



Kinetic Model of Chemical Organic Matter Removal in Facultative Pond Set A in Domestic Wastewater Treatment Plant (WWTP) Bojongsoang, West Java, Indonesia

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Abstract

Kinetic models are widely used to predict the performance of biological treatment systems. The facultative ponds are applied as a biological treatment for domestic wastewater in the Wastewater Treatment Plant (WWTP) located in Bojongsoang, Bandung Regency, West Java. This study aims to evaluate the suitability of several kinetic models for the chemical oxygen demand (COD) removal process that occurs in facultative ponds in WWTP Bojongsoang. The best kinetic model will provide a more accurate predictions of COD effluent concentrations in facultative ponds. Data series of COD influent and effluent concentration were collected from field data of water quality monitoring monthly from years 2019 to 2022. The kinetic models used in this study were the first-order kinetic model combined plug flow pattern, the first-order kinetic model with continuous stirred tanked reactor flow pattern, the plug flow k-C* model, and the Stover-Kincannon model. Model accuracy was evaluated using statistical methods by calculating the mean average percentage error (MAPE) to compare model data with measured observation data. The COD effluent prediction showed that the Plug Flow k-C* model had the smallest MAPE for both facultative ponds, namely 28.3% for facultative pond 1A and 30.2% for facultative pond 2A. Kinetic rate values for both facultative ponds using plug flow k-C* model respectively, 0.1818 m/day for F1A and 0.1750 m/day for F2A.

Keywords: kinetic model, kinetic constant rate, chemical oxygen demand, facultative pond, wastewater treatment

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1. Introduction

Stabilization ponds are biological wastewater treatments that are widely applied in developing countries. Domestic wastewater treatment using stabilization ponds shows good organic compound removal efficiency with an efficiency percentage of more than 80% - 90% (Bansah et al., 2016; Novia et al., 2024a). There are three principal types of WSPs, namely, anaerobic ponds, facultative ponds, and maturation ponds. These are often used in sequence for wastewater treatment systems. Facultative ponds, which receive water from the anaerobic pond, are normally shallower than anaerobic ponds. It has a typical depth of 1 and 2 m. These operate in aerobic conditions in the upper layers and anaerobic conditions close to the pond bottom (Li et al., 2018).

The performance of biological processing processes is greatly influenced by the selection of appropriate reaction rates through kinetic analysis (Mahapatra et al., 2022). Kinetic analysis aims to describe the performance of biological processing and also predict how biological processing will perform in the future (Sandhya and Swaminathan, 2006). The kinetic model analysis is necessary as a basis for designing facultative ponds. There are some kinetic models used for stabilization ponds namely, the first-order kinetic model combined plug flow pattern, the first-order kinetic model with continuous stirred tanked reactor flow pattern, the plug flow k-C* model, the Grau model, and the Stover-Kincannon model. The Stover-Kincannon model showed the best suitability in predicting the removal of organic compounds (BOD) in the stabilization pond at WWTP Birjand, Iran (Khosravi et al, 2013a).

Meanwhile, the second-order Grau model is most suitable for predicting COD concentrations from facultative ponds at the WWTP Esfarayen, Iran (Alavi and Ansari, 2022). Reaction rate analysis using kinetic models was also used to see the influence of climate on the processing process in stabilization ponds in Greece (Gratziou and Chalatsi, 2016).

One of the domestic wastewater treatment plants (WWTP) that applied facultative ponds is WWTP Bojongsoang, located in Bandung Regency, West Java. Apart from facultative ponds, WWTP Bojongsoang also uses anaerobic and maturation ponds in its domestic wastewater treatment system. The average COD inlet concentration in WWTP Bojongsoang in the year 2019 – 2022 was about in the range of 228.70 mg/L – 385.13 mg/L (Novia et al., 2024b). Based on a study conducted by Widyarani et al., (2022), COD concentration of domestic wastewater in Indonesia are in range 232 mg/L – 780 mg/L.

A previous study relevant to the kinetic equation of removing organic compounds from domestic wastewater treatment in Bojongsoang WWTP focused on the kinetic equation for biochemical oxygen demand (BOD) removal (Anisa, 2010). There is no similar study yet related to the suitability of some kinetic models to predict COD removal based on field data of facultative ponds in Bojongsoang WWTP. In this study, the most suitable kinetic model for the facultative pond at the Bojongsoang WWTP will be analyzed for COD removal. The results of this analysis can become a basis for developing more appropriate design parameters so that the performance of the facultative pond at the Bojongsoang WWTP is more optimal.

2. Methodology

2.1. Study Area

The treatment capacity of Bojongsoang WWTP is about 80,000 m³/day. The Bojongsoang WWTP is divided into 2 sets, namely Set A and Set B, where each set consists of 3 anaerobic ponds, 2 facultative ponds, and 2 maturation ponds. In this research, the scope of the research area is limited to facultative ponds in Set A (1A and 2A) due to the availability of data series.

2.2. Data Analysis

The kinetic models used in this study are the first-order kinetic model combined plug flow pattern, first-order kinetic model with

continuous stirred tanked reactor flow pattern, plug flow k-C* model, and the Stover-Kincannon model.

a) First-order kinetic model combined with plug flow pattern (k1)

The Kickuth equation, which was developed by combining first-order kinetic with the plug flow regime, can be seen in Equation 1.

$$k_1 = \frac{Q(\ln C_{in} - \ln C_{out})}{A} \quad (1)$$

Where Q is the daily flow rate (m³/day), C_{in} is COD concentration in inlet and outlet (mg/L), C_{out} is COD concentration in outlet (mg/L), A is surface area of pond (m²), k₁ is kinetic rate (m/day).

b) First order kinetic model with CSTR flow pattern (k2)

This model is an equation that combines first-order kinetics with CSTR flow, which can be seen in Equation 2.

$$k_2 = \frac{q(C_{in} - C_{out})}{C_{out}} \quad (2)$$

Where, q is hydraulic loading rate (m.day)

c) Plug Flow k-C* model (k3)

The following equation is a combination of the plug flow regime and mass balance in a wetland environment such as a facultative pond, which can be seen in Equation 3.

$$k_3 = q \cdot \ln \frac{(C_{in} - C^*)}{(C_{out} - C^*)} \quad (3)$$

$$C^* = 3,5 + 0,053 C_{in} \quad (4)$$

Where, C* is COD background concentration (mg/L).

d) Stover-Kincannon model (k4)

The Stover-Kincannon equation is widely used in various biological processing processes. In this equation, the rate of organic compound removal is described as a function of the rate of organic loading by mono-molecular kinetics in the biofilm reactor. The Stover-Kincannon equation can be seen in Equation 5.

$$\left(\frac{dC}{dt}\right)^{-1} = \frac{V}{Q(C_{in} - C_{out})} = \frac{Kb}{U_{max}} \left(\frac{V}{QC_{in}}\right) + \frac{1}{U_{max}} \quad (5)$$

Where, dc/dt is COD removal rate (g/L.day), K_b is saturation constant (g/L.d), U_{max} is maximum rate of substrate removal (g/L.d)

Model accuracy was evaluated using statistical methods, namely by calculating the mean average percentage error (MAPE) for comparing model data with field observation data. The calculation of MAPE can be seen in Equation 6.

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{Y_{observed,i} - Y_{model,i}}{Y_{observed,i}} \right| \quad (6)$$

Mathematical equations are used to predict COD effluent concentration based on kinetic rate from each model, presented in Equation 7 to Equation 11 (Alavi and Ansari, 2022).

- Model 1: first-order kinetic combined plug flow pattern

$$C_{out} = C_{in} e^{\frac{-k_1}{q}} \quad (7)$$

- Model 2: first order kinetic model with CSTR flow pattern

$$C_{out} = \frac{C_i}{\left(1 + \frac{k_2}{q}\right)} \quad (8)$$

- Model 3: plug flow k-C

$$C_{out} = C^* + (C_{in} - C^*) e^{\left(\frac{-k_3}{q}\right)} \quad (9)$$

- Model 4: Stover-Kincannon

$$C_{out} = \frac{C_{in} - (U_{max} C_{in} V)}{(K_b + Q C_{in})} \quad (10)$$

3. Results and Discussion

3.1. Kinetic model of facultative pond

There are two facultative ponds at WWTP Bojongsoang, namely facultative pond 1A (F1A) and facultative pond 2A (F2A). These facultative ponds have surface areas, respectively 148,120 m² and 143,205 m². The data used to determine the kinetic model for COD removal was secondary data on a monthly basis from the year 2019 to 2022. The data consisted of COD concentration in the inlet and outlet in the facultative ponds 1A and 2A.

The kinetic rate for COD in the facultative pond was obtained by assuming the ideal hydraulic patterns of the plug-flow model and completely mixed combined plug flow pattern.

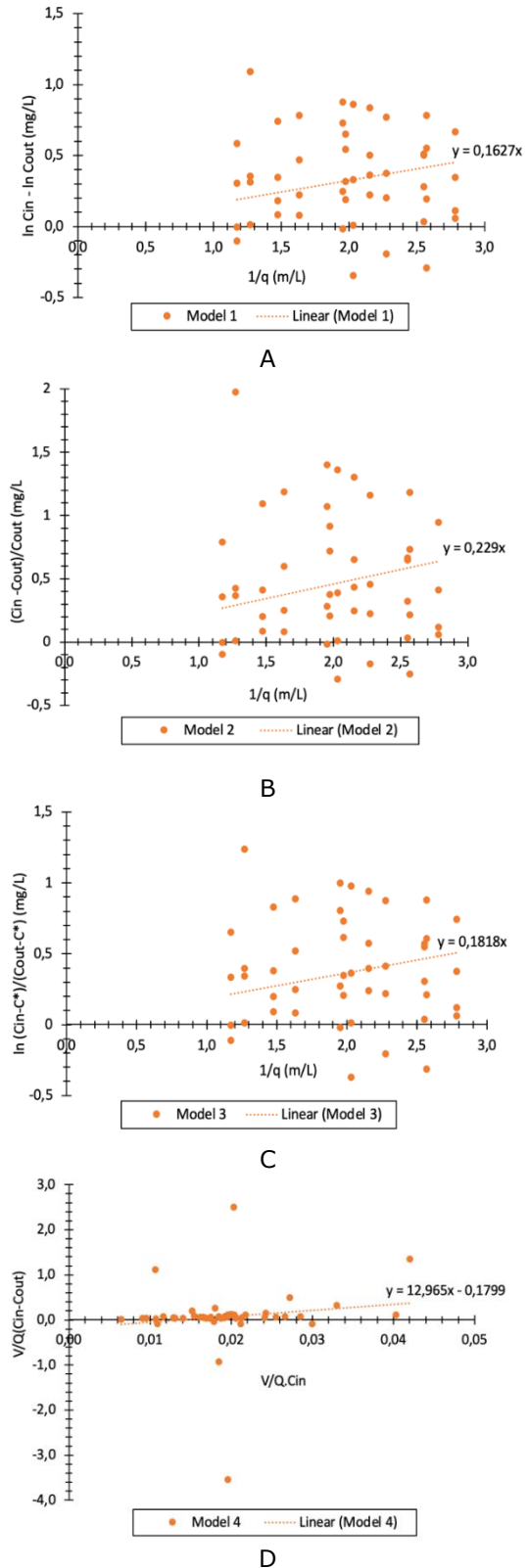


Figure 1. Kinetic rate coefficient of facultative pond in F1A with model (a) first-order kinetic combined plug flow pattern, (b) first order kinetic model with CSTR flow pattern (c) plug flow k-C, (d) Stover-Kincannon

The system followed a combination of first-order kinetics with a plug flow pattern, a first-order kinetic model with a CSTR flow pattern, the plug flow k-C* approach, and the Stover-Kincannon model. The kinetic rate values of each model are the intercept value of the plotting line between HRT ($1/q$) and difference concentration ($C_{out}-C_{in}$) based on equation models (1), (2), and (3). For the Stover-Kincannon model, the K_b value is the intercept of the plotting line, and the U_{max} value is the slope value of the plotting line based on the equation model (5).

The kinetic rate values for each model in facultative pond 1A, respectively k_1 is 0.1627 m/day, k_2 is 0.229 m/day, and k_3 is 0.1818 m/day. For the Stover-Kincannon model, U_{max} value is 5.56 g/L/day, and K_b is 72.07 g/L.day. The plotting of each model based on data in facultative pond 1A is presented in Figure 1.

The same procedures were applied to analyze the kinetic rate values in facultative pond 2A (F2A). The kinetic rate values for each model in facultative pond 2A (F2A) respectively, k_1 is 0.1562 m/day, k_2 is 0.2242 m/day, k_3 is 0.1750 m/day and for the Stover-Kincannon model, the U_{max} value is 2.3 g/L.day and K_b is 18.22 g/L.day. The plotting of each model based on data in facultative pond 2A is presented in Figure 2.

The result of kinetic rate in facultative ponds 1A and 2A showed similar values using model first-order kinetic combined plug flow pattern, first-order kinetic model with CSTR flow pattern, and plug flow k-C. In general, the kinetic rate values in F1A were slightly higher than the kinetic rate values in F2A. The result showed that the removal rate of COD in both facultative ponds had similar performance in removing COD. The values of kinetic rate using model first-order kinetic combined plug flow pattern, first-order kinetic model with CSTR flow pattern, and plug flow k-C* showed similar values reported by Alavi and Ansari (2022), where the value of k_1 was 0.152 m/d; k_2 was 0.4509 m/d and k_3 was 0.1891 m/d for stabilization pond in Iran.

This study found that the kinetic rate in a completely mixed model was greater than that in the plug flow model. This aligns with the findings of Alves et al. (2020), who reported that the kinetic rate of wastewater treatment in Brazil, as calculated using the completely mixed model, was higher compared to the plug flow model. The plug-flow regime in water and wastewater treatment ensures optimal mixing and efficiency (Goodarzi et al., 2022).

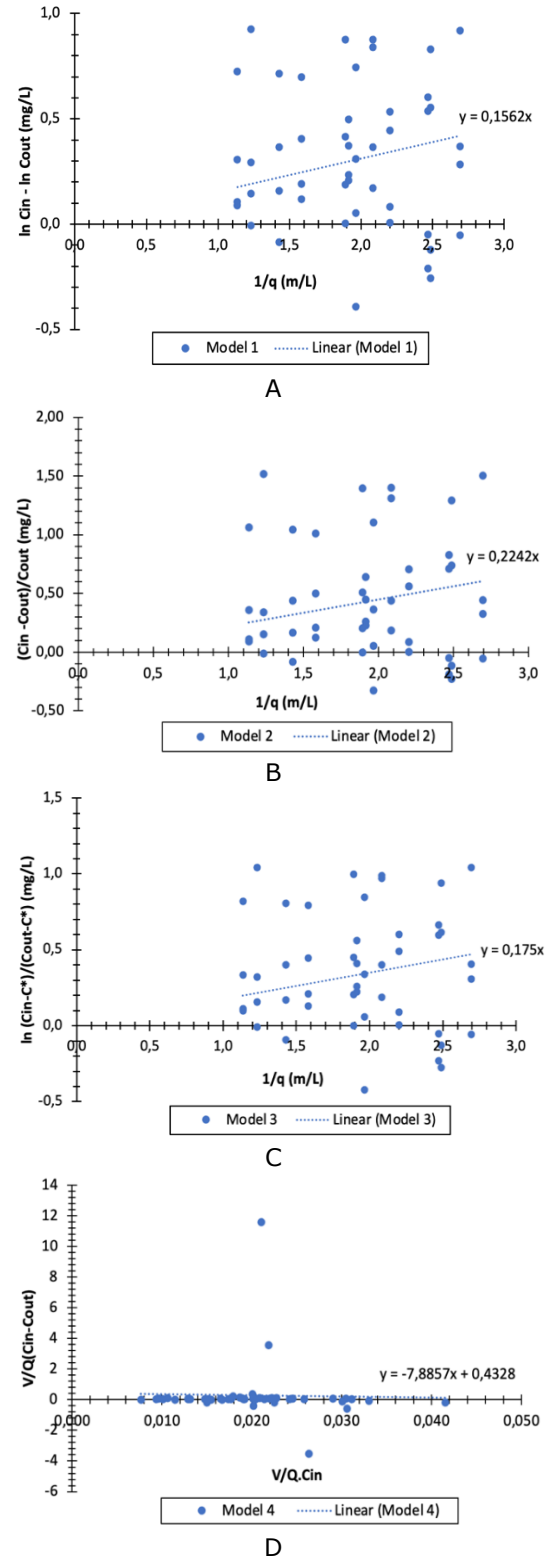


Figure 2. Kinetic rate coefficient of facultative pond in F2A with model (a) first-order kinetic combined plug flow pattern, (b) first-order kinetic model with CSTR flow pattern (c) plug flow k-C*, (d) Stover-Kincannon

The kinetic rate based on the Stover-Kincannon model in both facultative ponds showed not-so-similar conditions. The maximum rate of substrate removal ($U_{\max}$) in F1A was higher than in F2A. The value of saturation constants (K_b) in F1A was also much higher than in F2A. The substrate in biological processes refers to organic matter such as COD, and the result showed that COD removal in F1A occurred more compared to F2A. Meanwhile, the saturation constant refers to the concentration of limiting nutrients that support half of the maximum growth of microorganisms. The value of $U_{\max}$ and K_b in this study ($U_{\max} = 5.56$ g/L.day; $K_b = 72.07$ g/L.day for F1A and $U_{\max} = 2.31$ g/L.day; $K_b = 18.22$ g/L.day for F2A) were lower than the values reported by Khosravi et al (2013b), where the value were ($U_{\max} = 23.81$ g/L.day; $K_b = 128.5$ g/L.day) for COD removal in stabilization pond WWTP Birjand, Iran. The value of $U_{\max}$ for both facultative ponds in this study was lower than the value of $U_{\max}$ in facultative pond in Iran WWTP (80.65 g/L.day), while the value of K_b showed similar values (Alavi and Ansari, 2022).

3.2. Evaluation of Kinetic Model

The reaction rate value from each model is used to predict the COD of effluent from the

facultative pond. The effluent COD concentration from the model is then compared with the COD concentration from field data. The level of accuracy of the model was analyzed using the Mean Average Percentage Error (MAPE) value, where the model with the smallest MAPE is the best model to predict effluent COD in facultative ponds. The kinetic rate and MAPE values for each model can be seen in Table 1.

Table 1. MAPE evaluation of kinetic models

M	Kinetic Rate F1A	MAPE (%)	Kinetic Rate F2A	MAPE (%)
1.	0.1627	28.4	0.1562	30.5
2.	0.2290	109.7	0.2242	119.2
3.	0.1818	28.3	0.1750	30.2
4.	$U_{\max}=5.56$ $K_b = 72.07$	41.5	$U_{\max}=2.31$ $K_b=18.22$	49.3

The result showed that the plug flow k-C* model was the best model to predict COD effluent, where the MAPE value was 28.3% for the facultative pond 1A. The comparison graphs between measured and predicted COD effluent concentration for each model in F1A are presented in Figure 3.

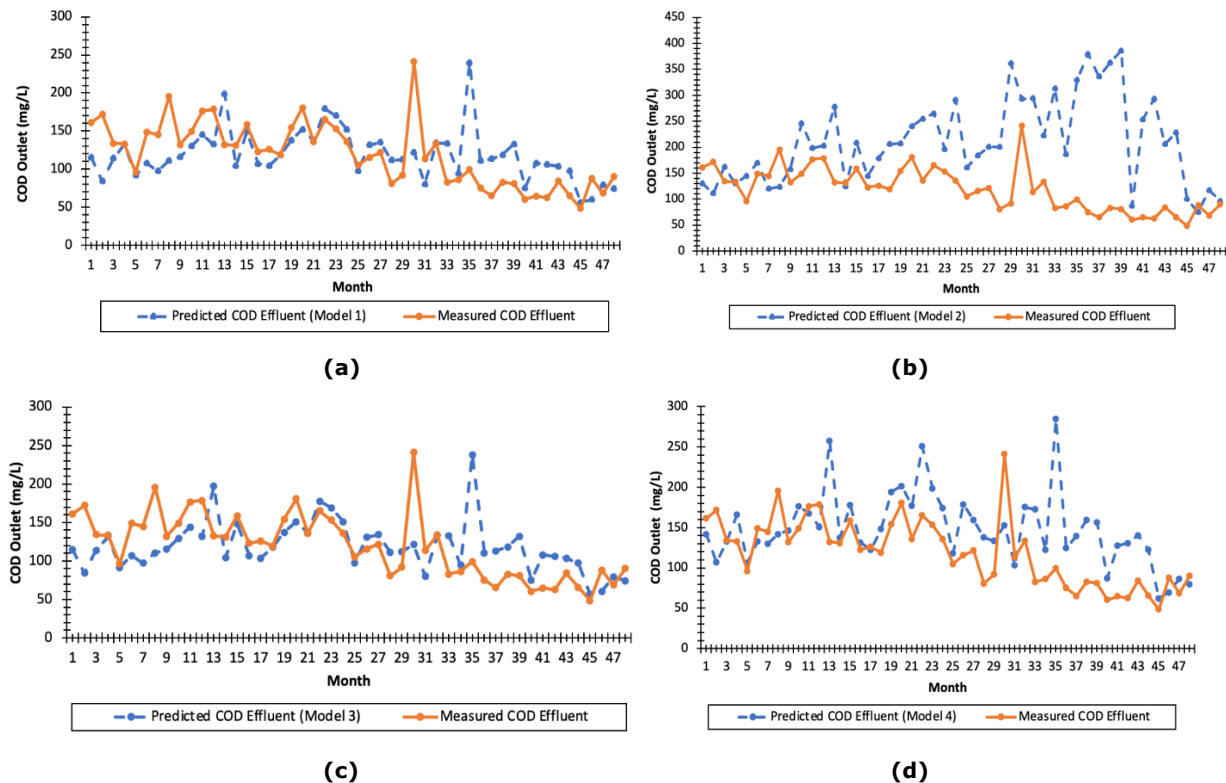


Figure 3. Comparison of predicted and measured COD effluent in F1A using kinetic rate coefficient of model (a) first-order kinetic combined plug flow pattern, (b) first-order kinetic model with CSTR flow pattern, (c) plug flow k-C*, (d) Stover-Kincannon

A similar result also showed that the plug flow k-C* model was the best model to predict COD effluent, where the MAPE value was 30.2% for the facultative pond 2A. The comparison graphs between measured and predicted COD effluent concentration for each model in F2A are presented in Figure 4.

The plug flow k-C* model is a combination of the plug flow regime and mass balance in a treatment wetland environment. Treatment wetlands are also considered as biological reactors (Von Sperling et al., 2023). Since the facultative pond has a similar process to horizontal flow wetlands, so the plug flow k-C* can be the best model to predict COD removal in facultative ponds. A similar result was reported by Araujo and Neto (2018) that the plug flow equation was most suitable for representing the removal kinetic of COD in facultative pond Fortaleza, Brazil.

The result indicated the suitability of the CSTR model was lower than the plug flow model. The lower suitability of the CSTR model is due to overestimated k value, while the higher suitability of the plug flow model is due to the reduced k value (Alves et al., 2020). This statement is similar to the result of this study that showed the suitability of the plug flow model was higher than CSTR model. The study conducted by Da Silva et al. (2010) also showed that the plug flow model was the best model to predict substrate removal in facultative ponds.

The plug flow k-C* model was modified by Kadlec et al. (2008) and included background concentration (C^*) as the irreducible effluent concentration that results from internal biogeochemical cycling and life cycle of biota, which produces some residual material within the facultative pond (Weerakoon et al., 2020).

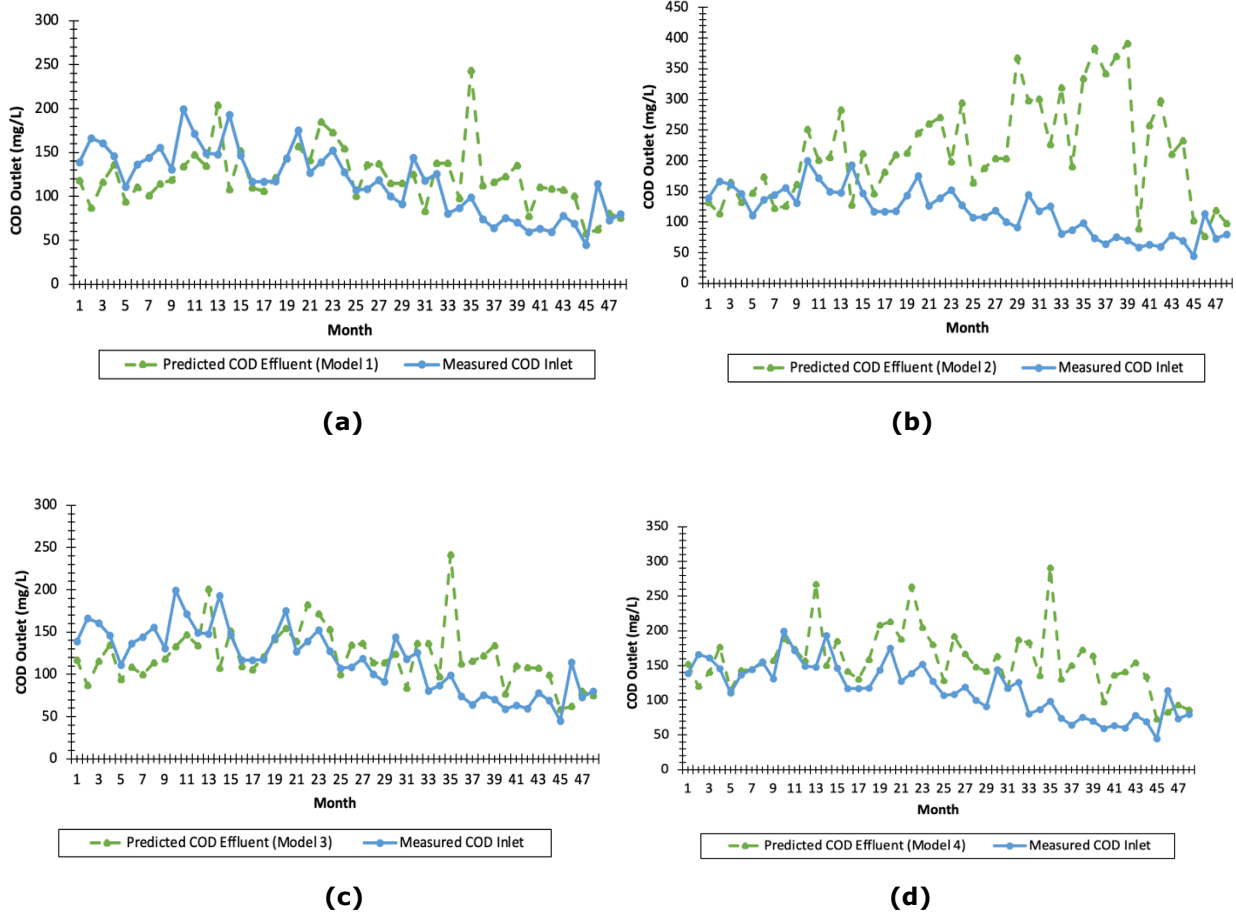


Figure 4. Comparison of predicted and measured COD effluent in F2A using kinetic rate coefficients of model (a) first-order kinetic combined plug flow pattern, (b) first-order kinetic model with CSTR flow pattern, (c) plug flow k-C*, (d) Stover-Kincannon

4. Conclusion

The kinetic rate of each model for both facultative ponds (1A and 2A) showed no significant difference value. The kinetic rate values for each model in facultative pond 1A are respectively k_1 is 0.1627 m/day, k_2 is 0.229 m/day, k_3 is 0.1818 m/day, and the Stover-Kincannon model has $U_{\max}$ value is 5.56 g/L.day and K_b is 72.07 g/L.day. For facultative pond 2A, the kinetic rate values for each model are respectively k_1 is 0.1562 m/day, k_2 is 0.2242 m/day, k_3 is 0.1750 m/day, and in the Stover-Kincannon model, the $U_{\max}$ value is 2.3 g/L.day and K_b is 18.22 g/L.day. The result showed that the plug flow k-C* model was the best model to predict COD effluent for both facultative ponds, where MAPE values were 28.3% for facultative pond 1A and 30.5% for facultative pond 2A. The plug flow k-C* model is a combination of the plug flow regime and mass balance in a treatment wetland. Since the facultative pond has a similar process to horizontal flow wetlands, the plug flow k-C* can be the best model to predict COD removal in facultative ponds. The kinetic rate value of this study indicated similar results to other studies conducted in similar climate conditions. Some of the studies showed that the Stover-Kincannon model was more applicable to COD removal kinetics. This discrepancy could be caused by the difference in organic loading rate and the wastewater characteristics. There were some limitations in this study. The process that occurs in facultative ponds is complex and affected by so many parameters such as wind, temperature, hydraulic regime, and pond geometry. Due to the lack of data available in the field, these influencing factors were not considered in the analysis. Additional studies are required to include these parameters in kinetic model analysis in WWTP Bojongsoang.

Author contribution statement

F.A: conceptualization, writing—first draft, supervision, data evaluation, interpretation of data, funding acquisition E.H: drafting the article, critical reviewing, data evaluation, interpretation of data. J.S: collecting secondary data, project administration.

Data availability statement

Available on request to the corresponding author.

Declaration of Competing Interest

The authors declare no conflict of interest.

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