydrogen which can then be fermented. This process is less used as it requires harsher temperatures and more expensive equipment in a more complicated process. The constituents of the bagasse are converted to syngas (CO, N2, CO2, CH4, H2) which is then fermented or catalytically converted to ethanol and water. This uses temperatures up to 800°C and different microbes (clostridium ljungdahlii) to convert the gas into ethanol than the previously discussed processes. A catalyst-based process may also be used to convert the gas into ethanol.

Biodiesel and Biobutanol

As an alternative to ethanol-only production, second generation fuels such as biodiesel and biobutanol could be produced from sugarcane. These fuels are beneficial as they can be used in current engine technologies, with biobutanol being used in a typical gasoline engine and biodiesel in a diesel engine. Biodiesel production would require a secondary source of input, typically oil from a soybean crop, in addition to the ethanol in a transesterification process to produce biodiesel[2]. This fuel emits less particulate matter, hydrocarbons and carbon monoxide than conventional fuels, however it produces more nitrates. This fuel could be either used exclusively in the machinery and vehicles used in the harvesting and processing phase or could be produced on a larger scale and sold to residential vehicles. Biobutanol production is a promising technology with the increased yield and availability of cellulosic resources. This pathway would produce a direct replacement to petroleum which is diminishing in supply, non-renewable and environmentally harmful. The process for the production of biobutanol is similar to that of ethanol, with a fermentation process being the most important stage. However, this technology would need to be significantly refined before commercialisation, with barriers such as microbial selection, recovery techniques and reactor selection still typically in a research phase[3].

Future Research and Commercial Viability

It is apparent that future technology in this area should concentrate on the production of ethanol from lignocellulosic feedstock to increase the conversion of available land to valuable product. While some technologies have already been implemented on a commercial scale and deemed viable, many areas of research are left open in this area to increase efficiencies and profitability. The cane juice to ethanol process has been used for many years now, and the bagasse to ethanol technology having also been proven. However, the technology has limited wider adoption of this method, being expensive and not efficient enough. Therefore the key to commercial viability for the future of lignocellulosic ethanol production lies in the improvement of technology. Some areas which should be focused on are discussed below, with some recommendations as to how to undertake such research and which may be most promising. Since relatively little is known about the sugarcane cell structure, further research should be undertaken in this area to enhance the yield of simple sugars, especially from the hemicellulose component. As we are educated in this area, microbes and enzymes that are effective in the breakdown and hydrolysis of these carbohydrates can be identified. For example phenols, which make up much of the lignin that provides cross-link cell wall polymers, can be studied to decrease enzyme inhibition and increase accessibility to polysaccharides. Another area of concern is the fermentation of pentose sugars. Hexose sugars have been easily fermented for many years by Baker’s yeast; however pentose sugars are more of a challenge and are present in large quantities in the hemicellulose material. Similarly, chemical hydrolysis to make these available to fermentation is not as effective as with hexose sugars. The improvement in these two areas will improve ethanol production drastically. One possibility is the genetic engineering of the saccharomyces yeast to include pentoses in their metabolising processes. Studies have been undertaken to realise other methods of effective hydrolysis. Fungi have been a focus of some studies into their ability to break down lignocellulosic materials. The possibility of this additional option, plus ever-increasing options of genetic engineering by biochemical engineers, may make fungi in conjunction with yeasts very efficient in converting most sugars in the lignocellulosic material. Research in this area would need to focus on gaining an understanding into how hydrolases act on cell wall polysaccharides. Another option would be to genetically engineer the plant itself so that cell walls are modified to increase the accessibility and willingness of polysaccharides to undertake hydrolysis without compromising sugar yield.

Conclusions

It is clear that the production of ethanol from sugarcane bagasse is not only possible, but should be an important area of research for the near future to increase the efficiency and yield of already sugarcane crops into ethanol, an important renewable energy. Lignocellulosic conversion technologies already exist, but further research into enzymes and microbes for treatment, hydrolysis and fermentation should pave the way for affordable and economically viable commercialisation of this process. Once this is achieved, second generation biofuels such as biobutanol and biodiesel can be considered as alternatives without the requirement for adaptation of car engines. However, whilst this is a technology that has much promise in the way of efficiency, environmental benefits and application, it should not be considered as a complete solution to future society’s energy and fuel needs. This is due to one single disadvantage of the technology, the amount of arable land needed to grow the feedstock, which is far too little than what would be required for such a demanding utilisation.