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Research Article

A MATHEMATICAL MODEL FOR ORGANIC MATTER REMOVAL IN CONSTRUCTED WETLANDS CASE STUDY: WASTEWATER TREATMENT PLANT OF QASR-E SHIRIN, IRAN

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Abstract

The ability of large aquatic plants (macrophytes) to assist the breakdown of human and animal derived wastewater, remove disease-causing microorganisms and pollutants has only recently been scientifically investigated. Since the mid-1980s, reed bed systems, with the advantage of low energy consumption and operating cost, have been increasingly used in the treatment of wastewater. Although a large number of reed beds have been built and operated, pollutant dynamics in these systems are still scarcely comprehended. The lack of understanding on pollutant dynamics can lead to inaccurate design, giving poor pollutant removal efficiency and operation problem. As most reed beds are applied in sewage treatment, organic matter (BOD) removal is the primary target of system design, which requires the kinetics of BOD removal and the flow pattern of wastewater to be pre-determined. This paper reports a comparative study of four kinetic models that can be applied in the design of subsurface horizontal flow reed beds for wastewater treatment, in The Ghasre Shirin Subsurface Constructed wetlands Constructed wastewater treatment plant. The models were developed from different combinations of Monod kinetics, first-order kinetics, and continuous stirred-tank reactor and plug flow patterns. Using statistical parameters, were analysis of these models. For predicting organic matter removal, the combination of Monod kinetics with plug flow pattern gave the closest match between theoretical predictions and actual performances of 80 horizontal flow reed beds. In all models, except for the combination of Monod kinetics with plug flow pattern, the coefficients of BOD removal were found to decrease slightly with BOD loading. The ratios of BOD/COD had no correlation with the coefficients, indicating that in the Subsurface flow reed beds the degradation of organic matter is insensitive to the nature of organics in the wastewater.

Keywords: Subsurface Constructed wetlands; Wastewater treatment; organic matter (BOD) removal; modeling; Ghasr-e-Shirin.

Introduction

Appropriate wastewater treatment and achieving the desired standard with operation and easy maintenance are among the most important aims of wastewater treatment. For this aim, various methods have been used globally such as activated sludge, tricking filter, stabilization ponds, constructed wetland and etc. (1-5). Stabilization ponds and constructed wetland are the most important natural wastewater treatment systems that used some part of the world(6-9).

From the mid-1980s, reed bed systems with very low power consumptions and low operating costs were increasingly used for wastewater treatment. The number of Reed beds in England from 1986 to 2007, rose from zero to 1027and the majority of them (n=755 beds) were used for domestic wastewater treatment (10, 11).The use of reed beds in treating other wastewaters such as agricultural, urban runoff and industrial waste is also developing (12-14)in artificial wetlands physical, chemical and biological processes are used for in wastewater treatment and various contaminants such as suspended solids, organic materials, nitrogen, phosphorus, heavy metals, pathogenic microbial agents, and chemically complex materials can be refined to an acceptable level (15, 16). Constructed wetlands as biological filters in a combination of physical chemical, and biological factors, have an effective role in reducing the number of bacteria from influent wastewater (17-21).Although a large number of reed beds has been built and utilized, but the dynamics of pollutants in these systems is still not well understood. To better understand the hydraulic conditions of wastewater fundamental researches and numerous scientific debates have been done over these systems (e.g. the pattern continuous tank flow vs. plug flow), identifying the kinetics of decomposition of pollutants separately (for example, first-order kinetics vs. Monod equation kinetics), strong wastewater treatment such as agricultural runoff (22) review and pursuit bacterial mass profiles and interactions between plants and microorganisms in the stem of a reed bed (23,24),study of greenhouse gas emissions and its relationship with the decomposition of organic matter in the system (25) and discovering new destructions in the decomposition of pollutants such as Anammox reaction is common in nitrogen contaminants removal (26, 27). Failure to understand the dynamics of contaminants in this system can lead to incorrect design that usually appears in the incorrect form of reed bed, poor efficiency of pollutant removal and cause exploitation problems such as clogging and short-circuit of waste water. In the England, despite over 20 years of major designers' experience, improper design problem much occurs.In most of reed beds used in wastewater treatment, removal of organic matter (BOD_5); is the primary purpose of the system design, thus initial determination of BOD_5 removal kinetics and sewage flow pattern is required. To this end, there are usually two assumptions: 1 - Removal of BOD_5 with first-order reaction equation2- the passage of sewage flow from reed bed in the form of Plug flow. Both of these assumptions have an important role in the design of these systems (28, 29).

Recently, several modeling studies have concentrated on the dynamic differences of various pollutants and isolation of a single bed in a set of ideal reactors (30, 31).Potentially such studies lead to the completion of the pollutant removal model for conducting an accurate design. Therefore gathering sufficient and highly qualitative data is difficult for the accuracy of such a model. When a complex model with environmental parameters and guesswork kinetic coefficients is applied, it can only lead to incorrect design. To this end, in 2001 the British Constructed Wetland Association (CWA) collected and compiled the data of 154Reed beds from 1986 onwards (32, 33).

Materials and Methods

- **Data Collection**

In this study experimentally conducted within six months of the year, including the hot months (July, august and September) and cold months (December, January and February) in 2009, on the constructed wetlands of Qasr-e Shirin. From among the constructed wetlands treatment system of Qasr-e Shir in (12 beds) because all had the same physical and hydraulic conditions in terms of design, one bed randomly selected which had common Phragmites or reeds. Beds had 25 meters long (current length) and 125 meters width of structures with a total surface area of 3125 square meters and bedding dip was 0.8%. Depth at the beginning of the bed was 75 cm and toward the end of the bed was 95 cm.Bed material in this system was 8-10 mm factory sand and the average depth of the sand layer in beds was 85 cm beds with porosity about 35%, taking into account the porosity of the bed, the actual size of the design is equivalent to 930 cubic meters. Wastewater before entering into the bed, first enters into the trash rack channel, and then passes through the grit chamber, and enters into the two anaerobic ponds. Therefore, reed beds, receive the output runoff of anaerobic ponds.In this study, the temperature parameters (PH, BOD_5 and COD) of 24 samples were tested and analyzed in the output and input of bed in the form of composite sampling. In this study output wastewater of anaerobic ponds were analyzed and sampled as the input wastewater of the reed beds. Sampling was carried out 2 times in a month for 6 months in a total of 12 times. At each sampling session, all samples were harvested at three intervals during a day and to increase the range and accuracy of data were analyzed separately.

Therefore sampling was done totally for 36 times from the input and output of bed. Finally, at each sampling session 6 samples (3 samples with different time frequencies for each point) were harvested from the two desired point for determined parameters. In total, 72 samples were harvested that with two times repetition in tests totally 576 tests were conducted.

All the tests were carried out in water and wastewater laboratory of civil engineering department at higher education and research complex of west. Concurrent with the sampling procedures, flow measurement and the data of input and output flow rates from wastewater treatment plant and reed beds were also recorded.

- **Kinetic models**

- **Kinetic modeling approach of four combined models**

As shown in Figure (1), the simple design equations which relate the values of the input and output data in a separate bed were developed by the combination of CSTR or Plug flow with kinetic Monod or first order equation.

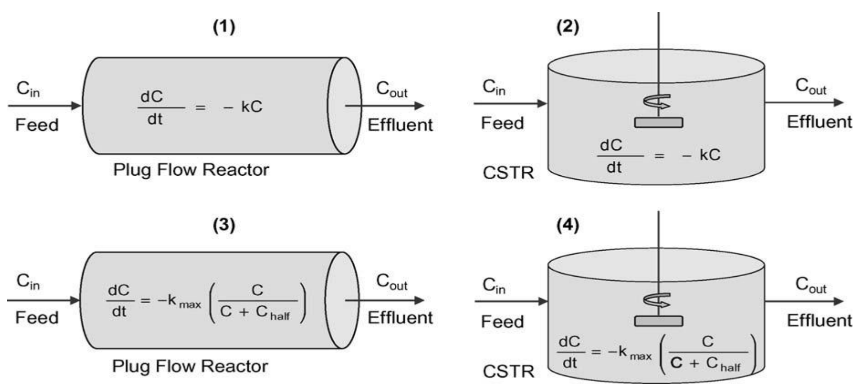

Figure-1: Four modeling methods for subsurface flow reed beds; (1): the combination of first-order Kinetics with Plug flow, (2): the combination of first-order Kinetics with CSTR, (3): the combination of Monod Kinetics with Plug flow, (4): the combination of Monod Kinetics with CSTR (20, 21).

The combination of Plug flow with first-order reaction kinetic, created the first design equation (Kickuth Equation) that commonly is used to design reed bed in the United Kingdom (11).

$$A_h = \frac{Q(\ln C_{in} - C_{out})}{K_1}$$

A_h: pond area based on m^2, Q: flow rate per m^3/d, C_{in}: BOD_5 input in terms of *mg / l*

C_{out}: is output BOD_5 based on *mg / l*, K_1: velocity constant *(m / d).*

Equation (1) is the simplest and most widely used design equation. Key parameter (K_1), first was determined in 1990 and based on the regression of input and output values of BOD5 of reed beds available in the UK and Denmark (32 and 35).Like the modeling compound of Eq. (1), modeling compound No. (2), the combination of CSTR flow with first-order kinetic equation, generated an equation that related to the simple form of input and output values of BOD5 from a reed bed with horizontal flow.

(Eq.2) $$\frac{dc}{dt} + \frac{1}{\tau} C_{in} = \frac{1}{\tau} C_{out}$$

(Eq.3) $$A_h = \frac{Q(C_{in} - C_{out})}{K_2 C_{out}}$$

In Eq. (2), τ represents the hydraulic retention time (d), and K_2 is the velocity constant based on m/d as in Eq. (1) (11). From the combination of simplified Monod's equation (Eq. 4) with Plug flow or CSTR modeling compounds of (3) and (4) were obtained from equations (5) and (6), respectively.

(Eq.4) $$\frac{dc}{dt} = -K_{\max} \frac{C}{C + C_{half}}$$

(Eq.5) $$A_h = \frac{Q(C_{in} - C_{out} + 60\ln(C_{in} / C_{out}))}{K_3}$$

(Eq.5) $$A_h = \frac{Q(C_{in} - C_{out})(C_{out} + 60)}{K_4 C_{out}}$$

K_{max} is the maximum amount of BOD_5 removed (g/m^3.d) in bed regardless the effect of temperature (g/m3.d) and assuming a constant bacterial population. C_{half} is the amount of wastewater BOD5 while the removed BOD5 value is half of K_{max}; which in this study has been considered equal to 60 mg/l that is the common value used in Monod's Eq(36).Also, in a study conducted in 2009 by Guangzhi and et al. on 80 reed beds, the $C_{half}$was considered 60 mg /L(20).

- **Evaluation Model**

Although it is more than two decades that equation (1) is used for the design of reed bedsbut equations 3, 5 and 6 were presented for the first time by Guangzhi et al in 2009 and used in this study. All four equations can be used in the design of reed bed and their accuracy and reliability can be assessed by comparing with the practical results, and referring to the available data. The more equations show closer mathematical calculation, the more accurate will be more the model.

All 1, 3, 5 and 6 equations can be adjusted by the following general formula:

(Eq. 7) $F(C_{in}, C_{out}) = K\frac{A_h}{Q}$

For each equation the value of K can be obtained from linear regression and for each reed bed the amount of F (C_{in}, C_{out}) and (A_h/Q) can be calculated using the available practical data for each bed.

Results and Discussion

- **Matching Design Equations**

The conformity of Equations 1, 3, 5 and 6 were evaluated by comparing the documented values F (C_{in}, C_{out}) with these equations and actual data of reed beds. As shown in Figure 2, the values of K_1, K_2, K_3 and K_4 were obtained through data regression along with the R^2 statistical parameter calculation for each regression.

For each of four equations, by placing the data in the general form of Equation 7, the value of K is obtained as following:

$K_1=0.079\ d^{-1}$ (Eq.1)

$K_2=0.199\ md^{-1}$ (Eq.3)

$K_3=9.53\ g\ BOD_5\ m^{-2}d^{-1}$ (Eq.5)

$K_4=16.76\ g\ BOD_5\ m^{-2}d^{-1}$ (Eq.6)

Linear relationship between F (C_{in}, C_{out}) and (A_h / Q) in Figure (2), in the equations 1, 3 and 6 are generally weak. Equation (1) (Kickuth equation) that usually is used in the design of reed bed creates the lower mathematical relationship between theory documents and actual results. As shown in Figure (2), the comparison of statistical parameters showed that the combination of two equations 1 and 3 has generated closer mathematical relations.

When the K_1 - K_4 coefficients obtained separately, the amounts of input BOD_5 were plotted versus organic load values as shown in Figure (3).The coefficients K_1 - K_4 distinct combined relationships were plotted versus the organic load values as shown in Figure (4).

To investigate the relationship between the ratio of BOD / COD and K_1 - K_4 values obtained from the combined relationships, the ratio of BOD / COD vs. K_1 - K_4 were plotted in Figure (5).

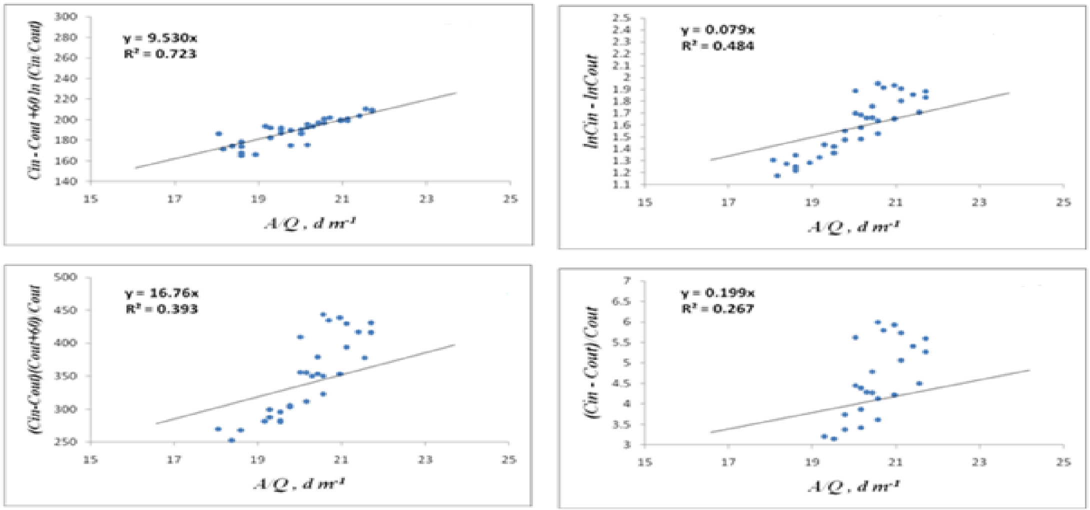

Figure-2. Diagram of the kinetic coefficients regression for modeling methods 1-4.

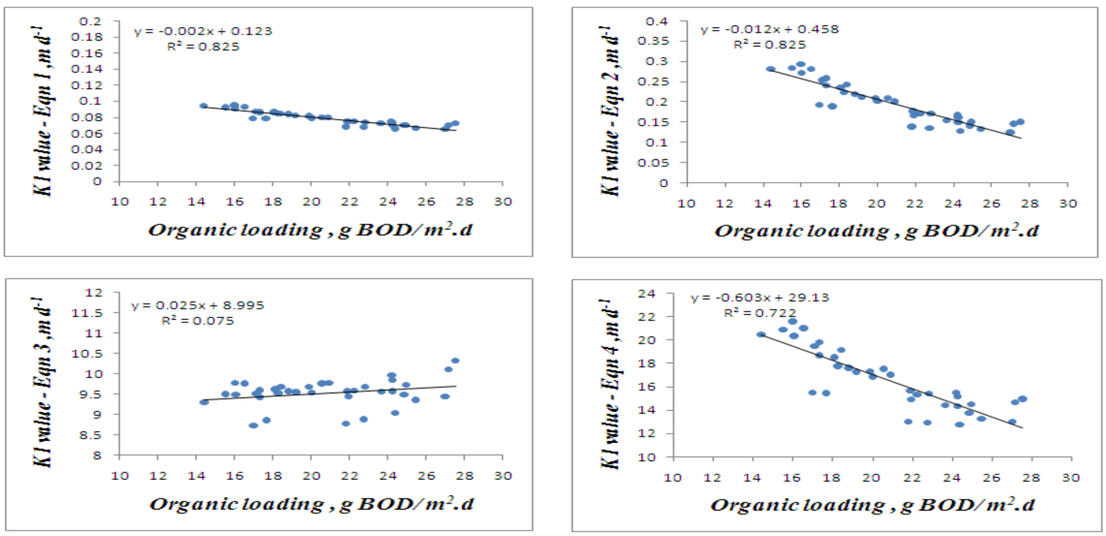

Figure-3.Diagram of the K_1 kinetic coefficients progress for combined methods of equations 1-4 versus the values of input BOD_5.

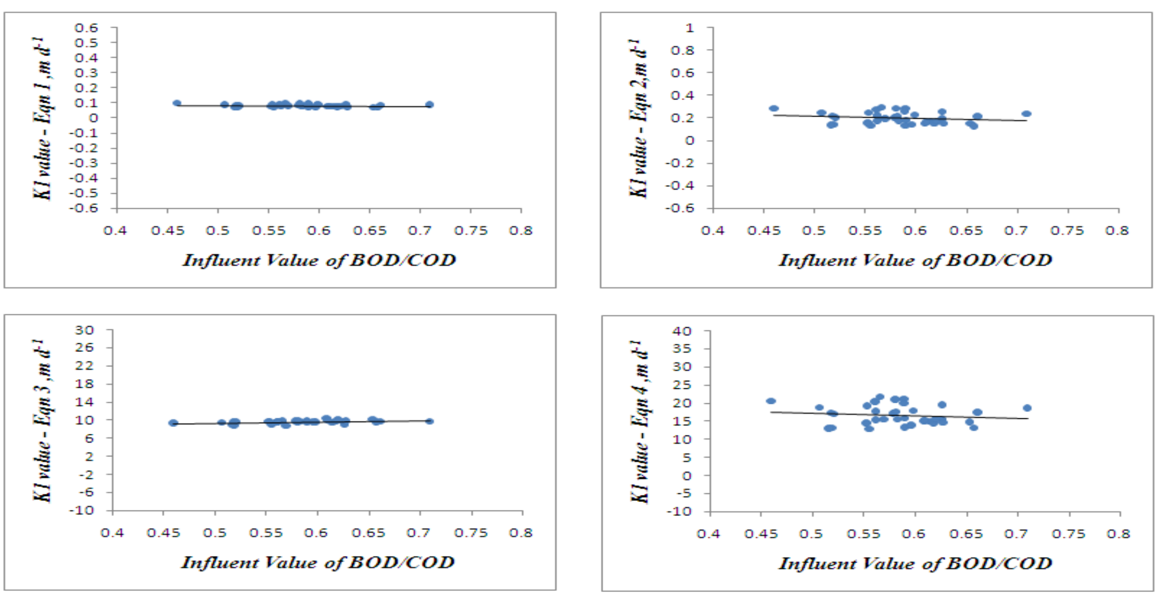

Figure-4.Diagram of the K_1 kinetic coefficients progress for combined methods of equations 1-4 versus the load values of input organic matter.

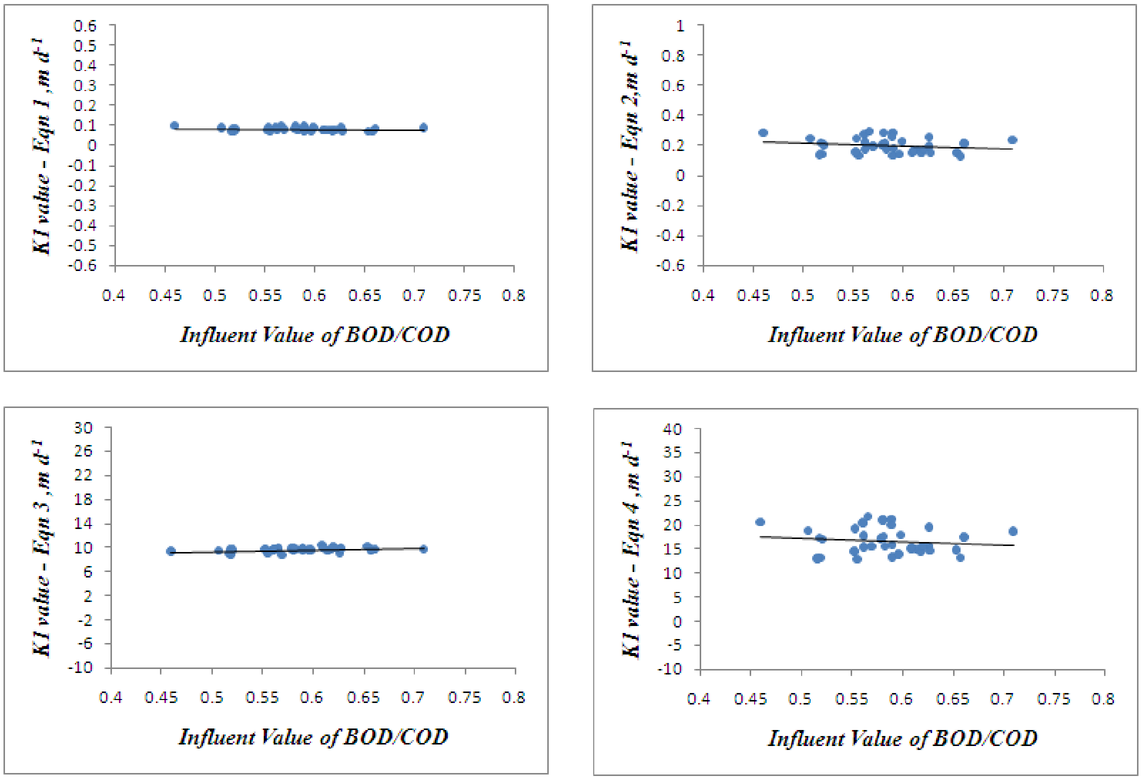

Figure-5. Diagram of the K_1 kinetic coefficients progress for combined methods of equations 1-4 versus theratio of input BOD / COD.

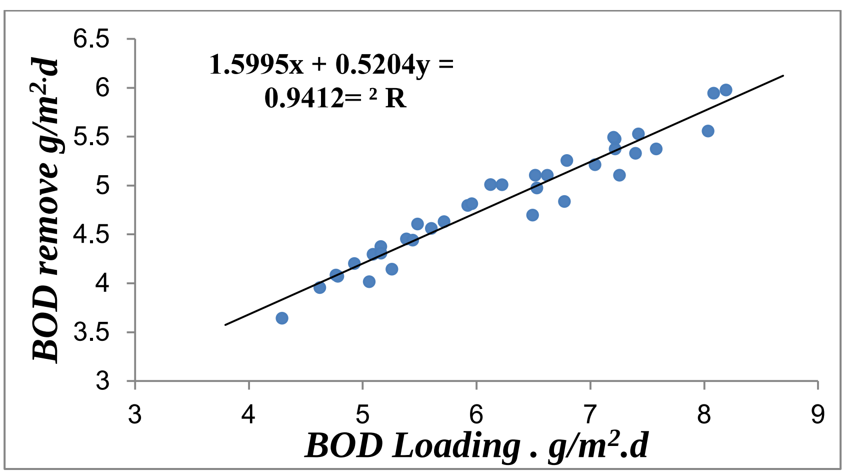

Figure-6.Regression diagram of BOD5 amounts removal versus the load of organic matter of system in the studied subsurface bed.

- **Variation of Kinetic coefficients**

BOD_5 and flow rate data provided the possibility to evaluate the changes of obtained coefficients through pollutant loading and BOD /COD ratio. When the K_1 - K_4 coefficients obtained from different beds, input vales of BOD_5 were plotted versus the organic load values, it revealed that in combined equations of 1, 2 and 4, the greater input BOD_5 values were consistent with the slightly lower kinetic coefficients (fig.3) while this status was reversed in the combined equation (3).Also by placing the value of organic load versus the kinetic coefficients, again combined equations 1, 2 and 4 the greater input BOD_5 values were consistent with the slightly lower kinetic coefficients (fig. 4),while this status as figure (3) in the combined equation (3) was reversed and the greater BOD_5 values were consistent with the slightly higher kinetic coefficients. Therefore figures (3) and (4) show that the in equations 1, 2 and 4the speed of biological reactions was almost constant and has not changed with change of input loading. Meanwhile Equation (3) illustrates that an increase in the input loading of system increases the rate of biological reactions reaction which confirms the applicability of predicted model of Monod and Plug flow regime for subsurface constructed wetland system of Qasr-e Shirin. The first-order kinetics and Monod with an increase in loading rates are able to increase the organic removal; this phenomenon has also been reported in several reed beds (37 and 38). Yet in another study, increased loading rates were consistent with slightly lower kinetic coefficients in all four models (11). However, in this study, only the Monod kinetics indicated this status (fig. 4)**.**

- **Effect of biodegradability of organic matters**

The BOD/COD ratio is commonly used as biodegradability index of organic matters. In the ratio of 0.5 or larger, organic matters can be considered as a simple biodegradable but the ratio 0.3 or less is considered as low biodegradable (36).Figure 5 shows no statistically significant relationship between the kinetic coefficients and the ratio of input BOD / COD. This has also been reported by Caselles-Osorio A and Guangzhi(11 and39). The efficacy of organic matter removal in the subsurface of reed beds is not sensitive to the nature of the organic matter, whether they are readily biodegradable or slowly. About the input loading to the system and the removal of organic matter (Figure 6), it was also determined that with an increase in input organic loading the removal of organic materials increases, which indicates the higher capacity and ability of the system in accepting organic loading rather than its current state (see Figure 3).

Conclusion

Through conducting the regression of equations and based on the R^2statistical parameter between both kinetic equation of the first order and Monod kinetics with Plug flow regime and CSTR hypotheses, it was identified that the Plug flow regime showed the closer mathematical data than CSTR flow regime which confirms that the Plug flow is the dominant flow regime in wastewater treatment plant of Qasr-e Shirin. Totally, among the four available models, the combined model of the Monod kinetics and Plug flow provided the best mathematical relationship between the theoretical predictions and the actual data of reed bed. Also, in a study conducted by Guangzhi and et al. in 2009 for the first time on 80 beds by using the combination of above mentioned four models, the combination of Monod kinetics and Plug flow model provided the best mathematical correlation. The obtained results of previous conducted researches and current study proves the dominance of Monod kinetics and Plug flow regime inthe subsurface reed beds. Also, the resulted models for the COD showed lower values of statistical parameters (especially R^2) and there was no significant correlation between the kinetics and equations of the flow regime.

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References

1. Almasi A, Sharafi K, Hazrati S, Fazlzadehdavil M. A survey on the ratio of effluent algal BOD concentration in primary and secondary facultative ponds to influent raw BOD concentration. Desalination and Water Treatment. 2015 Mar 27;53(13):3475-81.
2. Almasi A, Dargahi A, Amrane A, Fazlzadeh M, Mahmoudi M, Hashemian AH. Effect of the retention time and the phenol concentration on the stabilization pond efficiency in the treatment of oil refinery wastewater. Fresenius Environmental Bulletin. 2014;23(10a):2541-2548.
3. Dargahi A, Sharafi K, Almasi A, Asadi F. Effect of biodegradable organic matter concentration on phenol removal rate from oil refinery wastewater using anaerobic pond system. Journal of Kermanshah University of Medical Sciences. 2015; 18(12): 678-689.
4. Pirsaheb M, Fazlzadehdavil M, Hazrati S, Sharafi K, Khodadadi T, Safari Y. A survey on nitrogen and phosphor compound variation processes in wastewater stabilization ponds. Polish Journal of Environmental Studies. 2014;23(3): 831-834.
5. Sharafi K, Pirsaheb M, Khosravi T. Performance comparison of activated sludge systems with conventional and extended aeration in removal of protozoan cysts and parasite egg from wastewater: A case study, IRAN. Int. J. Applied Environ. Sci. 2012;7:281-7.
6. CWA. Constructed Wetlands Database. Version 11.01. Rugeley: Constructed Wetland Association; 2008.

7. Almasi A, Dargahi A, Pirsaheb M. The Effect of Different Concentrations of Phenol on Anaerobic Stabilization Pond Performance in Treating Petroleum Refinery Wastewater. Journal of Water and Wastewater. 2013;24,1(85);61-68.
8. Sharafi K, Moradi M, Karami A, Khosravi T. Comparison of the efficiency of extended aeration activated sludge system and stabilization ponds in real scale in the removal of protozoan cysts and parasite ova from domestic wastewater using Bailenger method: a case study, Kermanshah, Iran. Desalination and Water Treatment. 2015 Jul 31;55(5):1135-41.
9. Dargahi A, Almasi A, Soltanian M, ZArei P, Hashemian AH, Golestanifar H. Effect of Molasses on Phenol Removal Rate Using Pilot-Scale Anaerobic Reactors. Journal of Water and Wastewater. 2014; 25(4): 2-12.
10. Sharafi K, Pirsaheb M, Khosravi T, Dargahi A, Moradi M, Savadpour MT. Fluctuation of organic substances, solids, protozoan cysts, and parasite egg at different units of a wastewater integrated stabilization pond (full scale treatment plant): a case study, Iran. Desalination and Water Treatment. 2016; 57(11): 4913-4919.
11. Guangzhi Sun, and TanveerSaeeda.Kinetic modelling of organic matter removal in 80 horizontal flow reed beds for domestic sewage treatment . Process Biochemistry .2009; 44: 717–722.
12. Wood J, Fernandez G, Barker A, Gregory J, Cumby T. Efficiency of reed beds in treating dairy wastewater. Biosystems engineering. 2007;98(4):455-69.
13. Lee BH, Scholz M. What is the role of Phragmitesaustralis in experimental constructed wetland filters treating urban runoff?. Ecological Engineering. 2007;29(1):87-95.
14. Melián JH, Méndez AO, Arana J, Díaz OG, Rendón ET. Degradation and detoxification of formalin wastewater with aerated biological filters and wetland reactors. Process biochemistry. 2008;43(12):1432-5.
15. Sherwood C,ReedE,Joe Middlebrooks, Ronald W. Crites. Natural systems for waste management and treatment. McGraw- Hill Company, 1988.
16. Directorate Agricultural Information Services (DAIS). Wetland Values & Function. South Africa. 2002.
17. Gersberg RM, Elkins BV, Lyon SR, Goldman CR. Role of aquatic plants in wastewater treatment by artificial wetlands. Water Research. 1986;20(3):363-8.
18. Kadlec RH. The inadequacy of first-order treatment wetland models. Ecological Engineering. 2000;15(1):105-19.

19. Brix H. Macrophyte-mediated oxygen transfer in wetlands: transport mechanisms and rates. Constructed wetlands for water quality improvement. 1993:391-8.

20. Gersberg RM, Gearheart RA, Ives M. Pathogen Removal in Constructed Wetlands In Constructed Wetlands for Wastewater Treatment (Edited by Hammer DA). 1989; 431–445.

21. Van Oostrom AJ, Russell JM. Denitrification in constructed wastewater wetlands receiving high concentrations of nitrate. Water Science and Technology. 1994;29(4):7-14.

22. Vincent G, Dallaire S, Lauzer D. Antimicrobial properties of roots exudate of three macrophytes. Menthaaquatica. 1994:290-6.

23. Zhao YQ, Sun G, Allen SJ. Purification capacity of a highly loaded laboratory scale tidal flow reed bed system with effluent recirculation. Science of the Total Environment. 2004;330(1):1-8.

24. Münch C, Kuschk P, Röske I. Root stimulated nitrogen removal: only a local effect or important for water treatment?. Water Science and Technology. 2005;51(9):185-92.

25. Tietz A, Langergraber G, Watzinger A, Haberl R, Kirschner AK. Bacterial carbon utilization in vertical subsurface flow constructed wetlands. Water research. 2008;42(6):1622-34.

26. Inamori R, Gui P, Dass P, Matsumura M, Xu KQ, Kondo T, Ebie Y, Inamori Y. Investigating CH 4 and N 2 O emissions from eco-engineering wastewater treatment processes using constructed wetland microcosms. Process Biochemistry. 2007;42(3):363-73.

27. Paredes D, Kuschk P, Köser H. Influence of Plants and Organic Matter on the Nitrogen Removal in Laboratory-Scale Model Subsurface Flow Constructed Wetlands Inoculated with Anaerobic Ammonium Oxidizing Bacteria. Engineering in Life Sciences. 2007;7(6):565-76.

28. Sun G, Austin D. Completely autotrophic nitrogen-removal over nitrite in lab-scale constructed wetlands: Evidence from a mass balance study. Chemosphere. 2007;68(6):1120-8.

29. Rousseau DP, Vanrolleghem PA, De Pauw N. Model-based design of horizontal subsurface flow constructed treatment wetlands: a review. Water research. 2004;38(6):1484-93.

30. Marsili-Libelli S, Checchi N. Identification of dynamic models for horizontal subsurface constructed wetlands. Ecological Modelling. 2005;187(2):201-18.

31. Kadlec RH. Effects of pollutant speciation in treatment wetlands design. Ecological Engineering. 2003;20(1):1-6.
32. Job GD, Green MB, Shutes RB. Reed beds and constructed wetlands for wastewater treatment. Medmenham, Marlow, UK: WRc Publications; 1996.
33. Cooper PF, Job GD, Green MB, Shutes RB. Reed beds and constructed wetlands for wastewater treatment. European water pollution control. 1997;6(7):49.
34. Cooper PF. European design and operator guidelines for reed bed treatment systems. Prepared by the EC/EWPCA emergent hydrophyte treatment systems expert contact group. Stevenage: WRc Publications; 1990.
35. Schierup HH, Brix H. Danish experience with emergent hydrophyte treatment systems (EHTS) and prospects in the light of future requirements on outlet water quality. Water science and technology. 1990;22(3-4):65-72.
36. Metcalf E. Inc., wastewater engineering, treatment and reuse. New York: McGraw-Hill. 2003.
37. Sun G, Zhao Y, Allen S. Enhanced removal of organic matter and ammoniacal-nitrogen in a column experiment of tidal flow constructed wetland system. Journal of biotechnology. 2005;115(2):189-97.
38. Sun G, Zhao Y, Allen S, Cooper D. Generating "tide" in pilot-scale constructed wetlands to enhance agricultural wastewater treatment. Engineering in Life Sciences. 2006;6(6):560-5.
39. Caselles-Osorio A, García J. Performance of experimental horizontal subsurface flow constructed wetlands fed with dissolved or particulate organic matter. Water research. 2006;40(19):3603-11.

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