BIOKINETIC OPTIMIZATION OF ADSORPTION–MODIFIED BIOFILM REACTOR FOR POLLUTANT REMOVAL AND *n*-PROPANOL PRODUCTION FROM PALM OIL MILL EFFLUENT

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Bogor, July 2026

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RINGKASAN

FRANS EDVAN SETIAWAN. Optimasi Biokinetika Reaktor Biofilm Termodifikasi–Adsorpsi untuk Penyisihan Polutan dan Produksi *n*-Propanol dari Limbah Cair Kelapa Sawit. Dibimbing oleh ALLEN KURNIAWAN, dan SITI NIKMATIN.

n-Propanol merupakan bahan kimia bernilai tambah yang memiliki berbagai aplikasi industri, dan produksinya secara biologis dari limbah organik terbarukan mendukung pemulihan sumber daya dan ekonomi sirkular berbasis hayati. Limbah cair pabrik kelapa sawit (LCKS) merupakan sumber karbon terbarukan yang potensial untuk produksi *n*-propanol karena kandungan bahan organik biodegradable yang tinggi, tetapi beban pencemarnya yang tinggi memerlukan pengolahan yang efektif. Oleh karena itu, penelitian ini mengembangkan sistem terintegrasi yang terdiri atas adsorpsi tandan kosong kelapa sawit (TKKS) termodifikasi-*Anaerobic Rotating Biological Contactor* termodifikasi (AnRBC)-*Moving Bed Biofilm Reactor* (MBBR)-sedimentasi untuk meningkatkan penyisihan pencemar dan produksi *n*-propanol. Model terintegrasi *Anaerobic Digestion Model No. 1* (ADM1)-*Activated Sludge Model No. 1* (ASM1) juga dikembangkan untuk memprediksi kinerja reaktor dan mendukung optimasi proses. Percobaan skala laboratorium dilakukan pada HRT 1, 2, dan 3 hari. Serat TKKS termodifikasi yang disiapkan menggunakan metode sol–gel digunakan sebagai adsorben untuk menyisihkan O&G sebelum proses biologis. Kinerja reaktor dievaluasi berdasarkan pH, kebutuhan oksigen kimia total (TCOD), kebutuhan oksigen biokimia (BOD), total padatan tersuspensi (TSS), minyak dan lemak (O&G), dan nitrogen total (TN). Model ADM1 dan ASM1 yang dimodifikasi dikalibrasi untuk memprediksi produksi *n*-propanol dan penyisihan TCOD, kemudian dievaluasi menggunakan koefisien determinasi (R^2), koefisien korelasi Pearson, dan galat akar kuadrat rata-rata (RMSE). Sistem terintegrasi adsorpsi TKKS termodifikasi–AnRBC termodifikasi–MBBR mencapai efisiensi penyisihan rata-rata sebesar 95,38% BOD, 96,97% TCOD, 94,58% TSS, 93,35% O&G, dan 81,78% TN, dengan pH efluen sebesar 8,18 dan produksi *n*-propanol rata-rata sebesar 9,81 mg/L. Namun, hanya pH akhir memenuhi baku mutu. HRT berpengaruh signifikan terhadap penyisihan polutan dan produksi *n*-propanol. Peningkatan HRT meningkatkan kinerja pengolahan, dengan HRT 3 menghasilkan penyisihan tertinggi serta mempertahankan pH efluen 8,09. Meskipun konsentrasi *n*-propanol tertinggi (37,35 mg/L) diperoleh pada HRT 2, HRT 3 menghasilkan produksi *n*-propanol rata-rata yang lebih tinggi serta kinerja pengolahan keseluruhan yang terbaik. Model biokinetik terintegrasi ADM1–ASM1 berhasil dikembangkan untuk memprediksi produksi *n*-propanol pada AnRBC termodifikasi dan penyisihan TCOD pada MBBR. Parameter ADM1 optimum (K_S = 0.50 kgCOD/m^3, $k_{m,c3}$ = 60 /d, dan D_{prOH} = 8 × 10^{-10} m^2/s) menghasilkan kinerja yang baik (R^2 = 0.84, korelasi Pearson = 0.89, RMSE = 1.09 mg/L). Sementara itu, parameter ASM1 (Y_H = 0.75, $\mu_{H,max}$ = 0.10 /d, K_S = 25 mgCOD/L, dan D_S = 9.77 × 10^{-9} m^2/s) memberikan prediksi TCOD efluen yang sangat baik (R^2 = 0.91, korelasi Pearson = 0.95, RMSE = 466.88 mg/L).

Kata kunci: integrasi pengolahan air limbah; limbah cair kelapa sawit; *n*-propanol; pemodelan biokinetika; waktu tinggal hidraulik.

SUMMARY

FRANS EDVAN SETIAWAN. Biokinetic Optimization of Adsorption–Modified Biofilm Reactor for Pollutant Removal and *n*-Propanol Production from Palm Oil Mill Effluent. Supervised by ALLEN KURNIAWAN, and SITI NIKMATIN.

n-Propanol is a promising value-added chemical with broad industrial applications, while its biological production from renewable organic wastes offers an opportunity for resource recovery and circular bioeconomy development. Palm oil mill effluent (POME) is a promising renewable carbon source for *n*-propanol production due to its high biodegradable organic content, but its high pollutant load requires effective treatment. Therefore, this research developed an coupled system consisting of oil palm empty fruit bunch (OPEFB) adsorption-modified Anaerobic Rotating Biological Contactor (modified AnRBC)-Moving Bed Biofilm Reactor (MBBR)-sedimentation to enhance pollutant removal and *n*-propanol production. An integrated Anaerobic Digestion Model No. 1 (ADM1)–Activated Sludge Model No. 1 (ASM1) was also developed to predict reactor performance and support process optimization. Laboratory-scale experiments were conducted at HRT of 1, 2, and 3 d. Modified OPEFB fibers prepared using the sol–gel method were used as adsorbents for O&G removal before biological treatment. Reactor performance was evaluated based on pH, total chemical oxygen demand (TCOD), biochemical oxygen demand (BOD), total suspended solids (TSS), oil and Grease (O&G), total nitrogen (TN), and *n*-propanol production. The modified ADM1 and ASM1 models were calibrated to predict *n*-propanol production and TCOD removal, respectively, and evaluated using the coefficient of determination (R^2), Pearson correlation coefficient, and root mean square error (RMSE). The coupled modified OPEFB adsorption–modified AnRBC–MBBR system achieved average removal of 95.38% BOD, 96.97% TCOD, 94.58% TSS, 93.35% O&G, and 81.78% TN, with an effluent pH of 8.18 and average *n*-propanol production of 9.81 mg/L. However, only the final pH complied with the Indonesian wastewater discharge standard, indicating that additional polishing treatment is required before discharge. HRT significantly affected both pollutant removal and *n*-propanol production. Increasing HRT significantly improved treatment performance, with HRT 3 achieving the highest removal, while maintaining the effluent pH at 8.09. Although the highest *n*-propanol concentration (37.35 mg/L) occurred at HRT 2, HRT 3 achieved a higher average production and the best overall treatment performance. The integrated ADM1–ASM1 biokinetic model was successfully developed to predict *n*-propanol production in the modified AnRBC and TCOD removal in the MBBR. The optimized ADM1 parameters (K_S = 0.50 kgCOD/m^3, $k_{m,c3}$ = 60 /d, and D_{prOH} = 8 × 10^{-10} m^2/s) achieved satisfactory performance (R^2 = 0.84, Pearson correlation = 0.89, RMSE = 1.09 mg/L). The optimized ASM1 parameters (Y_H = 0.75, $\mu_{H,max}$ = 0.10 /d, K_S = 25 mgCOD/L, and D_S = 9.77 × 10^{-9} m^2/s) showed excellent prediction of TCOD effluent (R^2 = 0.91, Pearson correlation = 0.95, RMSE = 466.88 mg/L).

Keywords: biokinetic modeling; coupled wastewater treatment; hydraulic retention time; *n*-propanol; palm oil mill effluent.

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PREFACE

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Bogor, July 2026

Frans Edvan Setiawan

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Q	= Flow rate (L/s)
V, V_{liq}	= Volume of the POME (L)
m	= Mass of the OPEFB (g)
t	= Time (s)
$S_{in,i}$, $S_{liq,i}$, S_s, S_O, and S_{NO}	= Substrate influent, liquid, COD, DO, and nitrate/nitrite concentration (kgCOD/m^3)
$\rho_j v_{i,j}$	= Biochemical reactions component (kgCOD/m^3.d)
S_{pro}, S_{bu}, S_{prOH}, S_{va}, and S_{h2}	= total concentrations of propionate, butyrate, propanol, valerate, and hydrogen (kgCOD/m^3)
Y_{pro}, Y_{c4}, Y_{prOH}, Y_{c3}, and Y_H	= biomass yields on propionate, C4 substrates (valerate and butyrate), propanol, C3 substrates (propionate and propanol), and heterotrophic
$k_{m,pr}$, $k_{m,c3}$, and $k_{m,c4}$	= Monod maximum specific uptake rates for propionate, C3 substrates (propionate and propanol), and C4 compounds (valerate and butyrate) (d^{-1})
I_2, I_{ph}, $I_{IN,lim}$, and I_{h2}	= Inhibition factor, inhibition factors for pH, inorganic nitrogen, and hydrogen
K_S, $K_{O,H}$, and K_{NO}	= Half-saturation constant, oxygen and nitrate/nitrite saturation constants for heterotrophic biomass (kgCOD/m^3)
pH_{UL} and pH_{LL}	= Upper and lower pH limits

X_{pro}, X_{c3}, X_{c4}, and $X_{B,H}$	= Biomass propionate, C4 substrates (valerate and butyrate), C3 substrates (propionate and propanol) degraders, and concentration of heterotrophic biomass (kgCOD/m^3)
$\hat{\mu}_H$	= Specific growth rate of heterotrophic biomass (d^{-1})
Θ	= HRT (d)
x_i and y_i	= Individual data points from two variables
$\bar{x}$ and $\bar{y}$	= Means of the two variables
n	= Number of ordered pairs
d	= Difference between the two ranks
$p(\lambda)$	= The parameter update vector for the next iteration
J	= Jacobian matrix of the residual function
λ	= Damping factor, adjusting the convergence rate
D	= Diagonal matrix implementing regularization control
f	= Residual factor
r	= Pearson correlation
$S(\theta)$	= Total error as the sum of squared residuals
Y_i	= Actual observed value at the i-th data point
$f(X_i,\theta)$	= Model-predicted value at input point X_i with parameter vector θ
θ	= Parameter vector to be estimated
$S_{in,prOH}$	= Influent n-propanol concentration (kgCOD/m^3)
$S_{liq,prOH}$	= Liquid-phase n-propanol concentration (kgCOD/m^3)
D_{prOH}	= Effective diffusion coefficient of n-propanol in the biofilm (m^2/s)
D_S	= Substrate diffusion coefficient in the biofilm (m^2/s)
L_f	= Biofilm thickness (m)
z	= Spatial coordinate across the biofilm thickness (m)
η_B	= Correction factor for anoxic growth of heterotrophic biomass
Q_{air}	= Air flow rate (m^3/d)
f_{O2}	= Oxygen mass fraction in air
ρ_{air}	= Air density (kg/m^3)
O_2	= Oxygen mass flow rate (kg O_2/d)
$O_{2,transfer}$	= Oxygen transferred to the liquid phase (kg O_2/d)
OTE	= Oxygen transfer efficiency
OTR	= Oxygen transfer rate (mg O_2/L·d)
OUR	= Oxygen uptake rate (mg O_2/L·d)
SEC	= Specific energy consumption (kWh/kgCOD removed)
R^2	= Coefficient of determination
RMSE	= Root mean squared error
MAPE	= Mean absolute percentage error

GLOSSARY

Seeding and acclimatization	:	Initial stages in a bioreactor process for adapting microbial communities to environmental and substrate conditions until stable activity is reached.
Biomass	:	The total mass of living and active microorganisms participating in anaerobic digestion plays a crucial role in the degradation of organic matter and biogas production.
Palm Oil Mill Effluent (POME)	:	An organic wastewater generated from the processing of oil palm fruits is characterized by high concentrations of dissolved organic matter, oil and grease, and suspended solids.
Oil Palm Empty Fruit Bunches (OPEFB)	:	A solid lignocellulosic biomass waste is generated after separating fruits from the bunch during palm oil processing.
Adsorption	:	A physicochemical process in which molecules of a substance (adsorbate) accumulate on the surface of a solid or liquid phase (adsorbent), without penetrating its internal structure.
Anaerobic Rotating Biological Contractor (AnRBC)	:	A biological wastewater treatment system that utilizes rotating discs covered with anaerobic biofilm to degrade organic matter without oxygen.
Moving Bed Biofilm Reactor (MBBR)	:	A bioreactor that utilizes mobile carriers as biofilm growth media, thereby increasing the contact surface area between microorganisms and the substrate
n-propanol	:	A linear chain alcohol produced from bioconversion with promising potential as a renewable energy source, either as a fuel additive to improve quality or as a sustainable biofuel blending component.
Hydraulic Retention Time (HRT)	:	The average time that a fluid remains in a reactor or treatment unit is a critical parameter to ensure effective degradation or purification of wastewater.
Anaerobic Digestion Model No.1 (ADM1)	:	A mathematical model was established to simulate the anaerobic digestion process, encompassing biochemical and physicochemical stages including hydrolysis, acidogenesis, acetogenesis, and methanogenesis.
Activated Sludge Model No.1 (ASM1)	:	ASM1 is a stoichiometric kinetic model used to simulate organic compound degradation, incorporating biomass growth, nitrification, and oxygen consumption through 13 components, 8 processes, and mass balance equations with around 20 kinetic parameters.