PRODUCTION OF BIODIESEL VIA A SUPERCRITICAL METHANOL TRANSESTERIFICATION PATHWAY

GOVERNMENT POLICY AND ENVIRONMENTAL PRACTICES IN THE MALAYSIAN BIODIESEL MARKET

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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

To reduce greenhouse gas (GHG) emissions and curb the negative effects of climate change, global markets have investigated biodiesel as an alternative energy source. As one of the world's top biodiesel producers, Malaysia plans to implement a biodiesel B20 mandate for transportation and promote bioenergy policies in order to reduce their reliance on fossil fuels (Rashidi et al., 2022). To reach this goal and expand the biodiesel market, Malaysia will need to design and implement biodiesel production technologies at an industrial scale. I will develop the design for an industrial scale biodiesel plant via a supercritical methanol transesterification pathway. Using supercritical conditions will allow lower quality feedstocks, in this case waste cooking oil (WCO), to be used which lowers cost and does not compete with food supply. Because the development of the biodiesel market is affected by both technical and social factors, it is important to understand how complex relationships between technical, social, political, environmental, and economic factors impact technological outcomes. I will use the science, technology and society (STS) framework of actor-network theory to examine how government policies and palm oil plantation practices influenced the progress of the biodiesel market in Malaysia. If biodiesel producers focus only on optimizing industrial biodiesel production, but do not address the environmental, political, and economic challenges of their design, then they risk failing to produce a product that is socially accepted and economically viable. Because the challenge of producing economically viable biodiesel on an industrial scale 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 an industrial scale biodiesel plant design via a supercritical methanol transesterification pathway and an STS project proposal for examining government policies and environmental practices in the Malaysian biodiesel market.

Technical Proposal

In an increasingly mechanized world that demands higher energy usage, the resulting costs of this shift - climate change and pollution control - have become a dominant global issue. 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 Sun's infrared radiation and causing Earth's surface to warm at accelerated rates. 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). When compared to traditional highway petroleum (low-sulfur) diesels, 100% biodiesel fuels (B100) reduce carbon emissions by 79%, and 15% blends reduce emissions by only about 16% (Sheehan et al., 1998). 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. 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 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 currently in use. (Nagapurkar & Smith, 2023).

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 on the catalyst surface reducing the catalyst's effectiveness, thus reducing methyl ester yield. Also, 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,

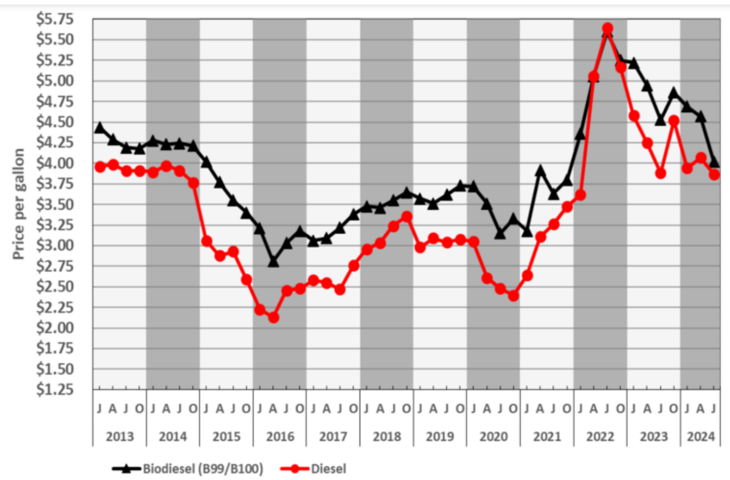

Figure 1: Cost of B100 fuel versus petroleum diesel since 2011. Copied from the U.S. Department of Energy Clean Cities and Communities Alternative Fuel Price Report from July 2024.

catalyst maintenance, and catalyst replacement, catalytic transesterification methods are not economically viable (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 separation 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 waste cooking oil (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

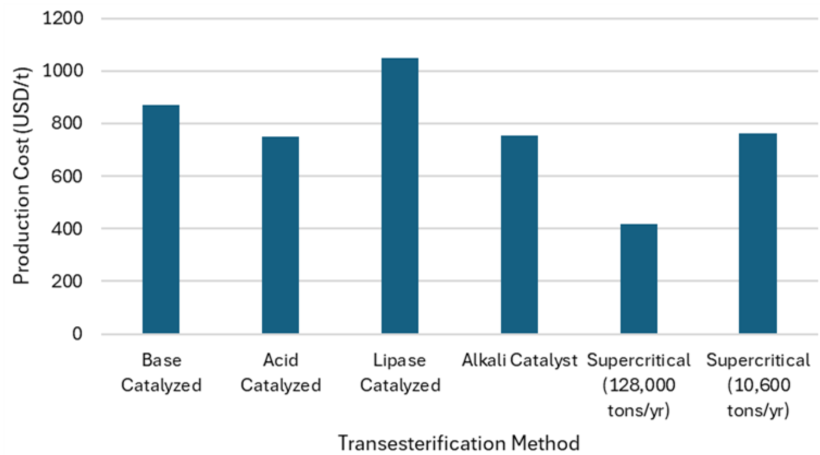

Figure 3: Production cost of biodiesel from WCO. Modeling of supercritical processes shows lowest production cost per ton.

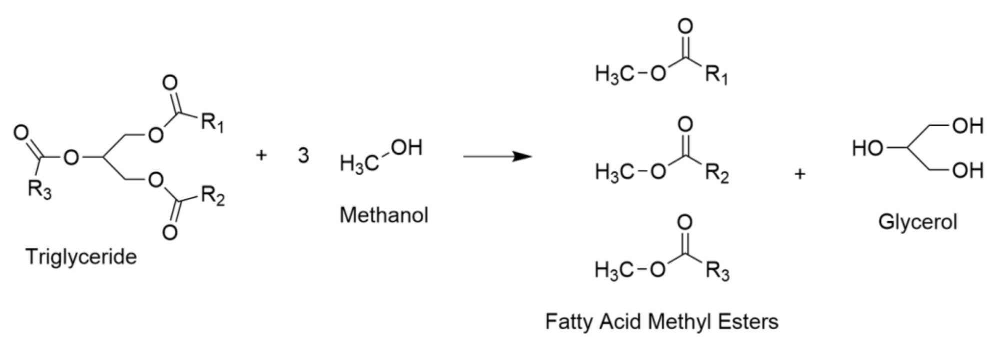

Fig 2. Production of fatty acid methyl esters (biodiesel) and glycerol from the reaction of triglycerides and methanol. Adapted from Van Kasteren and Nisworo

represented in Figure 3, the use of a supercritical pathway is the most promising (Brahma et al., 2022; 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 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

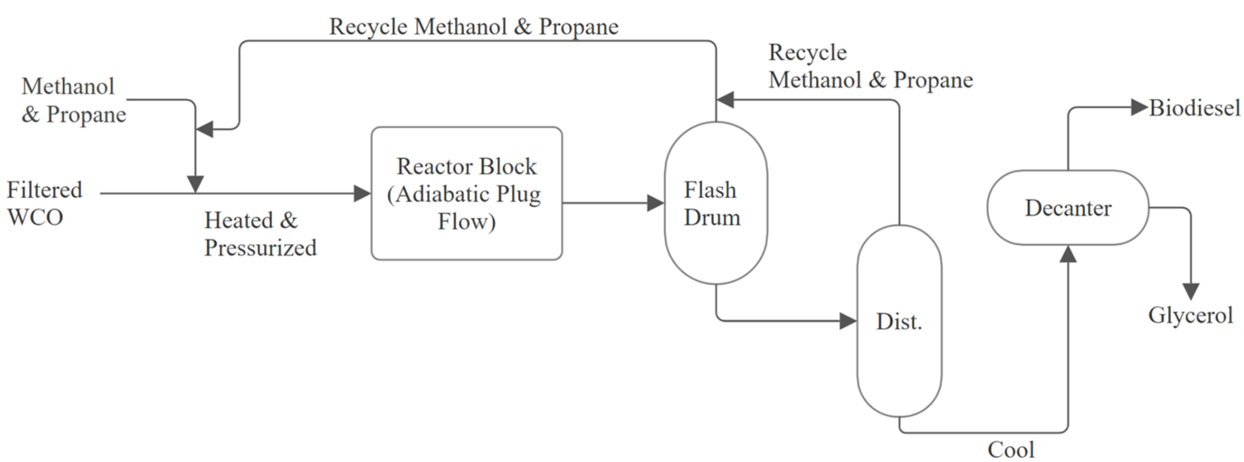

Figure 4: Simplified process diagram for the production of biodiesel from WCO
Adapted from Nagapurkar & Smith (2023) and Van Kasteren & Nisworo (2007)

plant siting information will be detailed in the Design Basis Memo 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 Proposal

In recent years, the energy demand in Malaysia has increased significantly. Coal and natural gas are the country's primary energy sources; however, renewable energy sources are being explored due to the negative environmental impacts of fossil fuels. Malaysia has an abundance of biomass due to its tropical climate and large palm oil industry, making it a promising contender for commercial biodiesel production (Rashidi et al., 2022). Despite the benefits of expanding renewable energy use and policy incentives towards the adoption of bioenergy technology, Malaysia has been slow to increase the production of biodiesel (Rashidi et al., 2022).

Previous studies have investigated the development of the biodiesel industry in Malaysia through isolated analyses of technical, economic, social, environmental, and organizational factors (Rashidi et al., 2022). Specifically, current discourse cites the unavailability of technical experts, high capital expenditure, competition with traditional fossil fuels, hesitation from investors, community acceptance, land use conversion, biodiversity loss, and food security as reasons for the lack of adoption of biofuel technology at a large scale (Rashidi et al., 2022). One study used the Institutional Feasibility Study (IFS) framework to analyze the cultivation and commercialization of *Jatropha Curcas* as a biofuel feedstock in Malaysia (Mintz-Habib, 2013).

IFS considers the interactions between various regulatory and cultural actors and contends that institutions provide a connection between global priorities and local effects (Mintz-Habib, 2013).

Although these approaches provide valuable context to the lack of industrial biodiesel plants in Malaysia and opposition to the technology, they fail to consider key elements of the problem. Only focusing on the individual effects of each actor cannot fully encompass the shortcomings of a system. Rather, understanding the complex network of interactions between various actors is highly important. While the IFS framework considers the interactions between institutions, it heavily emphasizes the economic outcomes on the global value chain as the primary defining factor of biodiesel industry success. This focus on institutions as actors and economic outcomes can overlook the importance of non-human or non-institutional actors such as cultural traditions and land characteristics on biodiesel market expansion.

By emphasizing the equal importance of all human and non-human actors and focusing specifically on their interactions, I will provide a more robust understanding of the development of the Malaysian biodiesel market. I argue that the connections between exploitation of government policies, unsustainable practices around palm oil plantation development, lack of economic incentive and technological challenges are slowing the progress of the biodiesel industry in Malaysia. I will also analyze the ways in which these networks have evolved over time through the implementation of new policy and changing international trade relationships.

I will use actor-network theory (ANT) framework, which was developed by science, technology, and society (STS) scholars including Michel Callon, Bruno Latour, and John Law, to support my analysis of the Malaysian biodiesel market. ANT proposes that a technology's development is shaped by the complex relationships between heterogeneous actors (Cressman, 2009). Specifically, network builders construct these heterogeneous networks composed of both human and non-human actors to solve a problem or accomplish a goal. A key component of ANT is the equal power given to all actors, both human and non-human. This idea is semiotic in nature since the power and meaning of the various actors depends on the context and interactions with others (Cressman, 2009). Translation, developed by Callon and French philosopher Michel Serres, is another facet of ANT that describes how technological development and actor networks are formed, changed, and maintained over time (Callon, 1981). I will use the concept of translation to analyze the formation of the Malaysian biodiesel actor network and how various rogue actors have slowed biodiesel market development. To support my argument, I will use Malaysian government reports, interviews with leadership of biodiesel trade bodies, publications from the Roundtable on Sustainable Palm Oil (RSPO), among other primary sources to provide evidence.

Conclusion

The supercritical methanol transesterification method of biodiesel production is a novel approach that will allow for the use of low-quality feedstocks and potentially lower process costs. The industrial scale design of this process will provide valuable insight to energy producers who are considering implementing the technology. By investigating the relationships between political, environmental, and economic factors in the Malaysian biodiesel market, I will develop a comprehensive understanding of the challenges and progress of biodiesel production. The use of actor-network theory framework will identify how both human and non-human factors such as government policies, land quality, and oil palm tree farmers are connected and work together to define biodiesel development.

Word Count: 2204 (Chemical engineering student working with Professor Anderson)

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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