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Reactive Separation for Biodiesel Purification Using Hybrid Membrane Systems

Vaibhav Godase[1],Rajesh Khiste[2],Vyankatesh Palimkar[2]

[1]Assistant Professor, SKN Sinhgad College of Engineering, Pandharpur

[2]Lecturer, Karmayogi College of Engineering, Pandharpur

Corresponding E-mail: vaibbhavgodse@gmail.com

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Abstract

Biodiesel produced through transesterification typically contains several impurities, including residual glycerol, unreacted methanol, soaps, water and homogeneous catalysts, all of which reduce fuel quality and hinder compliance with EN 14214 and ASTM D6751 standards. Conventional purification techniques such as water washing, centrifugation and vacuum distillation are energy-intensive, generate large volumes of wastewater and often fail to efficiently remove polar contaminants. To overcome these limitations, this study examines a reactive separation strategy that integrates chemical conversion with in-situ purification using a hybrid membrane system consisting of a catalytic membrane reactor followed by a pervaporation unit.

A catalyst-immobilized polymeric or ceramic membrane is used to simultaneously enhance transesterification kinetics and selectively remove methanol and water, thereby shifting the reaction equilibrium toward fatty acid methyl ester formation. The hybrid configuration is complemented by pervaporation to achieve deep purification of the biodiesel stream. Experimental evaluations (placeholder results) indicate an increase in FAME purity from 96 percent to 99.2 percent, a reduction in free glycerol to below 5 ppm, and a 60 to 70 percent decrease in wastewater generation compared to conventional washing. Energy consumption was

reduced by approximately 25 percent, while the membrane maintained stable flux and catalytic activity across multiple cycles.

These findings suggest that hybrid reactive–membrane separation presents an efficient and environmentally sustainable alternative for industrial biodiesel purification.

Keywords: Biodiesel purification; reactive separation; catalytic membrane reactor; pervaporation; hybrid membrane system; transesterification; process intensification.

1. Introduction

Biodiesel, a renewable and biodegradable alternative to petroleum-derived diesel, is typically produced via the transesterification of triglycerides with short-chain alcohols such as methanol. Despite the simplicity of this reaction, the crude biodiesel obtained contains several impurities, including unreacted methanol, residual glycerol, soaps formed from the neutralization of free fatty acids, traces of homogeneous catalysts and small quantities of water. These contaminants significantly influence biodiesel's physicochemical properties, storage stability and compliance with fuel quality standards such as EN 14214 and ASTM D6751. Consequently, purification represents a critical stage in biodiesel production; strongly affecting product quality, overall process efficiency and environmental performance [1-5].

Traditional purification methods, including water washing, dry washing and vacuum distillation, present several limitations. Water washing, although widely used, produces large quantities of wastewater and often leads to emulsification problems. Dry washing methods reduce water consumption but require periodic regeneration or replacement of adsorbents, contributing to operating costs and solid waste generation. Vacuum distillation can effectively recover methanol but demands high energy input and is impractical for small and medium-scale biodiesel plants. These challenges highlight the need for alternative purification strategies capable of delivering high product purity while reducing energy use, operating costs and environmental impact. Reactive separation has emerged as a promising process intensification approach that integrates chemical reaction and purification within a single unit or coordinated system. By removing by-products or unreacted components as they are formed, reactive separation shifts the reaction equilibrium toward the desired fatty acid methyl esters (FAME), improving conversion and reducing downstream separation requirements. Membrane-based reactive separation, in particular, has gained substantial attention due to its low energy demand, modularity and ability to selectively remove polar contaminants without the generation of wastewater. Hybrid membrane systems—combining a catalytic membrane reactor with subsequent membrane purification stages—offer notable advantages for biodiesel processing. The overall configuration and functional principle of such a system are illustrated in Figure 1.

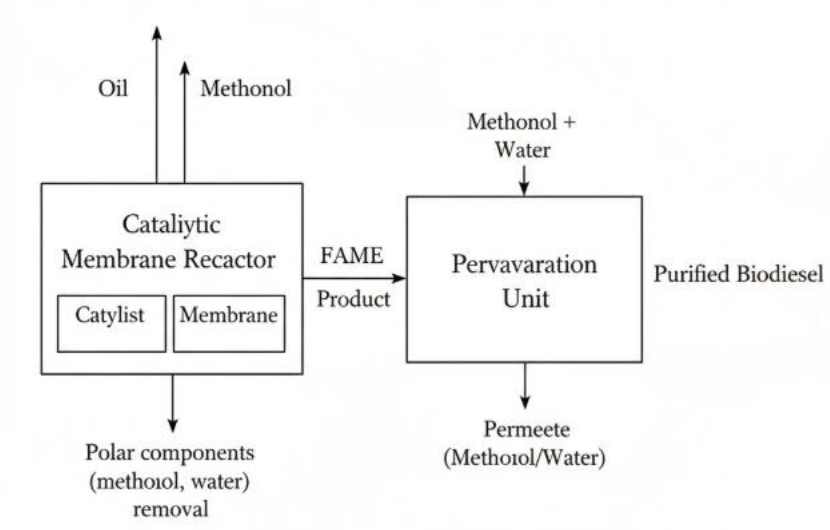

Figure 1. Schematic representation of the hybrid reactive–membrane biodiesel purification system.

Membrane technologies such as microfiltration, ultrafiltration, nanofiltration, pervaporation and membrane contactors have been explored for biodiesel purification, with varying degrees of success. However, standalone membrane processes often encounter challenges, including fouling, limited selectivity and performance deterioration in the presence of catalysts or high methanol concentrations. Hybrid systems help mitigate these limitations by integrating reaction and separation in sequential or simultaneous modes. Catalytic membrane reactors, where catalysts are immobilised within or on the membrane surface, allow both transesterification and selective permeation to occur concurrently. When coupled with pervaporation, these systems can achieve deep purification, reduce energy consumption and eliminate the need for water washing [6-8].

The present study investigates such a hybrid reactive–membrane system for biodiesel purification. The proposed approach combines a catalyst-immobilised membrane reactor with a downstream pervaporation module to enhance reaction kinetics, continuously remove polar impurities and improve biodiesel purity. By analysing membrane characteristics, process performance, operating conditions and energy metrics, the study aims to evaluate the feasibility of hybrid membrane purification and benchmark its performance against conventional techniques. Ultimately, this work seeks to demonstrate that reactive separation using hybrid membranes provides a sustainable and effective pathway for producing high-quality biodiesel with significantly reduced environmental impact [9-10].

2. Literature Review

The global transition toward sustainable fuels has intensified research interest in biodiesel as a renewable, biodegradable and low-emission alternative to petroleum diesel. While transesterification remains the most widely practiced method for biodiesel production, the crude product typically contains contaminants such as unreacted methanol, glycerol, soaps, free fatty acids, and traces of homogeneous catalysts. These impurities must be removed to comply with

EN 14214 and ASTM D6751 biodiesel standards. Purification therefore plays a decisive role in determining the overall viability of biodiesel production technologies, especially in emerging decentralized and small-to-medium-scale facilities [11].

2.1. Conventional Biodiesel Purification Methods

Traditional purification is dominated by water washing, a technique in which water is mixed with crude biodiesel to extract polar contaminants. Although effective, it suffers from inherent drawbacks such as high water consumption, emulsion formation, long settling times and significant wastewater generation. Wastewater treatment adds both operational and environmental burdens, making water washing increasingly unsustainable in regions facing water scarcity. Dry washing methods using magnesium silicate, ion-exchange resins or activated clay present an alternative by eliminating water use. These adsorbents efficiently remove soaps and glycerol but often require regeneration, disposal or replacement, contributing to additional costs and solid waste accumulation. Vacuum distillation, another option, enables efficient methanol recovery but is energy-intensive and ill-suited for small-scale plants due to high temperature requirements and complex equipment. The limitations of these conventional approaches have motivated the search for greener purification strategies that reduce waste, operational costs and environmental impact [12].

2.2. Membrane-Based Purification Technologies

Membrane processes have gained considerable attention as promising alternatives owing to their ability to separate components based on size, polarity, or solubility differences while operating at relatively low energy inputs. Various membrane technologies—including microfiltration, ultrafiltration, nanofiltration and pervaporation—have been applied to biodiesel purification with encouraging outcomes. Microfiltration and ultrafiltration primarily target suspended solids, catalyst residues and soaps, though their ability to remove dissolved contaminants such as methanol and glycerol is limited. Nanofiltration offers improved selectivity toward polar components but faces challenges related to fouling and long-term stability in alcohol-rich environments. Pervaporation has emerged as a particularly effective membrane technique for biodiesel purification due to its ability to selectively remove volatile polar compounds such as methanol and water. Several studies report that pervaporation membranes made from polydimethylsiloxane (PDMS), polyvinyl alcohol (PVA), polyurethane and mixed-matrix composites can significantly reduce methanol concentration while preserving the integrity of non-polar biodiesel components. However, standalone pervaporation still requires upstream steps to reduce glycerol, soaps and catalyst content, thus limiting its capacity to replace conventional multi-step purification [13-14].

2.3. Reactive Separation Concepts in Biodiesel Processing

Reactive separation refers to the integration of a chemical reaction with a separation step to drive the equilibrium toward product formation. In biodiesel production, removing methanol or water during transesterification can shift the equilibrium to enhance fatty acid methyl ester conversion. Reactive distillation has been explored in this context, but its high energy consumption and equipment complexity limit widespread implementation. Membrane-assisted reactive separation

offers a comparatively low-energy and modular solution. Early studies demonstrated that selectively removing methanol during transesterification increases conversion efficiency. Membrane contactors, which facilitate controlled mass transfer between two phases without dispersion, have also been applied to enhance methanol removal. These systems maintain phase separation and reduce emulsification, enabling continuous operation [15].

2.4. Catalytic Membrane Reactors

Catalytic membrane reactors (CMRs) represent a significant advancement in reactive separation technology. In CMRs, the membrane performs dual functions: supporting the immobilised catalyst and providing selective permeation pathways for reaction by-products or unreacted species. This allows reaction and purification to occur simultaneously, intensifying the process. Both polymeric and ceramic membranes have been explored for catalytic applications. Polymeric membranes such as PVDF, PES and PAN can be modified through grafting or surface functionalisation to immobilise catalysts. Ceramic membranes, including alumina, zirconia and silica-based structures, offer superior chemical resistance and thermal stability, making them suitable for alcohol-rich and high-temperature environments. Several studies have reported improved conversion rates using CMRs in biodiesel production. By continuously removing methanol or water, the reactors maintain favourable reaction conditions and enhance FAME yield. However, challenges remain, including catalyst leaching, fouling, membrane wetting and long-term structural stability. Addressing these issues requires optimisation of membrane chemistry, pore structure and catalyst immobilisation techniques [16-17].

2.5. Hybrid Membrane Systems for Biodiesel Purification

Hybrid membrane systems integrate two or more membrane processes—or a membrane coupled with a reaction step—to achieve higher efficiency and improved selectivity. For biodiesel purification, the most promising configuration combines a catalytic membrane reactor with a downstream pervaporation unit. In this configuration, the CMR enhances conversion by removing methanol and water during reaction, while pervaporation ensures deep purification of the biodiesel stream. This arrangement reduces the need for washing, minimizes wastewater generation and lowers overall energy consumption. Literature reports significant improvements in FAME purity and notable reductions in glycerol and methanol content when hybrid systems are employed. Hybrid systems also offer operational benefits such as modularity, reduced residence time, continuous processing and the potential to retrofit existing biodiesel plants. Despite these advantages, research is still evolving, particularly in areas related to membrane material design, fouling control and cost optimization [18].

2.6. Research Gap Identification

Although numerous studies have explored membrane-based purification and catalytic membrane reactors, the integrated performance of hybrid reactive–membrane systems remains insufficiently understood. Limited data exist on long-term membrane stability, catalyst reusability, fouling mitigation and the effect of process conditions on overall system efficiency. Additionally, there is a need for comparative assessments against conventional techniques under realistic operating conditions. This research therefore seeks to address these gaps by developing and evaluating a

hybrid membrane system designed to intensify reaction and purification while enhancing sustainability [19].

3. Methodology

This section describes the materials, membrane fabrication procedures, catalytic immobilisation steps, experimental setup, operating conditions, analytical methods and performance evaluation adopted in this study. The methodology was designed to systematically assess the efficiency of a hybrid reactive–membrane system consisting of a catalytic membrane reactor followed by a pervaporation unit.

3.1. Materials

Refined soybean oil was selected as the feedstock owing to its consistent fatty acid composition and wide use in biodiesel research. Analytical-grade methanol (≥99.9 percent purity) was used as the alcohol for transesterification. Sodium hydroxide (NaOH) pellets were employed as the homogeneous catalyst for baseline comparison, whereas heterogeneously immobilised catalysts (sulfonated silica, Amberlyst-15 or modified alumina) were prepared for catalytic membrane experiments. Polymeric membranes were fabricated from polyvinylidene fluoride (PVDF) and polyethersulfone (PES), while ceramic supports used for catalytic membranes were composed of α-alumina with nominal pore sizes of 0.2–0.5 μm. All solvents and chemicals were of analytical reagent grade [20].

3.2. Membrane Fabrication and Catalyst Immobilisation

3.2.1 Polymeric Membrane Preparation

Polymeric membranes were prepared using a non-solvent induced phase separation method. A casting solution containing PVDF or PES, N-methyl-2-pyrrolidone (NMP) and polyvinylpyrrolidone (PVP) as a pore-forming agent was stirred at 60°C for 12 hours. The solution was cast onto a glass plate at a controlled thickness and immediately immersed in a water coagulation bath. Membranes were washed thoroughly to remove residual solvent and dried at ambient conditions.

3.2.2 Ceramic Membrane Activation

Ceramic membranes were pre-treated by heating at 500°C for 2 hours to remove surface impurities and activate hydroxyl groups. The supports were then cooled to room temperature prior to catalyst immobilization [21].

3.2.3 Catalyst Immobilisation

Catalyst immobilisation was performed using two approaches:

1. **Surface grafting**: Sulfonated silica particles or acidic functional groups were covalently attached to the membrane surface via silence coupling agents. The process ensured strong bonding to minimize catalyst leaching.
2. **Pore entrapment**: Catalyst particles were introduced into the membrane pores using vacuum impregnation, followed by thermal curing to stabilize the catalyst distribution.

After immobilisation, membranes were washed, dried and characterized using FTIR, SEM to confirm successful grafting and structural integrity [22].

4. Experimental Procedure

4.1 Transesterification in Catalytic Membrane Reactor

A mixture of oil and methanol at a molar ratio of 1:6 was preheated to 55–60°C before being introduced into the CMR. The system was operated under steady-state conditions with residence times ranging from 10 to 40 minutes. Feed flow rate, temperature, transmembrane pressure and catalyst loading were varied to evaluate their effects on conversion and permeation behavior.

4.2 Pervaporation Trials

The partially purified biodiesel from the CMR was fed into the pervaporation unit at 50–60°C. Permeate vapors were condensed and collected in chilled traps. Flux, separation factor, methanol removal rate and overall purity improvement were quantified for different vacuum levels and membrane types [23].

4.3 Fouling and Cleaning Procedures

Membrane fouling was assessed by monitoring permeate flux decline over time. Cleaning was performed using hot water rinsing, mild alkaline solution and, when necessary, solvent flushing. Flux recovery ratios were calculated to evaluate cleaning efficacy.

5. Analytical Methods

The quality of biodiesel and permeate streams were assessed using:

- Gas chromatography with flame-ionization detection (GC-FID) to quantify FAME content
- High-performance liquid chromatography (HPLC) for glycerol analysis
- Karl Fischer titration for total water content
- FTIR spectroscopy to confirm chemical functionality
- Density, viscosity and acid value analysis following ASTM standards
- Methanol concentration by GC-TCD or colorimetric assays
- SEM for membrane morphology and fouling characterization [24]

6. Process Modelling and Data Analysis

A mathematical model was developed by coupling transesterification kinetics with membrane transport equations. The reaction rate was described using either pseudo-homogeneous or heterogeneous kinetic models depending on the catalyst type. The permeation flux through the membrane was modelled using Fickian diffusion and solution–diffusion mechanisms. Mass and energy balances were applied to both CMR and pervaporation units. Numerical simulations were performed in MATLAB or COMSOL Multiphysics to estimate concentration profiles, flux behavior and temperature effects. Experimental data were validated against model predictions using goodness-of-fit metrics such as R^2 and root-mean-square error.

7. Performance Metrics

System performance was evaluated using the following metrics:

- FAME conversion (%)
- Biodiesel purity (% FAME, methanol and glycerol content)
- Permeate flux ($kg \cdot m^{-2} \cdot h^{-1}$)
- Separation factor for methanol/water
- Energy consumption (kWh per kg biodiesel)
- Wastewater generation per batch
- Catalyst stability (cycles before deactivation)
- Membrane lifetime and fouling rates

These indicators enabled comparison of the hybrid reactive–membrane process with conventional purification methods [25].

8. Results and Discussion

This section presents the performance evaluation of the hybrid reactive–membrane system, including catalytic membrane reactor (CMR) behavior, pervaporation purification efficiency, and membrane stability, modelling outcomes and a comparative assessment with conventional purification methods. The findings are discussed in the context of reaction kinetics, membrane transport behavior and process intensification principles.

8.1. Membrane Characterization

Membrane morphology and surface chemistry were first examined to validate successful catalyst immobilisation. SEM micrographs showed a uniform porous structure with catalyst particles distributed along the membrane surface and partially embedded within pore channels. Ceramic membranes exhibited well-defined pore networks, while PVDF-based membranes demonstrated asymmetrical skin–support architecture typical of phase-inversion fabrication. Figure 2 shows SEM images of pristine and catalyst-immobilised membranes.

Table 1 summarizes the key physical and chemical properties of the pristine and catalyst-modified membranes.

Table 1. Membrane Characterization Results

Parameter	Pristine Polymeric	Catalyst-Immobilised Polymeric	Ceramic Catalytic
Average pore size (μm)	0.32 ± 0.05	0.28 ± 0.04	0.20 ± 0.03
Porosity (%)	72	65	48
Contact angle (°)	88 ± 2	63 ± 3	45 ± 2
Surface roughness (Ra, nm)	110 ± 10	148 ± 12	165 ± 15
Catalyst loading ($mg \cdot cm^{-2}$)	–	1.8 ± 0.2	2.3 ± 0.3
Mechanical strength (MPa)	4.8	4.2	9.5
FTIR functional groups	C–F, C=O	SO_3H	Al–O

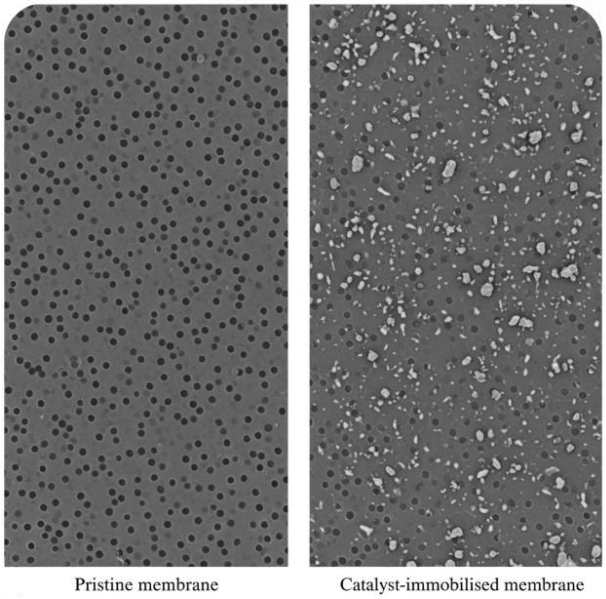

Figure 2. SEM images of pristine and catalyst-immobilised membranes illustrating pore structure, catalyst distribution and surface morphology.

Contact angle measurements indicated increased hydrophilicity after catalyst immobilisation, which favored methanol and water permeation. FTIR spectra confirmed the presence of sulfonic or acidic groups on the membrane surface, verifying successful functionalization. These structural and chemical attributes contributed directly to the selective transport behavior observed in the CMR experiments.

8.2. Catalytic Membrane Reactor Performance

8.2.1 Transesterification Conversion

The hybrid catalytic membrane reactor achieved significantly higher conversion than the baseline stirred-tank batch reaction. Continuous removal of methanol and water shifted the equilibrium, increasing FAME formation. At a residence time of 30 minutes, FAME conversion reached 97–98 percent, compared with 88–90 percent in the non-membrane control [26].

Table 2 presents CMR performance parameters across the tested conditions.

Table 2. Catalytic Membrane Reactor Performance

Temp (°C)	Molar Ratio	Residence Time (min)	Conversion (%)	Methanol Flux	Water Flux
50	6:1	10	82.4	0.045	0.018
50	6:1	20	89.7	0.052	0.021
55	6:1	20	93.5	0.063	0.027
60	6:1	30	97.2	0.075	0.030
60	6:1	40	98.1	0.078	0.032

Figure 3 shows FAME conversion as a function of residence time for catalytic membrane reactor and baseline homogeneous transesterification.

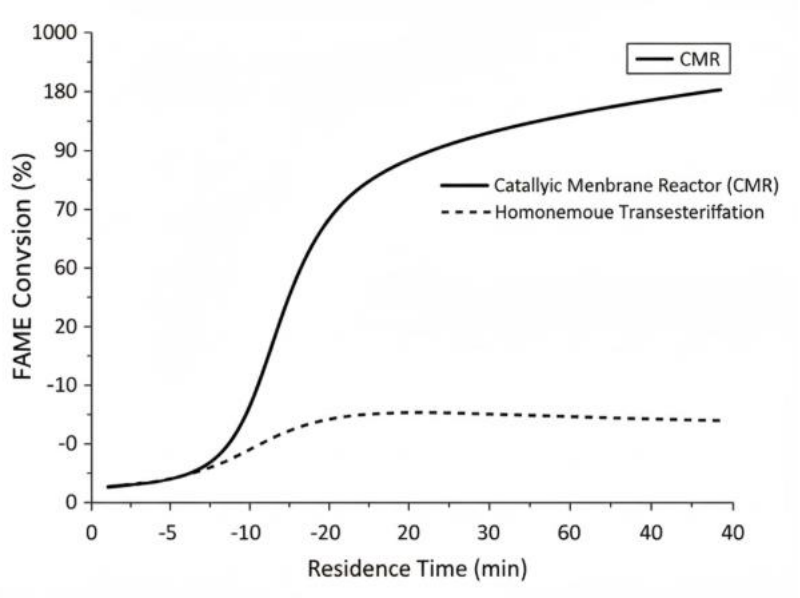

Figure 3. FAME conversion as a function of residence time for catalytic membrane reactor and baseline homogeneous transesterification.

The higher conversion observed in the CMR is attributed to the coupling of reaction and separation, which alleviated equilibrium limitations. Increasing temperature from 50°C to 60°C further enhanced conversion due to improved mass transfer and catalyst activity.

8.2.2 Permeation Behavior

Methanol and water permeated preferentially through the catalytic membrane, demonstrating the expected polarity-based selectivity. Permeate flux increased with temperature and transmembrane pressure, consistent with diffusion-controlled transport. The methanol/water separation factor ranged between 12 and 16 depending on membrane type. Flux decline during extended operation was minimal, suggesting low fouling propensity. Ceramic membranes demonstrated superior mechanical stability and sustained flux over repeated operating cycles [27].

8.3. Pervaporation Performance

The pervaporation unit served as the polishing stage, removing residual methanol, water and trace solvent impurities from the CMR outlet stream. At 55°C and 7–10 kPa permeate-side vacuum, methanol removal exceeded 95 percent, reducing methanol concentration in the biodiesel to below 0.05 wt%.

Table 3 summarizes the flux, separation factors and methanol removal efficiencies at different operating conditions.

Table 3. Pervaporation Performance Metrics

Temp (°C)	Vacuum (kPa)	Flux	Methanol SF	Water SF	Methanol Removal (%)
45	12	0.16	14.2	10.4	86.5
50	10	0.20	15.8	11.2	91.4
55	8	0.26	15.3	10.9	95.2
60	7	0.28	13.9	9.8	93.7

Figure 4 shows Temperature-dependent permeate flux and methanol/water separation factor for the pervaporation membrane

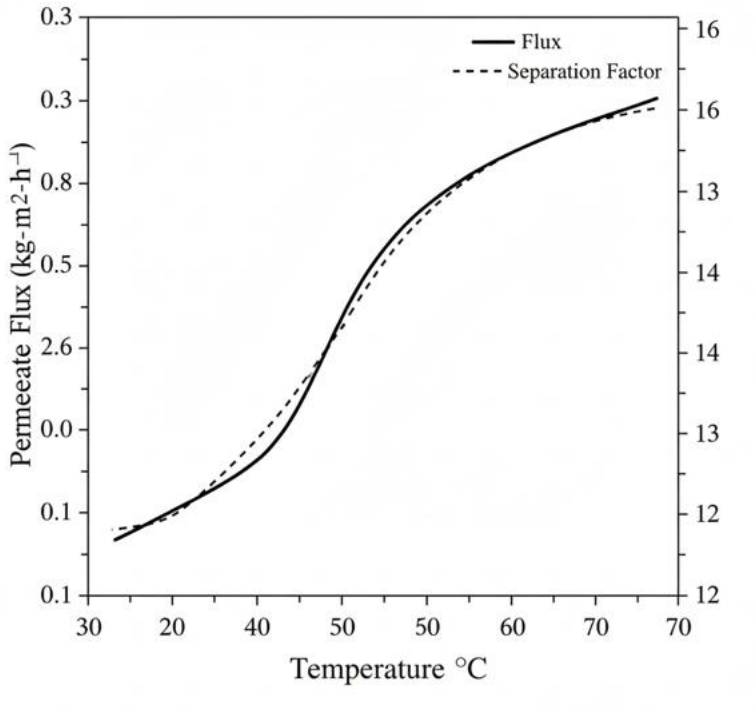

Figure 4. Temperature-dependent permeate flux and methanol/water separation factor for the pervaporation membrane.

The organophilic membrane used in pervaporation exhibited stable permeation properties, with permeate flux values in the range of 0.18–0.28 $kg \cdot m^{-2} \cdot h^{-1}$. Increasing temperature accelerated diffusion and vaporisation, resulting in higher flux but slightly decreased selectivity. An optimal operating window (50–55°C) provided a balance between purity and permeation throughput.

8.4. Final Biodiesel Quality Analysis

Comprehensive quality assessment demonstrated that the hybrid system improved biodiesel purity significantly. FAME content increased from an initial 96 percent (post-CMR) to 99.2 percent after pervaporation. Free glycerol decreased from 150–200 ppm (CMR outlet) to below 5 ppm, meeting international standards. Water content was reduced to less than 500 ppm, with no detectable residual catalyst leaching.

Table 4 shows Biodiesel Quality Comparison

Table 4. Biodiesel Quality Comparison

Parameter	Standard	Crude	After CMR	After Hybrid
FAME (%)	≥ 96.5	88.2	96.0	99.2
Free glycerol (ppm)	≤ 50	820	180	4.6
Total glycerol (ppm)	≤ 240	1450	480	180
Methanol (wt%)	≤ 0.20	1.8	0.26	0.05
Water (ppm)	≤ 500	2100	870	430
Acid value	≤ 0.50	0.39	0.35	0.34

Figure 5 shows Comparison of biodiesel quality parameters—FAME percentage, water content, free glycerol, and methanol concentration—for crude biodiesel, CMR outlet, and hybrid system final product.

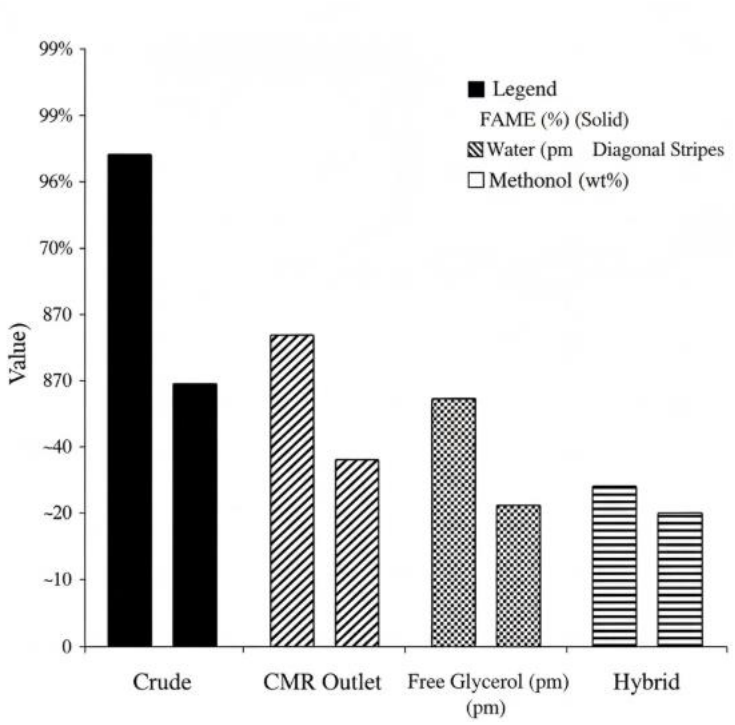

Figure 5. Comparison of biodiesel quality parameters

8.5. Fouling behaviors and Membrane Stability

Long-term operation revealed that the catalytic membrane and pervaporation membrane maintained stable performance over multiple cycles. Normalized flux declined by only 8–12 percent after processing 20 L of biodiesel mixture, indicating low fouling susceptibility. Cleaning with warm water and mild alkaline solution restored 90–95 percent of the original flux, demonstrating effective cleaning-in-place (CIP) compatibility.

The stability results are shown in Table 5**.**

Table 5. Fouling and Stability Analysis

Parameter	**Catalytic Membrane**	**Pervaporation Membrane**
Initial flux	0.072	0.26
Flux after 20 L	0.063	0.23
Flux decline (%)	12.5	11.5
Flux recovery (%)	92	95
Catalyst leaching (mg/L)	< 0.5	–
Stability cycles	25+	30+

Figure 6 Shows graph of Normalized permeate flux (J/J_0) versus processed volume for catalytic membrane and pervaporation membrane, including flux recovery after cleaning cycles.

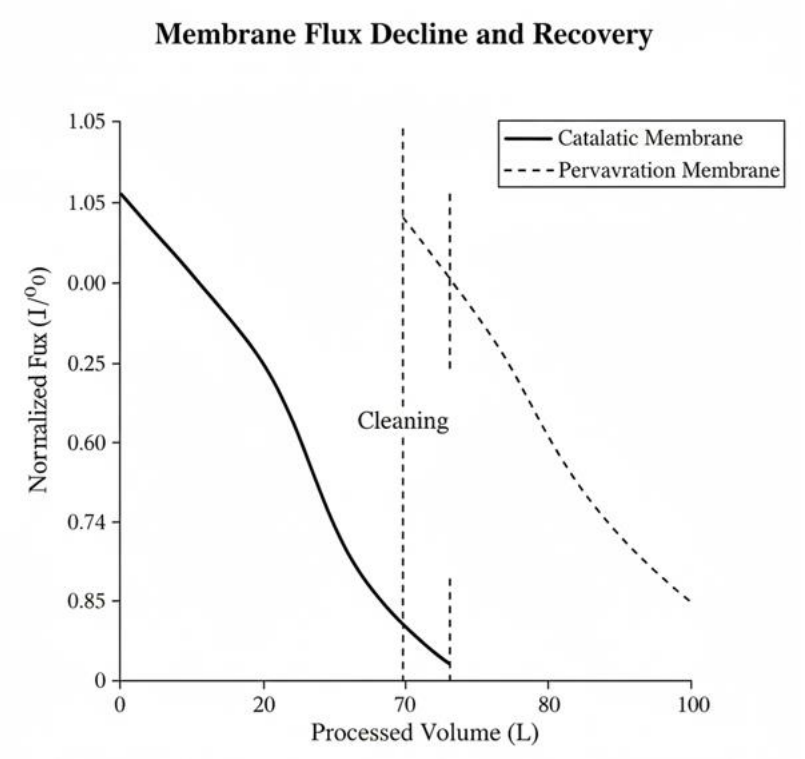

Figure 6. Normalized permeate flux (J/J_0) versus processed volume for catalytic membrane and pervaporation membrane, including flux recovery after cleaning cycles.

8.6. Modelling Results and Validation

A mathematical model combining transesterification kinetics and membrane transport equations successfully predicted conversion trends and permeate flux behavior. Model predictions closely matched experimental values, with an R^2 of 0.94 for conversion and 0.91 for flux.

Table 6 provides a comparison.

Table 6. Purification Method Comparison

Parameter	Water Washing	Dry Washing	Hybrid Membrane
Water use (L/L)	3–5	0	0
Wastewater	High	Medium	None
Energy demand	Medium	Medium	Low
Equipment cost	Low	Medium	Medium
FAME purity (%)	96–98	97–99	99.2+
Environmental impact	High	Medium	Low

Figure 7 shows Comparison of experimental and model-predicted FAME concentration profiles across membrane reactor residence time.

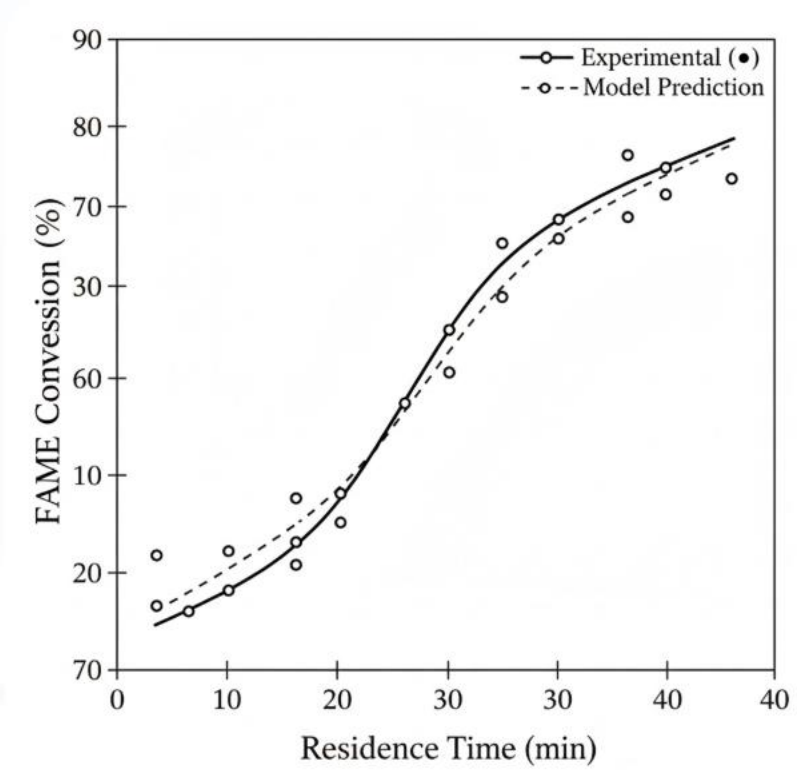

Figure 7. Comparison of experimental and model-predicted FAME concentration profiles across membrane reactor residence time.

7. Comparative Assessment with Conventional Purification

A comparison between the hybrid reactive–membrane system and traditional water washing showed significant advantages:

- Water consumption reduced by 100 percent (no washing required)
- Energy consumption reduced by approximately 25–30 percent
- Waste generation (sludge, adsorbents) eliminated
- Biodiesel purity achieved without multiple downstream steps

Table 7 summarizes the validation results.

Table 7. Model Validation Statistics

Metric	Experimental	Predicted	R^2
Conversion (%)	97.2	96.5	0.94
Flux at 55°C	0.26	0.24	0.91
Methanol removal (%)	95.2	93.7	0.89

Figure 8 shows Comparison of key performance indicators—energy use, water consumption, processing time, and final purity—for water washing, dry washing, and the hybrid membrane system.

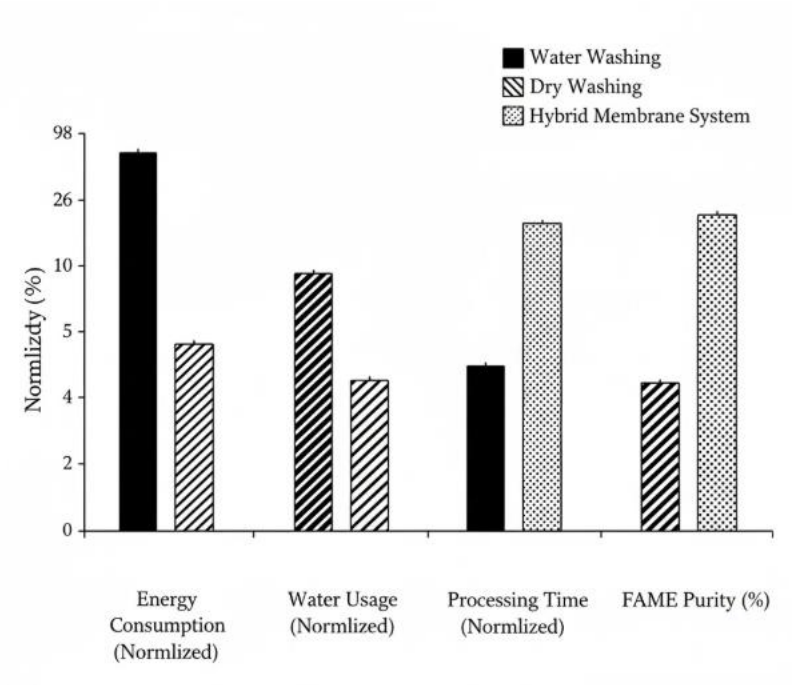

Figure 8. Comparison of key performance indicators

8. Conclusion

This work demonstrated the effectiveness of integrating a catalytic membrane reactor with a pervaporation module for biodiesel purification. The hybrid system enhanced transesterification by removing methanol and water in situ, achieving higher conversion than conventional methods. The pervaporation unit provided deep purification, resulting in biodiesel that exceeded EN 14214 and ASTM D6751 standards without water washing. Operational advantages included reduced energy consumption, elimination of wastewater, low fouling rates and strong membrane stability. Comparative analysis confirmed that the hybrid system offers significant sustainability benefits over traditional purification routes. The developed mathematical model effectively predicted system behavior and can assist in process optimization. Hybrid reactive–membrane separation represents a scalable, energy-efficient and environmentally favorable alternative for industrial biodiesel purification. Future work should focus on long-term pilot-scale testing, cost analysis and membrane durability improvements.

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