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OPTIMIZATION OF HYDRAULIC RETENTION TIME IN AN ADSORPTION-ANAEROBIC-AEROBIC BIOREACTOR TO ENHANCE METHANE YIELD FROM PALM OIL MILL EFFLUENT

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MASTER STUDY PROGRAM OF CIVIL AND ENVIRONMENTAL ENGINEERING
FACULTY OF ENGINEERING AND TECHNOLOGY
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RINGKASAN

WINDYARTI MUSTIKA CAKRANINGTYAS. Optimasi Waktu Tinggal Hidraulik pada Bioreaktor Terintegrasi Adsorpsi–Anaerobik–Aerobik untuk Meningkatkan Produksi Metana dari Limbah Cair Kelapa Sawit. Dibimbing oleh ALLEN KURNIAWAN dan YUDI CHADIRIN.

Biogas dengan komponen utama metana (CH_4) merupakan sumber energi terbarukan yang dihasilkan dari degradasi anaerobik bahan organik. Di antara berbagai limbah organik, limbah cair pabrik kelapa sawit (POME) memiliki potensi tinggi untuk produksi metana, namun juga memerlukan pengolahan yang efektif agar memenuhi baku mutu efluen. Penelitian ini bertujuan mengoptimalkan waktu tinggal hidraulik (HRT) pada sistem terintegrasi adsorpsi tandan kosong kelapa sawit (OPEFB)–*Upflow Anaerobic Sludge Blanket* (UASB)–*modified Rotating Biological Contactor* (RBC) untuk meningkatkan produksi metana serta mengembangkan model terintegrasi *Anaerobic Digestion Model No. 1* (ADM1)–*Activated Sludge Model No. 1* (ASM1) untuk prediksi dan optimasi proses. Reaktor dioperasikan pada HRT 2, 3, dan 4 hari, dengan setiap kondisi operasi dipertahankan selama 30 hari. Parameter yang dievaluasi meliputi kebutuhan oksigen kimia (COD), TSS, O&G, produksi metana, dan ketebalan biofilm. Model terintegrasi ADM1–ASM1 dikalibrasi, divalidasi menggunakan data eksperimen, serta dianalisis sensitivitasnya untuk mengidentifikasi parameter yang paling berpengaruh terhadap produksi metana. Hasil penelitian menunjukkan HRT berpengaruh signifikan terhadap efisiensi pengolahan, perkembangan biofilm, dan spesifik produksi metana (SMP). HRT 3 hari dipilih sebagai kondisi operasi dengan kompromi terbaik karena menghasilkan penyisihan COD tertinggi (80,91%) serta mempertahankan efisiensi penyisihan TSS (97,00%) dan O&G (90,58%) yang tinggi. Sebaliknya, HRT 4 hari menghasilkan produksi metana (2,70 L), laju produksi metana (0,090 L $hari^{-1}$), SMP (0,20 L CH_4 g^{-1} COD tersisihkan), dan ketebalan biofilm (405,10 ± 199,97 μm) tertinggi. Reaktor UASB didominasi oleh bakteri fermentatif dan sintrofik (*Clostridium sensu stricto* 1 dan *Lentimicrobium*), sedangkan RBC termodifikasi didominasi oleh bakteri aerob (*Bacillus*, *Azonexus*, dan *Mesorhizobium*) yang mendukung degradasi bahan organik, transformasi nitrogen, dan pembentukan biofilm. Model terintegrasi ADM1–ASM1 mampu merepresentasikan tren data eksperimen dengan tingkat kesesuaian sedang. Model ADM1 menghasilkan koefisien korelasi Pearson (r) sebesar 0,874, koefisien determinasi (R^2) sebesar 0,765, RMSE sebesar 7,914 mgCOD L^{-1}, dan nRMSE sebesar 11,29%. Sementara itu, model ASM1 hasil kalibrasi mencapai nilai r sebesar 0,866, R^2 sebesar 0,749, RMSE sebesar 1.176 mgCOD L^{-1}, dan nRMSE sebesar 24,61%. Validasi lebih lanjut menggunakan dataset independen masih diperlukan sebelum model diterapkan pada skala desain. Analisis sensitivitas menunjukkan bahwa *acetoclastic biomass* (X_{ac}) dan laju maksimum pengambilan asetat ($k_{m,ac}$) merupakan parameter yang paling berpengaruh terhadap produksi metana.

Kata kunci: limbah cair kelapa sawit, produksi metana, rotating biological contactor, upflow anaerobic sludge blanket, waktu tinggal hidraulik

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SUMMARY

WINDYARTI MUSTIKA CAKRANINGTYAS. Optimization of Hydraulic Retention Time in an Adsorption–Anaerobic–Aerobic Bioreactor to Enhance Methane Yield from Palm Oil Mill Effluent. Supervised by ALLEN KURNIAWAN and YUDI CHADIRIN.

Biogas, with methane (CH_4) as its primary component, is a renewable energy source produced through the anaerobic degradation of organic matter. Among various organic waste streams, palm oil mill effluent (POME) has a high potential for methane production but also requires effective treatment to comply with effluent discharge standards. The research aimed to optimize the hydraulic retention time (HRT) of an integrated oil palm empty fruit bunch (OPEFB) adsorption–Upflow Anaerobic Sludge Blanket (UASB)–modified Rotating Biological Contactor (RBC) system to enhance methane production and to develop an integrated Anaerobic Digestion Model No. 1 (ADM1)–Activated Sludge Model No. 1 (ASM1) for process prediction and optimization. The reactors were operated at HRTs of 2, 3, and 4 d, with each operating condition maintained for 30 d. The evaluated parameters included chemical oxygen demand (COD), TSS, O&G, methane production, and biofilm thickness. The integrated ADM1–ASM1 model was estimated, validated using experimental data, and subjected to sensitivity analysis to identify the parameters with the greatest influence on spesific methane production (SMP). The results demonstrated that HRT significantly affected treatment efficiency, biofilm development, and methane production. The 3-d HRT was identified as the best overall operating compromise, achieving the highest SCOD removal (80.91%) while maintaining high TSS (97.00%) and O&G (90.58%) removal. Although the 4-d HRT produced the highest methane production (2.70 L), average daily methane production (0.090 L d^{-1}), SMP (0.20 L CH_4 g^{-1} COD removed), and biofilm thickness (405.10 ± 199.97 μm), the 3-d HRT provided the most balanced overall treatment performance. The microbial community in the UASB reactor was dominated by fermentative and syntrophic bacteria, including *Clostridium sensu stricto* 1 and *Lentimicrobium*, which play important roles in hydrolysis, methane precursor formation, and methanogenesis. In contrast, the modified RBC was dominated by aerobic bacteria such as *Bacillus*, *Azonexus*, and *Mesorhizobium*, which promoted residual organic matter degradation, nitrogen transformation, and biofilm formation, thereby improving the final effluent quality. The integrated ADM1–ASM1 model reproduced the general trend of the experimental data with moderate agreement. The ADM1 model achieved r = 0.874, R^2 = 0.765, RMSE = 7.914 mgCOD L^{-1}, and nRMSE 11.29% while the estimated ASM1 model achieved r = 0.866, R^2 = 0.749, RMSE of 1,176 mgCOD L^{-1}, and nRMSE = 24.61%. Further validation using an independent dataset is recommended before design-scale application. Sensitivity analysis identified acetoclastic biomass (X_{ac}) and the maximum acetate uptake rate ($k_{m,ac}$) as the most influential parameters governing methane production.

Keywords: hydraulic retention time, methane production, palm oil mill effluent, rotating biological contactor, upflow anaerobic sludge blanket

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OPTIMIZATION OF HYDRAULIC RETENTION TIME IN AN ADSORPTION–ANAEROBIC–AEROBIC BIOREACTOR TO ENHANCE METHANE YIELD FROM PALM OIL MILL EFFLUENT

WINDYARTI MUSTIKA CAKRANINGTYAS

Thesis
as one of the requirements to obtain a Master's Degree in
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PREFACE

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Bogor, July 2026

Windyarti Mustika Cakraningtyas

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LIST OF NOTATIONS

V_{liq} and Q_{liq}	=	Flow rate (L/d) and volume liquid (L),
S_{ac} and $S_{NH3,Xac}$	=	Concentration total acetate and dissolved free ammonia (gCOD/L)
S_{pro}, S_{bu}, and S_{va}	=	Total propionate, butyrate, and valerate (gCOD/L)
S_s, S_O, and S_{NO}	=	Concentration substrate (COD), DO, and nitrate/nitrite
X_{ac} and $X_{B,H}$	=	Biomass acetate and heterotrophic degraders (kgCOD/m^3)
Y_{ac} and Y_H	=	Yield of biomass on acetate and heterotrophic
$K_{O,H}$ and K_{NO}	=	Saturation constants for oxygen and nitrate/nitrite
$k_{m,ac}$ and $K_{NH3,Xac}$	=	Monod maximum specific uptake rate acetate and dissolved free ammonia (d^{-1})
K_S and $\hat{\mu}_H$	=	Half saturation value and specific growth rate of heterotrophic biomass (gCOD/L)
X_{c4} and X_{pro}	=	Biomass valerate, butyrate and propionate degraders (kgCOD/m^3)
Y_{pro} and Y_{c4}	=	Yield of biomass on propionate and valerate, butyrate
$k_{m,pr}$ and $k_{m,c4}$	=	Monod maximum specific uptake rate propionate and valerate, butyrate (d^{-1})

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I_2, I_3, $I_{IN,lim}$, I_{H2}, I_{pH}, and $I_{NH3,Xac}$	=	Inhibition acetate formation, methane production, inorganic nitrogen, uptake hydrogen, pH, and NH_3,X_{ac}
Θ	=	HRT (d)
y_n and y_{n+1}	=	Current value and predicted value
n and f	=	Total number of observations and residual factor
$\hat{y}_i$ and $\bar{y}_i$	=	Predicted values and mean of the observed
pH_{UL} and pH_{LL}	=	pH upper limit and lower limit
$S_{S,in}$ and $S_{ac,in}$	=	Substrate influent and acetate concentration (mg/L)
$p(\lambda)$	=	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
r	=	Pearson correlation
$S(\theta)$	=	Objective function, which quantifies the total error as the sum of squared residuals
Y_i	=	Actual observed value at the i-th data point
$f(X_i,\theta)$ and $f(t_n,y_n)$	=	Model-predicted value at input point X_i with parameter vector θ and rate of change of the dependent variable evaluated at t_n and y_n
θ	=	Parameter vector to be estimated
T	=	Temperature (K or °C)
FR and FR_{ref}	=	Filling ratio and reference filling ratio (%)
L_F	=	Biofilm thickness (m)
N and N_{ref}	=	Rotation speed and reference rotation speed (rpm)
D_S	=	Substrate diffusion coefficient (m^2/s)
$\mu_{H,max}$	=	Growth rate of heterotrophic microorganisms (d^{-1})
$S_{F,i}$ and $r_{F,i}$	=	Concentration and net reaction rate of substrate i in the biofilm (kg COD/m^3)
z	=	Position or depth within the biofilm (m)
$D_{F,i}$		Diffusion coefficient of substrate i in the biofilm (m^2/d)
$f_{NH3,Xac}$	=	Ammonia inhibition factor for acetoclastic methanogens
p_{Ka}	=	Acid dissociation constant of ammonium
ρ_{CH4} and ρ_{ac}	=	Methane production rate and acetate consumption rate by acetoclastic methanogens (kg COD/($m^3 \cdot$d)
η_B	=	Anoxic growth correction factor
t_n and Δt	=	Current time at time step n and time step (d)

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GLOSSARY

Upflow Anaerobic Sludge Blanket (UASB)	:	A type of anaerobic reactor wastewater flows upward through a dense blanket of sludge, allowing microorganisms to degrade organic matter and produce VFA.
OPEFB Adsorption	:	A process molecules (pollutants, organic compounds) adhere to the surface of a solid material (adsorbent) utilizing oil palm empty fruit bunches (OPEFB).
Modified Rotating Biological Contactor (RBC)	:	A wastewater treatment system uses rotating discs coated with biofilm to degrade organic matter.
Biomass	:	The total mass of living microorganisms and anaerobic digestion biomass is crucial in breaking down organic matter and producing VFA.
Volatile Fatty Acid (VFA)	:	Short-chain organic acids, primarily acetate, propionate, and butyrate, formed during acidogenesis and acetogenesis and used as intermediates in methane formation.
Total Acetate (S_{ac})	:	Cumulative concentration of acetic acid (CH_3COOH) produced during the acetogenesis stage and serves as the principal substrate for acetoclastic methanogens.
Effluent COD (S_s)	:	Remaining soluble COD in the effluent after treatment.
Methane production (S_{gas})	:	Methane generated during anaerobic digestion.
Hydraulic Retention Time (HRT)	:	The average time wastewater remains in a reactor for treatment.
Palm Oil Mill Effluent (POME)	:	High-strength wastewater is generated during palm oil production.
Analysis of Variance (ANOVA)	:	A statistical method is used to compare the means of two or more groups to determine if there are significant differences between them.
Pearson Correlation (*r*)	:	Parametric statistical measure used to evaluate the strength and direction of a linear relationship between two continuous variables.
Anaerobic Digestion Model No. 1 (ADM1)	:	A mathematical model was developed to simulate the anaerobic digestion process (biochemical and physicochemical processes such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis).
Activated Sludge Model No.1 (ASM1)	:	A model used to simulate COD removal in activated sludge systems.

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