

PROCESS SIMULATION OF BIODIESEL SYNTHESIS FROM MICROALGAE VIA A HETEROGENEOUS-CATALYZED HYDROLYSIS-ESTERIFICATION PROCESS

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Abstrak. Hidrolisis-esterifikasi merupakan proses alternatif produksi biodiesel yang dirancang untuk konversi biomassa mikroalga basah secara langsung tanpa melalui tahap pengeringan dan ekstraksi pelarut yang memiliki konsumsi energi tinggi. Pada jalur ini, lipid dihidrolisis menjadi asam lemak bebas (FFA) dalam kondisi sub-kritis air, dan diesterifikasi menjadi biodiesel (FAME) dengan bantuan katalis heterogen Amberlyst-15. Simulasi proses menggunakan Aspen Plus V12 dilakukan dengan umpan biomassa *Chlorella* sp. sebesar 30.000 kg/jam, dengan tripalmitin dipilih sebagai lipid representatif. Tahap hidrolisis menghasilkan sekitar 60 kmol/jam asam palmitat dan 20 kmol/jam gliserol, sedangkan tahap esterifikasi mencapai konversi FFA sekitar 82% pada kondisi optimal (60–70 °C, rasio molar metanol terhadap FFA 6:1). Hasil analisis sensitivitas menunjukkan bahwa kenaikan rasio metanol mampu meningkatkan konversi, tetapi juga meningkatkan konsumsi energi pada tahap pemisahan dan pemurnian. Kebutuhan utilitas pada kolom distilasi meningkat dari 13,71 MW (rasio metanol 3:1) menjadi 16,04 MW (6:1). Meskipun demikian, rangkaian pemisahan dan pemurnian mampu menghasilkan biodiesel berkualitas tinggi (>99 wt% FAME, <0,25 wt% FFA) dan pemulihan metanol lebih dari 95%. Secara keseluruhan proses ini menunjukkan potensi kelayakan teknis dan penyederhanaan proses untuk sintesis biodiesel dari mikroalga, meskipun masih diperlukan pengembangan pada aspek stabilitas katalis, dan kondisi operasi untuk mendukung keberlanjutan dan penerapan industri.

Kata kunci: biodiesel, mikroalga, hidrolisis-esterifikasi, katalis heterogen

Abstract. The hydrolysis-esterification route is an alternative process for biodiesel production from wet microalgae biomass that eliminates the energy-intensive drying and lipid extraction. In this route, lipids are hydrolyzed under subcritical water conditions to produce FFA, then esterified using heterogeneous catalyst. Process simulation was conducted using feedstock of 30,000 kg/h of *Chlorella* sp. biomass. Tripalmitin was selected as the representative triglyceride of microalgal lipids. The hydrolysis stage produced 60 kmol/h of palmitic acid and 20 kmol/h of glycerol. The esterification stage achieved 82% FFA conversion to FAME under optimum operating conditions of 60–70 °C and a methanol-to-FFA molar ratio of 6:1. Sensitivity analysis showed that increasing the methanol-to-FFA ratio enhanced FFA conversion. It also increased energy consumption in separation process. The duty on distillation column increased from 13.71 MW at methanol-to-FFA ratio of 3:1 to 16.04 MW at a ratio of 6:1. Nevertheless, separation and purification sections successfully produced high quality biodiesel (>99 wt% FAME and <0.25 wt% FFA) while achieving methanol recovery of up to 95%. Overall, the process demonstrates promising technical feasibility and process simplification for biodiesel production from microalgae. However, further improvements are required regarding catalyst stability and operating conditions to support industrial scale implementation.

Keywords: biodiesel, microalgae, hydrolysis-esterification, heterogeneous catalyst

1. Introduction

Environmental concerns and the depletion of fossil fuel reserves have encouraged the transition from fossil-based energy to renewable energy sources. This transition includes decarbonization efforts, which have driven the development of sustainable biofuels. Among various renewable resources, microalgae have emerged as a promising feedstock due to their rapid growth rate, high lipid content, and low requirements for land and freshwater. In addition, microalgae can utilize CO₂ through photosynthesis, which may help reduce greenhouse gas emissions. The CO₂ source can be obtained from concentrated emissions such as power plant flue gas, making microalgae an attractive option for biofuel production (Liu et al., 2025).

Despite these advantages, biodiesel production from microalgae is still difficult to implement on an industrial scale because of high production costs and several technical challenges (Gaurav, Neeti and Singh, 2024). Therefore, improving process efficiency and developing alternative conversion routes are important to enhance economic feasibility. One approach is the use of heterogeneous catalysts, which offer advantages such as easier separation, reusability, and improved selectivity (Akubude, Nwaigwe and Dintwa, 2019). Conventionally, biodiesel is produced through the transesterification of triglycerides (TAG) with methanol in the presence of a catalyst. However, this process often faces problems when crude or wet microalgal oil is used because it may contain high amounts of FFA, water, and other impurities. These components can cause soap formation, catalyst deactivation, and lower biodiesel conversion, leading to more complicated downstream purification (Pandey et al., 2024).

As an alternative, the hydrolysis–esterification route has been proposed, where TAG are first hydrolyzed into FFA and glycerol, followed by esterification of FFA to produce FAME. This route offers several advantages, especially for processing feedstocks with high FFA content and improving overall conversion by separating the reaction steps (Takisawa et al., 2013). However, the hydrolysis step requires high temperature and pressure, while esterification is an equilibrium-limited reaction that requires excess methanol and proper water management. Previous studies have shown that with suitable process design and operating conditions, the hydrolysis–esterification route can be a promising alternative for biodiesel production from microalgae (Song et al., 2016).

Therefore, this study aims to simulate and evaluate the hydrolysis–esterification route using a heterogeneous catalyst through process simulation software. The simulation is intended to provide insight into mass flows, conversion performance, and potential process bottlenecks, which can support future optimization and industrial development of microalgae-based biodiesel production.

2. Methods

2.1. Materials

The materials used in this simulation were wet *Chlorella* sp. biomass, methanol, and Amberlyst-15 catalyst. The lipid content of the microalgae was represented by tripalmitin (C₅₁H₉₈O₆) as a model triglyceride. Palmitic acid (C₁₆H₃₂O₂) was used to represent the FFA formed during the hydrolysis stage. Methanol was used as the alcohol reactant for the esterification process to produce FAME. Amberlyst-15, a sulfonated polystyrene–divinylbenzene ion-exchange resin with strong acidic properties, was selected as the heterogeneous catalyst for the esterification reaction.

2.2. Process Description

This study simulated the conversion of wet microalgae biomass into biodiesel without considering the cultivation and harvesting stages. The harvested wet biomass was

assumed to be directly available as feedstock. A hydrolysis–esterification route was used instead of conventional transesterification, as shown in Figure 1. The process includes hydrolysis of TAG into free fatty acids FFA, esterification of FFA into biodiesel/FAME, and biodiesel purification. Compared with conventional transesterification, this route avoids the need for drying and solvent extraction, reduces soap formation caused by high FFA levels, and simplifies downstream purification (Song et al., 2016). The esterification reaction was carried out using a heterogeneous catalyst. Unlike homogeneous catalysts, the catalyst can be easily separated from the reaction mixture, eliminating the need for additional separation steps. As a result, the process becomes simpler and requires less energy for downstream processing.

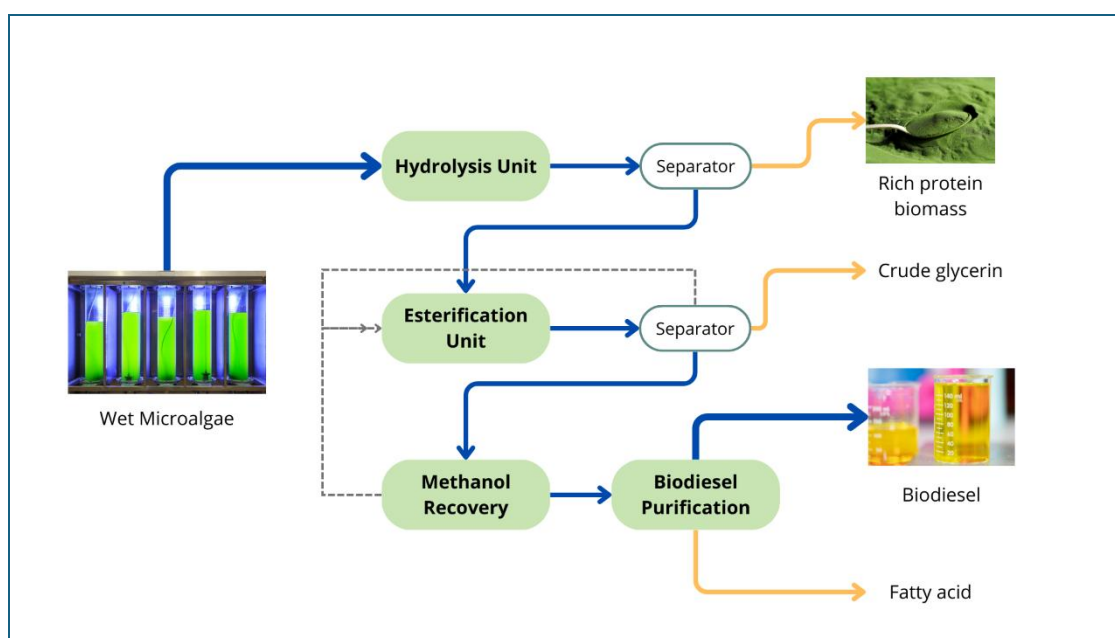


Figure 1. Hydrolysis-Esterification General Process

2.3. Simulation Setup

The process simulation was carried out using Aspen Plus V12. The NRTL-RK property method was selected to accurately model the non-ideal behavior of the system, particularly for mixtures involving FAME, methanol, and glycerol.

The feed stream was defined as 3000 kmol/h of wet microalgae biomass, which had been harvested and directly used. The dry biomass of *Chlorella* sp. typically contains 15–40 wt% lipids, 30–50 wt% proteins, and 10–50 wt% carbohydrates (Lafarga, 2019). In this simulation, the microalgal biomass was modeled as consisting of 50% proteins (represented by phenylalanine), 20% carbohydrates (represented by sucrose), and 30% lipids. Phenylalanine and sucrose were considered inert solids which is separated during the process and does not participate in the reactions. The lipid fraction was assumed to consist of fatty acids, which serve as the main reactants in the subsequent hydrolysis–esterification process. The fatty acid composition of the microalgae oil consists of:

Table 1. Fatty acid composition of *Chlorella* sp. (Putnarubun et al., 2018)

Fatty Acid	Composition (%)
C16:0 (Palmitic acid)	73
C16:1 (Palmitoleic acid)	21

Fatty Acid	Composition (%)
C18:2 (Linoleic acid)	4
C18:0 (Stearic acid)	2

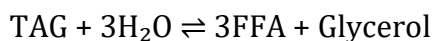
Given the dominance of C16:0, the lipid component in the simulation was represented by tripalmitin as a simplified model triglyceride. The hydrolysis reaction was modeled using an Equilibrium Reactor in Aspen Plus, which allows for equilibrium-based conversion of TAG into FFA and glycerol without the need for detailed kinetic data. The reactor was operated at 250 °C and 50 bar to ensure complete thermal decomposition of the lipid content under high-pressure conditions (Menalla et al., 2024).

The esterification reaction, which is the main focus of this study, was simulated using a plug flow reactor (PFR). The reactor was operated at 60 °C with a methanol-to-FFA molar ratio of 6:1 and Amberlyst 15 as the catalyst. Amberlyst 15 was selected because it can promote esterification effectively at relatively low temperatures, helping maintain catalyst stability while providing sufficient reaction rates (Tempelman et al., 2021).

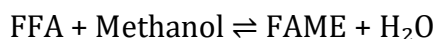
The separation and purification section consisted of two distillation columns. Both columns were modeled using the DSTWU block in Aspen Plus. The first column was used to recover unreacted methanol and operated at atmospheric pressure with 10 stages and a reflux ratio of 2.5. Most of the methanol was recovered in the distillate stream and recycled to the process. The second column was used to separate biodiesel from residual FFA. To reduce the risk of thermal degradation, the column was operated under vacuum conditions. The column was configured with 15 stages and a reflux ratio of 3.5. The purified biodiesel product contained more than 99 wt% FAME, while the residual FFA content was below 0.25 wt%.

2.4. Reaction Conditions

The simulation focused on two main chemical conversions. First, the hydrolysis of triglycerides (tripalmitin) into FFA and glycerol according to the following reversible reaction:



The hydrolysis reaction was carried out under subcritical water conditions at a temperature of 250 °C and a pressure of 50 bar to promote the cleavage of triglyceride molecules into free fatty acids and glycerol. Second, the esterification of FFA with methanol to form biodiesel (FAME) and water, represented by the reversible reaction:



The esterification reaction was simulated at atmospheric pressure (1 bar) with reaction temperatures varied from 50 to 80 °C to investigate the effect of temperature on biodiesel yield.

The esterification reaction was modeled using a Langmuir–Hinshelwood–Hougen–Watson (LHHW) kinetic approach to account for catalytic surface reactions and competitive adsorption phenomena. The reaction rate expression used is :

$$-r_s = k_s \left[\frac{K_A K_B C_{A0}^2 (1 - X_A)(M - X_A) - \left[\frac{K_E K_W (C_{A0} X_A)^2}{K_S} \right]}{\{1 + K_A C_{A0} (1 - X_A) + K_B C_{A0} (M - X_A) + C_{A0} X_A (K_E + K_W)\}^2} \right]$$

(Subhash Bhatia, 2004)

where r_s is the reaction rate, k_s is the surface reaction rate constant, C_{A0} represents the concentrations of the species, and K_A , K_B , K_E , K_W denotes the adsorption equilibrium constant of FFA, alcohol, FAME and water respectively.

3. Results and Discussion

3.1. Overall Simulation Result

The simulation models the process of biodiesel synthesis from microalgae through a hydrolysis-esterification route, using 30,000 kg/h of wet microalgae as feed, as illustrated in Figure 1.

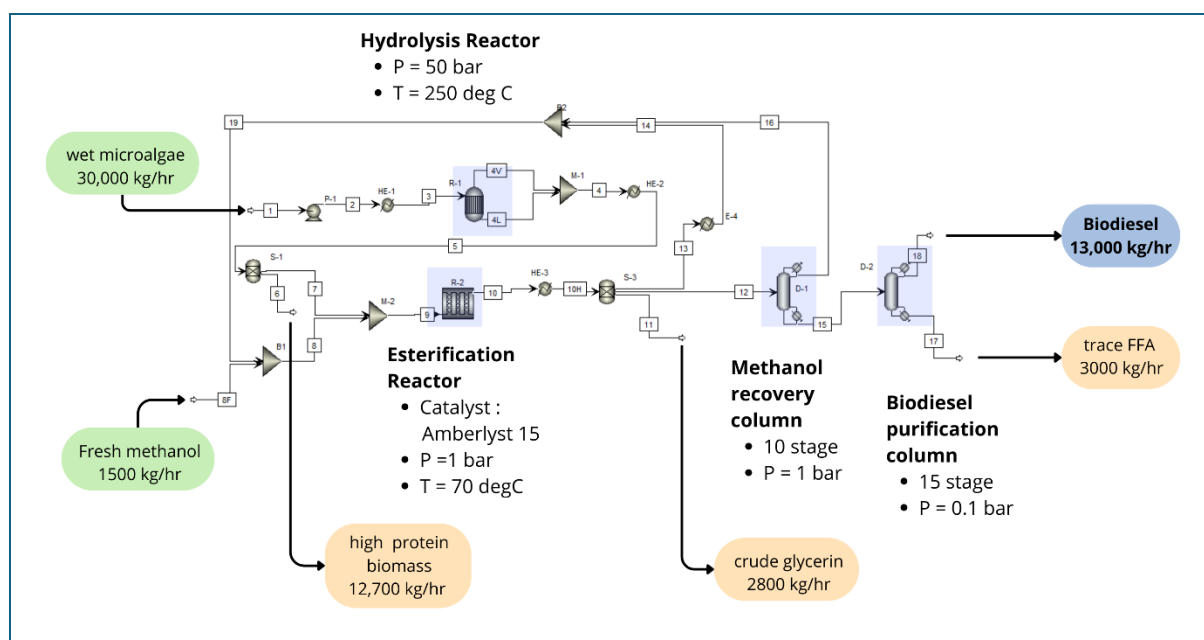


Figure 2. Hydrolysis-Esterification Process Flow Diagram

In the first stage, tripalmitin undergoes hydrolysis under sub-critical water conditions, producing palmitic acid as FFA and glycerol. Specifically, 20 kmol/h of tripalmitin are converted into 60 kmol/h of palmitic acid and 20 kmol/h of glycerol. After hydrolysis, the microalgae biomass is separated from the FFA-rich layer, resulting in approximately 12,600 kg/h of solid biomass. This fraction mainly contains proteins and carbohydrates and can be further processed into value-added products, such as functional foods and other bioproducts (Saeed et al., 2025).

In the next esterification step, palmitic acid reacts with methanol in the presence of an acid catalyst. The process utilizes 360 kmol/h of methanol, corresponding to a methanol-to-FFA molar ratio of 6:1. The reactor operates at 65 °C and 1 bar, conditions typical of low-temperature, acid-catalyzed esterification. Under these conditions, 82% of the palmitic acid is converted, leading to the production of approximately 11,700 kg/h of biodiesel. This conversion is consistent with the performance generally reported for solid

acid catalysts such as Amberlyst-15, which typically achieve 30–80% conversion (Ansari et al., 2025). The moderate yield can be explained by the equilibrium-limited nature of the esterification reaction, the diffusion constraints within the porous Amberlyst structure, and the inhibitory effect of water formed as a byproduct. Consequently, the obtained biodiesel yield reflects a realistic outcome under the given operating conditions. The esterification effluent is first directed to a three-phase separator, producing three distinct streams: a methanol-rich phase, a FAME-rich phase, and a glycerol-rich phase. Most of the excess methanol is removed at this stage before further recovery in the first distillation column. The heavy phase contains approximately 1,830 kg/h of glycerol together with 930 kg/h of water, while the middle phase consists primarily of FAME and unreacted FFA. More detailed mass balance information can be found in Table 2. The FAME-rich stream is then purified through a two-column distillation. In the first column, the remaining methanol is recovered for recycle.

Table 2. Stream Properties and Material balance

Stream No.	1	2	3	4	5	6	7	8	8F	9
Temperature (°C)	25	31	250	116	45	45	45	60	30	57
Pressure (bar)	1	50	50	1	1	1	1	1	1	1
Mass flow rate (kg/h)	30000	30000	30000	30000	30000	12698	17302	11802	1555	29103
Composition (%wt)										
Palmitic Acid	0.00	0.00	0.00	0.51	0.51	0.00	0.89	0.00	0.00	0.53
Tripalmitin	0.54	0.54	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Methanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	1.00	0.40
H2O	0.27	0.27	0.27	0.23	0.23	0.55	0.00	0.01	0.00	0.01
FAME (Biodiesel)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Glycerol	0.00	0.00	0.00	0.06	0.06	0.00	0.11	0.00	0.00	0.06
Sucrose	0.06	0.06	0.06	0.06	0.06	0.13	0.00	0.00	0.00	0.00
Phenilalanine	0.14	0.14	0.14	0.14	0.14	0.32	0.00	0.00	0.00	0.00

Stream No.	10	10H	11	12	13	14	15	16	17	18	19
Temperature (°C)	65	80	80	80	80	65	306	62	205	101	62
Pressure (bar)	1	1	1	1	1	1	1	1	0.01	0.01	1
Mass flow rate (kg/h)	29103	29103	2856	16100	10147	10147	16000	100	2943	13057	10247
Composition (%wt)											
Palmitic Acid	0.10	0.10	0.00	0.18	0.00	0.00	0.19	0.00	1.00	0.00	0.00
Tripalmitin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Methanol	0.34	0.34	0.00	0.01	0.97	0.97	0.00	0.99	0.00	0.00	0.97
H2O	0.04	0.04	0.33	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.01
FAME (Biodiesel)	0.45	0.45	0.00	0.81	0.01	0.01	0.81	0.00	0.00	1.00	0.01

Glycerol	0.06	0.06	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sucrose	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phenilalanine	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The bottom stream, comprising about 13,000 kg/h of FAME and 2,900 kg/h of unreacted FFA, is subsequently fed to the second column, where FFA is separated to achieve a biodiesel product with less than 2.5 wt% FFA. This final step results in high-purity biodiesel (>99%), while the overall separation and purification train achieves more than 95% recovery of excess methanol and generates glycerol as a valuable byproduct.

3.2. Reaction Performance in Esterification of Palmitic Acid

The esterification of palmitic acid with methanol is a reversible reaction catalyzed under moderate thermal conditions. Key operating parameters such as temperature, methanol-to-FFA molar ratio, and water content significantly influence the conversion.

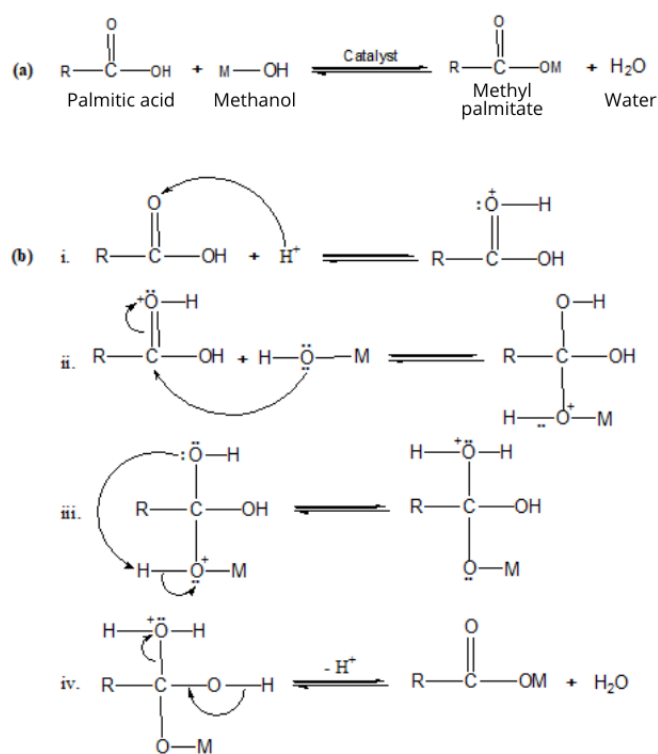


Figure 3. Mechanism of acid-catalyzed esterification of free fatty acids with methanol: (i) protonation of the carbonyl group; (ii) nucleophilic addition of methanol to form a tetrahedral intermediate; (iii) proton rearrangement within the intermediate; and (iv) dehydration and reformation of the carbonyl bond, yielding fatty acid methyl ester (FAME) and water.

3.2.1. Effect of Temperature on Conversion

Temperature significantly influences the performance of the esterification reaction, particularly due to its impact on both reaction kinetics and catalyst stability. In this study, the reaction temperature was varied from 40 °C to 90 °C to evaluate its effect on the conversion of FFA to FAME. As shown in Figure 4, the conversion increased with

increasing temperature and reached a maximum value of approximately 83% at 70 °C. This increase is mainly attributed to the higher reaction rate at elevated temperatures, which promotes the reaction between FFA and methanol.

However, a decline in conversion was observed at temperatures above 85 °C. Although Amberlyst-15 can operate at temperatures up to 120 °C, its optimum performance is generally reported around 60 °C, and a decrease in catalytic activity has been observed at higher temperatures (Landazábal et al., 2025). This reduction in activity may be associated with structural changes in the catalyst or degradation of the sulfonic acid groups that serve as the active sites for esterification (Sheikh et al., 2023). In this study, the conversion decreased to about 50% at 85 °C and further dropped to only 9% at 90 °C, indicating that excessive temperatures adversely affected catalyst performance.

In addition, practical operating considerations should also be taken into account. Methanol, which is supplied in excess to drive the esterification reaction, has a relatively low boiling point of about 64.7 °C. At temperatures above this value, methanol evaporation may become significant, reducing the effective reactant concentration and potentially affecting process performance. The use of Amberlyst-15 may also introduce mass transfer limitations because the reactants must diffuse through the catalyst pores before reaching the active sulfonic acid sites.

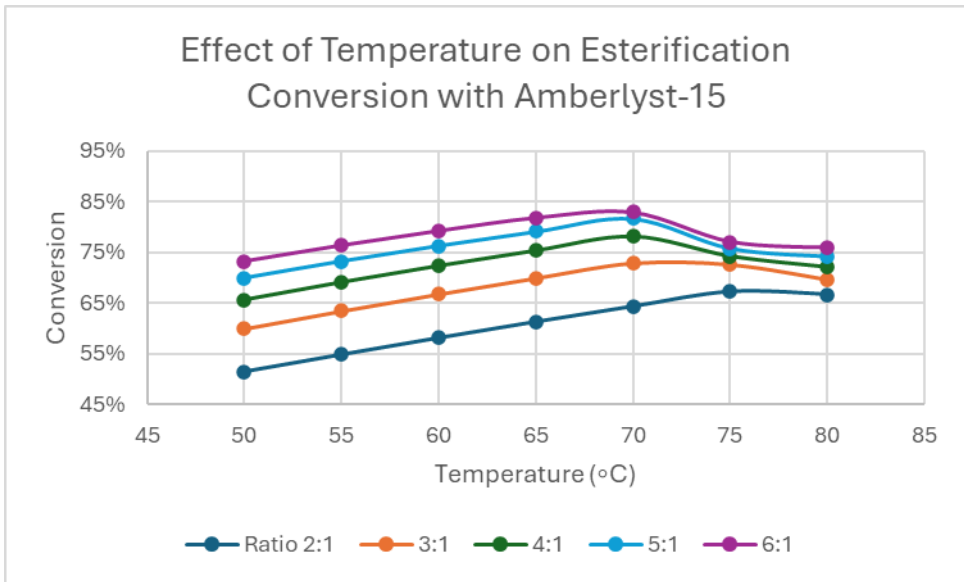


Figure 4. Effect of Temperature and Methanol-to-FFA Rasio on Esterification Reactor Conversion

Considering these factors, a reaction temperature between 60 °C and 70 °C appears to be the most suitable operating range. Within this range, FFA conversion remains high while methanol losses can be minimized and catalyst performance can be maintained. Therefore, operating within this temperature window provides a good compromise between reaction efficiency, catalyst stability, and overall process performance.

3.2.2. Effect of Methanol-to-FFA Ratio on Conversion

Since the esterification of FFA to FAME is a reversible reaction, the use of excess methanol is essential to drive the reaction toward higher conversion. In this simulation,

the effect of methanol-to-palmitic acid molar ratio was investigated in the range of 2:1 to 6:1.

As shown in Figure 4, the FFA conversion increases with higher methanol ratios, reaching a maximum of approximately 95% at a 12:1 ratio. At lower ratios (2:1 to 4:1), the increase in conversion is significant due to the favorable shift in equilibrium and improved availability of methanol molecules for reaction, a phenomenon that has also been reported in other processes employing Amberlyst (Song et al., 2021). Once the molar ratio reaches 4:1, the increase in conversion becomes narrower compared to the preceding ratios. The difference observed in the conversion curve between incremental ratios becomes less apparent, and additional methanol no longer contributes substantially to higher conversion. Furthermore, the methanol ratio also affects the temperature of maximum conversion. At lower ratios, the peak occurs at higher temperatures, while at higher ratios it shifts to lower temperatures, reflecting the combined influence of methanol availability and thermal conditions on the equilibrium. While higher methanol ratios enhance conversion, they also introduce challenges in the downstream separation process. Excess unreacted methanol must be recovered and recycled, which increases the energy demand of the separation unit and impacts overall process efficiency and economics.

Based on these considerations, a methanol-to-FFA ratio of around 6:1 offers a reasonable balance. This ratio yields high conversion (about 80%) while limiting the burden on the separation system, making it suitable for practical application in continuous esterification systems.

3.2.3. Effect of Water Content on Conversion

Water in the feed is generally known to inhibit the esterification reaction, as it interferes with the reaction equilibrium (Takisawa et al., 2013). As shown in Figure 5, increasing water content in the feed results in a decline in FFA conversion. At a reaction temperature of 70 °C, the conversion decreases from 81% at 0.2% water content to 74% at 1%. This reduction becomes more pronounced at lower reaction temperatures. For instance, at 50 °C, the conversion drops from 69% at 0.2% water content to 59% at 1%.

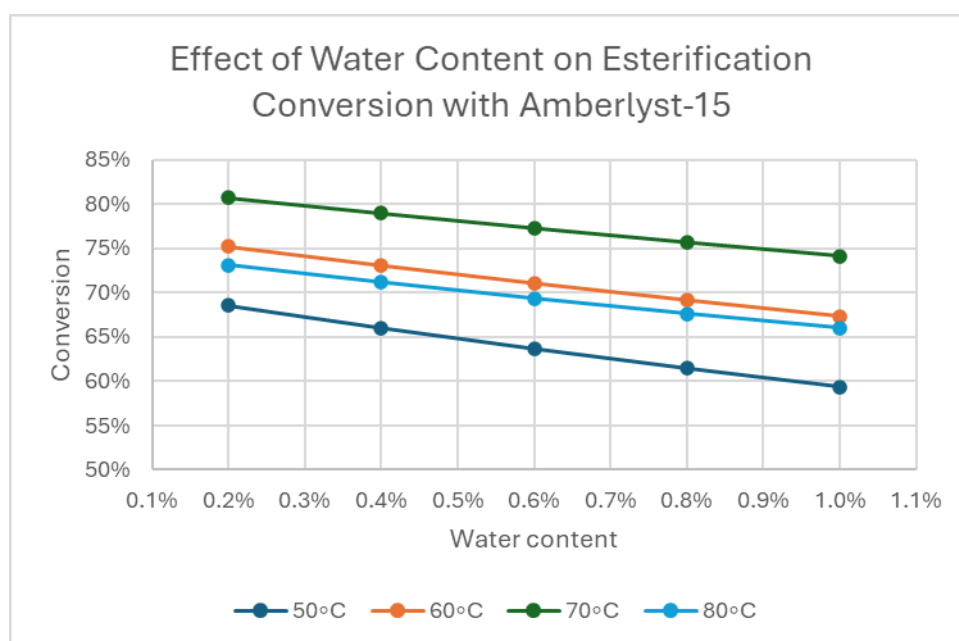


Figure 5. Effect of Water Content on Esterification Reactor Conversion

These findings suggest that water competes with FFA for the active sites of the Amberlyst catalyst and shifts the equilibrium toward the reactants, leading to lower overall conversion. From a process design perspective, this highlights the importance of minimizing water content throughout the system. An effective separation step upstream of the reactor such as a decanter, flash unit, or drying column should be implemented to reduce water in the feed. In addition, water generated as a byproduct during esterification must also be removed continuously to prevent equilibrium limitations. A practical solution is the integration of a molecular sieve, which selectively captures water from the reaction mixture and helps sustain higher conversion (Dange and Rathod, 2017). Without these separation strategies, even small amounts of water can significantly reduce conversion, particularly at lower operating temperatures where the system becomes more sensitive to inhibition. Hence, careful integration of water removal units both before and after the esterification reactor is essential to ensure stable operation and to maximize FFA conversion.

3.3. Energy Consumption in Separation Section

The evaluation of energy consumption in the separation section was carried out by analyzing the utility duties of the reboilers and condensers in the two distillation columns under different methanol-to-FFA molar ratios. In the first distillation column, which is designed for methanol recovery, the reboiler duty is greater than the condenser duty, reflecting the higher energy demand required to vaporize excess methanol from the reaction mixture. Conversely, in the second distillation column, which is used for biodiesel purification and operates under vacuum conditions, the condenser duty exceeds the reboiler duty. This occurs because vacuum operation lowers the boiling points of high-boiling components, thereby reducing the reboiler load but increasing the demand on the condenser to manage vapor condensation and ensure biodiesel purity.

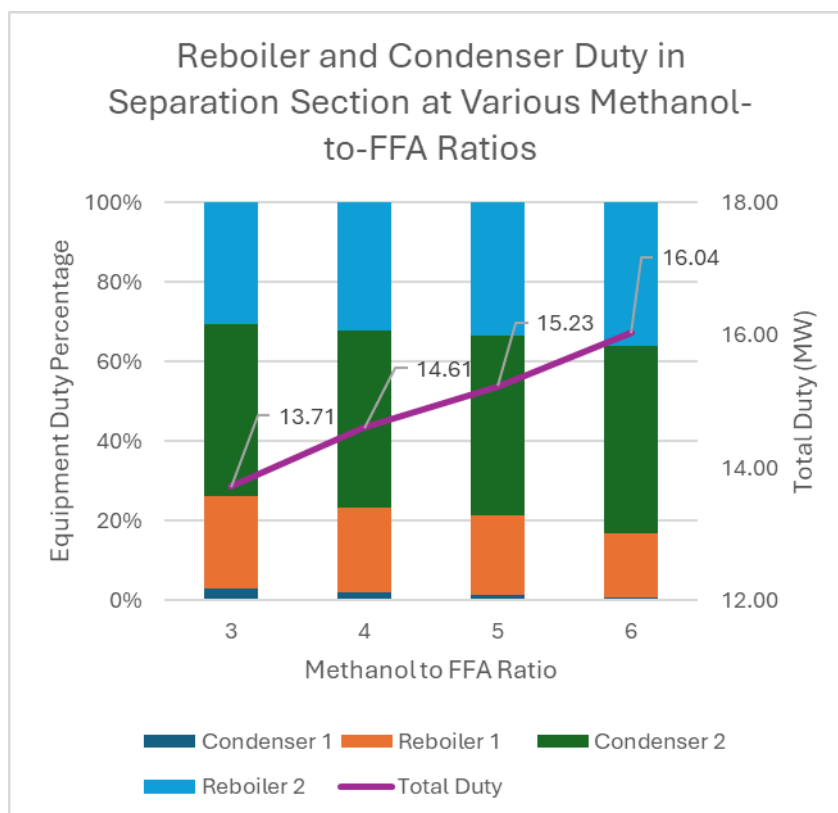


Figure 6. Effect of Water Content on Esterification Reactor Conversion

As shown in Figure 6, the total utility duty increases with higher methanol-to-FFA molar ratios. When the ratio increases from 3:1 to 6:1, the total duty rises from 13.71 MW to 16.04 MW. The majority of this energy consumption originates from the second distillation column, which operates under vacuum and at a relatively high reflux ratio. The high reflux ratio is required to ensure that biodiesel is effectively separated from residual FFA to meet the product specification of less than 0.25% FFA. Consequently, as the methanol ratio increases, the condenser duty of this column becomes progressively larger, reflecting the combined effects of reflux operation and vacuum conditions on energy demand.

4. Conclusion

This study has demonstrated the technical feasibility of biodiesel production from wet microalgae via a hydrolysis-esterification route using Aspen Plus simulation. The process successfully eliminates the need for energy-intensive drying and avoids soap formation, while employing Amberlyst-15 as a heterogeneous catalyst to achieve moderate FFA conversions under low-temperature conditions.

The results indicate that the esterification performance is strongly influenced by temperature, methanol-to-FFA molar ratio, and water content. The optimal reaction temperature range was identified as 60–70 °C, where favorable kinetics and catalyst stability are balanced. Increasing the methanol ratio enhances FFA conversion but with diminishing returns beyond 4:1, and excessive methanol introduces a significant energy penalty in downstream separation. Water was shown to exert a negative effect on

conversion, particularly at lower operating temperatures, underscoring the importance of effective water removal strategies such as decanters or molecular sieves.

In the separation section, energy consumption was dominated by the biodiesel purification column, which operates under vacuum and at high reflux ratios to meet the stringent purity requirement of <0.25% FFA. The total utility duty increased from 13.71 MW to 16.04 MW as the methanol ratio increased from 3:1 to 6:1, highlighting the trade-off between reaction conversion and separation energy demand.

Overall, the hydrolysis–esterification pathway provides a promising alternative for biodiesel production from wet microalgae, offering process simplification and high-purity biodiesel. Future optimization should focus on integrating efficient water removal and minimizing energy consumption in the separation section to enhance overall process sustainability.

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