PRODUCTION OF SUSTAINBALE BIODIESEL FROM WASTE COOKING OIL USING A SUPERCRITICAL TRANSESTERIFICATION PATHWAY

SOCIOTECHNICAL ANALYSIS OF SUGARCANE LAND EXPANSION IN BRAZIL

A Thesis Prospectus
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Bachelor of Science in Chemical Engineering

By
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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.

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Introduction

Over the last 20 years, the consumption of biodiesel within the United States has skyrocketed from only 10.21 million gallons in 2001 to 1,939 million gallons in 2022 (*Alternative Fuels Data Center*, 2024). This demand continues to rise, with a 70% increase in biodiesel production projected by 2030 (*Is the Biofuel Industry Approaching a Feedstock Crunch?*, 2022). With the growing interest in biodiesel, higher percentages of the world's agricultural land must be converted into feedstock crops – such as corn, soy, and sugarcane. Currently, over 38% of the world's landmass is devoted to agriculture, and to meet global oil demands, 66-71% of this land must be repurposed (Auyeung, 2008; *Land Use in Agriculture by the Numbers*, 2020). However, to maintain land for traditional demands, such as food production, agricultural land must be expanded rather than converted. The expansion of agricultural land, therefore, has the potential to encroach on indigenous and subsistence populations in regions growing biodiesel feedstocks. In order to meet growing fuel demands and mitigate concerns surrounding environmental risks and land usage requirements, research into non-agricultural feedstocks is becoming prominent (Monika et al., 2023).

My team and I propose the development of a biodiesel plant using a feed of waste cooking oil (WCO). This method not only reduces the need for land-intensive feedstocks, but also, due to a supercritical transesterification pathway, can reduce biodiesel production costs. Procurement of fuel feedstocks and the production of the fuel itself, both petroleum-based and biodiesel, have requirements which cause the technology itself to have an inherent political nature. These inherent politics can dictate the societal impacts on an area or a population. Therefore, to understand the potential effects of alternative feedstocks, I will draw on the STS framework of technological politics to examine how the political nature of traditional agricultural feedstocks socially, technically, and politically impacts subsistence communities. Specifically, I will analyze how the advancement of ethanol biodiesel technologies and its increasing demand has promoted the expansion of sugarcane plantations into lands occupied by indigenous tribes in Brazil (Roundtable on Environmental Health Sciences et al., 2014).

Addressing only the social impacts on subsistence populations from agricultural feedstocks limits the understanding of how the technology's specific technical factors individually contributed to these societal effects. Through the coupling of social, technical, and political factors related to biodiesel technology, the potential results of non-agricultural feedstocks can be better predicted and prepared for. Therefore, because the challenge of land expansion for biodiesel feedstock growth is sociotechnical in nature, it requires attending to both its technical and social aspects to accomplish successfully. In what follows, I set out two related research proposals: a technical project proposal for developing a biodiesel production process using a WCO feedstock and an STS project proposal that examines the social and political forces that promote sugarcane planation expansions in Brazil using the STS framework of technological politics.

Technical Prospectus

In an increasingly mechanized world that demands higher energy usage, the associated environmental impact, including climate change and pollution control, have become dominant global issues. As a result, there is growing concern about automobile emissions and the impact of greenhouse gasses (GHG). These emissions, primarily consisting of CO_2, CH_4, and N_2O, act like a blanket when released into the atmosphere, absorbing the Earth's infrared radiation and preventing heat loss into Space. This accelerates the warming of Earth's surface. To mitigate these effects, the Environmental Protection Agency (EPA) has set an ambitious goal of achieving net-zero GHG emissions across the economy by 2050, aiming to create a clean and affordable mobility system (US EPA, 2023). In 2016, the transportation sector overtook power in GHG emissions (Bleviss, 2021). Since then, GHG emissions from transportation have continued to rise, now encompassing over 28% of global carbon emissions (US EPA, 2015). Therefore, transitioning vehicles to cleaner and more sustainable fuels is vital to reaching the EPA's goal and protecting our planet against climate change.

Biodiesel, made from the reaction of biomass – such as vegetable oils or animal fats – and alcohols, has been seen as a potential alternative to petroleum based diesel fuels (Sheehan et al., 1998). Traditional highway petroleum (low-sulfur) diesel introduces new carbon into the atmosphere that was previously held as underground reserves, such as crude oil. However, biodiesel utilizes carbon sources that have already been in the atmosphere, including carbon absorbed by plants during photosynthesis. In America, most highway diesel sold as gas stations is a 5% biodiesel blend (Hearst Autos Research, 2020). Increasing access to higher percentage blends is key to reducing carbon emissions. Increasing access to higher percentage blends is key to reducing carbon emissions. While the biodiesel market is on the rise, having produced 21.8 billion gallons in 2024 compared to only 25 million gallons in 2005, its cost remains a hindrance for large- scale adoption (Greer, 2024; Hearst Autos Research, 2020). Figure 1 shows

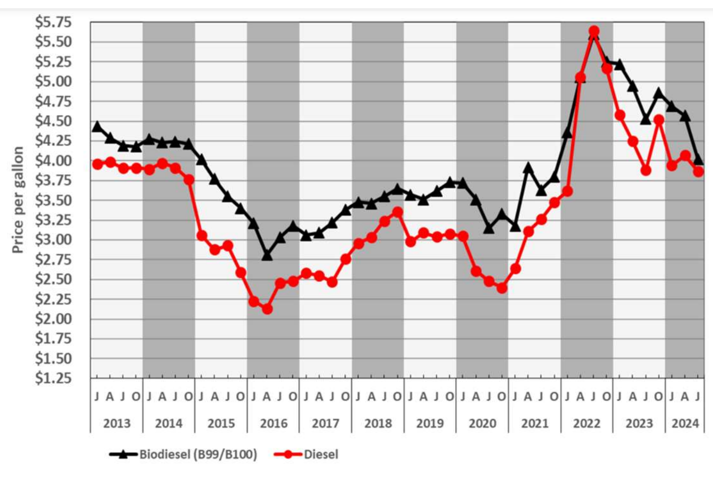

Figure 1: Cost of B100 fuel versus petroleum diesel since 2011. Copied from the U.S. Department of Energy Clean Cities and Communities Alternative Fuel Price Report from July 2024.

the cost of B100 compared to traditional petroleum diesel prices over the last 11 years (U.S. Department of Energy, 2024). These higher prices are most likely a result of the expensive production methods and raw materials currently in use. (Nagapurkar & Smith, 2023).

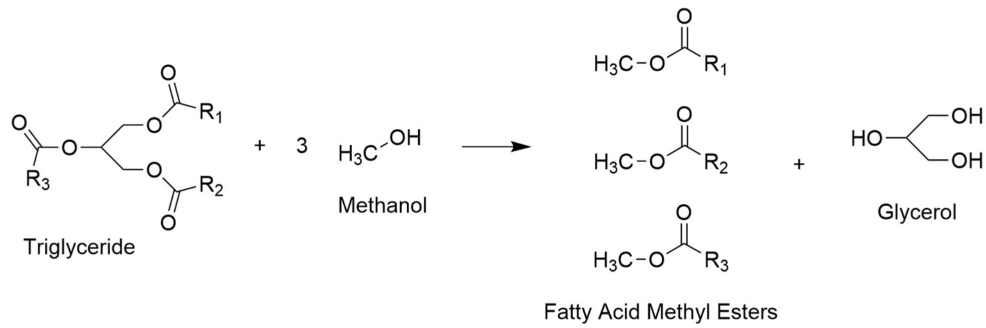

Fig 2. Production of fatty acid methyl esters (biodiesel) and glycerol from the reaction of triglycerides and methanol. Adapted from Van Kasteren and Nisworo (2007)

Current methods of biodiesel production require the use of alkali, acid, or enzymatic catalysts to transesterify the triglycerides found in the lipids of biomass. This process involves using an alcohol, such as methanol, to help convert these triglycerides into free fatty acid methyl esters (FAME), commonly known as biodiesel (Figure 2) (Zeng et al., 2014). These processes have significant limitations, including slow reaction rates and sensitivity to water and free fatty acids, which increase operation costs (Van Kasteren & Nisworo, 2007; Zeng et al., 2014). Specifically, when free fatty acids found in waste oils react with alkali catalysts, the most common catalyst in use, soaps form. This unsalable waste stream wastes raw materials and reduces methyl ester yield. Furthermore, enzymatic catalysts, such as lipases, are expensive and deactivate in the presence of methanol (Zeng et al., 2014). Therefore, due to pre-treatment costs to remove water and fatty acids, catalyst maintenance, and catalyst replacement, all catalytic transesterification methods have costly inhibitors to their full adoption in biodiesel production (Nagapurkar & Smith, 2023; Zeng et al., 2014).

However, recent developments in supercritical transesterification pathways have pointed towards potential cost-reductions in biodiesel production. This method capitalizes on the fact that at supercritical conditions, changes in pressure alter the solubility of the reactant and products and cause the fluid, methanol, to behave like both a liquid and a vapor (Zeng et al., 2014). As a result, catalysts are not required to assist in the reaction and the sep aration of products is simpler (Van Kasteren & Nisworo, 2007). Furthermore, supercritical pathways are insensitive to water and fatty acids which eliminates the need for extensive pretreatment. This allows for lower-grade feedstocks such as WCO, the focus of our project, to undergo transesterification, and ultimately lowers feed costs. Overall, when comparing the economic viability of catalyzed vs supercritical transesterification, as represented in Figure 3, the use of a supercritical pathway is the most promising (Brahma et al., 2022; Nagapurkar & Smith, 2023).

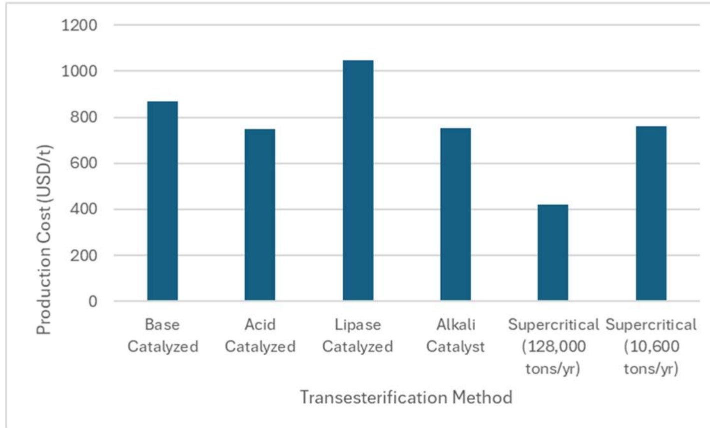

Figure 3: Production cost of biodiesel from WCO. Modeling of supercritical processes shows lowest production cost per ton.
Adapted from Brahma et al. (2022) and Nagapurkar & Smith (2023)

The goal of this project is to design and assess the economic feasibility of a biodiesel plant. Biodiesel, conforming to ASTM D6751 biodiesel standards (Appendix A), and pharmaceutical-grade glycerol will be produced via a supercritical methanol transesterification pathway (D02 Committee, 2024). Propane will be used as a co-solvent because it decreases the supercritical temperature and pressure and reduces the required methanol to oil ratio (Van Kasteren & Nisworo, 2007). The basic process operations for this proposal were adapted from Van Kasteren & Nisworo

(2007) and Nagapurkar & Smith (2023). WCO and a fresh methanol and propane stream will be combined with a recycle stream containing propane and methanol. The combined stream will be heated and pressurized to approximately 280 °C and 128 bar using thermal energy exchangers (Van Kasteren & Nisworo, 2007). This stream will be fed to an adiabatic plug flow reactor in which the transesterification reaction will take place. Then, the high-pressure products will be expanded in a flash drum to approximately 5 bar, where the unreacted liquid methanol and propane vaporize and are sent to the recycle stream. Remaining methanol will be recovered and recycled using a distillation column. The bottoms product of the distillation column will be cooled and sent to a decanter that will separate the biodiesel product from glycerol. Previous studies have shown that it is possible to achieve pharmaceutical-grade glycerol from this process, which will be sold as a profitable by-product (Nagapurkar & Smith, 2023). Figure 4 includes the simplified process design.

The team will use Aspen Plus V14 Simulation software to model the transesterification process for biodiesel production from waste cooking oil (WCO) in supercritical systems. Aspen Plus simulates complex chemical processes using robust thermodynamic models. The Soave-Redlich-Kwong (SRK) equation of state will be used to model the reactor block since it is useful

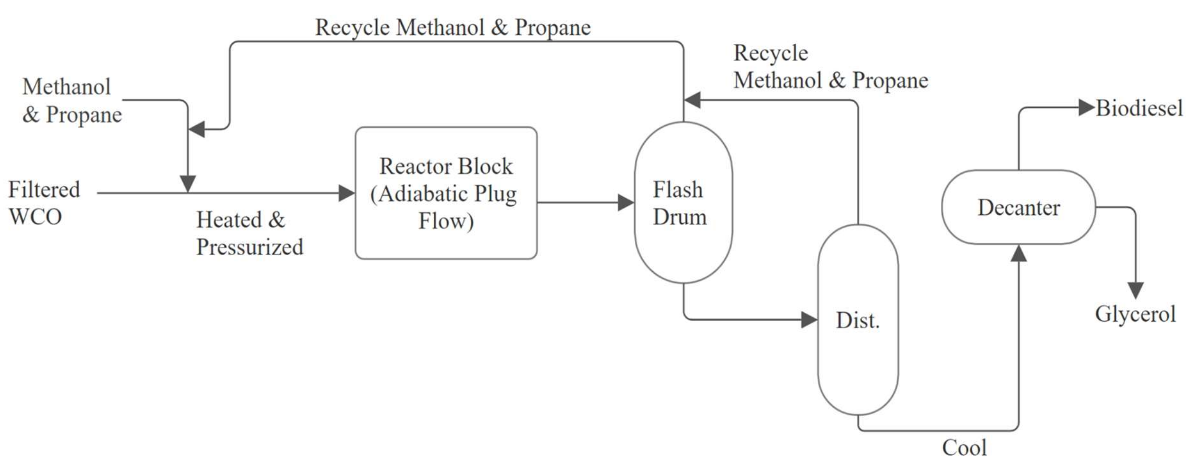

Figure 4: Simplified process diagram to produce biodiesel from WCO
Adapted from Nagapurkar & Smith (2023) and Van Kasteren & Nisworo (2007)

for operations requiring high pressures and temperatures. This model accurately simulates the behavior of methanol in its supercritical state, optimizing the reaction without the need for traditional catalysts. To ensure safety in designing for high-pressure systems, we will consult with Professor Ronald Unnerstall, who brings decades of experience in process safety, particularly in high-pressure environments and the biofuel industry, on necessary safety practices and equipment. His insights will be invaluable in addressing the safety challenges posed by operating under supercritical conditions. For kinetic data, we will leverage past studies on supercritical systems using WCO and other plant oil feedstocks. This data will inform our reaction rates, system design, and overall process efficiency. Specific compositions of WCO and plant siting information will be detailed in the Design Basis Memorandum in November 2024. The project will take place over two semesters through CHE 4474 and 4476, with the team delegating tasks based on individual strengths and familiarity with specific aspects of the process. Regular cross-checks and collaboration will ensure a cohesive and accurate final design, culminating in a detailed report in April 2025.

STS Project Proposal

In 2009, the European Union defined sugarcane as a high target crop for advanced biofuel production. As a result, sugarcane farming for ethanol production boomed within Latin American nations, such as Brazil and Colombia (Roundtable on Environmental Health Sciences, 2014). In Brazil specifically, new agricultural zones within the Amazon and Pantanal regions have been explored (Lima et al., 2020). Within these regions, over 350 indigenous groups reside (Cardoso, 2024). With the increasing demand for land, sugarcane plantations may encroach upon the lands of indigenous groups.

Researchers have examined analogous cases on biodiesel's impact on subsistence and pastoral populations from palm oil production in Malaysia, sugarcane plantations in Colombia, and Jatropha cultivation in Ghana (Aha & Ayitey, 2017; Roundtable on Environmental Health Sciences, 2014). The loss of land in these cases has been attributed to land grabs by private investors, weak protection of land rights, and communal land ownership. Moreover, the acquired lands, previously used for pastoralism and subsistence living, are converted into feedstock crop plantations to meet biofuel quotas established by their governments (Aha & Ayitey, 2017; Gilbert, 2020).

These cases consider the social factors affecting indigenous populations in Malaysia, Colombia, and Ghana, but the effect on Brazilian tribes has yet to be considered. Furthermore, while most of these factors associated with these cases are applicable, a 2019 legislation overturning the ban on expanding sugarcane cultivation in Brazil, sheds new light on how the technical advancements in sugarcane biofuel can impact a nation's politics (Lima et al., 2020). While the biodiesel advancements are technical in nature, these changes have direct impacts on the nation's social groups. These social impacts can be amplified by supporting politics. Therefore, understanding the political and social forces caused by biofuel advances and demand can shed light on how the resulting agricultural expansion privileges farmers and landowners, while overlooking the Brazilian indigenous tribes.

My argument will draw upon Langdon Winner's sociotechnical theory of Technological Politics. Winner claims that technological artifacts individually have politics, which means that they can directly affect the relationships of power and privileges between different social groups by advantaging certain groups and marginalizing others. He compares the influence of these artifacts to, "legislative acts or political foundings," (Winner, 1980). Moreover, Winner separates technologies into two categories: those with and without inherent ties to power and authority. While Intentional political ties have explicit biases, unintentional political ties with implicit biases can still carry a political nature. This determines whether a technology can be altered by the social, political, or economic systems within an environment (Winner, 1980). To support my argument, I will analyze the 2019 legislation overturning sugarcane farming bans; statements of the Guarani peoples, an indigenous group directly impacted by expanding sugarcane plantations; and opinions shared by Brazil's sugarcane farmers and politicians (*Coca-Cola Dragged into Brazilian Indians' Land Struggle*, 2013; Egeskog et al., 2016; Roundtable on Environmental Health Sciences et al., 2014).

Conclusion

The development of a biodiesel plant with a WCO feed will provide an alternative to the land intensive, agricultural based feedstocks, used in traditional biodiesel production. This development, coupled with the analysis of social and political effects caused by sugarcane ethanol production in Brazil, will provide insight into the need for alternative biodiesel feeds. Using Winner's theory of Technological Politics, I will examine how sugarcane ethanol production is inherently political, and how that affects the relationships with indigenous peoples. These findings will help identify the political nature of biofuels, which can guide future non-agricultural biofuels decisions to lessen the likelihood of disadvantaging certain populations.

Word Count: 1,061 (without technical project) 2,241 (with technical project)

Appendix

Appendix A: Properties of Biodiesel from ASTM D751 and EN 14214 Standards

Properties	ASTM D6751	EN 14214
Flash point, min (°C)	100–170	≥120
Cloud point (°C)	−3–−12	- *
Pour point (°C)	−15–−16	- *
Kinematic viscosity at 40 °C (mm^2/s)	1.9–6.0	3.5–5.0
Specific gravity at 15 °C (kg/L)	0.88	0.86–0.90
Density at 15 °C (kg/m^3)	820–900	860–900
Cetane number, min	47	51
Iodine number, max	- *	120
Acid number, max (mg KOH/g)	0.50	0.50
Ash (wt %)	0.02	- *
Sulphated ash, max % (m/m)	0.02	0.02
Oxidation stability, min (h, 110 °C)	3	6
Water and sediment, max (*v*/*v* %)	0.05	0.03
Water content, max	0.03 (*v*/*v*)	500 (mg/kg)
Free glycerol, max (mass %)	0.02	0.02
Total glycerol, max (mass %)	0.24	0.25
Sulphur content, max	0.05% (m/m)	10 mg/kg
Phosphorus content, max	0.001% (m/m)	10 mg/kg

* Not specified.

Copied from Zahan & Kano (2018)

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