Dynamic Modeling of Hydrogen Production from Photo-Fermentation in Microbial Electrolysis Cell using Sago Waste

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Abstract. Hydrogen has a great potential as an alternative energy and produces zero emissions, but most of hydrogen is produced from non-renewable fossil fuels via reforming. Thus, biomass is a promising replacement to fossil fuels where hydrogen can be sourced from. In this project, sago waste is chosen as raw material in a microbial electrolysis cell (MEC) to produce hydrogen fuel. A mathematical model with the integration of MEC with photo-fermentation has been developed and modified by using sago effluent as a substrate in a batch process. The main parameter such as concentration of microbial community has been observed in this project as it gives a huge influence on the gas product of MEC. In conclusion, the develop model was to observe the behavior of the microbial electrolysis cell where a maximum of 3.8 L/day (t = 4 days) of hydrogen production and 0.38A of MEC current were obtained.

1. Introduction
With rapid urbanization and industrialization, energy has become increasingly essential to human lives. For instance, energy is needed for various applications such as the manufacturing industry, electrical generation, and fuel for transportation. However, the major source of energy comes from non-renewable fossil fuels. As the world population continues to grow, the demand for energy is also expected to rise. This poses a challenge to the world as the number of fossil fuels available will begin to diminish and be bound to run out in the future. Furthermore, fossil fuels also bring negative impacts to the environment, releasing pollutants like nitrogen oxide (NOx), sulfur oxide (SOx), and volatile organic compounds (VOCs) which contribute to decrease air quality as well as global warming [1]. In recent years, renewable energy resources are gaining momentum in its development and have become popular because they are inexhaustible and clean. Nonetheless, there are still years to come before the world can depend on renewable energy entirely because renewable energy has not been utilized to their full potential and other limitations.

The development of renewable energy must be intensified to reduce the world’s reliance on fossil fuels and eventually eliminate the usage of fossil fuels. A viable alternative to fossil fuels is hydrogen because it is widely available in nature, renewable and pollution-free. Unlike fossil fuels, hydrogen is environmentally friendly where it produces zero emissions. The only by-products from the combustion of hydrogen are steam and heat. The utilization of hydrogen as a fuel is imperative towards the goal of
a sustainable future. Hydrogen has great potential as an alternative because it is energy-efficient where it has a high energy content of 122kJ/g, which is approximately 3 times greater compared to that of hydrocarbon fuels [2]. However, hydrogen is not inefficient renewable energy resource currently as most hydrogen is produced from fossil fuels, through the means of reformation. Reforming is a chemical process used to convert petroleum refinery naphtha into high-octane liquid products, producing significant amounts of by-product hydrogen gas [3]. For a sustainable future, biomass is a promising replacement to fossil fuels where hydrogen can be sourced from.

Sago exists in abundance in Sarawak as a result of the commercialization of sago through estate planning. Currently, Malaysia is the third-largest sago producer in the world, after Indonesia and Papua New Guinea [4]. Not only is sago used in the food industry, but it is also utilized in biotechnology, manufacturing industry, poultry industry, and paper industry [5]. Due to its versatility in usage and potential for export, sago’s production will be expected to rise and correspondingly, the sago’s waste will increase as well. If not properly treated, sago waste could cause a negative environmental impact. Therefore, a good waste management strategy for sago factories would be utilizing the sago waste to their full potential, making it as a raw material in a microbial electrolysis cell (MEC) to produce hydrogen fuel. The sago waste presents an enticing and low-cost feedstock for hydrogen production.

Until recently, MECs are emerging as a promising method for hydrogen production from the pure substrate like glucose, industrial wastewater, and solid waste. In MECs, electrochemically active bacteria are used to oxidize organic matter to produce hydrogen with the aid of externally supplied voltage [6]. Applications of MECs are vast, including an alternative to fossil fuels to run a vehicle, ammonia production, and power generation [7]. Thus, this project is conducted to establish mathematical modeling for biohydrogen production in the MECs to study the chemical reaction in-depth.

2. Overview of Microbial Electrolysis Cell (MEC)

In a MEC, electrochemically active bacteria oxidize organic matter and generate protons, electrons, and carbon dioxide. The bacteria transfer the electrons to the anode and the protons are released to the solution. The electrons then travel through a wire with the help of external voltage and combine with free protons in the electrolyte to produce hydrogen gas at cathode [8]. The current which indicates the amount of electron flow directly measures the hydrogen production rate. The membrane between the cathode and anode acts as a physical barrier to only allow free-protons (H+) to pass. Moreover, it also reduces the cross-over of bacteria and maintains the purity of the hydrogen gas evolved at the cathode. Membranes commonly used in MEC are proton-exchange membranes (PEM), anion-exchange membranes (AEM), charge-mosaic membrane (CMM), and bipolar membrane [9].

3. Integration of MEC with Photo-Fermentation

MECs alone break down carbohydrates slowly and results in low H2 production, making it not efficient as a process to treat complex wastewater. Thus, MECs are usually paired with fermentation to achieve complete and efficient conversion. Photo-fermentation is preferred over dark fermentation because dark fermentation has an intrinsic upper limit of 4 mol of H2/mol hexose due to incomplete oxidation [10]. On the other hand, photo-fermentation produces complete conversion to H2 and CO2. Table 1 shows the comparison between fermentation, MEC, and MEC with fermentation in terms of various properties.

| Properties                        | Fermentation | MEC | MEC with fermentation |
|-----------------------------------|--------------|-----|-----------------------|
| H2 yield [%]                      | 14-27        | 23-71 | >85                   |
| H2 production rate [m³ H2/m³ reactor/day] | 0.2-10      | 0.1-3.4 | >10                   |
| Complex biomass degradation       | Yes but incomplete | No  | Yes and complete |
| Complete organic to H2 conversion | No           | Yes | Yes                   |
| Produce H2 at high yield          | No           | Yes | Yes                   |
Produce $\text{H}_2$ at a high rate | Yes | No | Yes
---|---|---|---
Produce $\text{H}_2$ at low temperature | Difficult | Possible | Possible
Produce $\text{H}_2$ with high purity | No | Possible | Possible
Treat wastewater for reuse/discharge | No | Possible | Possible
Waste biorefinery application | Long-term | Long-term | Nearer-term

### 4. Mathematical Model

The kinetic model proposed by Gadhamshetty et al. [11] is deemed the best kinetic model as it takes into account the inhibitory effects of high biomass concentration and excess light. Higher biomass concentration reduces the light intensity inside the photo-fermentation biohydrogen reactor (PBR), causes self-shading effects, and limits the substrate diffusion. The declining effect of excess light on biomass growth as the surplus absorbed light energy may result in damage and degradation of the reaction center involved in the photosynthetic process.

Then, MEC performance strongly depends on the activity and efficiency of the anode and cathode catalysts. The reaction occurs at the anode are as follows [12,13].

$$
\begin{align*}
\text{C}_2\text{H}_4\text{O}_4 + \text{H}_2\text{O} + 4\text{M}_{\text{ox}} & \rightarrow 4\text{M}_{\text{red}} + \text{CO}_2 \\
4\text{M}_{\text{red}} & \rightarrow 4\text{M}_{\text{ox}} + 8e^- + 8\text{H}^+ \\
\text{C}_2\text{H}_4\text{O}_4 & \rightarrow \text{CH}_4 + \text{CO}_2 \\
\text{CO}_2 + 4\text{H}_2 & \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}
\end{align*}
$$

Among all the mathematical models, models proposed by Azwar et al. [12] and Pinto et al. [13] are adequate to describe the process in MEC. However, the model implemented by Azwar et al. [12] was derived from the model proposed by Pinto et al. [13]. Then, the model implemented by Pinto et al. [13] is more comprehensive and inclusive where it describes the MEC in three biofilm layers, and meanwhile, a model proposed by Azwar et al. [12] considered only two biofilm layers. Thus, the model proposed by Pinto et al. [13] is chosen as the best option, but since it is describing a continuous MEC operation, equations would be adjusted accordingly to fit the batch process model for this study. The substrate material balance is written as in equations (1) and (2).

$$
\begin{align*}
\frac{dS}{dt} &= -q_{i}\text{f}_x + D(S_0 - S) \\
\frac{dA}{dt} &= -q_{e}\text{f}_x + q_{m}(x_{m,1} + x_{m,2}) + D(A_0 - A) + Y_{\text{cod}}q_{r}\text{f}_x
\end{align*}
$$

The outer biofilm (Layer 1) mass balance equations are formulated as in equations (3) and (4).

$$
\begin{align*}
\frac{dx_{f}}{dt} &= u_{f}\text{f}_x - K_{d,f}\text{f}_x - a_{f}\text{f}_x \\
\frac{dx_{m,1}}{dt} &= u_{m}\text{x}_{m,1} - K_{d,m}\text{x}_{m,1} - a_{m}\text{x}_{m,1}
\end{align*}
$$

The inner biofilm (Layer 2) mass balance equations are written as in equations (5) and (6).

$$
\begin{align*}
\frac{dx_{e}}{dt} &= u_{e}\text{e}_x - K_{d,e}\text{e}_x - a_{2}\text{e}_x \\
\frac{dx_{m,2}}{dt} &= u_{m}\text{x}_{m,2} - K_{d,m}\text{x}_{m,2} - a_{2}\text{x}_{m,2}
\end{align*}
$$

The cathodic biofilm (Layer 3) mass balance is formulated as in equation (7).

$$
\frac{dx_{h}}{dt} = u_{h}\text{h}_x - K_{d,h}\text{h}_x - a_{2}\text{h}_x
$$

Meanwhile, the mass balance for the intracellular is as in equations (8) and (9).

$$
M_{\text{total}} = M_{\text{red}} + M_{\text{ox}}
$$
\[
\frac{dM_{ox}}{dt} = -Y_{m} q_{e} + \gamma \frac{I_{MEC}}{V_{X_{e}} mF}
\]  

(9)

Furthermore, as referring to equations (10) – (15), the fermentative and acetoclastic methanogenic microorganisms are assumed to follow Monod kinetic equations, being limited by the organic substrate concentration while the electricigenic microorganisms are assumed to follow Monod kinetic equations, being limited by the organic substrate concentration and the oxidized form of the mediator.

\[
u_{f} = u_{max,f} \frac{S}{K_{s,f} + S}
\]  

(10)

\[
q_{f} = q_{max,f} \frac{S}{K_{s,f} + S}
\]  

(11)

\[
u_{m} = u_{max,m} \frac{A}{K_{A,m} + A}
\]  

(12)

\[
q_{m} = q_{max,m} \frac{A}{K_{A,m} + A}
\]  

(13)

\[
u_{c} = u_{max,c} \left( \frac{A}{K_{A,c} + A} \right) \left( \frac{M_{ox}}{K_{m} + M_{ox}} \right)
\]  

(14)

\[
q_{c} = q_{max,c} \left( \frac{A}{K_{A,c} + A} \right) \left( \frac{M_{ox}}{K_{m} + M_{ox}} \right)
\]  

(15)

The hydrogenotrophic methanogens are assumed to have a growth that is dependent on the H2 in catholyte. Since H2 has a solubility in water, zero-order growth kinetics is assumed if there is no H2 produced or no current in which can be expressed as in equation (16).

\[
\mu_{h} = \begin{cases} 
\mu_{max,h} & \text{if } I_{MEC} > 0 \\
0 & \text{if } I_{MEC} = 0 
\end{cases}
\]  

(16)

Apart from that, as referring to equations (17) – (19), the biofilm retention is assumed to be limited by maximum attainable biomass concentration (X_{max}), said to be saturated when X_{max} is exceeded. The biofilm retention constants have the symbol a.

\[
a_{1} = \frac{u_{f} x_{f} - K_{d,f} x_{f} + u_{m} x_{m,1} - K_{d,m} x_{m,1}}{x_{f} + x_{m,1}}
\]  

(17)

\[
a_{2} = \frac{u_{e} x_{e} - K_{d,e} x_{e} + u_{m} x_{m,2} - K_{d,m} x_{m,2}}{x_{e} + x_{m,2}}
\]  

(18)

\[
a_{3} = u_{h} - K_{d,h}
\]  

(19)

Then, the current is calculated by using the equations (20) – (21).

\[
I_{MEC} = \frac{E_{CEF} + E_{applied} - \frac{RT}{mF} \ln \left( \frac{M_{Total}}{M_{red}} \right) - \frac{RT}{\beta mF} \sinh^{-1} \left( \frac{I_{MEC}}{A_{sur,A'}} \right)}{R_{int} - \frac{RT}{\beta mF} \sinh^{-1} \left( \frac{I_{MEC}}{A_{sur,A'}} \right)}
\]  

(20)

\[
R_{int} = R_{MIN} + (R_{MAX} - R_{MIN}) e^{-K_{s} X_{e}}
\]  

(21)

Lastly, the hydrogen production generated from this MEC is determined by using the equation (22).
5. Result and Discussion

As mentioned in the previous paragraph, a mathematical model developed by Pinto et al. [13] is referenced to study the behavior of the microbial electrolysis cell in biohydrogen production. The total time is set to be 20 days. The substrate used by Pinto et al. [13] was wastewater and meanwhile, for this project, the substrate is sago effluent. Due to similar nature where the substrate is highly diluted by water, the sago effluent is assumed to have the same behavior as wastewater. Apart from that, equations have been slightly modified because the model implemented by Pinto et al. [13] described a continuous process and the sago effluent is in a batch process inside the microbial electrolysis cell (MEC).

\[ Q_{H_2} = Y_{H_2} \left( \frac{I_{\text{MEC}} \cdot RT}{m_{H_2} \cdot F} \right) - Y_{h \text{h}} u_{h} x_{h} V \]  \hspace{1cm} (22)

Figure 1. Substrate concentration over time

The initial substrate concentration of 1500 mg/L is chosen. The substrate concentration decreases very steeply from 1500 mg/L to 12 mg/L on the third day (t = 3 days), as seen in figure 1. Subsequently, the substrate concentration slowly decreases to 0 mg/L because the organic matter in sago is broken down to acetate by the microorganisms called fermentative microorganisms. The fermentative microbes metabolize complex carbon chains and convert them to acetate. The behavior of fermentative microorganisms is exhibited in figure 2.

Figure 2. Concentration of fermentative microorganisms over time
The phenomena illustrated in figure 2 follows that the pattern of substrate concentration in figure 1. This is due to the fact that at the beginning (t = 0 day), the fermentative microorganisms are breaking down substrate rapidly, leading to the growth of fermentative microorganisms up until the third day (t = 3 days), reading its maximum concentration of 50 mg/L. On the third day (t = 3 days), the substrate has been used up by the fermentative microorganisms, thus from that point onwards, the concentration of fermentative microorganisms decreases gradually to a small number of 18 mg/L. This happens in Layer 1 which is the outer biofilm layer at the anode.

![Figure 3. Acetoclastic methanogens over time](image)

Based on figure 3, the concentration of acetoclastic methanogens, with an initial concentration of 50 mg/L, rises slowly to 63 mg/L on the seventh day (t = 7 days). This is due to the availability of acetate as a result of microbial fermentation and the lack of competition from electricigenic microorganisms in the first few days. The concentration of electricigenic microorganisms only starts to increase on around the third day (t = 3 days). Therefore, the acetoclastic methanogens are actively consuming the acetate until the seventh day (t = 7 days). From the seventh day (t = 7 days), the concentration of microbes decreases gradually to 15 mg/L at the last day (t = 20 days). This means that acetate is being converted to methane for these 20 days. However, the amount of methane production is negligible due to a small concentration of acetoclastic methanogens relative to the concentration of electricigenic microorganisms (Xmax for acetoclastic methanogens is 65 and Xmax for electricigenic microorganisms is 512.5). Based on figure 3, it can be deduced that acetoclastic methanogens have failed to compete with electricigenic microorganisms which grow at a much faster rate and experience no decline in concentration.

![Figure 4. Electricigenic microorganism over time](image)
In figure 4, the concentration of electrigenic microorganisms remain almost dormant in the first 2 days \((t = 2 \text{ days})\) because of the low initial concentration. Unlike the concentration of acetoclastic methanogens which starts with 50 mg/L, the concentration of electrigenic microorganisms starts with 1 mg/L. With the initial condition of 1 mg/L, it has to take some time for growth and reproduction to increase to a substantial amount. From the second day \((t = 2 \text{ days})\), the concentration of electrigenic microorganisms starts to increase exponentially to 512.5 mg/L, which is the maximum biofilm density after 4 days. Layer 2 represents the inner biofilm at the anode, containing electrigenic and acetoclastic methanogens. Competition exists between electrigenic and acetoclastic methanogens in consuming the same carbon source, which is the acetate. Electrigenic microorganisms convert acetate to carbon dioxide, proton, and electron while acetoclastic methanogens convert acetate to methane. From both figures 3 and 4, it can be deduced that the growth of acetoclastic methanogens is lower than that of electrigenic microorganisms. This results in a more microbial community composed of the majority of electrigenic microorganisms and little to none acetoclastic methanogens at the end \((t = 20 \text{ days})\). This is imperative because the type of microbial community present in the MEC has a huge influence on the gas product of MEC. A MEC with a microbial population composed mainly of acetoclastic methanogens produces methane instead of hydrogen and vice versa. Thus, to make sure that the MEC produces hydrogen instead of methane, it is important to ensure that the MEC has a microbial community made up of a large proportion of electrigenic microorganisms.

Figure 5 illustrates the behavior of hydrogenotrophic methanogens in the MEC and this represents the situation in Layer 3. Layer 3 is the biofilm at the cathode, mainly populated by the hydrogenotrophic methanogens. It can be observed that the hydrogenotrophic methanogens present in a very small amount in the cathode compartment in the MEC in the beginning, with the initial value of 10 mg/L. This is due to the lack of current, which indicates the flow of electrons in the first 3 days. According to the equation (16), there will be no growth for hydrogenotrophic methanogens if no current is formed in the MEC. This is reasonable as the presence of current indicates that there is a flow of electrons and with the flow of electrons hydrogen production is feasible. From the third day \((t = 3 \text{ days})\), there is shown to be a gradual increase of current which signifies that the electrigenic microorganisms are actively breaking down the acetate to carbon dioxide, proton, and electron, as exhibited in figure 6. With more protons flowing to the cathode and forming more hydrogen, hydrogenotrophic methanogens consume hydrogen as a source of energy will thrive in the environment. Hydrogenotrophic methanogens convert hydrogen to methane. This is an undesirable side microbial reaction arisen from the abundance of hydrogen in the cathode compartment. However, it is unavoidable in the cathode compartment in MEC which is a hydrogen-rich environment. From the third day \((t = 3 \text{ days})\), the hydrogenotrophic methanogens slowly increase, due to the formation of current and hydrogen. At this point \((t = 3 \text{ days})\), the concentration of hydrogenotrophic methanogens is still very low, at 10 mg/L and it takes some time for growth and reproduction to increase to a substantial amount. From the sixth day \((t = 6 \text{ days})\), the concentration of hydrogenotrophic methanogens can be observed to grow exponentially. This shows the clear correlation between MEC current and concentration of hydrogenotrophic methanogens as well as the correlation between hydrogen production and concentration of hydrogenotrophic methanogens. Nevertheless, the biofilm density in Layer 3 will reach a maximum value of 1680 mg/L on day 16. That means the biofilm density is saturated and any growth of hydrogenotrophic microorganisms is not possible.
The close relationship between MEC current and electricigenic microorganisms can be observed in figure 6. It can be seen that the point of ascending of MEC current (t = 3 days) is identical with that of the concentration of electricigenic microorganisms, shown in figure 4. Electricigenic microorganisms metabolize on acetate, converting it to carbon dioxide, proton, and electron. This effect of electron production has caused the flow of current in the MEC. Its growth is happening exponentially due to the abundance of acetate from the third day (t = 3 days), fermented from the sago effluent. This phenomenon is inconsistent with equation (21), which explains that the high concentration of electricigenic microorganisms, encouraging the transfer of electrons, which in turn results in the decrease in internal resistance. The decrease in internal resistance gives rise to the increase of MEC current. The current in MEC is also observed to reach a maximum value of 0.38A, due to the maximum concentration of electricigenic microorganisms limited by its maximum biofilm density, which cannot increase further to produce more electrons. The minimum internal resistance of MEC is said to be reached. Thus, 0.38A is the maximum current attainable due to imitation of growth of electricigenic microorganisms and minimum internal resistance of MEC.

Based on figure 7, the correlation between hydrogen production and MEC current as well as the correlation between hydrogen production and electricigenic microorganisms are observed as they have the same point of ascending (t = 3 days). The occurrence of hydrogen production is expected to follow
the trend of current and electricigenic microorganisms because during the process where electricigenic microorganisms consume acetate, they do not only produce electrons, but they produce protons as well. With the combined of both electric potential that results from the microbial activity of electricigenic microorganisms and the additional voltage supplied from the outside source, the voltage is high enough to reduce the proton to hydrogen gas. In figure 7, the hydrogen production rate increases sharply from the third day ($t = 3$ days) until the fourth day ($t = 4$ days) to a value of 3.8 L/day, then it can be seen that the hydrogen production rate slowly decreases from the fourth day ($t = 4$ days) to sixteenth day ($t = 16$ days) to a value of 3 L/day. The decrease of hydrogen production can be attributed to Layer 3 biofilm, which is populated by the microbial community of hydrogenotrophic methanogens. These hydrogenotrophic methanogens, in the environment that is rich in hydrogen, aggressively consume the hydrogen in the cathode compartment and reproduces in a rapid manner, which causes the hydrogen production rate to drop further. At day 16 ($t = 16$ days), the biofilm at the cathode compartment has reached saturation and maximum hydrogen consumption is achieved. Therefore, from that day onwards, the hydrogen production rate is sustained at the rate of 3 L/day.

![Graph of hydrogen production rate over time](image)

**Figure 7.** Hydrogen production over time

### 6. Conclusion

A mathematical model of the microbial and electrolysis cell in hydrogen production has been developed and modified by using sago effluent as a substrate in a batch process. Based on the results, more microbial community with a majority of electricigenic microorganisms and little to none acetoclastic methanogens which leads more hydrogen production, with a maximum of 3.8 L/day ($t = 4$ days) and 0.38A of MEC current compared to low concentration of hydrogenotropic methanogen with only 10 mg/L, indicating methane production. As conclusion, the model is able to predict and correlate between hydrogen production with concentration of electricigenic microorganisms and MEC current.

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### Nomenclature

- $A$: Acetate concentration in the MEC anodic compartment [mg-A/L]
- $A_0$: Acetate concentration in the MEC’s influent [mg-A/L]
- $\text{CH}_4$: Methane [mol]
- $\text{C}_2\text{H}_4\text{O}_2$: Methyl formate [mol]
CO₂ : Carbon dioxide [mol]  
D : Dilution rate [1/day]  
e⁻ : Electron [mol]  
ECEF : Counter-electromotive force for MEC [V]  
F⁻ : Faraday constant [Admol/e]  
H⁺ : Proton [mol]  
H₂O : Water [mol]  
I_MEC : MEC current [A]  
K : Half-saturation (Monod) constant [mg-X/L]  
m : Number of electrons transferred mol of H₂ (mol-e/mol-H₂)  
Mox : Oxidized mediator fraction [mol]  
Mred : Reduced mediator fraction [mol]  
M_Total : Total mediator weight percentage in each electricigenic microorganism [mg-M/mg-X]  
qₑ : Substrate consumption rate by electricigenic microorganisms [mg-A/mgX d]  
qᵥ : Substrate consumption rate by fermentative microorganism [mg-S/mgX d]  
qₘ : Substrate consumption rate by methanogenic microorganisms [mg-S/mgX d]  
R : Ideal gas constant [J/K mol]  
R_int : MEC internal resistance [ohm]  
S : Organic substrate concentration in the MEC anodic compartment [mg-S/L]  
S₀ : Organic substrate concentration in the MEC’s influent [mg-S/L]  
T : MEC anodic compartment temperature [K]  
uₑ : Electricigenic microorganisms growth rate [1/d]  
uᵥ : Fermentative microorganisms growth rate [1/d]  
uₕ : Hydrogenotrophic methanogenic microorganisms growth rate [1/d]  
uₘ : Methanogenic microorganisms growth rate [1/d]  
V : MEC anodic compartment volume [L]  
xₑ : The concentration of electricigenic microorganisms in the MEC biofilm Layer 2 [mg-X/L]  
xᵥ : The concentration of fermentative microorganisms in the MEC biofilm Later 1 [mg-X/L]  
xₕ : The concentration of hydrogenotrophic methanogenic microorganisms in the MEC biofilm Layer 3 [mg-X/L]  
xₘ,₁ : The concentration of acetoclastic methanogenic microorganisms in MEC biofilm Layer 1 [mg-X/L]  
xₘ,₂ : The concentration of acetoclastic methanogenic microorganisms in MEC biofilm Layer 2 [mg-X/L]  
Y_cod : Acetate yield from the organic substrate [mg-S/mg-A]  
Y_m : Mediator yield [mg-M/mg-S]  
γ : Mediator molar mass [mg-M/mol-M]  
α : Dimensionless biofilm retention constant  
β : Dimensionless reduction or oxidation transfer coefficient

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