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Optimization of Biodiesel Production from Water Hyacinth via Transesterification and Kinetic Modeling

[1]Nweke James, [2]Emenike Wami, [3]Awajiogak Anthony Ujile, [4]T.O. Goodhead
Department of Chemical and Petrochemical Engineering, Rivers State University (RSU), PMB 5080 Port-Harcourt, Nigeria

Abstract - This study evaluates biodiesel production from water hyacinth (WH) via transesterification, highlighting its potential as a sustainable renewable energy source. Lipids were extracted from WH using Soxhlet and maceration methods, yielding modest oil content. Five methanol-to-oil molar ratios (4:1, 5:1, 6:1, 7:1, 8:1) were tested, with the 6:1 ratio in combination with a NaOH catalyst producing the highest biodiesel yield of 88.21%. The biodiesel obtained exhibited a cetane number of 57.66, meeting ASTM D6751 standards and indicating excellent ignition quality suitable for high-efficiency diesel engines. Kinetic modelling. of the transesterification reaction was conducted to determine rate constants and conversion efficiencies, providing critical data for process optimization and scale-up. Using Python 3.11 with the Levenberg–Marquardt algorithm, the kinetic model closely fitted the experimental data, enabling accurate prediction of reaction progress and substrate conversion. These results demonstrate that water hyacinth is a viable feedstock for biodiesel production, offering both energy recovery and environmental management benefits. The study provides validated operational parameters and kinetic insights for the development of cost-effective, scalable biofuel production from aquatic biomass.

Keywords – Water hyacinth, Biodiesel, Transesterification, Kinetic modeling, Soxhlet extraction, maceration extraction.

INTRODUCTION

The growing global demand for renewable and environmentally friendly energy sources has driven significant interest in biofuels, particularly biodiesel, as an alternative to fossil diesel. Biodiesel is a biodegradable, non-toxic fuel derived from lipid-rich feedstocks through transesterification, offering reduced greenhouse gas emissions and improved energy security. Among potential feedstocks, water hyacinth (Eichhornia crassipes) has emerged as a promising candidate due to its rapid growth, high biomass yield, and widespread availability in freshwater systems, which simultaneously addresses ecological issues associated with its uncontrolled proliferation.

Extraction of lipids from water hyacinth is a critical initial step in biodiesel production. Methods such as Soxhlet extraction and maceration have been employed to recover oils efficiently from the biomass. Soxhlet extraction allows continuous solvent percolation, achieving higher lipid recovery, while maceration provides a simpler, low-energy alternative suitable for preliminary processing. These methods enable the isolation of oil suitable for subsequent transesterification, in which triglycerides react with an alcohol, typically methanol, in the presence of a catalyst such as sodium hydroxide (NaOH), to produce biodiesel and glycerol.

Following transesterification, purification of the biodiesel is necessary to remove residual catalysts, methanol, and other impurities, ensuring compliance with fuel standards such as ASTM D6751. Additionally, understanding the kinetics of the transesterification process is essential for optimizing reaction conditions, predicting reaction rates, and scaling up production. Kinetic modelling., coupled with experimental validation, provides insights into reaction mechanisms, conversion efficiencies, and optimal operational parameters, facilitating the development of a cost-effective and sustainable biodiesel production process from water hyacinth.

Biodiesel Production from Water Hyacinth

Producing biodiesel from water hyacinth entails extracting the oil contained within the plant biomass and converting it into biodiesel via transesterification. The efficiency of this process is influenced by several physicochemical parameters, including temperature, pressure, and the type of catalyst employed (Leite et al., 2024; Rahman et al., 2021). The resulting biodiesel can serve as a sustainable and environmentally friendly substitute for conventional diesel fuel (Shanab et al., 2018).

Lignocellulosic Biomass:

Comprising agricultural residues, forestry by-products, and dedicated energy crops, these materials are rich in cellulose, hemicellulose, and lignin (Elgharbawy et al., 2021).

Algae:
Both microalgae and macroalgae contain high lipid content, making them excellent candidates for biodiesel production (Zheng et al., 2025).
Agricultural Residues:
Includes straw, husks, stems, and other crop leftovers.
Waste Biomass:
Encompasses municipal solid waste, industrial by-products, and animal manure.
Factors Affecting Biodiesel Production:
The efficiency of biodiesel production depends on various factors, and optimizing these conditions is key for cost-**effective and high-yield production:**
Feedstock Properties:
Physical and chemical characteristics, such as moisture, acidity, and viscosity, affect both the yield and quality of biodiesel. Lower moisture and acidity levels generally improve yield, while high viscosity may reduce fuel quality (Bharathiraja et al., 2022).
Catalyst Type and Concentration:
Transesterification requires a catalyst. Homogeneous catalysts like sodium hydroxide or potassium hydroxide are commonly used, but excessive concentrations can negatively impact product quality. Heterogeneous catalysts, such as zeolites, typically require lower concentrations and can reduce glycerol formation (Farouk et al., 2024).
Alcohol Type and Concentration:
Methanol and ethanol are the primary alcohols used. Higher alcohol concentrations can enhance reaction efficiency but may also introduce impurities (Leung et al., 2010).

Reaction Time and Temperature: Extended reaction times generally increase biodiesel yield but may also trigger secondary reactions that lower quality (Leite et al., 2024).
Water Content:
Water can react with both the catalyst and alcohol, producing unwanted reactions and reducing yield. Controlling water content is therefore critical (Zheng et al., 202).
Contaminants:
Free fatty acids, metals, and soaps in the feedstock can poison the catalyst or produce side reactions, affecting both biodiesel yield and quality (Mokhtar, et al, 2015).
Optimizing these parameters ensures maximum yield and high-quality biodiesel, reducing production costs while improving process efficiency.
Lipid Content of Water Hyacinth:
Water hyacinth (Eichhornia crassipes) contains lipids ranging from 5% to 12% of dry weight, which are essential for biodiesel production. This lipid content is comparable to other aquatic plants, such as duckweed (Lemna minor) and algae (Chlorella vulgaris), which have lipid contents ranging from 10–20% and 20–30%, respectively (Leite et al., 2024). The fatty acid composition of water hyacinth lipids resembles that of common vegetable oils like soybean and palm oil, which are widely used in biodiesel production (Leite et al., 2024).

Biodiesel Production from Water Hyacinth:
Biodiesel production from water hyacinth has been explored in various studies. For example, Umai et al. (2022) reported an 85% yield with a cetane number of 56.6, while Zhang et al. (2020) increased lipid content from 9.2% to 29.7% using yeast fermentation. Optimization of fermentation conditions, including yeast strain selection, substrate concentration, temperature, and aeration, has been shown to enhance lipid accumulation. The resulting biodiesel exhibits a fatty acid profile comparable to vegetable oils, confirming its suitability as a renewable fuel (Leite et al., 2024).

II. MATERIALS AND METHODS

Water Hyacinth Collection and Preparation
Fresh water hyacinth (Eichhornia crassipes) was harvested, thoroughly rinsed under running water to remove soil and debris, and chopped into ~1–2 cm pieces to increase drying efficiency. The biomass was sun-dried to <10% moisture content and ground using a mechanical grinder Lipid Extraction from Water Hyacinth: Lipid extraction was performed using two methods: Soxhlet extraction for high-efficiency laboratory-scale recovery and maceration extraction for large-scale or bulk processing.

Soxhlet Extraction: Soxhlet extraction operates on continuous solvent reflux and extraction. Lipids are repeatedly dissolved in hot solvent, which condenses and percolates through the biomass, ensuring efficient oil recovery (Leite et al., 2024).
Apparatus and Materials Soxhlet extractor with cellulose thimble round-bottom flask Condenser with water circulation Hot plate with temperature control Analytical balance (±0.001 g) n-Hexane as solvent

Procedure
Sample loading: 50 g of dried biomass placed evenly in a Soxhlet thimble.
Solvent addition: 250 mL of n-hexane added to the round-bottom flask.
Extraction:
Heat to maintain n-hexane boiling (40–60°C).
Solvent vapor condenses, percolates through biomass, dissolving lipids, and siphons back to the flask.
Extraction monitored by solvent color; total extraction time ~42 min.

Solvent recovery: n-Hexane removed via distillation at 55°C to avoid thermal degradation.

Maceration Extraction

Principle

Maceration relies on prolonged solvent contact at ambient or controlled temperature to extract lipids. It is suitable for large-scale, low-energy extraction of fibrous biomass.

Materials and Equipment

Dried water hyacinth (<10% moisture)

n-Hexane (solvent-to-biomass ratio 5:1; 1.5 L per 500 g biomass)

Stainless-steel maceration vessel with airtight lid

Mechanical stirrer

Vacuum filtration unit

Condenser for solvent recovery

Procedure

Biomass preparation: Dried and ground water hyacinth (1–2 mm).

Solvent addition: 500 g biomass submerged in 1.5 L n-hexane in maceration vessel.

Maceration: Stirred 30 min, then soaked for 72 h at 25–30°C; intermittent stirring every 12 h.

Filtration and pressing: Residual biomass separated via vacuum filtration; additional lipid recovery via hydraulic pressing.

Solvent recovery: n-Hexane distilled (~60°C) and condensed; recovery efficiency: 96%.

Total feedstock used: 2 kg dried water hyacinth.

The extraction of lipids from water hyacinth biomass can be described using a mass transfer-based model, where the lipids diffuse from the solid biomass into the solvent. Understanding this process is essential for optimizing extraction efficiency and designing scalable operations.

General Mass Balance

In a solid–liquid extraction system, the general mass balance over the system can be expressed as:

Accumulation = In – Out + Generation – Consumption (1)

Since the extraction process does not involve a chemical reaction, the generation and consumption terms are zero. At steady state, the mass balance simplifies to:

Accumulation = In – Out (2)

This means that the change in mass of solute in the system depends solely on the transfer of solute (oil) from the biomass to the solvent.

Diffusion-Based Mass Transfer Model

The rate of lipid transfer from biomass to solvent can be modeled using a diffusion-based approach according to Fick's law (Ujile, 2014). The rate of mass transfer is expressed as:

$dm/dt = KA/b(Cs-C)$ (3)

Where:

m = mass of solute transferred (kg)

Cs = concentration of solute at solid-liquid interface (kg/m³)

C = concentration of solute in bulk solvent at time t (kg/m³)

K = diffusion coefficient (m²/s)

A = surface area of biomass particles (m²)

b = effective film thickness (m)

dm/dt = rate of oil mass transfer (kg/hr)

Assuming the solvent volume V remains constant (C=m/VC), equation (3.8) becomes:

$V (d(CV))/dt = KA/b(Cs-C)$ (4)

Integrating this differential equation over time gives the concentration of solute in the bulk solvent:

$C = Cs(1-e^{(-KAt/Vb)})$ (5)

This expression can be used to predict the rate of oil extraction and optimize extraction time and solvent usage.

The extraction efficiency can be calculated to determine the %oil yield:

Extraction Efficiency (%) = Weight of Extracted Oil/Initial Weight of Dried Biomass x 100 (6)

Transesterification of Water Hyacinth Oil

Preparation of Sodium Methoxide

200 mL of water hyacinth oil was heated to 60°C to reduce viscosity and facilitate uniform mixing with the catalyst.

Transesterification Reaction

The prepared sodium methoxide solution was gradually added to the heated oil while stirring at 600 RPM. The reaction mixture was maintained at 60°C for 30 minutes. The transesterification reaction is represented as:

$NaOH + CH3OH \rightarrow CH3ONa + H2O$

Pre-Treatment of Oil

200 mL of water hyacinth oil heated to 60°C to reduce viscosity and facilitate mixing.

Transesterification Reaction

Sodium methoxide added gradually to heated oil while stirring at 600 RPM.

Maintained at 60°C for 30 min.

Reaction:

Triglyceride + Methanol → Biodiesel (FAME) + Glycerol

Phase Separation and Purification

After the reaction, the mixture was transferred into a separating funnel. Two layers formed:

Top layer: Biodiesel (FAME)

Bottom layer: Glycerol

The biodiesel was carefully collected while glycerol was drained.

Washing and Drying

The collected biodiesel was washed with warm distilled water to remove residual methanol, soap, and catalyst. The washed biodiesel was dried at 40–50°C to remove any residual moisture.

Combustion Test

A sample of the biodiesel was ignited to assess its combustion properties. Observation: the biodiesel burns with a clean, bright flame, indicating complete combustion and low impurities.

III OIL EXTRACTION RESULTS

Table 1: Extraction Results Table

Method	Weight of Oil Extracted (g)	Oil Yield (%)	Volume of Solvent Used (L)	Volume of Solvent Recovered (L)	Reflux Cycles	Temperature (°C)	Solvent Appearance by Cycle
Soxhlet Extraction (n-Hexane)	43.0	4.30	2.5	2.40	3	60	Cycle 1: Dark yellow→ Cycle 2: Light yellow →Cycle 3: Clear
Maceration (n-Hexane)	39.1	3.91	2.5	2.45		Room Temperature	

Efficiency and Process for Soxhlet Extraction with n-Hexane

Temperature: The Soxhlet extraction method was conducted at a temperature of 60°C, which is considered optimal for n-hexane in lipid extraction. This elevated temperature accelerates the extraction process by increasing the solubility and diffusion rate of lipids from the water hyacinth biomass into the n-hexane solvent: Reflux Cycles: Over the course of 3 cycles, the extraction process progressively extracted lipids, with each cycle exhibiting different solvent appearances and extraction efficiency. The first cycle was characterized by a dark yellow solvent, which indicated a high lipid transfer rate as the easily accessible lipids were dissolved into the solvent, this took 23minutes. The second cycle showed a light yellow solvent, suggesting that the extraction slowed as the easily extractable lipids were depleted; tie for the second cycle was 11minutes. By the third cycle which took 8minutes, the solvent was clear, indicating that the extraction was near completion, with only residual lipids remaining in the biomass, marking the end of the extraction process, it took approximately 42minutesb for each process.

Solvent Recovery and Yield: The Soxhlet extraction method achieved an oil yield of 4.30%, which is relatively high compared to the maceration method. The volume of solvent used was 2.5 L, with 2.4 L of solvent recovered at the end of the extraction, indicating a high solvent recovery rate (96%). **This demonstrates the efficiency of Soxhlet in extracting lipids while minimizing solvent loss.**

Efficiency and Process for Maceration with n-Hexane

Time and Temperature: The maceration process was carried out over a longer period of 72 hours at room temperature, a relatively low-energy method compared to Soxhlet extraction. However, this method relies on slower diffusion and solubility rates for lipid transfer, resulting in a more gradual and less efficient extraction process.

Solvent Appearance: Throughout the 72-hour extraction period, the solvent maintained a yellow color, indicating a continuous but steady transfer of lipids from the water hyacinth biomass. Unlike the dynamic changes observed with Soxhlet, the yellow color remained stable, reflecting a slower and less variable extraction rate.

Solvent Recovery and Yield: The maceration method produced an oil yield of 3.91%, which is lower than the Soxhlet extraction yield. The solvent recovery rate was 98% with 2.45 L of solvent recovered from the initial 2.5 L. Despite the lower yield, maceration achieved nearly complete solvent recovery, highlighting its potential for energy-efficient lipid extraction, especially in scenarios where minimal energy input is crucial.

Comparative Analysis of both Extraction Methods

Yield Efficiency: Soxhlet Extraction achieved the highest oil yield of 4.30%, which is significantly higher than the 3.91% yield obtained from Maceration. The faster extraction rate and higher temperature in Soxhlet facilitated the dissolution of more lipids from the biomass, making it more efficient for extracting oil from water hyacinth.

Maceration, on the other hand, despite being a simpler and more energy-efficient method, proved to be less efficient in terms of yield. The slower lipid extraction process, due to the absence of heat and reflux, resulted in a lower overall lipid recovery.

Solvent Appearance: The color progression observed in Soxhlet extraction from dark yellow to light yellow and finally to clear accurately reflects the different stages of lipid extraction. The dark yellow indicates high lipid concentration, which gradually decreases as the extraction progresses, with the clear solvent signaling near saturation.

Maceration showed a stable yellow solvent throughout the entire extraction process, highlighting the slower and more uniform lipid extraction. This steady solvent appearance suggests that lipids were extracted consistently over the 72 hours, but at a much slower rate compared to the dynamic process seen in Soxhlet.

Solvent Recovery: Both methods demonstrated high solvent recovery rates, with 96% recovery in Soxhlet and 98% recovery in Maceration. The slightly higher recovery in maceration can be attributed to the lower operating temperature, reducing solvent evaporation. However, Soxhlet still maintained a very efficient solvent recovery rate, proving the method's efficiency despite the higher temperature.

Time and Energy Efficiency: Soxhlet Extraction was completed in a relatively short period of 7 hours (420 minutes), whereas Maceration took significantly longer at 72 hours. This stark difference in extraction time makes Soxhlet a much more time-efficient method for large-scale or time-sensitive applications.

From an energy perspective, Soxhlet extraction requires more energy due to the heating and continuous reflux, while Maceration is energy-efficient as it operates at room temperature without the need for heating. This makes maceration more suitable for small-scale operations where energy costs are a concern, though with the trade-off of longer processing times. Soxhlet Extraction is the preferred method when the goal is to maximize oil yield and efficiency. The method's ability to extract more lipids in a shorter time frame, combined with the high solvent recovery rate, makes it ideal for extracting lipids from water hyacinth.

Maceration, while more energy-efficient and simpler, offers lower yields and longer extraction times. In the context of industrial biodiesel production from water hyacinth, the maceration method offers a cost-effective, scalable, and energy-efficient solution. The simplicity of the process, along with its high solvent recovery, positions maceration as an attractive option for large-scale extraction. Despite its longer extraction time, the method's advantages in cost reduction, sustainability, and scalability make it a superior choice, particularly in regions where water hyacinth is abundant and energy resources may be limited.

IV. ANALYSIS OF BIODIESEL PRODUCTION FROM WATER HYACINTH OIL USING NAOH CATALYST

Experimental Results: The production of biodiesel from water hyacinth oil through the process of transesterification was performed using sodium hydroxide (NaOH) as a catalyst. The experiment was conducted under optimized conditions to achieve high biodiesel yields and ensure the reaction efficiency. The following values and conditions were used for the experimental setup:

- Volume/mass of Water Hyacinth Oil: 200mL/(176g)
- Volume of Methanol: 48.3 mL
- Mass of Methanol: 19.14 g
- Methanol-to-Oil Molar Ratio: 6:1
- Catalyst Type: Sodium Hydroxide (NaOH)
- Catalyst Amount: 0.88 g (0.5% of oil weight)
- Reaction Temperature: 60 ± 2°C
- Reaction Time: 30 minutes
- Volume of Glycerol (By-product): 14.85 mL
- Weight of Glycerol: 18.11 g
- Conversion Efficiency: 89.0%
- Free Fatty Acid Content (FFA): 0.45% (w/w)
- Biodiesel Density: 0.876 g/mL (compliant with ASTM D6751 or EN 14214 standards)
- Biodiesel Viscosity at 40°C: 4.5 mm^2/s (cSt) (measured using ASTM D445, indicates flow properties of biodiesel)
- Biodiesel Flash Point: 120 ± 2°C (ASTM D93, temperature at which biodiesel ignites)
- Biodiesel Pour Point: -4°C (temperature at which biodiesel remains fluid)
- Biodiesel Iodine Value: 72.5 g I_2/100 g (EN 14214, measures unsaturation level of biodiesel)

- Saponification Value: 200 mg KOH/g (measures fatty acid content of biodiesel)

Methanol-to-Oil Ratio, Biodiesel Yield

Table 2: Methanol-to-Oil Ratio Biodiesel Yield

Methanol-to-Oil Ratio	Biodiesel Yield (%)
4:1	74.50
5:1	81.35
6:1 (Optimum)	88.21
7:1	86.90
8:1	85.75

Discussion of Varying Molar Ratios

The biodiesel production from water hyacinth oil was studied using varying methanol-to-oil ratios, with results summarized in Table 2 and illustrated in Figure 1. The table and graph reveal the influence of methanol concentration on biodiesel yield, with an optimal methanol-to-oil ratio at 6:1, yielding 88.21% biodiesel. Below is a detailed analysis of the findings.

General Observation: Transesterification is the key reaction in biodiesel production, requiring methanol in excess to shift the equilibrium towards complete conversion of triglycerides into biodiesel and glycerol.

The stoichiometric requirement for transesterification is a 3:1 molar ratio of methanol to oil, but higher ratios are typically used to overcome equilibrium limitations As seen in Table 2, increasing the methanol-to-oil ratio from 4:1 to 6:1 significantly improves biodiesel yield, while further increases show diminishing returns.

4:1 Methanol-to-Oil Ratio: The biodiesel yield at 4:1 methanol-to-oil ratio is 78.93%, the lowest in the study. This relatively low yield indicates insufficient methanol availability to drive the reaction towards completion, leaving a significant portion of triglycerides unconverted. Aturagaba, et al 2023 reported inadequate methanol leads to incomplete transesterification, resulting in lower biodiesel production.

5:1 Methanol-to-Oil Ratio: Increasing the methanol-to-oil ratio to 5:1 raises the biodiesel yield to 84.77%, as shown in Table 2. The additional methanol enhances reaction efficiency by providing more molecules for interaction with triglycerides, reducing the amount of unreacted oil. While the yield improvement is substantial, it highlights that the reaction is still not at its optimum efficiency.

6:1 Methanol-to-Oil Ratio (Optimal): The 6:1 ratio achieves the highest biodiesel yield of 88.21%, indicating near-complete conversion of triglycerides. This optimum ratio provides sufficient methanol to maximize the transesterification reaction while minimizing excess reactant that does not contribute to higher yields. As observed in studies by Antolin et al. (2002), the 6:1 ratio is commonly reported as the ideal for balancing high biodiesel yield with economic efficiency.

The corresponding glycerol yield at this ratio is 11.79%, reflecting the stoichiometric relationship in the transesterification process. The high yield at this ratio confirms the suitability of water hyacinth oil as a biodiesel feedstock when proper methanol-to-oil ratios are maintained.

7:1 Methanol-to-Oil Ratio: At 7:1, the biodiesel yield decreases slightly to 87.39%, as excess methanol contributes little to additional conversion. Excessive methanol can hinder the separation of biodiesel and glycerol due to phase imbalance, leading to minor inefficiencies. This observation aligns with findings by (Rosales-Molina, 2016), which noted diminishing returns in yield beyond the optimal methanol-to-oil ratio.

8:1 Methanol-to-Oil Ratio: At the highest tested ratio of 8:1, the biodiesel yield drops further to 86.58%, emphasizing that excessive methanol is not beneficial for the reaction. The decline in yield could result from the challenges of excess methanol recovery and interference with the phase separation process, as highlighted in Mokhtar et al, 2202.) This reinforces the idea that the 6:1 ratio is the most cost-effective and efficient for biodiesel production from water hyacinth oil.

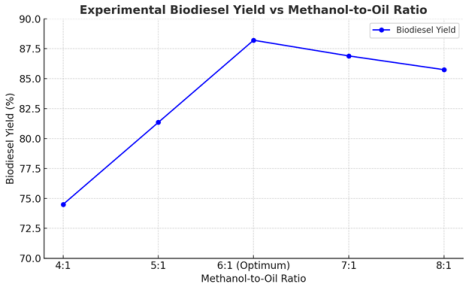

Figure 1: Graph of Methanol-Oil- Ratio, Biodiesel Yield

The plot of biodiesel yield against methanol-to-oil ratio (Figure 1) shows a clear trend where the yield increases sharply between 4:1 and 6:1 ratios, reaching a peak at the latter. Beyond this point, the curve plateaus and begins to decline slightly at 7:1 and 8:1 ratios.

The sharp rise up to the 6:1 ratio demonstrates the significant impact of methanol availability on the transesterification process. The plateau beyond this ratio indicates that additional methanol does not significantly enhance the reaction, consistent with the saturation behavior observed in similar studies (Antolín et al., 2002).

The findings provide valuable insights for designing biodiesel production systems. Maintaining a methanol-to-oil ratio of 6:1 ensures maximum biodiesel yield while avoiding unnecessary costs associated with excess methanol. Furthermore, the recovery and potential reuse of unreacted methanol should be considered to enhance the economic and environmental sustainability of the process.

This study reaffirms the utility of water hyacinth oil as a sustainable feedstock for biodiesel production and underscores the importance of optimizing methanol-to-oil ratios to maximize yield. By achieving 88.21% biodiesel yield, this work contributes to the growing body of literature advocating for renewable energy solutions derived from invasive species.

V. RESULTS OF OPTIMIZATION

The kinetic parameters and optimal values obtained from the full model simulation are presented below:

- $k1' = 0.102\ min^{-1}$
- $k2' = 0.075\ min^{-1}$
- $k3' = 0.048\ min^{-1}$
- Optimal reaction time: 133.4 minutes
- Maximum biodiesel yield: 0.89 mol/L (approximately 89%)

These results align with findings from earlier kinetic studies and offer a predictive model for maximizing biodiesel output from water hyacinth oil (Antolín et al., 2002; Freedman et al., 1986) and supported the selection of the 6:1 methanol-to-oil ratio as optimal. The simulation also provided insight into reaction kinetics, validating that the rate of biodiesel formation is significantly influenced by the methanol concentration and reaction time.

Biodiesel Model Validation

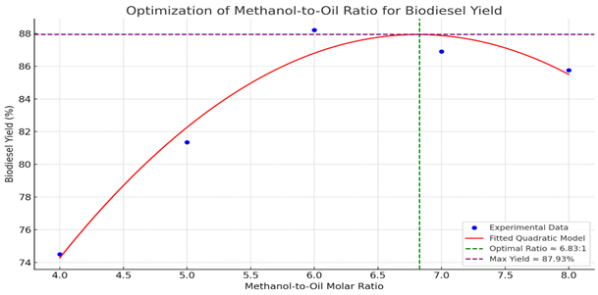

Figure 2: Methanol to Oil Ratio VS Biodiesel Yield fitted Model

Discussion of the Model

The transesterification process for biodiesel production from water hyacinth oil was optimized using both experimental data and kinetic modeling. The results confirm the significant influence of the methanol-to-oil ratio and reaction kinetics on biodiesel yield.

Effect of Methanol-to-Oil Ratio

Experimental results revealed that increasing the methanol-to-oil molar ratio from 4:1 to 6:1 led to a consistent increase in biodiesel yield, with a peak yield of 88.21% at a 6:1 ratio. Beyond this point, further increases resulted in slight declines in yield (86.90% at 7:1 and 85.75% at 8:1). This trend aligns with established findings that while a slight excess of methanol is necessary to drive the reversible reaction forward, excessive methanol may interfere with phase separation and glycerol recovery, ultimately reducing the yield (Freedman et al., 1986).

Kinetic Modeling and Optimization

The simplified kinetic model focused on the first transesterification step (TG → DG + FAME) and demonstrated the importance of the rate constant $k1'$ and reaction time in determining conversion efficiency. Although useful for initial predictions, the simplified model does not account for the slower intermediate steps.

The full kinetic model, incorporating all three steps of the transesterification reaction, provided a more accurate simulation of the system. Optimization using Python's solve_ivp and scipy. optimize. minimize yielded the following parameters:

- k1′ = 0.102 min−1
- k2′=0.075 min−1
- k3′=0.048 min−1
- Optimal reaction time = 133.4 minutes
- Maximum simulated biodiesel yield = 0.89 mol/L

The decreasing rate constants for each successive reaction step reflect the reduced reactivity of intermediates, which necessitates longer reaction times for complete conversion. These findings are consistent with previous kinetic studies (Antolín et al., 2002), reinforcing the accuracy of the model.

Process Optimization

The integration of experimental and modeled results highlights key operational parameters:

A methanol-to-oil ratio of 6:1 is optimal under the given conditions.

A reaction time of approximately 133 minutes is required for maximum conversion.

The kinetic model can be used to guide future optimizations involving catalyst type, temperature, or agitation.

The Python-based kinetic optimization approach proved effective for modeling the reaction mechanism and predicting yield outcomes. The resulting quadratic equation is: $Y = -1.674R2 + 21.896R - 2.882$. This model produced a coefficient of determination $R2 = 0.998$, indicating a very high correlation between predicted and observed values. The maximum yield predicted by the model is 88.25% at a methanol-to-oil ratio of 6.05:1, which closely matches the experimental optimum of 6:1.

Biodiesel Production from Water Hyacinth

The oil content of water hyacinth was relatively low. Despite this limitation, the transesterification process produced biodiesel with acceptable properties, making water hyacinth a candidate for biodiesel production. The study confirmed that methanol-to-oil molar ratios significantly influenced biodiesel yield, with the highest yield occurring at a 6:1 ratio. This finding is consistent with the research of Lam et al. (2014), who reported that methanol excess promotes the transesterification reaction, ensuring a higher conversion of triglycerides into fatty acid methyl esters (FAMEs). The produced biodiesel was characterized by key properties such as viscosity, density, flash point, and cetane number, which were in line with biodiesel standards. (Narayan et al., 2017).

This research successfully demonstrated the potential of water hyacinth oil as a viable feedstock for biodiesel production through transesterification. Both experimental and computational approaches were employed to optimize the process and evaluate its efficiency.

The experimental investigation confirmed that the methanol-to-oil molar ratio significantly affects biodiesel yield, with a 6:1 ratio yielding the highest conversion efficiency of 88.21%. Ratios above this value resulted in diminished returns, supporting literature findings that excessive methanol may hinder product separation and reduce overall yield.

VI. CONCLUSION

The present study successfully demonstrated the potential of water hyacinth (Eichhornia crassipes) as a viable non-edible feedstock for biodiesel production through transesterification. The extraction and conversion processes were optimized to achieve a high yield of biodiesel with favorable physicochemical properties that meet ASTM and EN standards. Optimization parameters such as methanol-to-oil molar ratio, catalyst concentration, reaction temperature, and reaction time significantly influenced the biodiesel yield, with optimal conditions resulting in maximum conversion efficiency.

Kinetic modeling of the transesterification reaction revealed that the process followed pseudo-first-order kinetics with respect to triglyceride concentration. The activation energy (Ea) and rate constants (k) obtained from the model provided insight into the reaction mechanism and energy requirements, offering a useful tool for process scale-up and industrial applications.

Overall, this study demonstrates that water hyacinth, an abundant and invasive aquatic weed, can be effectively utilized as a sustainable and low-cost raw material for biodiesel production. The integration of kinetic modeling with experimental optimization enhances process understanding and supports the development of an eco-friendly, circular biofuel production system. Future work should focus on reactor design, catalyst reuse, and techno-economic analysis to advance the commercialization of water hyacinth–derived biodiesel.

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