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Simulation of a Pilot-Scale Plant to Produce Biodiesel from Waste Cooking Oil

Farrukh Najam[2], Muhammad Huzaifa[1], Mehmood Ali[2]*

[1]Department of Chemical Engineering, NED University of Engineering and Technology, Karachi, Pakistan
[2]Department of Environmental Engineering, NED University of Engineering and Technology, Karachi, Pakistan

*Corresponding Author E-mail: mehmood@neduet.udu.pk

Abstract: The increasing demand for alternative fuels and the environmental concerns surrounding fossil fuels have increased interest in biodiesel as a biodegradable and renewable fuel. This study focuses on the simulation of a pilot-scale biodiesel production plant using waste cooking oil (WCO) as the primary feedstock. The process was modeled using Aspen Plus software including the crucial stages of the process and production process simulated by two step reactions. The property method selection and reaction kinetics were implemented to ensure realistic and industrially relevant simulation results. The simulated process was optimized for conversion efficiency, product quality, and energy utilization. The simulated process produced 84.38% and 10.5% by mass of biodiesel and glycerol, respectively, while the excess methanol is collected and charged back into the reactor. The method also yields glycerol, a valuable by-product that is utilized as a raw ingredient in numerous process industries. The experimental yields of biodiesel and glycerol via mass production were 89.74% and 10.26%, respectively. The biodiesel produced through this route meets ASTM standards, confirming its suitability as an alternative fuel. The use of WCO not only adds value to a commonly discarded waste but also aligns with the goals of waste minimization and circular economy. This work provides a scalable and environmentally conscious framework for biodiesel production, demonstrating the practicality of integrating simulation-based design into real-world renewable energy systems.

Keywords: Biodiesel, transesterification, simulation, waste cooking oil, alternative fuel.

Introduction

The increasing global demand for energy has so far increased emissions and created a depletion of fossil fuels, many alternatives have been explored including nuclear, thermal and so forth. Biodiesel has proved to be a green alternative to fulfill the energy demands while keeping the CO_2, SO_x and NO_x emissions at a minimal (Aksoy et al., 2009; Kus, 2011, Salehi et al., 2019). Diesel engines are used in trucks, buses, trains, ships, and industrial off-road vehicles, as well as power generators, industrial machinery and equipment (Pereira et al., 2012; Reşitoğlu et al., 2015; Santana et al., 2021). These engines have a high demand because of their high energy efficiency, low operating costs, and high durability.

However, diesel engines provide great disadvantage of high emissions of particulate matter and smoke that contribute into the air pollution. Diesel engines burn the fuel and released a complex mixture of hydrocarbons, gases, sulfur and particulates into the atmosphere (Organization 2006, Pereira et al., 2012; Santana et al., 2020; Santana et al., 2021).

Using biodiesel instead of diesel fuel for combustion can help reduce toxic emissions with diesel engines. This is because biodiesel contains more oxygen than diesel oil, thus having complete combustion and does not produce aromatic or sulfurous compounds. The levels of unburned hydrocarbons, polycyclic aromatic hydrocarbons, carbon monoxide (CO), and particulate matter (PM) from biodiesel combustion are reduced by 90%, 75–90%, 43%, and 55%, respectively, compared to diesel fuel combustion (Selley et al., 2019; Santana et al., 2021).

Several feedstocks have been utilized for extracting biodiesel to fulfil energy demands. Cooking oils are derived from either plant-based lipid, such as corn oil, margarine, coconut oil, palm oil, olive oil, soybean oil, grape seed oil, and canola oil, or animal-based lipids, like butter, ghee and fish oil. Palm oil is the most commonly used cooking oil due to its lower cost compared to other sources like coconut, corn, or soybean oils (Yaakob et al., 2013). The use of edible oils as a feedstock for biodiesel has faced significant criticism around the globe due to competition with the food supply, increasing hunger and starvation issues, as well driving up the demand for vegetable oils. Additionally, it leads to deforestation as forests are cleared for plantation disrupting ecosystems. On the other hand, utilizing WCO for biodiesel production could help alleviate some of these problems, such as reducing water pollution and blockages in drainage systems, which would otherwise require additional cleaning efforts. WCO can be easily collected from households and restaurants by placing recycling bins, providing a more sustainable alternative to using edible oils (Yaakob et al., 2013). The production process of biodiesel from WCO was simulated using Aspen Plus software that followed a two-step procedure. The biodiesel's 99.6% purity level validated the simulation's viability. To establish a trustworthy standard for the industrial biodiesel production from WCO, the simulation's processing parameters for the methanol rectification tower and the biodiesel rectification tower were improved.

This study develops a simulation of a pilot plant for biodiesel production using WCO in ASPEN PLUS V11.0 to evaluate process efficiency, energy consumption, and the extent to which the produced biodiesel meets biodiesel properties with international standard (ASTM D 6751).

Materials and Methods

Simulation of a process involves selecting the right material, choice of thermodynamic property package, defining the unit capacity based on the locally available feed and defining the input feed conditions to the plant including the feed flow rate, temperature, and pressure. Palm oil is used as the WCO feed in which triolein ($C_{57}H_{104}O_6$) and tripalmitin ($C_{51}H_{98}O_6$) are the major constituents with a fraction of 0.45 each while among the minor constituents, oleic acid ($C_{18}H_{34}O_2$) and N-hexa-decanoic acid ($C_{16}H_{32}O_2$) are the significant components making up the remaining 0.1 fractions of the WCO with each having a composition of 50% present in it. The conversion of WCO involves both esterification and transesterification reactions which involve intermediate and final product constituents including Methyl-Oleate ($C_{19}H_{36}O_2$) and Methyl-Palmitate ($C_{17}H_{34}O_2$-N_1) for which MeOH (CH_3OH) is used as a reagent. In addition, glycerin ($C_3H_8O_3$) is a by-product of this process.

The process simulation is carried out by the Aspen Plus using Peng Robinson property package, which is fully focused on various aspects of process calculation, involving polar compounds such as methanol (MeOH). NRTL (Non-Random Two-Liquid) model is paired with the package for polar compound treatment, to make it more realistic while dealing with the polar substances. Besides, it is also required by Peng Robinson to calculate activity coefficients for materials contained in WCO. With the use of both Peng Robinson and NRTL models, the simulation offers reliable and precise results, which are needed for the successful processing of material within the system. The dual approach gives a broader observational base regarding the interactions and behavior of the compounds in the system, which further strengthens overall efficiency and accuracy during process simulation. The process of conversion of WCO to biodiesel involves two main reactions namely esterification and transesterification.

1. *Esterification reaction:*

Esterification reaction involves the conversion of free fatty acids present in WCO into their respective methyl esters by reacting with methanol. This reaction reduces the free fatty acid content, preventing soap formation and improving biodiesel yield.

- Esterification of Oleic Acid:

$$C_{18}H_{34}O_2 + CH_3OH \rightarrow C_{19}H_{36}O_2 + H_2O \quad (1)$$

Oleic Acid + Methanol → Methyl Oleate + Water

- Esterification of Palmitic Acid:

$$C_{16}H_{32}O_2 + CH_3OH \rightarrow C_{17}H_{34}O_2 + H_2O \quad (2)$$

Palmitic Acid + Methanol → Methyl Palmitate + Water

2. *Transesterification:*

Transesterification is the process in which triglycerides react with methanol to produce methyl esters (biodiesel) and glycerin as a by-product. This reaction is essential for breaking down complex triglycerides into usable fuel components.

- Transesterification of Triolein:

$$C_{57}H_{104}O_6 + 3CH_3OH \rightarrow 3C_{19}H_{36}O_2 + 3C_3H_8O_3 \quad (3)$$

Triolein + Methanol → Methyl Oleate + Glycerin

- Transesterification of Tripalmitin:

$$C_{51}H_{98}O_6 + 3CH_3OH \rightarrow C_{17}H_{34}O_2 + 3C_3H_8O_3 \quad (4)$$

Tripalmitin + Methanol → Methyl Palmitate + Glycerin

The process of biodiesel production begins with charging WCO with MeOH in excess (made in the presence of KOH as a catalyst 5% by weight of oil), 24.85% by mole into a CSTR. The residence time of the feed was 60 min in the reactor. Esterification and transesterification reactions take place here at atmospheric pressure and at a temperature of 60^{o}C. Esterification converts the FFA content present into their corresponding methyl esters while producing water as a byproduct, as shown in the reactions as above.

This step is necessary as it retards soap formation and increases the yield of biodiesel simultaneously, while the transesterification reaction converts triglycerides present in WCO in major composition into biodiesel producing glycerin as a by-product. Doing both reactions in the same reactor

Table 1. Comparison of experimental parameters of biodiesel with ASTM D6751 standard.

Parameters	ASTM D6751	Experimental results	Simulation results
Biodiesel yield % by mass	-	89.74	84.38
Glycerol yield % by mass	-	10.26	10.05
Density (g/cm^3)	0.860 -0.900	0.872	0.860
Kinematic Viscosity (mm^2/s)	1.9 - 6.0	4.6	4.99
Flash Point (°C)	min 130	177.64	129
Calorific Value (MJ/kg)	>35	41.55	39.64

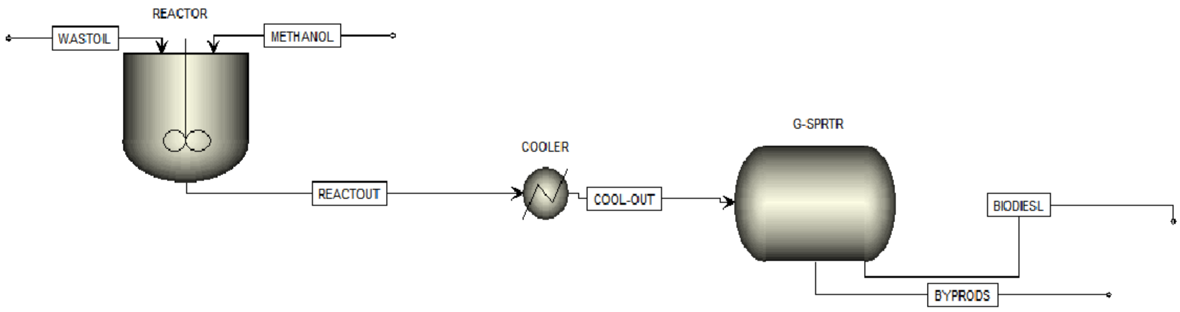

Fig. 1 Process diagram of simulation waste cooking oil into biodiesel.

also reduces the energy consumption as transesterification reaction is endothermic while esterification reaction liberates heat. The reactor effluent is charged into a separator where on the basis of gravity difference the products (biodiesel and glycerol) are separated into valuable products by providing proper settling time. Process diagram of simulating a pilot scale biodiesel from waste cooking oil is shown in Figure 1.

Results and Discussion

Biodiesel is a sustainable product to meet high energy requirements and a green alternative to diesel. To ensure that the biodiesel performs as diesel as a proper alternate to it, it is mandatory to meet with ASTM D6751 standardized parameters and experimental results which have been concluded on the basis of results obtained from Aspen Plus simulation and were found to be in accordance with the experimental and standard values presented in Table 1 (Ali et al., 2023).

The yield of biodiesel and glycerol from the simulated process were found to be 84.38% and 10.05 % by mass, while the excess methanol is recovered and is charged back to the reactor. Glycerin is also obtained as a valuable by-product of the process which is a raw material for various process industries. The experimental yield of biodiesel and glycerol were 89.74% and 10.26% by mass production respectively. The total production, of the unit was found to be 23400 liters of biodiesel per annum, assuming an operating period of 10 months per year.

The unit also generates 1667 liters of glycerin as a valuable by-product as a market commodity

used in soap, cosmetics, and pharmaceutical industries. The energy requirements of the unit

sum up to 15 kW including a 0.5kW motor-driven stirrer and remaining is the net duty of cooling requirement. Utility requirements for the plant will include electricity for the purpose of driving the electric motors, and the remaining energy requirement will be fulfilled using tap water.

Conclusion

The successful simulation of a pilot-scale biodiesel production plant using waste cooking oil (WCO) highlights the viability of adopting waste-derived feedstocks for clean fuel generation. Through modeling of each stage of process, the study confirms that WCO can be effectively converted into biodiesel, while minimizing resource consumption and environmental impact. The process was designed with cost-efficiency and sustainability in mind, which further enhances its industrial appeal. The use of Aspen Plus allowed precise control over process parameters, enabling a high degree of customization and optimization. The excess methanol is recovered and charged back to the reactor, the simulated process yielded 84.38% and 10.5% by mass of biodiesel and glycerol, respectively.

Glycerol, a valuable by-product of the process, is also obtained and is used as a raw material in a variety of process industries. By mass manufacturing, the experimental yields of glycerol and biodiesel were 10.26% and 89.74%, respectively. Key performance indicators such as conversion efficiency and product purity were achieved at levels consistent with commercial

biodiesel standards. Additionally, the inclusion of recycling streams and proper waste handling underscores the process's environmental responsibility and economic feasibility. This work serves as a foundational model for future experimental validation and scale-up efforts. It

provides a useful simulation framework for academic researchers and industry stakeholders looking to invest in biodiesel technology using waste cooking oil. The integration of waste with renewable energy production, as demonstrated in this study, holds great potential for advancing sustainable energy practices

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