

PERFORMANCE OF A MOVING BED BIOFILM REACTOR (MBBR) IN THE REMOVAL OF COD, TSS, AND SURFACTANTS FROM LAUNDRY WASTEWATER

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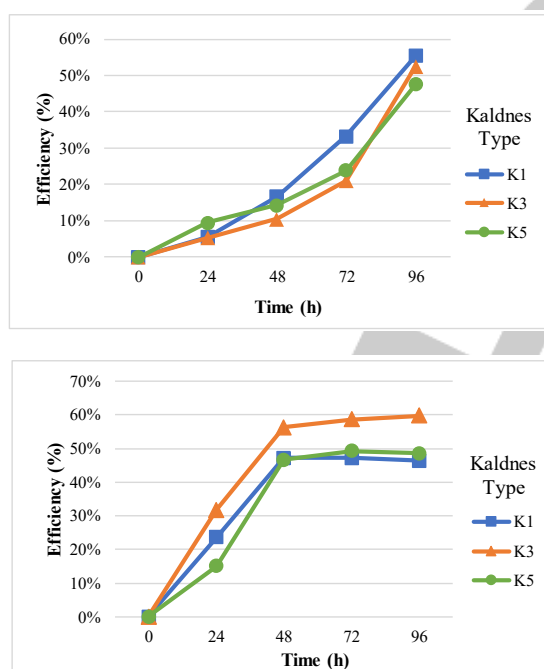
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Graphical abstract



ABSTRACT

Laundry liquid waste contains organic materials and chemical compounds that can reduce environmental quality if not treated properly. One applicable treatment method is the Moving Bed Biofilm Reactor (MBBR) process using Kaldnes carriers. This study aims to determine the effect of retention time and type of Kaldnes carriers on pollutant removal efficiency and to analyze the kinetic characteristics of microorganism growth on each carrier. The study was conducted using three aerobic MBBR reactors with variations of K1, K3, and K5 Kaldnes carriers. The retention time used was 0, 24, 48, 72, and 96 hours. The kinetic parameters analyzed included specific growth rate (μ), biomass yield (Y), specific substrate consumption rate (q), and Monod kinetic parameters in the form of $\mu_{\max}$ and K_s . The results indicated that the optimal removal efficiency for all parameters was achieved at a Hydraulic Retention Time (HRT) of 96 hours. The highest TSS removal of 56% was observed in the reactor using Kaldnes K1 carriers, whereas the highest efficiencies for surfactant and COD were achieved in the reactor using Kaldnes K5 carriers, with 60% for surfactant and 62% for COD. The μ values in Kaldnes K1 was 0.0025 h^{-1} , while for both Kaldnes K3 and K5 it was 0.0027 h^{-1} . The Y values are $0.80 \text{ mg VSS/mg COD}$ for Kaldnes K1 and K5 and $0.76 \text{ mg VSS/mg COD}$ for Kaldnes K3. The q value for the Kaldnes K1, K3, and K5 were 0.0031 h^{-1} ; 0.0035 h^{-1} ; and 0.0033 h^{-1} . Based on the Monod approach for the Kaldnes K1, K3, and K5, the $\mu_{\max}$ values were 0.0035 h^{-1} ; 0.0047 h^{-1} ; and 0.0045 h^{-1} , while the K_s value is 239.23 mg/L ; 477.85 mg/L ; and 420 mg/L .

Keywords: Laundry Waste, MBBR, COD, TSS, Surfactants, and Monod Kinetic

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1. INTRODUCTION

Laundry services are increasingly in demand because they offer practicality and efficiency for urban people who have limited time to wash their own clothes. However, behind this convenience, the increase in the number of laundry businesses also has implications for the increase in the volume of waste produced. In general, laundry wastewater contains a high organic load and suspended substances due to the presence of various chemicals in detergents (Amzan et al., 2025). Among them are surfactants as the main components of detergents and phosphate as builders that function to improve detergent performance (Kinasih & Astuti, 2023). The use of detergents containing high levels of chemical substances has the potential to increase water pollution. Despite this, many laundry businesses still discharge their wastewater directly into water bodies without undergoing prior treatment (Rengkugegana & Farahdiba, 2023).

To control the impact of pollution from laundry wastewater, it is necessary to treat wastewater before it is directly discharged into water bodies. Based on its characteristics, laundry wastewater is biodegradable so it is more suitable for processing by biological methods (Putri et al., 2021). Among the various biological treatment options, the Moving Bed Biofilm Reactor (MBBR) is one of the suitable technologies for processing laundry wastewater. Unlike conventional biofilm reactors, the MBBR process uses carriers that move freely within the reactor, so that it does not require sludge recirculation; microorganisms grow and stick to the surface of the carriers (Slamet et al., 2023). The MBBR process operates under aerobic conditions, with oxygen supplied through an aeration system that supports biofilm growth while keeping the carrier media in motion. The media in the MBBR reactor must remain continuously mobile to prevent excessive biofilm accumulation, which may reduce treatment efficiency (Kang & Kim, 2021). In general, the media that is often used in the MBBR process is Kaldnes. Kaldnes are made of plastic material and are available in several types, among which the most common are Kaldnes types K1, K3, and K5 (Dhuhan et al., 2021). Each type of Kaldnes has differences in terms of dimensions (diameter and height), specific surface area for biofilm growth, as well as certain design features that affect the biofilm performance and MBBR reactor performance. In addition to the type of media, the duration of stay (HRT) in the reactor is also an important factor that affects the efficiency of MBBR processing (Bering et al., 2020). The detailed specifications of each Kaldnes carrier type are summarized in Table 1.

Table 1. Specifications of Kaldnes Carrier

Specifications Of Kaldnes Carrier		
Kaldnes K1	Value	Figure
Diameter	10 mm	
Height	10 mm	
Surface Area	500 m ² /m ³	
Kaldnes K3	Value	Figure
Diameter	25 mm	
Height	10 mm	
Surface Area	650 m ² /m ³	
Kaldnes K5	Value	Figure
Diameter	25 mm	
Height	5 mm	

Specifications Of Kaldnes Carrier	
Surface Area	1000 m ² /m ³



Based on this background this study was conducted to evaluate the comparative removal performance of different Kaldnes media and retention times. Unlike previous MBBR studies by Bering et al., (2020) and Kusuma et al., (2019) that typically evaluated a single carrier type or focused mainly on removal performance on laundry wastewater, this study compares the effects of Kaldnes type (K1, K3, and K5) and retention time on the reduction of COD, TSS, and surfactants in laundry wastewater using MBBR batch reactors. In addition, an approach based on Monod kinetic modeling is applied to predict the microbial growth rate as a function of substrate concentration. Understanding how microbes grow is very important to measure how easily a material decomposes. The results can be compared and used in real environmental conditions, so practical guidance based on the growth of microorganisms is needed.

2. MATERIALS AND METHODS

The equipment used consisted of three reactors and three types of carriers (Kaldnes K1, Kaldnes K3, and Kaldnes K5) were used in this study. Each reactor had a diameter of 28 cm and a height of 26 cm, as shown in Figure 1. In addition, the materials required for wastewater treatment include EM4 (Effective Microorganisms 4) as a starter and several nutrients.

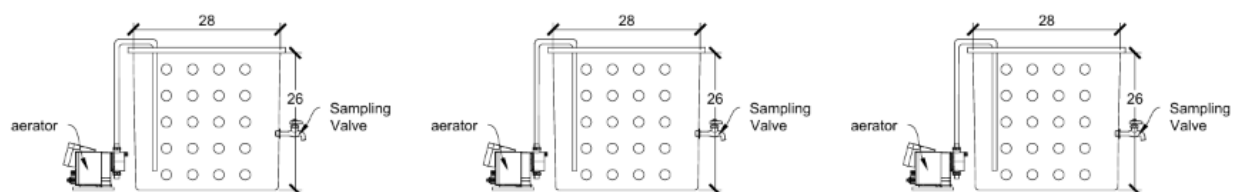


Figure 1. Reactor Design

This research was carried out using an MBBR reactor on a laboratory scale. The first step that must be done to carry out biological processing using the MBBR reactor is seeding. The *seeding* process is carried out by adding *starters* and nutrients to prepare and cultivate microorganisms. After the *seeding process*, the acclimatization process is then carried out as a phase of self-adjustment of microorganisms to the new environment. Acclimatization is carried out in stages by gradually increasing the percentage of wastewater. After the seeding and acclimatization processes were completed, the main treatment process in the MBBR reactors could be initiated.

This study used a batch system MBBR of three reactors with a media filling ratio of 40% in each reactor. Treatment is carried out aerobically with oxygen supply using an aerator to keep the media moving. The aerobic biological process was carried out under controlled pH (7-8) and temperature (25-35°C). The reactors were operated at different retention times of 0, 24, 48, 72, and 96 hours. Wastewater samples were taken at the beginning of the operation ($t = 0$) and at the end of the HRT period ($t = \text{HRT}$) to analyze changes in the concentration of water quality parameters. The water quality parameters measured in this study include COD (Chemical Oxygen Demand), TSS (Total Suspended Solids), and MBAS (Methylene Blue Active Substances), with initial concentrations of the

raw laundry wastewater were 923 mg/L for COD, 480 mg/L for TSS, and 6.3 mg/L for MBAS. The efficiency of the allowance of each parameter will be calculated based on the comparison between the initial and final concentrations using the equation:

$$\% \text{ Efficiency} = \frac{C(\text{initial}) - C(\text{final})}{C(\text{initial})} \times 100\% \quad (1)$$

3. RESULT AND DISCUSSION

A. Efficiency of Dispensing

The Effect of Retention Time and Type of Kaldnes on TSS Removal

In aerobic biofilm systems, organic particles are hydrolyzed into dissolved organic compounds that are utilized by heterotrophic microorganisms. MBBR is mainly used to remove organic matter and nitrogenous compounds through biofilm activity, but biological activity can also take place in suspended biomass. Therefore, TSS elimination is not entirely caused by biodegradation. TSS organic fractions can be transformed and decomposed by microorganisms, while inorganic fractions as well as biomass detached from the medium must be separated through physical processes (Sumiyati & Hadiwidodo, 2014).

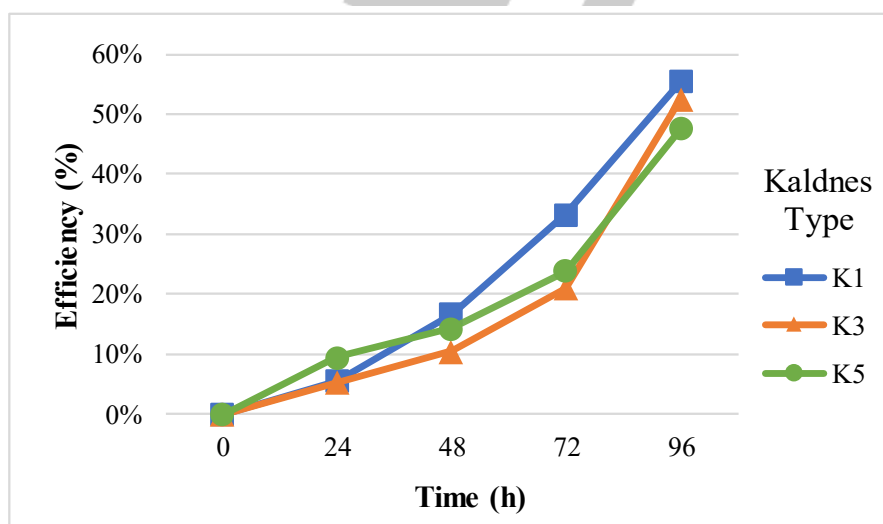


Figure 2. Effect of HRT and Kaldnes Type on TSS Removal

Based on the results of the analysis, the highest percentage of TSS removal was obtained at a retention time of 96 hours for all variations of Kaldnes carriers. Under these conditions, the percentage of TSS removal reached 56% in Kaldnes K1, 53% in Kaldnes K3, and 48% in Kaldnes K5. When compared by media type, Kaldnes K1 showed the highest TSS removal ability with a percentage of 56%, but the efficiency was lower than the results reported by Kholif et al. (2018), which is 88.7% at 4 days of operation under aerobic conditions. Although the two studies used approximately the same dwell time, the percent value of the disposal was different. These differences may be related to different wastewater characteristics, in particular the composition and biodegradability of the solid fraction. TSS is not entirely composed of biodegradable materials, so the properties of solids in laundry wastewater, including the influence of detergents and surfactants—can affect their disposal mechanism and efficiency.

The Effect of Retention Time and Type of Kaldnes on Surfactant Removal

Surfactants in laundry wastewater primarily attribute to the use of detergents during the washing process. Surfactants are one of the active ingredients in detergents that function to help remove dirt from clothes by lowering the water surface tension. During the washing and rinsing process, surfactants will be carried along with the water and enter the wastewater. One type of surfactant that is widely used in detergents is anionic surfactants, such as Linear Alkylbenzene Sulfonate (LAS). The presence of anionic surfactants in wastewater can be analyzed using the Methylene Blue Active Substances (MBAS) parameter.

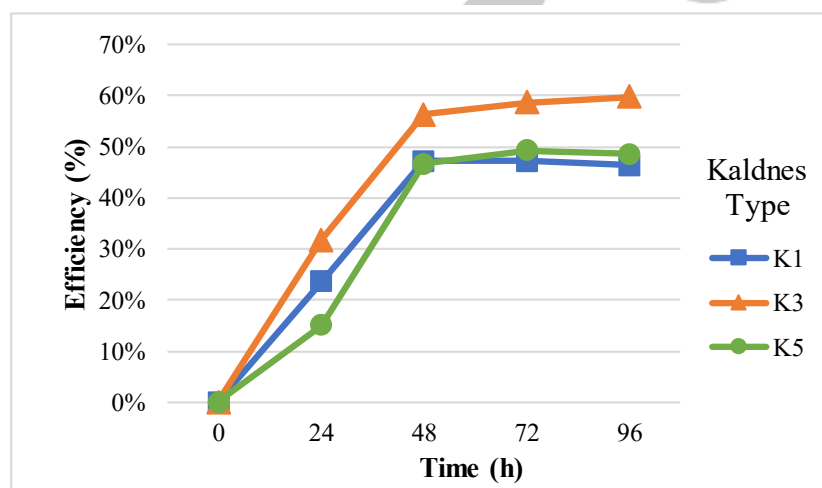


Figure 3. Effect of HRT and Kaldnes Type on Surfactant Removal

In these conditions, the preparation efficiency obtained was 46% in Kaldnes K1, 49% in Kaldnes K3, and 60% Kaldnes K5. Kaldnes K5 media produced the highest removal efficiency compared to the other two media, which was 60%, but the removal efficiency was relatively lower compared to the results reported by Kusuma et al., (2019) with a stay time of 6 days (144 hours), which reported that the efficiency of surfactant elimination in laundry waste reached 82%. This condition is related to the characteristics of microorganisms contained in the starter used. This study utilized EM4 or the microbial starter. The effectiveness of LAS biodegradation depends on the presence and activity of bacteria that are able to use or transform surfactants as substrates. One of the bacteria that has the potential to play a role for surfactant removal is *Pseudomonas sp.*, as used in the study by Anindya et al. (2025). However, these bacteria are not necessarily the dominant microorganisms in the EM4 consortium. If the number is low or has not adapted to the concentration of surfactants and the operating conditions of the reactor, the biodegradation process can be slow. In addition, surfactant-degrading bacteria must compete with other microorganisms in obtaining substrates, oxygen, and growth space in biofilm media. Therefore, the existence of a consortium of microorganisms in EM4 does not necessarily result in high MBAS elimination efficiency.

The Effect of Retention Time and Type of Kaldnes on COD Removal

Organic matter can appear in laundry wastewater derived from clothes, detergents, and fabric softeners. When the washing process takes place, these various materials can be released and carried along with the water, increasing the content of organic matter in the wastewater (Dewi et al., 2015).

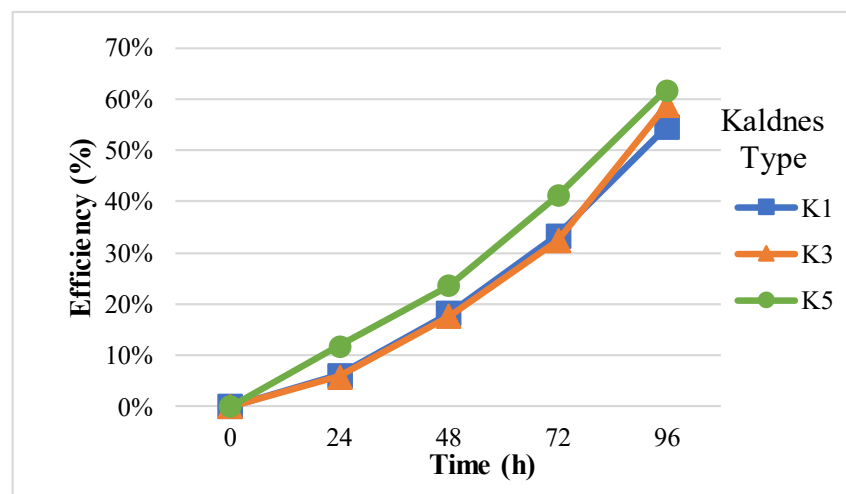


Figure 4. Effect of HRT and Kaldnes Type on COD Removal

The efficiency of COD removal shows a tendency to increase as the dwell time increases across all variations of Kaldnes media. At 96 hours of retention time, Kaldnes K1, Kaldnes K3, and Kaldnes K5 produce COD removal efficiency of 54%, 59%, and 62%, respectively. Of the three types of carriers, Kaldnes K5 achieved the highest COD removal performance. The obtained COD removal efficiency did not exceed the 63–78% reported by Wardoyo et al. (2020) at a 48-hour retention time. This gap in performance may be related to variations in COD characteristics, the microorganisms growing within the system, and their use of Polyurethane Foam rather than the Kaldnes carriers utilized in this study. In addition, the study by Anindya et al. (2025) using *Pseudomonas aeruginosa* bacteria as a starter also obtained a relatively high COD removal efficiency, which is 84%. This value is higher than the results of this study which only reached 62%. This difference highlights the significant impact of the microbial starter type on system performance.

B. Biodegradation Kinetics

Table 2. Biodegradation Kinetics Parameters

Parameter	Kaldnes Media Type		
	K1	K3	K5
μ (h^{-1})	0.0025	0.0027	0.0027
Y (mg VSS/mg COD)	0.8	0.76	0.8
q (h^{-1})	0.0031	0.0035	0.0033
μ_{max} (h^{-1})	0.0035	0.0047	0.0045
K_s (mg/L)	239.23	477.85	420

Specific Growth Rate (μ)

Specific growth rate is a parameter that represents the ability of microorganisms to multiply and adapt. Heterotrophic microorganisms consume organic matter contained in the wastewater as

a source of carbon and energy to support their growth and activity (Kovárová-Kovar & Egli, 1998). In biological processes, microbial biomass tends to experience exponential growth in the initial phase (*log phase*), where the increase in the amount of biomass (dX) in units of time (dt) is directly proportional to the amount of existing biomass (X). This concept can be expressed in differential form.

$$\frac{dX}{dt} = \mu X \quad (2)$$

Description:

dX = increased amount of biomass (MLVSS, mg/l)

dt = time

μ = specific growth rate (hours⁻¹)

X = biomass concentration (MLVSS) (mg/l)

For the purposes of experimental data analysis, the equation can be solved analytically and reduced to logarithmic form as follows:

$$\ln\left(\frac{X_n}{X_0}\right) = \mu t \quad (3)$$

Description:

X_0 = initial biomass concentration (MLVSS, mg/L)

X_n = biomass concentration at n th time (MLVSS, mg/L)

t = time (hours⁻¹)

μ = specific growth rate (hours⁻¹)

Based on these equations, μ values can be calculated by comparing the MLVSS concentrations at two time points by reducing the equation to the following:

$$\mu t = \frac{\ln\left(\frac{X_2}{X_1}\right)}{t_2 - t_1} \quad (4)$$

Graphically, if the value $\ln(X_n/X_0)$ is plotted against time (t), then the slope of the linear regression result line shows the value of μ . Based on the calculations, all three reactors containing different carrier types exhibited varying biomass growth patterns, but showed an overall increase in biomass during the observation period. From the linear regression results, the K1 Kaldnes media had a μ value of 0.0025 hours⁻¹, while the K3 and K5 Kaldnes had the same μ values, which was 0.0027 hours⁻¹. A higher μ value indicated that the biomass was growing at a faster rate. Thus, Kaldnes K3 and Kaldnes K5 show a slightly higher biomass growth rate than Kaldnes K1. However, the difference in μ values between media is relatively small, so the biomass growth rate in the three media can be said to be relatively similar. The goodness-of-fit of each linear regression was evaluated using the coefficient of determination (R^2). The corresponding R^2 values for all three carriers were 0.99. These values indicate the proportion of variance in $\ln(X_n/X_0)$ that is explained by time; R^2 values close to 1 suggest that the linear model adequately represents the biomass growth data and that the estimated μ values are reliable.

Biomass Yield (Y) Calculation

In addition to the specific growth rate, biomass growth can also be seen based on the biomass yield (Y) value. Biomass yield is a parameter that shows the amount of biomass of microorganisms formed from each unit of substrate consumed. Biomass yield (Y) is the coefficient of comparison between the amount of biomass formed (dX) and the amount of substrate consumed (dS) in a biodegradation process. Biomass yield states that the increase in biomass (dX) is always proportional to the decrease in substrate (dS). Biomass yield (Y) can be expressed with the following equation:

$$\frac{dX}{dS} = Y \quad (4)$$

$$\frac{\Delta X}{\Delta S} = Y \quad (5)$$

$$\frac{X - X_0}{S_0 - S} = Y \quad (6)$$

$$X - X_0 = Y(S_0 - S) \quad (7)$$

Description:

- Y = yield coefficient (mg MLVSS/mg COD)
- X = final biomass concentration (MLVSS, mg/L)
- X_0 = initial biomass concentration (MLVSS, mg/L)
- S = final substrate concentration (COD, mg/L)
- S_0 = initial substrate concentration (COD, mg/L)

Based on the results of linear regression, Kaldnes K1 and Kaldnes K5 have the same yield value, which is 0.80 mg VSS/mg COD, while Kaldnes K3 has a yield value of 0.76 mg VSS/mg COD. Higher yield values indicate that more substrates are converted into biomass. The yield coefficient obtained in this study was higher than the 0.39 reported by Madan et al. (2023) and 0.45 mg VSS/mg COD by Ahmadi et al. (2017). However, the yield value in this study is still in the range of 0.40–0.80 mg VSS/mg COD reported by Strotmann et al. (2004). Differences in yield values between studies can occur because biomass formation is influenced by wastewater characteristics, substrate concentration, inoculum source, substrate-to-inoculum ratio, microorganism conditions, and reactor operating conditions. Therefore, although this study and previous studies both used MBBR under aerobic conditions, differences in waste characteristics and operating conditions can lead to different yield values. The corresponding R^2 values for the linear regressions were 0.98 for Kaldnes K1, 0.95 for Kaldnes K3, and 0.97 for Kaldnes K5, indicating a strong fit between the linear model and the observed relationship between substrate consumption and biomass production.

Calculation of Substrate Consumption Rate (q)

The yield value is related to the consumption rate of specific substrates (q), because biomass growth requires substrates as a source of energy and materials for cell formation. Substrate consumption rate (q) to determine how fast microorganisms consume substrate per unit of biomass.

The value of substrate consumption rate can be calculated based on the relationship between biomass growth rate (μ) and biomass growth rate (Y) with the following equation:

$$q = \frac{\mu}{Y} \quad (8)$$

Where:

Y = yield coefficient (mg MLVSS/mg COD)

μ = microbe-specific growth rate (hours⁻¹)

q = substrate consumption rate (hours⁻¹)

Based on the calculation results, the q value in Kaldnes K1 is 0.0031 hours⁻¹, Kaldnes K3 is 0.0035 hours⁻¹, and Kaldnes K5 is 0.0033 hours⁻¹. The highest q value was obtained in Kaldnes K3, this shows that microorganisms in Kaldnes K3 have a slightly higher rate of consumption of specific substrates than Kaldnes K1 and Kaldnes K5. The q value is related to the value of μ and yield (Y), which can be mathematically expressed through the relationship. With this relationship, the q value is not only influenced by the magnitude of the biomass growth rate, but also by the ability of microorganisms to convert the substrate into biomass. A higher μ combined with a lower Y value tends to result in a larger q value. Therefore, a higher q value indicates a greater need for the consumption of a specific substrate to support biomass growth, but cannot be directly interpreted as better processing performance.

Calculation of saturation constant (K_s) and Maximum Growth Rate (μ_{max})

In the process of biodegradation, the growth rate of microorganisms is greatly influenced by the availability of substrates. To illustrate this relationship, the Monod kinetics model is used, which states that the specific growth rate (μ) is directly proportional to the concentration of the substrate (S), considering the saturation constant (K_s) and the maximum growth rate (μ_{max}). The model is written as:

$$\mu = \frac{\mu_{max} \cdot S}{K_s + S} \quad (9)$$

For the purposes of linear analysis, these equations can be changed to the Lineweaver–Burk form of enzymes.

$$\frac{1}{\mu} = \frac{K_s}{\mu_{max}} \cdot \frac{1}{S} + \frac{1}{\mu_{max}} \quad (10)$$

Where:

μ = specific growth rate (h⁻¹)

μ_{max} = maximum growth rate (hours⁻¹)

K_s = substrate saturation constant (mg/L)

S = substrate concentration (mg/L)

By plotting a value of $1/\mu$ against $1/S$, a straight line is obtained, with slope = K_s/μ_{max} and intercept = $1/\mu_{max}$. Based on the calculation results, the μ_{max} values in the Kaldnes K1, Kaldnes K3, and Kaldnes K5 were 0.0035 hours⁻¹, 0.0047 hours⁻¹, and 0.0045 hours⁻¹, respectively. In the Monod model, the specific growth rate depends on μ_{max} and substrate concentration, whereas K_s

represents the substrate concentration at which the growth rate reaches half of $\mu_{\max}$. The K_s values obtained in Kaldnes K1, Kaldnes K3, and Kaldnes K5 were 239.23 mg/L, 477.85 mg/L, and 420 mg/L, respectively. The corresponding R^2 values were 0.85 for Kaldnes K1, 0.96 for Kaldnes K3, and 0.70 for Kaldnes K5, indicating a very good fit for K3, a reasonably good fit for K1, and a moderate fit for K5 between the linearized Monod model and the experimental data.

Based on these results, Kaldnes K3 had the highest $\mu_{\max}$ value, which was 0.0047 hours⁻¹. This shows that based on the Monod model approach, microorganisms in Kaldnes K3 have the highest maximum growth rate potential compared to the other two media. However, the $\mu_{\max}$ does not represent the actual growth rate observed during the study, as the realized growth rate also depends on the available substrate concentration. This is reflected in the observed μ values, which are relatively similar across the three media despite the differences in $\mu_{\max}$. Thus, the growth of biomass in this study is not only influenced by the maximum growth potential of microorganisms, but also by the availability of substrates during the processing process.

When viewed from the K_s value, Kaldnes K1 has the lowest K_s value, which is 239.23 mg/L. Thus, Kaldnes K1 exhibits a higher affinity to substrates than Kaldnes K3 and Kaldnes K5. Meanwhile, Kaldnes K3 has the highest $\mu_{\max}$, but also has the highest K_s value. These conditions indicate that Kaldnes K3 has a greater maximum growth potential when a high amount of substrate is available, but requires a higher concentration of substrate to achieve an optimal growth rate. Therefore, the results of kinetic parameters show a difference in the growth characteristics of microorganisms in each medium, where Kaldnes K3 has the highest maximum growth potential, while Kaldnes K1 shows a higher affinity to substrates.

4. CONCLUSION

The conclusion of this study shows that the elimination of COD at 96 hours of stay produces the highest efficiency in Kaldnes K5 by 62%, followed by Kaldnes K3 by 59% and Kaldnes K1 by 54%. The results of the kinetic calculation showed that the specific growth rate (μ) in Kaldnes K1, Kaldnes K3, and Kaldnes K5 was 0.0025; 0.0027; and 0.0027 hours⁻¹, respectively. These values showed that Kaldnes K3 and Kaldnes K5 had a slightly higher biomass growth rate than Kaldnes K1.

The value of biomass yield (Y) in Kaldnes K1, Kaldnes K3, and Kaldnes K5 was 0.80; 0.76; and 0.80 mg VSS/mg COD, respectively. Meanwhile, the value of the consumption rate of specific substrates (q) was 0.0031 each; 0.0035; and 0.0033 mg COD/(mg VSS·hr). The highest q value was obtained in Kaldnes K3, while the lowest value was obtained in Kaldnes K1. This shows that microorganisms in Kaldnes K3 have a higher need for specific substrate consumption to support their biomass growth compared to the other two media.

Based on the Monod kinetic approach, the $\mu_{\max}$ values in Kaldnes K1, Kaldnes K3, and Kaldnes K5 are 0.0035; 0.0047; and 0.0045 hours⁻¹, respectively. These values show that Kaldnes K3 has the highest potential maximum growth rate compared to Kaldnes K1 and Kaldnes K5. Meanwhile, the K_s score obtained was 239.23 each; 477.85; and 420 mg/L. Kaldnes K1 had the lowest K_s value, indicating a higher affinity of microorganisms to substrates than Kaldnes K3 and Kaldnes K5.

Overall, kinetic results showed that each medium had different substrate growth and utilization characteristics. In terms of treatment performance, the effluent after 96 hours of operation showed

that Kaldnes K5 had the best removal efficiency among all media. When compared against the wastewater quality standards set by the East Java Governor (Pergub Jatim No. 72/2013), which specify maximum limits of 250 mg/L for COD, 100 mg/L for TSS, and 10 mg/L for MBAS, the effluent met the standard for MBAS but still exceeded the limits for COD and TSS. This study has several limitations. First, the experiments were conducted at lab scale in batch mode over 96 hours operation, which may not fully represent continuous, long-term operation in real wastewater treatment plants. Second, the wastewater used were real laundry wastewater collected from a local laundry shop in Surabaya, which may differ in composition and variability from actual laundry/domestic wastewater. Third, this study did not analyze the types of microorganisms present in the biofilm on each Kaldnes media. Therefore, it is unclear whether the differences in kinetic parameters among the media are related to differences in microbial community composition.

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