Producing Cellulosic Ethanol from Waste Paper
(Technical Paper)

The Environmental and Economic Sustainability of Cellulosic Ethanol
(STS Paper)

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Introduction

Current estimates predict that fossil fuels will be exhausted by 2060 if consumption continues at current rates. In addition to the limited supply, fossil fuels are also a major contributor of greenhouse gasses that cause climate change. In the United States, petroleum-based fuels accounted for 91% of transportation sector energy use (U.S. EIA, 2020). Biofuels, such as ethanol made from corn starch or cane sugar, biodiesel made from soybean and rapeseed oil, and biodiesel made from algae have been proposed as possible renewable fuel alternatives. However, there are multiple issues with biofuels that need to be addressed in order to make them viable alternatives to fossil fuels. For example, corn-based ethanol barely recovers the energy used to create it and has less energy per gallon than gasoline. (Murphy, Hall, & Powers, 2011; U.S. DOE, n.d.). Also, biofuels may cause a net increase in emissions such as carbon dioxide due to land use change and because corn starch and cane sugar are typically sold as food products their use may negatively affect food security (DeCicco, 2016; Tenenbaum, 2008).

Although current biofuel production has many issues that need to be addressed the rapidly decreasing supply of fossil fuels means an alternative fuel source will soon be needed to replace petroleum-based fuels. Ethanol produced from cellulosic material has the potential to address many of the issues facing current biofuel production. Cellulosic ethanol is produced from many different types of cellulosic material including corn stover, wood chips, cardboard, and mixed paper making it both cheaper to produce and preventing competition with food crops. Cellulosic Ethanol also has negligible impacts on greenhouse gas emissions due to land use change or in some cases can even sequester carbon (Dunn, Mueller, & Kwon, 2013). My technical research group will be focusing on the production of cellulosic ethanol from mixed paper sourced from municipal solid waste streams. For my STS topic, I will be investigating the potential for cellulosic ethanol to provide an environmentally and economically sustainable alternative to petroleum-based fuels. These two projects will together help provide information on the economic and environmental cost of producing cellulosic ethanol in the United States.

Technical Topic - Producing Cellulosic Ethanol from Waste Paper

Scientist in the United States are currently searching for cleaner, sustainable alternatives to fossil fuels to meet the world's energy needs. A suitable alternative is needed since fossil fuels are in limited supply and release carbon dioxide to the atmosphere, contributing to adverse effects in climate change. Many environmentalists support the adoption of electric vehicles coupled with making the power grid sourced from renewable energy as the way to reduce use of fossil fuels. However, issues associated with charging electric vehicles and the expense of their batteries are barriers to widespread adoption. A better solution could be the use of biofuels as a replacement to gasoline in vehicles powered by internal combustion engines. One popular biofuel candidate is ethanol.

Life cycle emissions for ethanol are lower than those of gasoline because the carbon source for ethanol is from plants that recently obtained their carbon from the atmosphere, whereas, the carbon source for gasoline is crude oil with carbon that has been sequestered for millennia. And since the source material for ethanol-based biofuels is grown within a lifetime, it's considered a sustainable, renewable energy source, unlike fossil fuels.

Currently, corn ethanol is used extensively as a blended add-in for gasoline to allow for more complete combustion and lower emissions. Corn ethanol is affordable and easily fermented since corn kernels contain simple, fermentable sugars. However, production of corn ethanol competes with food production, effectively raising the price of food. Another common solution is using inedible, cellulosic sugar sources like corn stover, though corn stover is useful as fertilizer and animal feed. Moreover, for cellulosic ethanol, the cost of enzymes to break down cellulose and the price of feedstock make ethanol more expensive than gasoline to produce. Our project will lower the cost of ethanol production by using acid instead of enzymes to break down the cellulose and using a cheap and sustainable feedstock in the form of waste paper. Mixed paper is a desirable feedstock because it is available for low cost in large quantities and its theoretical yield of 128.3 gallons per dry ton is higher than corn stover, wood waste, and cardboard (Shi, Ebrik, Yang, & Wyman, 2009). Discarded mixed paper has no alternative use besides recycling, and currently, much of it is incinerated or stored in landfills at cost. The lack of demand for mixed paper makes it incredibly cheap at $12 per ton (May 2020). Mixed paper is also obtainable directly from municipal solid waste streams at a negative cost however paper sourced in this way must first be screened to remove no cellulosic contaminates such as plastics.

For this project, the research team will design a chemical process to produce fuel-grade ethanol from the cellulosic material in municipal mixed paper waste. The mixed paper feedstock will first be turned into a slurry, which will be pretreated using sulfuric acid (H_2SO_4). The pretreatment process will remove impurities, such as ink, from the feed stream. Sulfuric acid is then used to break cellulose into glucose and other sugars through a hydrolysis reaction (Kong-Win Chang, et al. 2018). After hydrolysis, the mixture is neutralized with lime (CaO) to make a calcium sulfate precipitate ($CaSO_4$) that is removed from the solution. Next, *Saccharomyces cerevisiae*, or brewer's yeast, is added and fermentation begins; the fermentation will take place in a series of four continuous stirred tank reactors (CSTRs) with a cell recycle stream as shown in Fig. 1.

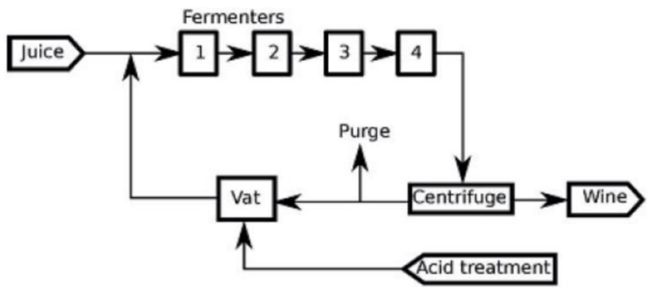

Fig. 1. Process flow diagram of fermentation scheme. Numbered fermenters are CSTRs (Fonseca, Costa, & Cruz, 2017).

A study by Fonseca, Costa, and Cruz using this method found that a continuous fermentation process will have a conversion of nearly 90% at a feed sugar weight concentration of 23% and even greater conversion rates at lower concentrations that are expected in a paper slurry (2017).

The ethanol produced must be purified before it is used as biofuel. Purification of ethanol will be accomplished via distillation. In order to overcome the azeotrope formed by an ethanol-water mixture, extractive distillation, similar to the design in Separation Processes, will be necessary, so toluene will be added as a solvent for ethanol. A two-column distillation system will be used, as shown in Fig. 2.

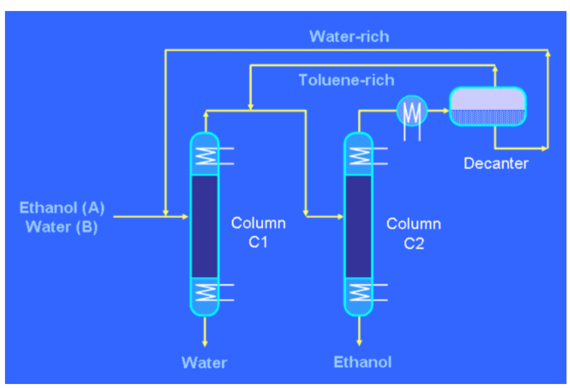

Fig. 2. Extractive Distillation of Ethanol and Water using Toluene (Separation Processes).

The first column isolates the water-ethanol azeotrope (water will come out of the bottom product and the azeotrope will come out of the top). The azeotrope will then be mixed with toluene, which creates a minimum boiling ternary azeotrope, which when fed to the second distillation column. The new azeotrope is recovered out of the top of the column and can be recycled, and fuel grade ethanol is recovered as the bottom product (Separation Processes).

Based on research of previous processes, the recycled azeotrope must undergo a separate separation process using a decanter, allowing the toluene rich portion to be recycled into the second distillation column, while the water rich portion would be removed as waste or recycled into the feed to the first column (Separation Processes).

This project will be executed by a five-member team over two semesters as part of CHE4438 and CHE4476. To divide the different parts of this project up, we have decided to divide into pairs. The parts of the project will be allocated as follows: Nick and Alicia will cover pretreatment, Nick and Michael will cover hydrolysis and neutralization, Brendan and Austin will cover fermentation, Alicia and Michael will cover distillation, and Brendan and Austin will analyze the overall utilities, material and energy balances, and the economics of the process. The entire group will be consulted to finalize major team deliverables and to work out problems that cannot be handled by the pairs alone. Data for understanding and calculating the pretreatment, hydrolysis, and fermentation necessary for this process will be taken from previously published literature about lab scale ethanol production from mixed paper, as well as public data about cellulose hydrolysis into glucose and yeast fermentation of glucose into ethanol. Microsoft Excel will be used for equation solving for the overall balances, utilities, and economics; MATLAB may be used for hydrolysis and fermentation data modeling; and Aspen Plus V11 will be used for overall process design and all distillation calculations.

STS Topic - The Environmental and Economic Sustainability of Cellulosic Ethanol

Although ethanol is a biofuel that is already being produced in large quantities, many critics believe that it is not a sustainable solution for a gasoline alternative in the United States.

Gasoline is a widely used fuel in the United States with the country consuming about 142.71 billion gallons in 2019 (EIA, 2020). While many biofuels work well in small scale production when they are theoretically applied as a replacement for all gasoline use in the U.S. many new issues appear and existing problems are magnified. Ethanol is a renewable fuel source but, there are multiple factors that may prevent its use as a replacement for gasoline in the United States.

One issue that needs to be considered when selecting a sustainable fuel is pollution. If sustainable fuels produce a net increase in atmospheric greenhouse gasses when being used the adverse effects of climate change caused by fossil fuels will continue to become more severe. Also, renewable fuels that require fertilizers for crop growth will increase the amount of nitrogen and prosperous pollution in bodies of water and cause algal blooms which negatively impact aquatic ecosystems. Theoretically ethanol has a negative or carbon neutral footprint because the carbon being released through combustion was originally removed from the environment as the plant or other biomatter source grows (EIA, 2019). This idea is challenged by research on emissions caused by land use change, the conversion of existing forest or grassland into field for crop growth, which shows that instead of lowering emissions ethanol production actually increases greenhouse gas emissions for years after the switch in land use (Searchinger, 2008).

The amount of land needed to grow biomass is another potential issue with large scale ethanol production. Depending on the crop used an acre of land can produce between 165 and 742 gallons of ethanol per acre (Cason, Satishchandra, Gokianluy, n.d.). As a result, fully replacing gasoline with ethanol may require the land typically used to produce food to be converted to growing crops needed for biofuel production. This will lower the supply of food produced in the U.S. and raise prices of food for consumers. Therefore, the ability to balance production of food and biomass for ethanol production needs to be considered in order to determine the viability of ethanol. While second gen ethanol not produced from feedstocks commonly used for food production it can still impact food availability and prices (Cason, Satishchandra, Gokianluy, n.d.). Corn stover for example is a source for second gen ethanol but is often used as feed for farm animals. As a result, using this material, the price of corn stover is raised and that increases the price beef or other animal-based products. Also, cellulosic material such as corn stover is often used as a fertilizer for fields and its consumption will increase the use of manmade fertilizers.

In order to analyze the long-term sustainability of cellulosic ethanol I will apply the concept of wicked problem framing to my research. Wicked problems are characterized as problems that have no single solution, lack a clear problem definition, and are perceived differently by various stakeholders due to contrasting views. One approach to wicked problems is to allowing different parties to develop their own solutions which are then compared directly to one another. While this method allows for the development of multiple solutions it prevents collaboration between different parties.

Ethanol sustainability fits many of the characteristics of a wicked problem. First the sustainability of ethanol is connected to many other issues such as food production and climate change. Also, long term sustainability is by definition an ongoing problem where there is not a final solution but rather an ongoing struggle to improve and solutions can take years or even decades to evaluate. In addition, there are multiple conflicting opinions on what aspects of sustainability are important and no one solution is likely to satisfy everyone. Also, electricity, hydrogen, and other biofuels are other potential sustainable fuel sources but, each have their own pros and cons and groups of people backing them. An analysis of the economic and environmental sustainability of ethanol is necessary to determine if ethanol is a potential replacement for gasoline or would it be better to research and invest in other alternatives. In order to analyze this problem, I will compare ethanol to other proposed renewable fuel sources and analyze the benefits of each solution.

Research Question and Methods

Research Question: How does transitioning to cellulosic ethanol as a source of fuel for transportation in the U.S. increase long term economically and environmentally sustainability?

To answer my research question, I will use both documentary research and historical case study methods. Combining these two methodologies will provide sufficient evidence to create a well-rounded presentation about the impacts of cellulosic ethanol. Beginning with background information, I will research land use change, greenhouse gas emissions, food security, and U.S. fuel consumption to give context to issues challenging the sustainability of ethanol production. I will also use case studies of existing starch and sugar-based ethanol plants to establish a point of reference for cellulosic ethanol. Then I will analyze research done on cellulosic ethanol production and the limited case studies available to discover the impacts of using a cellulosic feedstock. I will then assess the potential of cellulosic ethanol to replace petroleum-based fuel by calculating the required land, net emissions, impacts on food security, and overall cost of large-scale production.

Using these methods, the environmental and economic impacts of cellulosic ethanol will be explored and the results will help direct future research to remaining sustainability issues in order to continue improving the viability of biofuels.

Conclusion

This proposal covers an investigation of cellulosic ethanol manufacturing process as well as the environmental and economic consequences of large-scale cellulosic ethanol production in the United States. The team will design a chemical process to produce fuel grade ethanol using mixed paper as a feedstock. The design process will identify the location, raw materials, equipment, utilities, waste products, and production capacity of a theoretical cellulosic ethanol manufacturing plant. These results will provide a cost benefit analysis of our theoretical plant and will help identify if the location and scale of the plant would be a good investment.

Expanding on the Capstone topic, the STS Research Paper explores the benefits of second-generation biofuels, specifically analyzing the economic and environmental impacts of shifting towards cellulosic material as a feedstock for ethanol production. Large scale production of starch and sugar-based ethanol have faced criticism for increasing food prices, raising GHG emissions through land use change and providing insufficient raw material to support current fuel consumption. These issues are largely attributed to the use of corn starch and cane sugar as a feedstock for ethanol production. Switching to cellulosic material to produce ethanol can mitigate and or remove the issues preventing large scale adoption of ethanol as a replacement for fossil fuel. This research will identify the benefits of using cellulosic material to produce ethanol and show what issues still need to be addressed in order to make biofuels a viable alternative to fossil fuel use in the United States.

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