ANALYSIS OF MICROALGAE CARBON CAPTURE IN EXHAUST GAS FROM A SINGLE CYLINDER ENGINE IN A FLAT PANEL MODEL DESIGN

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Abstract

Carbon dioxide (CO_2) emissions from gasoline engines are one of the contributors to greenhouse gases in the atmosphere. Single-cylinder gasoline engines widely used in motorcycles produce exhaust gases containing CO_2 which has the potential to be used as a carbon source for microalgae. This study aims to analyze the potential for CO_2 absorption from single-cylinder gasoline engine exhaust gases using microalgae in a flat-panel photobioreactor through a mathematical modeling approach. The research method was carried out by determining engine parameters and microalgae kinetic parameters based on literature studies, then calculating exhaust gases and modeling CO_2 absorption using a mass balance, gas-liquid mass transfer, and the Monod model of microalgae growth kinetics. The calculation results show that the engine produces a CO_2 mass rate of approximately 1.545×10^{-3} kg/s. The analysis results indicate that microalgae have the potential to utilize CO_2 as a carbon source for biomass growth in a photobioreactor system.

Keywords: carbon capture, microalgae, photobioreactor, gasoline engine, mathematical modeling.

1. INTRODUCTION

The increase in carbon dioxide (CO_2) emissions due to fossil fuel-based transportation activities is one of the main causes of global warming and climate change. Gasoline-powered vehicles produce CO_2 in large quantities as the primary product of hydrocarbon combustion, which is directly released into the atmosphere. The accumulation of CO_2 intensifies the greenhouse effect and affects global climate stability. (Wataru Sakashita, 2021)

Single-cylinder gasoline engines, which are widely used in motorcycles and generator sets, produce exhaust gases with relatively high CO_2 content, particularly in four-stroke engines, where the CO_2 concentration in exhaust gas can reach approximately 14% by volume, (Amir Amir, 2021). Although catalytic converter technology can reduce toxic gas emissions such as CO and hydrocarbons through oxidation reactions, it does not significantly reduce CO_2 concentration in exhaust gas because CO_2 is already the primary product of hydrocarbon combustion (Sharma, 2025).

Microalgae have been widely studied as effective biological agents for CO_2 absorption due to their ability to perform photosynthesis at high rates, (Thamarys Scapini, 2024). Compared to higher plants, microalgae have higher biomass productivity and greater carbon absorption efficiency. Several studies have shown that microalgae can utilize CO_2 from industrial exhaust gases and flue gases as a carbon source in photobioreactor systems, (Hao Chen, 2023).

The use of photobioreactors enables better control of microalgae growth conditions, such as light intensity, temperature, and CO_2 supply, thereby increasing carbon biofixation efficiency, (Shaikh Abdur Razzak, 2024). In addition, microalgae growth and CO_2 consumption are often modeled using Monod kinetics, which describes the relationship between growth rate and substrate concentration, (Frungieri, 2022). Numerical simulation approaches based on differential equations have been widely applied to analyze biomass dynamics and CO_2 absorption in reactors, (Ruofan Wang, 2025).

Microalgae have been extensively investigated as a medium for CO_2 absorption in photobioreactor systems, particularly using CO_2 sources from industrial exhaust gases with relatively stable operating conditions, (Kai-Yuan Li, 2025). However, the utilization of vehicle exhaust gases, especially from single-cylinder gasoline engines, as a CO_2 source for microalgae remains limited, even though vehicle exhaust characteristics differ from industrial exhaust gases and tend to be more fluctuating. Furthermore, most studies only model microalgae growth or CO_2 absorption separately without integrating exhaust gas CO_2 mass balance, CO_2 mass transfer in photobioreactors, and microalgae growth kinetics into a single integrated mathematical model. (Shabnam Shahhoseyni, 2026). Therefore, this study develops a mathematical model by integrating several existing approaches, including exhaust gas CO_2 mass balance, CO_2 mass transfer modeling in photobioreactors, and microalgae growth kinetics. This integrated model is expected to provide a more comprehensive representation of the interactions between processes involved.

2. METHOD

Research Flow

The research was conducted through a systematic sequence of stages, starting from a literature review to the formulation of conclusions. The study began with a literature review to obtain the theoretical foundation, followed by problem identification and determination of parameters, including engine parameters, exhaust gas parameters, and microalgae growth kinetics parameters. The parameters were then evaluated to ensure their mathematical and physical suitability. If the parameters were not appropriate, adjustments were made; otherwise, the research proceeded to the design stage of the flat panel photobioreactor and system analysis, which was concluded with the formulation of conclusions.

Mathematical Model

The mathematical model in this study was developed to describe the relationship between the exhaust gas from a single-cylinder gasoline engine, CO_2 mass transfer, and microalgae growth inside a flat-panel photobioreactor (PBR). The approach used is based on mass balance and microalgae growth kinetics, which are solved numerically.

The mathematical model was developed based on the following assumptions:

1. The system operates under isothermal conditions (constant temperature).
2. The exhaust gas is assumed to be in a steady-state condition at a constant engine speed.
3. The gas mixture is considered homogeneous.
4. CO_2 mass transfer occurs only through the gas–liquid mechanism without external losses.
5. Microalgae growth is limited only by CO_2 availability.

1. CO_2 Exhaust Gas Mass Balance

The exhaust gas from the single-cylinder gasoline engine is modeled as a CO_2 source for the PBR. The CO_2 mass flow rate entering the system is calculated using the gas mass balance:

$$\dot{m}_{CO_2,in} = y_{CO_2}\,\dot{V}_{gas}\,\rho_{gas} \tag{1}$$

Where y_{CO_2} represents the CO_2 volume fraction in the exhaust gas, $\dot{V}_{gas}$ represents the exhaust gas volumetric flow rate, and ρ_{gas} represents the exhaust gas density. (Yunus, 2006) The CO_2 then enters the PBR and serves as a carbon source for microalgae.

2. CO_2 Transfer Model in a Flat-Panel PBR

CO_2 from the exhaust gas is transferred into the liquid phase of the microalgae culture medium through diffusion and gas–liquid mass transfer processes. The CO_2 transfer rate is modeled using the volumetric mass transfer equation:

$$\frac{\mathrm{dC}}{\mathrm{dt}} = \mathrm{k_L a}\,(\mathrm{C}^* - \mathrm{C}) - \mathrm{r_{CO_2}} \tag{2}$$

This model is widely used in photobioreactor studies because it can represent the effects of gas supply and biological consumption simultaneously. (Jeremy Pruvost, 2020)

3. Microalgae Growth Model

Microalgae growth is modeled using Monod kinetics, which relates the specific growth rate to substrate availability (dissolved CO_2). (Andre Lwoff, 1978)

$$\mu = \mu_{\max}\frac{C}{K_S + C} \tag{3}$$

The biomass mass balance of microalgae is expressed as: (Harvey W. Blanch, 1997)

$$\frac{dX}{dt} = \mu X \tag{4}$$

The Monod model is the most used approach for modeling microalgae growth in photobioreactor systems.

4. CO_2 Consumption Rate by Microalgae

CO_2 consumption by microalgae is assumed to be proportional to the biomass growth rate and is expressed by the following equation: (J-J, 2011)

$$r_{CO_2} = Y_{CO_2/X}\,\mu X \tag{5}$$

where:

y_{CO_2} = exhaust gas CO_2 fraction (13% vol.; Heywood, 1988),
$\dot{m}_{CO_2}$ = CO_2 mass flow rate (kg/s)
$\dot{V}_{gas}$ = exhaust gas volumetric flow rate ($m^3 \cdot s^{-1}$),
ρ_{gas} = exhaust gas density ($kg \cdot m^{-3}$).
$k_L a$ = volumetric mass transfer coefficient (s^{-1})
$C^*_{CO_2}$ = saturated CO_2 concentration in the liquid phase,
C_{CO_2} = dissolved CO_2 concentration,
r_{CO_2} = CO_2 consumption rate by microalgae.
X = Microalgae biomass concentration,
μ_{max} = maximum growth rate (s^{-1}),
K_s = Monod constant for CO_2.
$Y_{CO_2/X}$ = CO_2 yield coefficient with respect to microalgae biomass.

Exhaust Gas Equation of a Single-Cylinder Engine

The model parameters presented in Table 1 are used to represent microalgae growth and CO_2 absorption in the flat panel photobioreactor. The maximum growth rate (μmax) and Monod constant (Ks) determine the response of microalgae growth to the availability of dissolved CO_2. The CO_2 yield coefficient with respect to biomass (YCO_2/X) relates CO_2 consumption to biomass formation. The CO_2 transfer process from the gas phase to the liquid phase is modeled through the mass transfer coefficient (kLa) and the saturated CO_2 concentration (C*). The initial biomass concentration (X_0) is used as the initial condition for the calculation, while the exhaust gas CO_2 fraction (yCO_2) represents the carbon supply from the gasoline engine. The operating temperature (T) is assumed to be constant and serves to maintain the consistency of growth kinetics and CO_2 solubility within the system.

Table 1. Parameter Carbon Capture

Parameter	Symbol	Value	Unit	Source
Maximum growth rate	μmax	0.10	jam^{-1}	(Jérémy Pruvost, 2022)
Monod constant for CO_2	Ks	0.002	mol/m^3	(Jérémy Pruvost, 2022)
CO_2 / biomass yield	YCO_2/X	1.5	g CO_2/g biomassa	(Yuvraj Saxena, 2017)
Mass transfer coefficient	kLa	10	jam^{-1}	(Mbalo Ndiaye, 2018)
Saturated CO_2 concentration	C	0.005	mol/m^3	(Jérémy Pruvost, 2022)
Initial biomass	X_0	0.10	g/L	(Jérémy Pruvost, 2022)
Exhaust gas CO_2 fraction	yCO_2	13	% vol	(Jérémy Pruvost, 2022)
Operating temperature	T	25	°C	-

Exhaust Gas Equation of a Single-Cylinder Engine

1. Cylinder Swept Volume

This equation is used to calculate the volume of gas swept by the piston from Bottom Dead Center (BDC) to Top Dead Center (TDC) during one working stroke. The value of V_d determines the engine's cylinder capacity and serves as the basis for calculating the amount of air entering the combustion chamber in each cycle. (HEYWOOD, 1988)

$$Vd = \frac{\pi}{4} D2\, S \tag{6}$$

2. Combustion Chamber Volume

This equation is derived from the definition of the compression ratio (CR). The combustion chamber volume refers to the remaining volume above the piston when the piston is at Top Dead Center (TDC). This parameter is important because it affects the final pressure and temperature during compression, which in turn influences the combustion process and exhaust gas formation. (HEYWOOD, 1988)

$$V_c = \frac{V_d}{CR-1} \tag{7}$$

3. Total Cylinder Volume

The maximum volume occurs when the piston is at Bottom Dead Center (BDC), while the minimum volume occurs when the piston is at Top Dead Center (TDC). These two volumes represent the geometric limits of the combustion chamber during one engine working cycle.

a. Maximum volume (BDC): (HEYWOOD, 1988)

$$V_{max} = V_d + V_c \tag{8}$$

b. Top Dead Center (TDC): (HEYWOOD, 1988)

$$V_{min} = V_c \tag{9}$$

4. Intake Air Flow Rate

For a four-stroke engine, air is inducted only once every two crankshaft revolutions; therefore, the swept volume is divided by two. This equation is used to determine the volumetric flow rate of air entering the cylinder based on engine speed (RPM). (HEYWOOD, 1988)

$$\dot{V}_{udara} = \frac{V_d \cdot N}{2} \tag{10}$$

5. Intake Air Mass

a. Air Density (Ideal Gas Law)

This equation is used to calculate the density of intake air based on air pressure and temperature. Air density determines the amount of air mass available for combustion. (Yunus A. Cengel M. A., 2015)

$$\rho_{udara} = \frac{P}{RT} \qquad (11)$$

b. Air Mass Flow Rate

The air mass flow rate is obtained by multiplying the air density by the intake air volumetric flow rate. This value serves as a basis for determining fuel consumption and the amount of exhaust gas produced. (Yunus A. Cengel C. , 2018)

$$\dot{m}_{udara} = \rho \cdot \dot{V} \qquad (12)$$

6. Fuel Consumption

This equation uses the assumption of a stoichiometric gasoline air–fuel ratio (AFR) of 14.7. By knowing the air mass flow rate, fuel consumption can be directly calculated based on the air–fuel ratio. (HEYWOOD, 1988)

$$\dot{m}_{bb} = \frac{\dot{m}_{udara}}{AFR} \qquad (13)$$

7. Stoichiometric Combustion Reaction of Gasoline

This reaction shows that each 1 mole of octane fuel produces 8 moles of CO_2 during complete combustion. (HEYWOOD, 1988)

$$C_8H_{18} + 12{,}5(O_2 + 3{,}76N_2) \rightarrow 8CO_2 + 9H_2O + 47N_2$$

Where:

V_d = Cylinder swept volume (m^3)
π = Constant (3,14)
D = Cylinder diameter / bore (m/mm)
S = Piston stroke (m/mm)
ρ_{air} = Air density (kg/m^3)
P = Intake air pressure (Pa)
R = Specific gas constant of air (287 J/kg·K)
T = Intake air temperature (K)
$\dot{m}_{air}$ = Air mass flow rate (kg/s)
ρ = Air density (kg/m^3)
$\dot{V}$ = Volumetric flow rate of air (m^3/s)
$\dot{m}_{bb}$ = Fuel mass flow rate (kg/s)
$\dot{V}$ = Volumetric flow rate of air (m^3/s)

Single-Cylinder Engine Parameters

This table presents the main specifications of the single-cylinder gasoline engine used as the basis for exhaust gas calculations. The cylinder diameter (D) and piston stroke (S) determine the swept volume, which affects the amount of air and fuel entering each cycle. The compression ratio (CR) and maximum pressure (Pmax) describe the combustion conditions that influence CO_2 formation. The stoichiometric AFR is used to calculate fuel consumption based on the intake air mass, while the intake air temperature (T) is used to determine air density using the ideal gas law. These parameters form the basis for estimating the CO_2 mass flow rate in the engine exhaust gas.

Table 2. Parameter Mesin Single Silinder

Parameter	Symbol	Value	Unit	Source
Cylinder diameter	D	0.0524	m	(Manual, 2026)
Piston stroke	S	0.0579	m	(Manual, 2026)
Number of cylinders	z	1	-	-
Compression ratio	CR	9,3:1	-	(HEYWOOD, 1988)
Maximum pressure	P_{max}	3.5	MPa	(HEYWOOD, 1988), (R. S. Khurmi, 2014)
Allowable	σ	0.10	MPa	(Bhandari

Parameter	Symbol	Value	Unit	Source
piston stress				, 2010)
Stoichiometric AFR (Air-Fuel Ratio)	AFR	14.7	-	(HEYWOOD, 1988)
Intake air temperature	T	300	K	-

Flat-Panel Photobioreactor Design

The photobioreactor used in this study is a vertical flat-panel type. The flat-panel design was selected due to its high surface-area-to-volume ratio, which enhances light distribution within the microalgae culture medium and reduces the self-shading effect. The flat geometry enables more uniform light intensity compared to cylindrical reactors, thereby improving photosynthetic efficiency.

The culture chamber is designed as a rectangular thin-layer system to ensure optimal light penetration throughout the entire culture volume. The reactor structure is equipped with a supporting frame to maintain rigidity and stability during operation. This design also facilitates visual observation of culture conditions and supports accurate reactor volume calculations in mass balance analysis.

The exhaust gas CO_2 inlet system is located on the side of the reactor, while the gas outlet is positioned at the top. An upward gas flow configuration is adopted to enhance natural mixing and improve CO_2 mass transfer efficiency from the gas phase to the liquid phase. The photobioreactor is designed as a closed system to minimize contamination and CO_2 losses, and it serves as the basis for analyzing CO_2 absorption and microalgae growth using the mass balance approach and the mathematical model developed in this study.

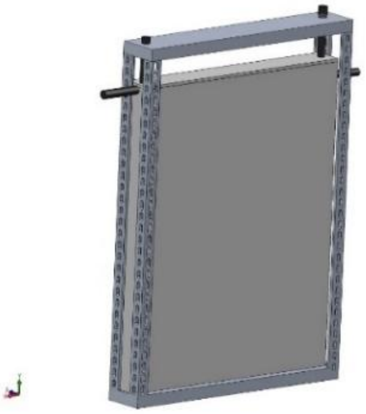
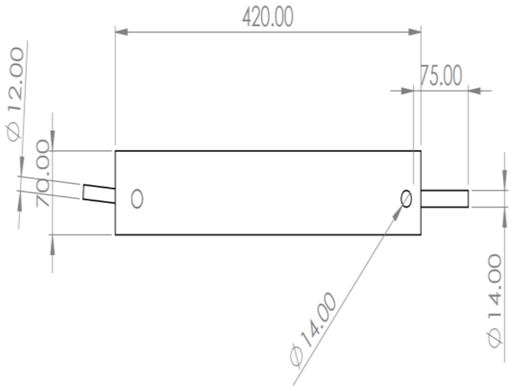
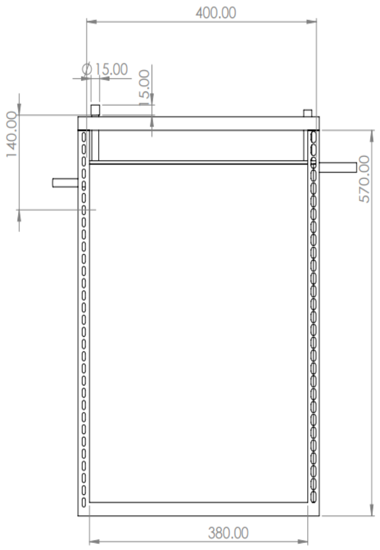


Figure 1. Flat-Panel Photobioreactor Design



(a)



(b)

(c)

Figure 2. (a), (b), (c) Parameter Design

3. RESULTS AND DISCUSSION

In this section, an analysis is conducted on the obtained calculation results to determine the characteristics of CO_2 absorption and microalgae growth in the photobioreactor system. The discussion focuses on the interpretation of the calculated results, their consistency with the literature, and their implications for system performance.

Estimation of CO_2 Emission Rate from a Single-Cylinder Engine

1. Cylinder Swept Volume

This volume is the volume of gas swept by the piston from Bottom Dead Center (BDC) to Top Dead Center (TDC) during one working stroke.

Given:

$D = 0{,}0524$ m
$S = 0{,}0579$ m

Cylinder swept volume is calculated using:

$$V_d = \frac{\pi}{4} D^2 S \quad (14)$$

$V_d = 124{,}9$ cm^3

2. Air Mass Flow Rate

Using the ideal gas law:

with:

P = 101325 Pa
R=287 J/kg.K
T = 300 K
$\rho_{air} = 1{,}176$ kg/m^3

Air mass flow rate:

$\dot{m}_{air} = \rho \dot{V}$
$\dot{m}_{air} = 1{,}176 \times 6{,}245 \times 10^{-3}$
$\dot{m}_{air} = 7{,}35 \times 10^{-3}$ kg/s

3. Fuel Consumption

With AFR = 14,7:

$$\dot{m}_{bb} = \frac{\dot{m}_{air}}{AFR}$$
$$\dot{m}_{bb} = \frac{7{,}35 \times 10^{-3}}{14{,}7}$$
$\dot{m}_{bb} = 5{,}0 \times 10^{-4}$ kg/s

4. CO_2 Mass Flow Rate

Mass ratio of CO_2 to fuel:

1 mol C_8H_{18} → 8 mol CO_2
MrC_8H_{18}=114
Mr CO_2 = 44

$$\frac{m_{CO_2}}{m_{bb}} = \frac{8 \cdot 44}{114}$$
$$\frac{m_{CO_2}}{m_{bb}} = 3{,}09$$

Therefore, the CO_2 mass flow rate is:
From the stoichiometric reaction:

1 kg gasoline → 3,09 kg CO_2

$\dot{m}_{CO2} = 3{,}09 \times \dot{m}_{bb}$
$\dot{m}_{CO2} = 3{,}09 \times 5{,}0 \times 10^{-4}$
$\dot{m}_{CO2} = 1{,}55 \times 10^{-3}$ kg/s
$\dot{m}_{CO2} = 1{,}55$ gram/s

In one hour:

= 5580 gram/hour

Cylinder swept volume and engine parameters are used to determine the air flow rate and fuel consumption. Based on the calculations, the fuel mass flow rate is obtained as 5.0×10^{-4} kg/s.

From the stoichiometric combustion reaction of gasoline (C_8H_{18}), it is known that 1 kg of fuel produces 3.09 kg of CO_2. Therefore, the resulting CO_2 emission rate is 1.55×10^{-3} kg/s, equivalent to 1.55 g/s.

These results indicate that engine exhaust gas has the potential to serve as a significant carbon source for use in photobioreactor systems. Compared with previous studies, this value is still within a reasonable range for small-scale engines.

Analysis of CO_2 Transfer in the Photobioreactor

1. Relationship with CO_2 Absorption in the Photobioreactor

If microalgae absorb CO_2 at a rate of:

$$\dot{m}_{CO_2,abs}$$

Then the CO_2 absorption efficiency is:

$$\eta_{CO_2} = \frac{\dot{m}_{CO_2,abs}}{\dot{m}_{CO_2,gas}} \times 100\%$$

2. Microalgae Growth Rate

$$\mu = 0{,}10 \times \frac{0{,}002}{0{,}002 + 0{,}002}$$
$$\mu = 0{,}05 \text{ hour}^{-1}$$

The microalgae growth rate obtained, 0.05 h^{-1}, indicates that the microalgae are in an active growth phase with sufficient CO_2 availability as a carbon source. This value is still within the range reported in the literature, which is 0.02–0.1 h^{-1}, indicating that the model used remains realistic.

An increase in dissolved CO_2 concentration will enhance the microalgae growth rate until a saturation condition is reached. Beyond this point, growth will be limited by other factors such as light intensity and nutrient availability.

3. Microalgae Biomass Growth

$$X(1) = 0{,}10 \times e^{0{,}05}$$
$$X(1) = 0{,}1051 \text{ g}\backslash\text{L}^{-1}$$

The results show that microalgae biomass increases from 0.10 g/L to 0.1051 g/L within one time interval. This increase indicates that microalgae are able to utilize CO_2 as a carbon source for biomass synthesis through the photosynthesis process.

The magnitude of this biomass increase is influenced by the growth rate and the availability of dissolved CO_2 in the culture medium.

4. CO_2 Mass Balance in the Liquid Phase

The CO_2 mass balance in the liquid phase is expressed as a balance between the rate of CO_2 transfer from the gas phase to the liquid phase and the consumption of CO_2 by microalgae. This model shows that CO_2 availability in the system strongly depends on the efficiency of mass transfer and the biological activity of microalgae.

$$\frac{dC}{dt} = k_L a(C^* - C) - \frac{1}{Y_{CO_2/X}} \mu X$$

the balance between the supply from exhaust gas and biological consumption.

5. Calculation of CO_2 Absorbed by Microalgae

$$CO_{2,absorbed} = 1{,}5 \times 0{,}0051$$
$$CO_{2,absorbed} = 0{,}00765 \text{ g}\backslash\text{L}^{-1}$$

The amount of CO_2 absorbed by microalgae, 0.00765 g/L, indicates that a portion of the CO_2 entering the system can be utilized for biomass growth. This value demonstrates that the photosynthesis process is occurring within the photobioreactor system.

However, the amount of CO_2 absorbed is still relatively small compared to the available CO_2, indicating that system optimization is required to improve absorption efficiency.

6. CO_2 Absorption Efficiency

With an assumed reactor volume 100 L:

$$CO_{2,in} = 11{,}23\ \mathrm{g\backslash L^{-1}jam^{-1}}$$

$$\eta_{CO_2} = \frac{0{,}00765}{11{,}23} \times 100\%$$

$$\eta_{CO_2} = 0{,}068\%$$

The CO_2 absorption efficiency obtained, 0.068%, indicates that only a small portion of CO_2 can be absorbed by microalgae under the modeled conditions.

This value suggests that the photobioreactor system still has limitations in utilizing CO_2 optimally. The low efficiency may be caused by several factors, such as low mass transfer rate, limited contact time, and non-optimal environmental conditions.

Therefore, further development of the photobioreactor design and optimization of operating parameters are required to improve CO_2 absorption efficiency.

The obtained CO_2 transfer rate of (8.34×10^{-6} mol/m^3·s) indicates that the mass transfer process from the gas phase to the liquid phase is driven by the concentration difference between saturated CO_2 and dissolved CO_2. This value shows that mass transfer efficiency still depends on parameters such as the mass transfer coefficient (kLa) and the photobioreactor design.

An increase in the kLa value will enhance the CO_2 transfer rate, resulting in a greater amount of CO_2 available in the liquid medium for utilization by microalgae. Therefore, an optimized photobioreactor design is essential to improve carbon absorption efficiency.

Calculation Results

Table 3. Calculation Results Parameter

Parameter	Value	Unit
Air mass flow rate	$7{,}35 \times 10^{-3}$	kg/s
Fuel mass flow rate	$5{,}0 \times 10^{-4}$	kg/s
CO_2 emission rate	$1{,}55 \times 10^{-3}$	kg/s
Microalgae growth rate (μ)	0,05	jam^{-1}
Final biomass	0,1051	g/L
CO_2 absorbed by microalgae	0,00765	g/L
CO_2 absorption efficiency	0,068	%

4. CONCLUSION

Based on the results of the mathematical analysis and modeling, the estimated CO_2 emission rate from the single-cylinder gasoline engine is 1.545×10^{-3} kg/s. This value is calculated based on cylinder geometry parameters, intake air flow rate, and the stoichiometric air–fuel ratio. It indicates that engine exhaust gas can serve as a potential CO_2 source for carbon capture systems based on microalgae.

The developed mathematical model integrates CO_2 mass balance from engine exhaust gas, gas–liquid mass transfer in a flat-panel photobioreactor, and microalgae growth kinetics using the Monod model. The analysis shows that microalgae can utilize CO_2 as a carbon source for biomass growth, where the absorption process is influenced by dissolved CO_2 concentration, mass transfer coefficient, and microalgae biomass concentration.

Overall, this study demonstrates that a flat-panel photobioreactor system has the potential to be used as a biological method for utilizing CO_2 from single-cylinder gasoline engine exhaust gas. The developed model can also serve as a basis for further research involving direct experimental validation.

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