Eksergi
Chemical Engineering Journal
Vol 23, No. 1. 2026

ISSN: 1410-394X
e-ISSN: 2460-8203

Simulation of Biodiesel Production from Waste Cooking Oil Using Methanol-Activated CaO Recycling Catalyst: Kinetic and Techno-Economic Evaluation

Jabosar Ronggur Hamonangan Panjaitan*

Chemical Engineering Program, Institut Teknologi Sumatera, Lampung 35365, Indonesia

Article history:

Submitted 19 October 2025
Revision 8 December 2025
Accepted 15 December 2025
Online 16 January 2026

ABSTRACT: Waste cooking oil is a food industry waste product that can be converted into biodiesel as an alternative fuel. The use of heterogeneous base catalysts such as commercial CaO offers advantages in biodiesel production due to its reusability. This study investigated biodiesel production from waste cooking oil using commercial CaO catalyst through simulations to evaluate kinetics and techno-economics of its production at plant scale. The simulations used in this study were divided into three process schemes. Scheme 1 was a scheme without CaO catalyst recycling, Scheme 2 was a scheme with 3x recycling of the commercial CaO catalyst, and Scheme 3 was a scheme with 10x recycling of the commercial CaO catalyst. The results showed that the recycling process of commercial CaO catalyst used affects the conversion value of waste cooking oil into biodiesel. Lower reaction conversion was obtained with increasing amounts of recycled commercial CaO catalyst. The highest conversion of waste cooking oil to biodiesel achieved in this study was 92.84% from scheme 1. Based on the techno-economic evaluation, scheme 1 was the most profitable compared to the other schemes, with a net present value of US$34,652,659. Schemes 2 and 3 had lower net present values due to the increase in total capital investment and operational costs for recycling commercial CaO compared to scheme 1. Meanwhile, based on CaO catalyst requirements, scheme 3 had the lowest CaO requirement which was 3.06 tons/year.

Keywords: biodiesel, CaO, simulation, techno-economics

1. Introduction

Waste cooking oil is a waste product from the food industry, resulting from the repeated heating of cooking oil (Lopresto et al., 2024). Waste cooking oil generally consists of various compounds such as triglycerides, free fatty acids, glycerol, monoglycerides, and diglycerides (Caporusso et al., 2025). Although considered waste, waste cooking oil can still be converted into high-value products such as the alternative fuel biodiesel (Lopresto et al., 2024). Biodiesel from waste cooking oil has significant potential for development in Indonesia. This is because Indonesia is the world's largest producer and consumer of palm oil, and the biodiesel development policy also supports the Indonesian government's Asta Cita mission of sustainable development and energy independence (Rahman et al., 2025). This Asta Cita mission was supported by government regulation in Peraturan Menteri ESDM Number 5 in 2025, which was the regulation about guidelines for power purchase agreements from new and renewable energy which aims to accelerate the development of new and renewable energy (ESDM, 2025a).

Waste cooking oil is a low-cost and effective feedstock that can be converted into biodiesel through a transesterification process using a base catalyst (Awogbemi & Desai, 2025). One heterogeneous base catalyst commonly used for biodiesel production was calcium oxide (CaO). CaO can be produced from eggshells through a calcination process. Furthermore, extensive research has been conducted on producing CaO biodiesel catalysts from natural materials such as eggshells (Basumatary et al., 2023). Although producing CaO catalysts from natural materials represents a significant breakthrough because it can produce catalysts from renewable sources, the availability of raw materials and the energy required for the calcination process were drawbacks of natural CaO catalysts. Therefore, research using commercial CaO catalysts needs to be evaluated in biodiesel production.

Biodiesel production using commercial CaO catalysts was limited. Kawashima et al. (2009) used commercial CaO catalyst that activated by methanol for biodiesel production. The research results indicated that methanol can be used to activate commercial CaO catalyst at 0.1 grams of CaO and 3.9 grams of methanol with 1.5 hours activation time which producing biodiesel with >90% yield (Kawashima et al., 2009). Prasertsit et al. (2014) optimized the response surface method for using commercial CaO catalyst to produce biodiesel. Their research results indicated that commercial

* Corresponding Author
Email address: jabosar.panjaitan@tk.itera.ac.id

CaO catalyst can be reused in biodiesel production (Prasertsit et al., 2014).

The potential of commercial CaO catalyst, such as its high yield and reusability, required further analysis of its process economics at a plant scale. Many studies have been conducted on the techno-economics of biodiesel production from waste cooking oil (Mwamba et al., 2025) (Al-sakkari et al., 2020) (Joshi et al., 2019) (Saetiao et al., 2023) (Lee et al., 2020) (Budiman Abdurakhman et al., 2018) (Ziyai et al., 2019). However, there has been no techno-economic research on biodiesel production from waste cooking oil using commercial CaO catalysts. Therefore, this study investigated the simulation of biodiesel production from waste cooking oil with commercial CaO catalysts activated by methanol according to the research of Kawashima et al (2009) and Prasertsit et al (2014). In the initial stage of this study, an evaluation of commercial CaO catalysts kinetics in biodiesel production was carried out. In the next stage, the obtained kinetic parameters used in a techno-economic simulation of biodiesel production from waste cooking oil using commercial CaO catalyst. This research was expected to show the potential of commercial CaO catalysts in plant scale biodiesel production.

2. Methods

2.1. Reaction Kinetic Analysis of Biodiesel Production with Commercial CaO Catalyst

This study analyzed reaction kinetics of biodiesel production with commercial CaO catalyst according to Kawashima et al. (2009) for 0.1 g CaO. The reaction kinetic model used in this study was the first-order heterogeneous catalyst reaction for biodiesel production because the excessive use of methanol as described in equation 1 (Sayed et al., 2023).

$$-In(1-X) = K_c.t \quad (1)$$

Which X was the reaction conversion or biodiesel yield, Kc was the reaction constant, and t was the reaction time. X and t data were taken from Kawashima et al. (2009). Plotting the linearization of X versus t will produce Kc value.

Table 1. Independent Research Variables

Scheme	Scheme description
Scheme 1	Biodiesel production without CaO recycling
Scheme 2	Biodiesel production with 3x CaO recycling
Scheme 3	Biodiesel production with 10x CaO recycling

2.2. Biodiesel production simulation using commercial CaO catalyst

Biodiesel production simulation using commercial CaO catalyst was conducted using SuperPro Designer 10 simulation software. The independent variable in this study was the amount of commercial CaO catalyst recycled in the transesterification reaction for biodiesel production based on Prasertsit et al. (2014). This independent variable was chosen to determine the amount of commercial CaO catalyst used in biodiesel production, thus relating it to the economics of biodiesel production. Three process schemes were used for CaO catalyst recycling such as scheme 1 (no CaO recycling), scheme 2 (three times CaO recycling), and scheme 3 (ten times CaO recycling) as shown in Table 1.

The dependent variable generated in this simulation was Net Present Value (NPV). Net Present Value (NPV) is the sum of the profits from all cash flows and capital investments. In addition, several constant variables used in economic simulation calculation include:

- The currency used in economic simulation was United States Dollars.
- The plant will be constructed over two years and will operate for 20 years.
- The total investment cost will be obtained through a loan with 10% compound interest per year.
- The year for the cost analysis was 2025.
- The plant raw material capacity was 2,000 kg of waste cooking oil per hour.
- The depreciation method used was the MACRS method with 15 years depreciation period.
- The Minimum Acceptable Rate of Return (MARR) used was 11%.
- The tax rate used was 25%.
- The product and raw material prices in this study can be seen in Table 2.
- Reaction condition in esterification and transesterification reactor can be seen in Table 3.

Tabel 2. Prices of Raw Materials and Product

Raw Materials	Price (US$/ton)	Reference
CaO catalyst	120	(Gebremariam and Marchetti, 2018)
Sulfuric acid	275	(Gebremariam and Marchetti, 2018)
Methanol	325	(Echemi, 2025)
Product	Price (US$/ton)	
Biodiesel	1,000	(ESDM, 2025)

The total investment cost or total capital investment (TCI) and total operational costs can be calculated using the following formula:

Total investment cost = fixed capital investment + startup costs + working capital (2)

Fixed capital investment (FCI) = 1.2 x equipment cost (3)

Startup costs = 5% x fixed capital investment (4)

Total operational costs = raw material costs + labor costs + facility costs + laboratory/quality control costs + waste processing costs (5)

Which equipment costs, working capital, labor costs, facility costs, laboratory/quality control costs, waste processing costs, total revenue was obtained from SuperPro Designer 10 simulation. The formula and method for calculating NPV were based on Peters (Peters et al., 2003). The block flow diagram of biodiesel production from waste cooking oil using commercial CaO catalyst can be seen in Figure 1.

ISSN: 1410-394X
e-ISSN: 2460-8203

Tabel 3. Reaction operating condition

Reactor	Operating condition	Reference
Esterification reactor	• Temperature = 60ºC • Time = 60 minutes • Ratio methanol/free fatty acid (FFA) = 10/1 • Sulfuric acid = 10% wt. FFA	(Jansri et al., 2011)
Transesterification reactor	Methanol-activated CaO: • Temperature = 25ºC • Time = 1,5 hours • Ratio CaO/methanol = 1/39 Transesterification: • Temperature = 60ºC • Time = 3 hours • Ratio CaO/methanol = 1/39	(Kawashima et al., 2009)

3. Results and Discussion

3.1 Reaction kinetics of biodiesel production using commercial CaO catalyst

The kinetic analysis of biodiesel production reaction with commercial CaO catalyst using data from Kawashima et al (2009) and kinetic model from Sayed et al (2023) was shown in Figure 2. Based on the linearization plotting of X vs t, the reaction constant was obtained at 0.0012 min^{-1}. In this study, variations in commercial CaO catalysts recycling were carried out in biodiesel production simulations using three schemes, so that the reaction constant of each scheme was needed to be calculated using comparison formula according to equation (1). Meanwhile, the conversion value of the transesterification reaction was obtained from the SuperPro Designer 10 simulation.

The comparison of reaction constant in each scheme can be seen in Table 4. Based on Table 4, it was known that conversion will decrease along with the increasing number of recycled commercial CaO catalysts used, although the decrease in conversion value that occurred was not too large. This is in accordance with the research of Prasertsit et al (2014) which stated that the conversion value will decrease by ± 5% using commercial recycled CaO catalysts.

Deactivation of the CaO catalyst during the transesterification reaction can be caused by several processes such as leaching of active sites, surface poisoning, and structural collapse. Leaching in CaO can be caused by the reaction between CaO and glycerol to form calcium diglyceroxide. In addition, the leaching process can also caused by the reaction between Ca ions and free fatty acids which produces calcium soaps.

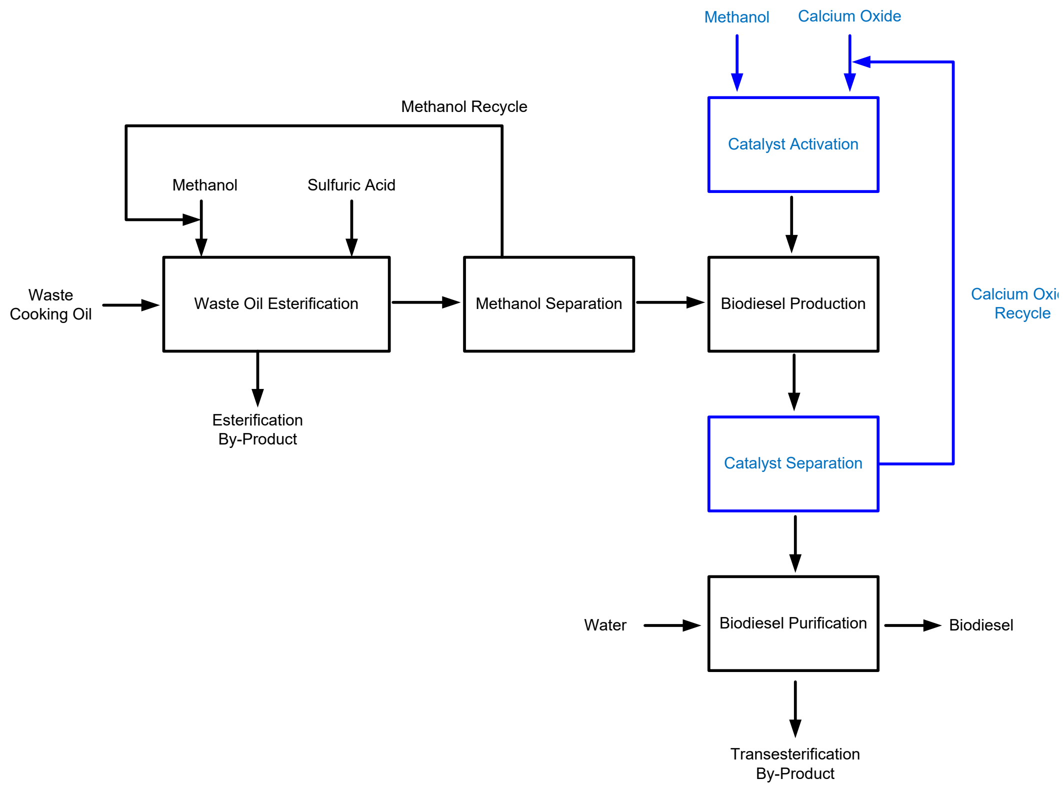

Figure 1. Block flow diagram of biodiesel production from waste cooking oil using CaO catalyst

Calcium soaps can form colloidal solutions that interfere CaO catalyst performance. In the case of surface poisoning, CaO can be deactivated by carbon dioxide CO_2 and moisture (H_2O). The reaction between CaO with CO_2 and H_2O produces calcium carbonate and calcium hydroxide. Meanwhile, in the case of structural collapse, the mesoporous structure of the CaO catalyst can be damaged due to heat from the moderate transesterification reaction temperature (Oueda et al., 2017).

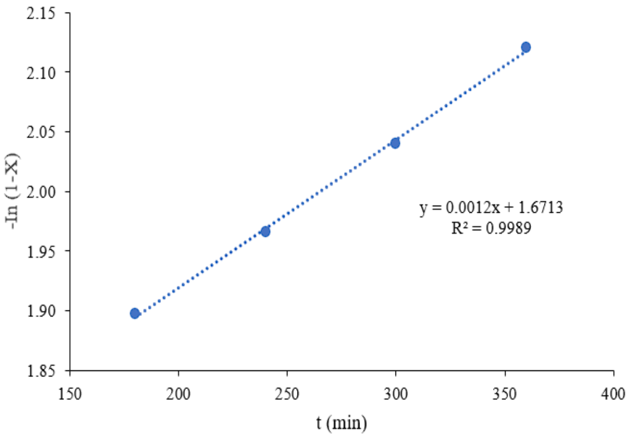

Figure 2. Linearization of X vs t in biodiesel production using commercial CaO catalyst

3.2 Economic evaluation of biodiesel production using commercial CaO catalyst

The economic evaluation of biodiesel production using commercial CaO catalyst was conducted using SuperPro Designer 10 simulation. Biodiesel production using a commercial CaO catalyst without recycling was shown in Figure 3, and biodiesel production using commercial CaO catalyst with recycling was shown in Figure 4.

Based on Figure 3, the biodiesel production process begins with the esterification of waste cooking oil using sulfuric acid in the esterification reactor (R-101) according to the reaction conditions based on Jansri et al (Jansri et al., 2011). The esterified waste cooking oil was then decanted to separate the by-products of esterification reaction and esterified waste cooking oil. Waste cooking oil then enters distillation column (C-101) to separate the methanol which can be used to activate the CaO catalyst in the mixer (MX-102). Meanwhile, excess methanol can be recycled back to the mixer (MX-101). The activation process of commercial CaO catalyst in MX-102 was based on Kawashima et al (2009). The commercial CaO catalyst activated by methanol and waste cooking oil then enter the transesterification reactor (R-102) to produce biodiesel. The operating conditions of transesterification reactor (R-102) were according to Kawashima et al (2009). The product from transesterification reactor (R-102) then passes through a plate and frame filter (PFF-101) to separate the spent solid CaO catalyst from the liquid product. The liquid product then undergoes a series of separation processes such as methanol separation, decantation, and water washing to purify the biodiesel. Modification of commercial CaO catalyst recycling process in Figure 3 can be seen in Figure 4. The commercial CaO catalyst recycling method in Figure 4 was carried out by directly using the commercial CaO catalyst after the transesterification reaction without any catalyst activation process according to Prasertsit et al (2014).

Table 4. Comparison of reaction constants

Scheme	Reaction constants (min-1)	Conversion (%)
Scheme 1	0.00120	92.84
Scheme 2	0.00109	92.23
Scheme 3	0.00103	91.78

Total operating cost calculation and economic evaluation of biodiesel production with commercial CaO catalyst can be seen in Table 5 and Table 6. Waste treatment cost was based on Rahman et al (2025). Based on Table 5, it showed that the amount of CaO waste in schemes 2 and 3 decreased significantly which caused the cost of CaO catalyst waste treatment to be very low compared to scheme 1. However, wastewater and reaction by-products showed a fairly large waste and high-cost treatment compared to CaO catalyst waste treatment. The total cost of waste treatment showed scheme 1 produced the smallest waste treatment cost compared to other schemes. Based on Table 6, the Net Present Value (NPV) of scheme 1 is more profitable compared to schemes 2 and 3. Based on Table 6, the Net Present Value (NPV) of scheme 1 is more profitable compared to schemes 2 and 3. This can be caused by the repeated use of commercial CaO catalyst in schemes 2 and 3 requiring additional equipment as shown in Figure 4. Reusing commercial CaO catalyst requires additional equipment such as flow splitters, bucket elevators, and mixers which result in increased investment and operational costs. In addition, the repeated use of commercial CaO catalysts caused a reduction in the conversion reaction of waste cooking oil into biodiesel which results in lower total revenue.

Although scheme 1 was more profitable than schemes 2 and 3, the advantage of schemes 2 and 3 was the low consumption of commercial CaO catalyst. This was a reason to continue using schemes 2 and 3, as they do not rely on the continuous use of fresh commercial CaO catalyst. Furthermore, the continuous generation of commercial CaO catalyst waste at the end of the process in scheme 1 presents a challenge that requires further management.

4. Conclusions

This study investigated the simulation of biodiesel production from waste cooking oil using commercial CaO catalysts which evaluated the reaction kinetics and techno-economics of plant scale production. Three biodiesel production schemes using commercial CaO catalysts were analyzed such as scheme 1 without CaO catalyst recycling, scheme 2 with 3x commercial CaO catalyst recycling, and scheme 3 with 10x commercial CaO catalyst recycling.

ISSN: 1410-394X
e-ISSN: 2460-8203

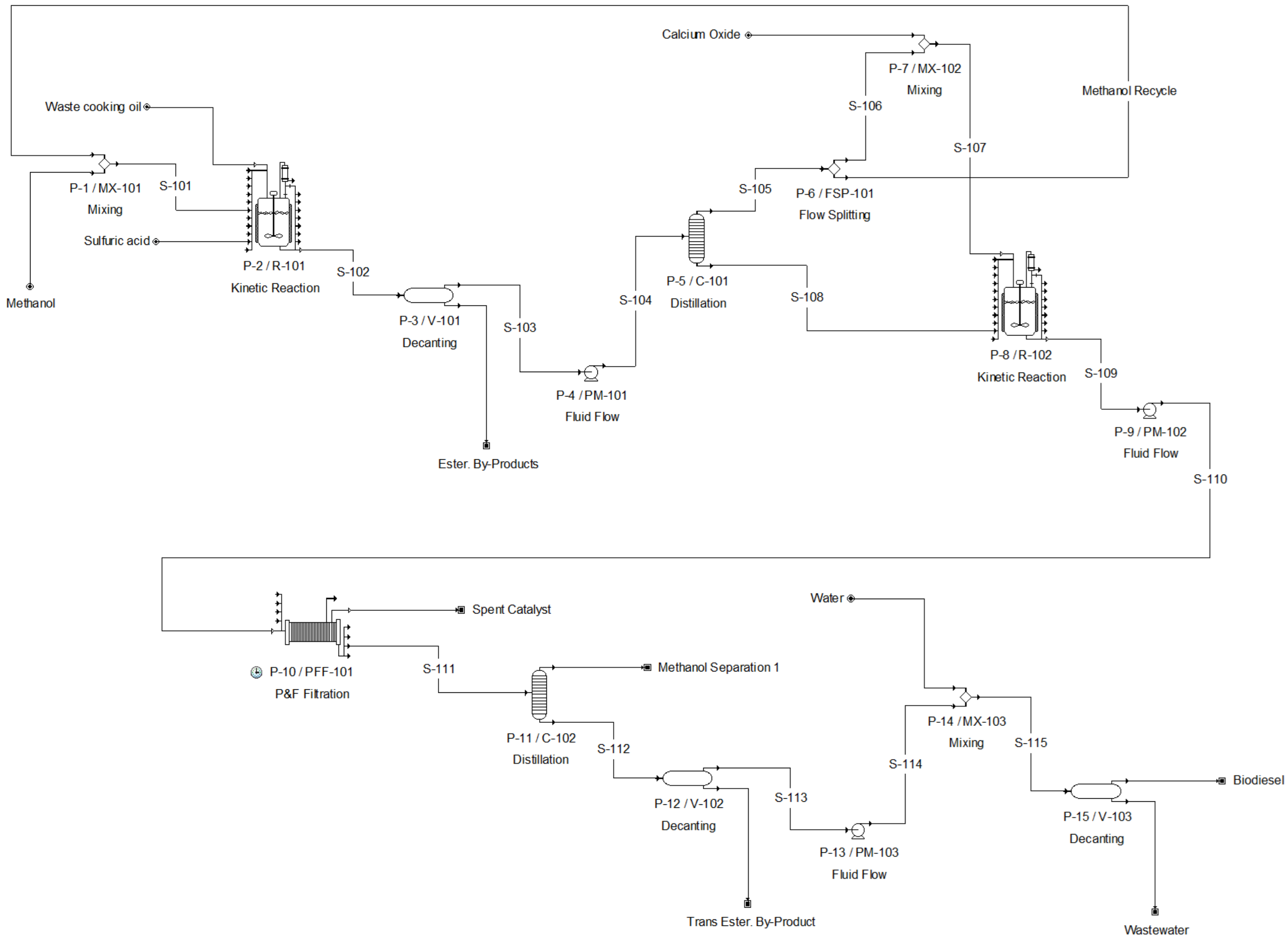

Figure 3. Biodiesel production using commercial CaO catalyst without recycling

Citation: Panjaitan, J. R. H. (2025). Simulation of Biodiesel Production from Waste Cooking Oil Using Methanol-Activated CaO Recycling Catalyst: Kinetic and Techno-Economic Evaluation . *Eksergi*, *23*(1), 23–31

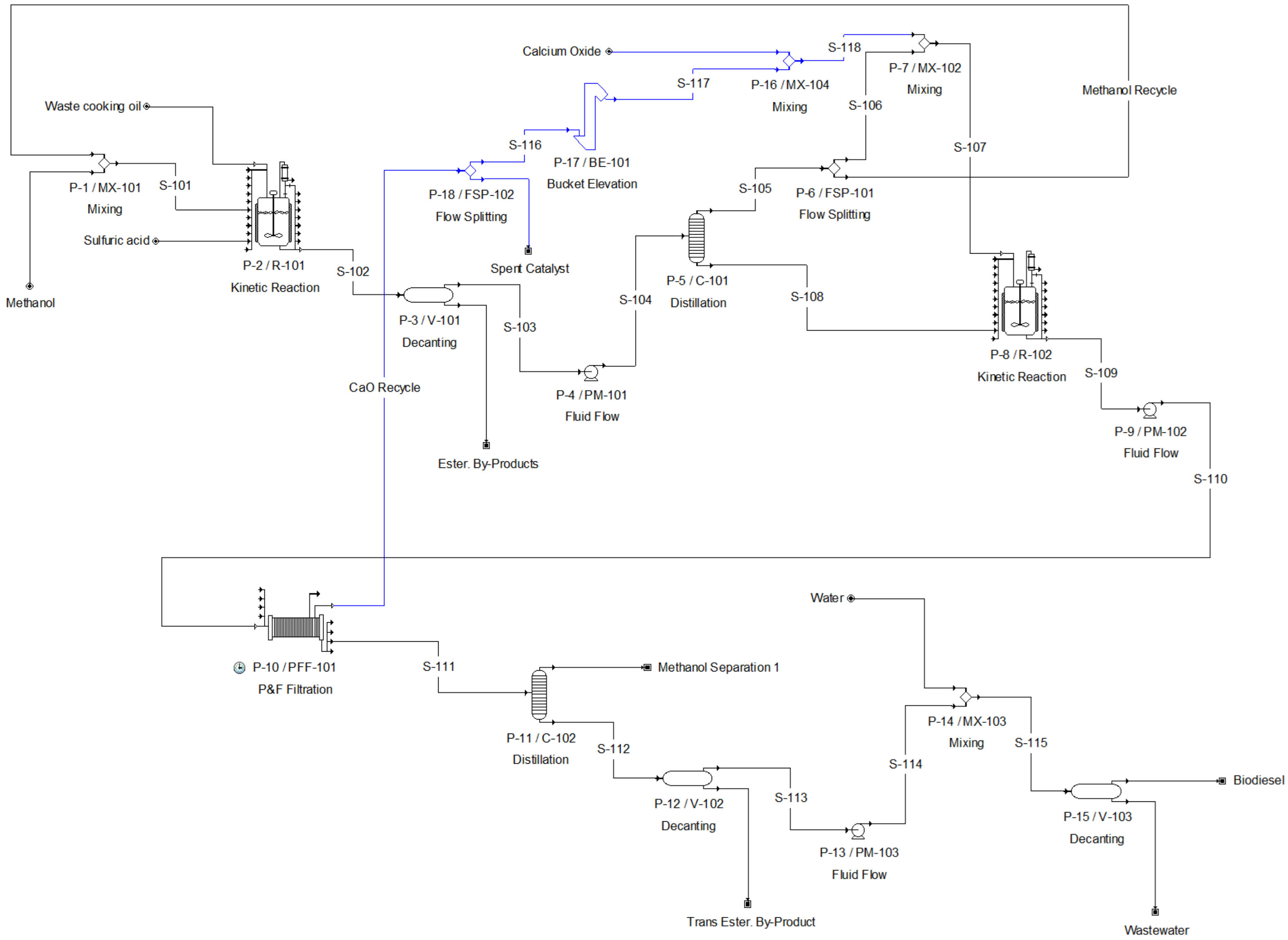

Figure 4. Biodiesel production using commercial CaO catalyst with recycling

ISSN: 1410-394X
e-ISSN: 2460-8203

Table 5. Total operating cost calculation

Operating cost parameters	Scheme 1		Scheme 2		Scheme 3	
Raw materials (US$/year)	61,428		58,976		58,118	
Labor-dependent (US$/year)	4,151,000		4,229,000			
Facility-dependent and utilities (US$/year)	3,114,000		3,148,000			
Laboratory/QC (US$/year)	623,000		634,000			
Waste treatment calculation	Annual amount (ton)	Annual cost (ton)	Annual amount (ton)	Annual cost (ton)	Annual amount (ton)	Annual cost (ton)
Waste CaO	30.65	633	10.21	211	3.06	63
Wastewater	3,771	96,123	3,863	98,468	3,930	100,176
Transesterification by-product	3,470	198,553	3,452	197,523	3,436	196,608
Esterification by-product	844	48,294	844	48,294	844	48,294
Waste treatment (US$/year)	343,603		344,496		345,141	
Total operating cost	8,293,031		8,414,472		8,414,258	

Table 6. Economic evaluation of biodiesel production with commercial CaO catalyst

Economic Parameters	Scheme 1	Scheme 2	Scheme 3
Total CaO catalyst requirement (ton/year)	30.65	10.21	3.06
Total cost of CaO catalyst (US$/year)	3,678	1,226	368
Total equipment cost (US$)	2,513,000	2,545,000	
Total capital investment (US$)	3,608,380	3,655,700	
Total operating cost (US$/year)	8,293,031	8,414,472	8,414,258
Total revenue (US$/year)	14,764,351	14,708,669	14,657,525
Net Present Value (NPV) (US$)	32,314,400	31,173,310	30,869,129

The results indicated that the commercial CaO catalyst recycling process significantly affects the conversion of waste cooking oil to biodiesel. The higher amount of catalyst recycling produce lower reaction conversion. The highest conversion in this study was 92.84% from scheme 1. Based on techno-economic comparisons, scheme 1 was the most profitable compared to the other schemes with a net present value of US$34,652,659. Schemes 2 and 3 have lower net present values than scheme 1 due to the increased in total capital investment and operational costs for recycling commercial CaO. Meanwhile, based on CaO catalyst requirements, scheme 3 was the lowest CaO catalyst requirement at 3.06 tons/year.

Acknowledgements

The author would like to thank Kementerian Pendidikan Tinggi, Sains, dan Teknologi Republik Indonesia for funding in "Program Penelitian dan Pengabdian kepada Masyarakat Tahun Anggaran 2025 Skema Penelitian Dasar Dosen Pemula" under contract number 1483cb/IT9.2.1/PT.01.03/2025.

Statement

The authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Jabosar Ronggur Hamonangan Panjaitan: Writing – original draft, review & editing, Visualization, Validation, Resources, Investigation, Formal analysis, Conceptualization

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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