



PYROLYSIS OPTIMIZED KAPOK FIBER ADSORPTION COUPLED WITH ELECTROCOAGULATION AND BIOFILM KINETICS FOR PALM OIL MILL EFFLUENT TREATMENT

SATRIO WALUYOJATI ALMAY WIDAGDO



**CIVIL AND ENVIRONMENTAL ENGINEERING STUDY PROGRAM
FACULTY OF ENGINEERING AND TECHNOLOGY
IPB UNIVERSITY
BOGOR
2026**



@Hak cipta milik IPB University

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

DECLARATION OF THE UNDERGRADUATE THESIS INFORMATION SOURCES AND COPYRIGHT TRANSFER

I hereby affirm that the undergraduate thesis entitled “Pyrolysis Optimized Kapok Fiber Adsorption Coupled with Electrocoagulation and Biofilm Kinetics for Palm Oil Mill Effluent Treatment” is my original work, conducted under the supervision of my advisors. This thesis has neither been published nor submitted to any other university in any form. All sources of information, whether unpublished or published, that are derived or quoted from other authors have been duly cited within the text and are listed in the bibliography at the conclusion of this thesis.

I hereby transfer the copyright of this undergraduate thesis to IPB University.

Bogor, June 2026

Satrio Waluyojati Almay Widagdo
F4401221063

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.



ABSTRACT

SATRIO WALUYOJATI ALMAY WIDAGDO. Pyrolysis Optimized Kapok Fiber Adsorption Coupled with Electrocoagulation and Biofilm Kinetics for Palm Oil Mill Effluent Treatment. Supervised by ALLEN KURNIAWAN and AQIL AZIZI.

Palm oil mill effluent (POME) contains high oil and grease (O&G) and chemical oxygen demand (COD) concentrations that disrupt electrocoagulation (EC)–Moving Bed Biofilm Reactor (MBBR) performance. This study aimed to develop a three-stage treatment system—calcium stearate (CaSt₂)-modified kapok fiber adsorption, EC, and MBBR—integrated through a series-connected dynamic kinetic model. One-way ANOVA on the main experiment confirmed 400°C as optimal ($\eta^2=0.894$; O&G removal 70.65%). Model calibration yielded $q_{\max}=30.50$ mg/g and $\mu_{\max}=3.0$ day⁻¹, with MAPE of 15.24% (adsorption), 17.05% (EC), and 5.97% (MBBR), while Monte Carlo sensitivity analysis identified q_{\max} dominant in adsorption (99.5%) and the $\mu_{\max}-\theta_h$ pair co-dominant in MBBR (95.3%). Scenario simulation showed sCOD ≤ 350 mg/L compliance reached at hydraulic retention time (HRT) ≈ 31.5 h or mixed liquor suspended solids (MLSS) $\approx 11,132$ mg/L, confirming HRT and MLSS as the most influential operational parameters, and total COD compliance requires experimental verification.

Keywords: calcium stearate, electrocoagulation, integrated kinetic model, kapok fiber, palm oil mill effluent

ABSTRAK

SATRIO WALUYOJATI ALMAY WIDAGDO. Pyrolysis Optimized Kapok Fiber Adsorption Coupled with Electrocoagulation and Biofilm Kinetics for Palm Oil Mill Effluent Treatment. Dibimbing oleh ALLEN KURNIAWAN dan AQIL AZIZI

Limbah cair pabrik kelapa sawit (LCPKS) mengandung konsentrasi O&G serta COD tinggi yang mengganggu kinerja EC–MBBR. Penelitian ini bertujuan mengembangkan sistem pengolahan tiga tahap—adsorpsi serat kapok termodifikasi kalsium stearat (CaSt₂), EC, dan MBBR—yang terintegrasi melalui model kinetika dinamis tersambung-seri. ANOVA satu arah pada eksperimen utama mengonfirmasi 400°C sebagai kondisi optimum ($\eta^2=0,894$; removal O&G 70,65%). Kalibrasi model menghasilkan $q_{\max}=30,50$ mg/g dan $\mu_{\max}=3,0$ hari⁻¹, dengan MAPE 15,24% (adsorpsi), 17,05% (EC), dan 5,97% (MBBR), sedangkan sensitivitas Monte Carlo mengidentifikasi q_{\max} dominan pada adsorpsi (99,5%) dan pasangan $\mu_{\max}-\theta_h$ ko-dominan pada MBBR (95,3%). Simulasi skenario menunjukkan kepatuhan sCOD ≤ 350 mg/L tercapai pada HRT $\approx 31,5$ jam atau MLSS ≈ 11.132 mg/L, menegaskan HRT dan MLSS sebagai parameter operasional paling berpengaruh, dan kepatuhan COD total memerlukan verifikasi eksperimental.

Kata kunci: kalsium stearat, elektrokoagulasi, pemodelan kinetika terintegrasi, serat kapok, limbah cair pabrik kelapa sawit



- Hak Cipta Dilindungi Undang-undang
1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
 2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

© Copyrighted by IPB University, 2026
Copyright is protected by Law

It is prohibited to quote parts or all of this paper without acknowledging or citing the source. Citation is only for the purposes of education, research, writing scientific papers, compiling reports, writing criticism, or reviewing a problem, and the citation is not detrimental to IPB University interests.

It is prohibited to publish and reproduce parts or all of this paper without IPB University's permission.



PYROLYSIS OPTIMIZED KAPOK FIBER ADSORPTION COUPLED WITH ELECTROCOAGULATION AND BIOFILM KINETICS FOR PALM OIL MILL EFFLUENT TREATMENT

SATRIO WALUYOJATI ALMAY WIDAGDO

Undergraduate thesis
as one of the requirements to obtain a Bachelor's Degree in
Program Study Civil and Environmental Engineering

**CIVIL AND ENVIRONMENTAL ENGINEERING STUDY PROGRAM
FACULTY OF ENGINEERING AND TECHNOLOGY
IPB UNIVERSITY
BOGOR
2026**



@Hak cipta milik IPB University

IPB University



IPB University
— Bogor Indonesia —

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

Examiner on Undergraduate Thesis Exam:
Jihan Nur Azizah S.T., M.T.



@Hak cipta milik IPB University

IPB University



IPB University
— Bogor Indonesia —

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.



Title

: Pyrolysis Optimized Kapok Fiber Adsorption Coupled with Electrocoagulation and Biofilm Kinetics for Palm Oil Mill Effluent Treatment

Name

: Satrio Waluyojati Almay Widagdo

Student ID

: F4401221063

@Hak cipta milik

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

Approved by

Supervisor:

Dr. Eng. Ir. Allen Kurniawan, S.T., M.T.

NIP. 19820729 201012 1 005



Co-supervisor:

Ir. Aqil Azizi., S.Pi., M.ApplSc., Ph.D., IPM

NIDN. 0304038305

Known by

Head of the Civil and Environmental Engineering Program Research:

Ir. Tri Sudiby, S.T., M.Sc., Ph.D., IPM

NIP. 19840530 201404 1 001



Exam Date: 22 June 2026

Graduate Date: 07 JUL 2026



PREFACE

The author expresses sincere gratitude to Almighty God, Allah SWT, for the health and blessings bestowed, which have enabled the completion of this undergraduate thesis entitled “Pyrolysis Optimized Kapok Fiber Adsorption Coupled with Electrocoagulation and Biofilm Kinetics for Palm Oil Mill Effluent Treatment” in a timely and proper manner. This thesis is submitted as partial fulfillment of the requirements for obtaining a bachelor’s degree in the Department of Civil and Environmental Engineering, IPB University.

On this occasion, the author would like to express sincere appreciation to all individuals who have provided support during the preparation of this thesis, especially to:

1. Ir. Guno Widagdo and Ir. Rina Rosdiana, MM., the author’s beloved parents, for their endless affection, support, and prayers throughout the study.
2. Faris Rafi Almay Widagdo, Raihan Hafiz Almay Widagdo, and Fadhil Fawwaz Almay Widagdo, the author’s beloved brothers, for their love, support, and prayers.
3. Dr. Eng. Ir. Allen Kurniawan, S.T., M.T. and Ir. Aqil Azizi.,S.Pi., M.ApplSc., Ph.D., IPM as supervisors who have provided advice and guidance from the beginning until the completion of this thesis.
4. Arif Nuryadin, as a laboratory staff, provided valuable assistance in discussions and in carrying out tests throughout the research process.
5. Adi Aryanto M, Azmya Prasetyaningtyas, Mikael Febrian Aritonang, Nathasia, Ryu Prananda Sultan Batubara, and Zidand Anand Hidayat, for their support, advice, and guidance throughout the lecture period.
6. Sylvia Wardani and Adi Aryanto M, as EC–MBBR teammates, for their cooperation, assistance, and support throughout the study.
7. Finally, sincere appreciation is extended to all friends and colleagues who cannot be mentioned individually for their assistance and support.

The author has made every effort to complete this thesis. However, the author realizes that there are still limitations in terms of content and language. Therefore, any constructive criticism and suggestions are highly appreciated for further improvement. The author hopes that this thesis will contribute beneficially and enrich the knowledge of its readers

Bogor, June 2026

Satrio Waluyojati Almay Widagdo

CONTENTS

ABSTRACT	ii
LIST OF TABLES	xi
LIST OF FIGURES	xi
LIST OF APPENDIX	xii
LIST OF NOTATIONS	xii
GLOSSARY	xiv
I INTRODUCTION	1
1.1 Background	1
1.2 Problem Formulation	3
1.3 Research Objectives	4
1.4 Scope of The Research	4
1.5 Research Significance	5
II LITERATURE REVIEW	6
III METHODS	9
3.1 Research Site and Timeline	9
3.2 Materials and Instruments	9
3.3 Experimental Design	11
3.4 Material Preparation and Characterization	11
3.4.1 POME Sample Collection and Characteristic Analysis	12
3.4.2 Kapok Fiber Adsorption Experiment	13
3.4.3 Kapok Fiber Characterization	15
3.4.4 Kapok Fiber Adsorption Test	16
3.5 Integrated Reactor Operation	16
3.5.1 Biomass Seeding and Acclimatization	16
3.5.2 Reactor Operation	16
3.5.3 Reactor Performance Evaluation	17
3.6 Statistical Analysis	18
3.6.1 Normality Test	18
3.6.2 Hypothesis Test	19
3.6.3 Response Surface Methodology	19
3.7 Kinetics Modeling	20
3.7.1 Adsorption Model	21
3.7.2 EC Model	22
3.7.3 MBBR Model	23
3.7.4 Model Validation	25
3.8 VBA and Solver Application	26
3.9 Sensitivity Analysis	28
3.10 Practical and Operational Scenario	29
3.11 Limitations of the Model	31
IV RESULTS AND DISCUSSION	32
4.1 Characterization of POME	32
4.2 Characterization of Kapok Fiber	33
4.2.1 Surface Morphology Characterization	33
4.2.2 Identification of Functional Groups	34
4.2.3 Surface Property Evaluation	37



4.3	Response Surface Optimization	39
4.4	Optimum Kapok Fiber	41
4.5	Statistics Analysis	42
4.5.1	Normality Test	42
4.5.2	Hypothesis Test	43
4.6	Microorganism Seeding and Acclimatization	44
4.7	Reactor Performance Evaluation	47
4.8	Kinetics Modeling	55
4.8.1	Adsorption Model	55
4.8.2	EC Model	57
4.8.3	MBBR Model Calibration	58
4.9	Model Validation	60
4.10	Sensitivity Analysis	61
4.11	Practical Operational Scenario	63
	CONCLUSION AND RECOMMENDATIONS	69
5.1	Conclusion	69
5.2	Recommendations	69
	REFERENCES	71
	APPENDIX	77
	AUTOBIOGRAPHY	113

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumunkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

LIST OF TABLES

Table 3.1 Specifications of Kaldnes Carrier Media Used in the MBBR	11
Table 3.2 Research instruments and chemicals	13
Table 3.3 Initial parameter bounds used for model calibration	27
Table 4.1 PTPN VIII POME characteristic value	32
Table 4.2 EDX analysis results	37
Table 4.3 Contact angle values of raw and pyrolyzed kapok fibers	38
Table 4.4 Effect of pyrolysis temperature (300–500 °C) on O&G removal efficiency of modified kapok fiber (0.4 M)	41
Table 4.5 Yield of modified kapok fiber	42
Table 4.6 Shapiro-Wilk and Levene test results for the main experiment	43
Table 4.7 One-Way ANOVA results for the main experiment	43
Table 4.8 Pairwise comparison results of Post-Hoc test	44
Table 4.9 Apparent biomass surface loading of kaldnes media	46
Table 4.10 Water quality parameters at sequential treatment stages of the integrated Adsorption–EC–MBBR system	47
Table 4.11 BOD and TN concentrations at the end of variation	54
Table 4.12 Optimal parameter for adsorption model	55
Table 4.13 Optimal parameter for EC model	57
Table 4.14 Optimal parameter for MBBR model	59
Table 4.15 Comparison of Kinetic Parameters with Other Study	59
Table 4.16 Statistical performance indicators of the validation models	61

LIST OF FIGURES

Fig. 2.1 The identified research gaps within the research group	8
Fig. 3.1 Modified configuration of the EC–MBBR reactor	10
Fig. 3.2 Flow chart of the research	12
Fig. 3.3 Preparation of CaSt ₂ modified kapok fiber	13
Fig. 3.4 Configuration of the integrated EC–MBBR reactor and sampling point	18
Fig. 3.5 Configuration of the reactor	18
Fig. 3.6 Workflow of parameter calibration using VBA and Excel Solver	28
Fig. 4.1 SEM images of kapok fiber: (a) Raw (b) 300 °C (c) 400 °C (d) 500 °C	34
Fig. 4.2 FTIR spectra for kapok fiber: (A) Raw (B) 300 °C (C) 400 °C (D) 500 °C	35
Fig. 4.3 Contact angle (A) Raw kapok (B) 300 °C (C) 400 °C	39
Fig. 4.4 Response surface contour plot showing the effect of pyrolysis temperature and CaSt ₂ concentration on O&G removal efficiency	40
Fig. 4.5 Concentrations of sCOD and MLSS during seeding and acclimatization (A) K1, (B) K3, and (C) K5	45
Fig. 4.6 O&G fluctuation of the integrated reactor	48

Fig. 4.7 sCOD fluctuation of the integrated reactor	49
Fig. 4.8 MLSS fluctuation of the integrated reactor	50
Fig. 4.9 pH and temperature fluctuation of the integrated reactor	52
Fig. 4.10 Calibration for adsorption model	56
Fig. 4.11 Calibration for EC model	58
Fig. 4.12 Calibration for MBBR model	60
Fig. 4.13 Sensitivity analysis (A) Adsorption, (B) EC, and (C) MBBR models	62
Fig. 4.14 Scenario S1 (adsorbent mass variation): effect of adsorbent mass on sCOD concentration (left axis) and removal efficiency (right axis)	64
Fig. 4.15 Scenario S2 (current variation): effect of current on sCOD concentration (left axis) and removal efficiency (right axis)	65
Fig. 4.16 Scenario S3 (HRT variation): effect of HRT on sCOD concentration (left axis) and removal efficiency (right axis)	67
Fig. 4.17 Scenario S4 (MLSS variation): effect of MLSS on sCOD concentration (left axis) and removal efficiency (right axis)	68

LIST OF APPENDIX

Appendix 1 O&G concentration measurement data	78
Appendix 2 sCOD concentration measurement data	79
Appendix 3 MLSS concentration measurement data	80
Appendix 4 pH measurement data	81
Appendix 5 Temperature measurement data	82
Appendix 6 The VBA code for adsorption model	83
Appendix 7 The VBA code for EC model	86
Appendix 8 The VBA code for MBBR model	89
Appendix 9 The python code for sensitivity analysis	92
Appendix 10 The python code for operational scenario	107

LIST OF NOTATIONS

α	=	Significance level (statistics) / perturbation range in Monte Carlo sensitivity analysis
η^2	=	Eta-squared; effect size from One-Way ANOVA
ρ_i	=	Spearman rank correlation coefficient of parameter i in sensitivity analysis
F	=	F-statistic in One-Way ANOVA and Levene's test
MAPE	=	Mean Absolute Percentage Error (%)

N	=	Total number of observations or Monte Carlo realizations
R^2	=	Coefficient of determination
RMSE	=	Root Mean Square Error (mg/L)
SSE	=	Sum of Squared Errors between observed and predicted values ((mg/L) ²)
W	=	Shapiro–Wilk statistic for normality testing
K	=	Adsorption affinity constant in HSFSG model (L/mg)
k_{LDF}	=	Linear Driving Force mass transfer coefficient; integrates external film, intra-particle, and surface site resistance (day ⁻¹)
m_{ads}	=	Mass of CaSt ₂ -modified kapok fiber adsorbent (g)
$1/n$	=	Sips heterogeneity exponent describing adsorption site energy distribution
ω	=	Lateral interaction parameter in Fowler–Guggenheim model; positive values indicate cooperative adsorption
q_e	=	Equilibrium adsorption capacity (mg/g)
q_{max}	=	Maximum monolayer adsorption capacity (mg/g)
Q	=	Volumetric flow rate through reactor (L/d)
θ	=	Fractional surface coverage of adsorption sites
D	=	Cu(OH) ₂ coagulant dose generated per unit EC reactor volume (mg/L)
F	=	Faraday's constant; 96,485 C/mol (C/mol)
η_1	=	Current efficiency: fraction of applied current used for copper electrode dissolution
I	=	Applied electric current to EC unit (A)
K_L	=	Langmuir affinity constant for O&G–Cu(OH) ₂ interaction (L/mg)
M_w	=	Molar mass of copper; 63.5 g/mol (g/mol)
$q_{max,EC}$	=	Maximum adsorption capacity of Cu(OH) ₂ floc for O&G (mg/g)
t_{op}	=	Electrode operating time per treatment cycle (s)
V_{EC}	=	Volume of EC reactor (L)
z	=	Valence number of dissolved Cu ²⁺ ion (= 2)
C_{inh}	=	O&G inhibitor concentration entering MBBR (= C ₂ from EC effluent) (mg/L)

Hak Cipta Dilindungi Undang-undang
1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.



K_I

= Inhibition constant in Hill inhibition model (mg/L)

K_S

= Substrate half-saturation constant in Monod kinetics (mg COD/L)

m

= Hill coefficient: describes cooperativity of O&G inhibition

μ_{max}

= Maximum specific growth rate of heterotrophic biofilm biomass (day^{-1})

θ_h

= Effective hydraulic retention time of MBBR (d)

X_b

= Active biofilm biomass concentration (mg VSS/L)

Y

= Biomass yield coefficient (gVSS/gCOD)

GLOSSARY

Adsorption

: A surface process in which molecules from a liquid phase (adsorbate) accumulate on a solid surface (adsorbent) through hydrophobic or electrostatic interactions.

Biofilm

: A structured community of microorganisms attached to a solid carrier surface (Kaldnes media), embedded within an extracellular polymeric substance (EPS) matrix.

Calcium Stearate
(CaSt₂)

: A calcium salt of stearic acid used as a surface modifier for kapok fiber. Its long hydrocarbon chain imparts hydrophobic and oleophilic surface properties.

Electrocoagulation
(EC)

: An electrochemical treatment in which applied current dissolves copper anodes to produce Cu(OH)₂ flocs that adsorb and settle oil and grease from wastewater.

HSFG Model

: Hybrid Langmuir–Sips–Fowler–Guggenheim (HSFG) adsorption model combining surface heterogeneity (Sips) and lateral adsorbate–adsorbate interactions (Fowler–Guggenheim) for dynamic simulation.

HRT (Hydraulic Retention Time)

: The average time wastewater remains in a reactor (V/Q). Longer HRT provides greater substrate–biomass contact, generally increasing biodegradation efficiency.

Kapak Fiber	: Natural hollow fiber from <i>Ceiba pentandra</i> with inherent hydrophobic and oleophilic properties. Modified with CaSt ₂ and pyrolysis to enhance O&G adsorption capacity.
MBBR (Moving Bed Biofilm Reactor)	: A biological reactor in which biomass grows attached to freely suspended Kaldnes plastic carriers. Combines advantages of activated sludge and fixed-film biofilm systems.
MLSS (Mixed Liquor Suspended Solids)	: Total suspended solids concentration in the biological reactor, comprising both suspended and biofilm-derived biomass. Used as a proxy for active biomass in model calibration.
O&G (Oil and Grease)	: Non-polar organic compounds extractable from wastewater including triglycerides, free fatty acids, and mineral oils. Discharge standard ≤ 25 mg/L (Ministry of Environment Regulation No. 5 of 2014).
POME (Palm Oil Mill Effluent)	: Highly polluted agro-industrial wastewater from palm oil processing, characterized by acidic pH (3.5–6.4), very high organic load (COD up to 250,000 mg/L), and elevated O&G.
Pyrolysis	: Thermal decomposition of organic material under limited or oxygen-free conditions, producing a porous carbon structure that enhances surface hydrophobicity and adsorption capacity.
sCOD (Soluble COD)	: COD fraction passing through a 0.45 μ m membrane filter, representing dissolved organics that serve as the primary substrate for biofilm biomass in the MBBR unit.
SEM (Scanning Electron Microscopy)	: Imaging technique using a focused electron beam to produce high-resolution images of material surface morphology and pore structure.
WCA (Water Contact Angle)	: Angle between a water droplet and a solid surface. $WCA > 90^\circ$ indicates hydrophobicity; $WCA < 90^\circ$ indicates hydrophilicity. Used to quantify adsorbent surface character.



@Hak cipta milik IPB University

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.