Modeling of microbial approach in wastewater treatment process: A case study of mPHO in Taman Timor oxidation pond, Johor, Malaysia

Cite as: AIP Conference Proceedings **1750**, 030023 (2016); https://doi.org/10.1063/1.4954559
Published Online: 21 June 2016

Amir S. A. Hamzah, Ali H. M. Murid, Zainal A. Aziz, et al.

Modeling of Microbial Approach in Wastewater Treatment Process: A Case Study of mPHO in Taman Timor Oxidation Pond, Johor, Malaysia

Amir S. A. Hamzah[2, a)], Ali H. M. Murid[1, 2, b)], Zainal A. Aziz[1, 2, c)], Akbar Banitalebi[1, d)], Hazzarita Rahman[3, e)] and Norazelah Hamdon[3, f)]

[1]*UTM Centre for Industrial and Applied Mathematics*
Universiti Teknologi Malaysia,
81310 Johor Bahru, Malaysia
[2]*Department of Mathematical Sciences, Faculty of Science*
Universiti Teknologi Malaysia,
81310 Johor Bahru, Malaysia
[3]*Johor Biotechnology & Biodiversity Corporation (J-Biotech)*
Level 2, UTM-MTDC Technology Centre,
Phase II Technovation Park,
81300 Skudai, Johor, Malaysia

[a)]Corresponding author: asahamzah@gmail.com, [b)]alihassan@utm.my, [c)]zainalaz@utm.my,
[d)]banitalebi.akbar@gmail.com, [e)]hazzarita@jbmi.my, [f)]norazelah@jbmi.my

Abstract. In this study, we consider the application of biological based product mPHO that contains Phototrophic bacteria (PSB) for the degradation of bacteria Coliform (pollutant) in Taman Timor Oxidation Pond, Johor, Malaysia. A mathematical model is developed to describe the reaction between microorganism and pollutant. The model facilitates the determination of mPHO optimum amount for achieving the maximum pollutant decontamination in the oxidation pond. A partial differential equation model with coupled equation is developed, and the parameters of the model are estimated using the real data collected from the oxidation pond under study. The numerical simulations are also presented to illustrate the performance of proposed model.

Keywords: Mathematical Model; Phototrophic Bacteria; Oxidation Pond.

INTRODUCTION

The human population continues to generate more and more waste materials either in their daily life or through industrial activities. These waste materials sooner or later are disposed into water resources such as rivers, lakes and sea. On the other hand, due to the rapid developments that took place in the area of inland, drinking-water sources are about to become fully utilized. Unfortunately, the effects of what are considered as unbalanced development have contributed in polluting the main source of natural environments on our planet, i.e. water. Recognizing the important interaction between water resources and human life, an attempt should be made to ensure that natural resources are being managed as good as possible and provide benefits to us. Water pollution to some extent will affects and disrupts the activities of human life in obtaining water supply and also for other domestic purposes.

An original source can be considered as contaminated if there are changes regarding its quality. Water pollution is caused by a combination of different types of environmental components such as organisms, organic materials, and inorganic materials. The major part of it is the result of human activities that contributes the largest part in pollution compared to other sources. Many studies have been conducted to ensure that wastewater treatment system could produce a good quality of water. Oxidation pond treatment has proved its effectiveness to meet the needs of medium-sized communities [1]. This treatment does not involve expensive construction and maintenance costs as compared to other treatment systems that are being widely used today. The procedure is primarily to decompose organic and inorganic contaminants in either anaerobic or aerobic reaction.

A pilot scale study has been carried out in Taman Timor oxidation pond, Tampoi, Johor, estimated about 1,909 m^2 and about 1.5 m in depth, 54 m in length and 2,864.13 m^3 of total volume of water [2, 3]. To ensure that maximum levels of decontamination can be achieved in the oxidation pond treatment, a biological-based product mPHO has been applied regularly within three months period of study [2, 3]. The effects of mPHO are observed through two sampling locations, which are CP1 (inlet and the application of mPHO) and CP2 (outlet) [2, 3]. Comparisons of data at both sampling points have shown that mPHO has a good effect in enhancing the degradation process of organic and inorganic matter. In this study, the relationship between mPHO and pollutant is highlighted by developing and simulating a mathematical model.

LITERATURE REVIEW

Almost all problems involving real-life applications can be modeled using mathematical modeling. In solving the real problems, the main issue should be taken seriously so that the nature of problems itself will not be affected. Therefore, we shall explore both sides of the problem, which are the physical phenomenon and its mathematical structure to construct a relationship between both. There are several issues that are being discussed globally such as water pollution in ponds, rivers and sea. When discussing issues related to the quality of water, one of the earliest manuscripts is believed to have been developed by Streeter and Phelps around 1925 [4] that discussed the relationship between biological oxygen demand (BOD) and dissolved oxygen (DO) in the River Cam, England. This model explains how the nature of BOD and DO can vary with the time of observation. Many mathematical models have been developed to help the conservation and preservation of water in a given locality. For instance, a study carried out on Tha Chin river stream in Thailand, which considered the effect of substances contaminated with dissolved oxygen [5]. This study proposed the model of two-dimensional coupled advection-dispersion equations for both state variables, respectively. In this model, contamination and oxygen concentration are permitted to fluctuate along the length of stream and these were dealt as homogeneous over the cross-segment of river, subjected to Dobbin's criterion [6].

Apart from that, there are also studies that were developed to study the important phenomena that occur in the water bodies such as eutrophication process [7]. It is the enrichment of an ecosystem with chemical nutrients, typically compounds containing nitrogen, phosphorus, or both. When household and industrial wastes are discharged into water, organic matters and nutrients presented in them are uptaken by bacteria and other biological species such as algae using dissolved oxygen in the interacting processes [8-10]. As these processes becoming the parts of a food chain in the water bodies, the level of DO decreased due to various interactive biochemical and biodegradation processes. This encourages the growth of algae (algal bloom) and other aquatic plants. Following this are the occurrences of overcrowding and plants compete for sunlight, space and oxygen. Eutrophication can be a natural process occurring in lakes, ponds or rivers as they age through time. Considering the biodegradation process involving the relationship between biological species and its nutrient, the Michaelis-Manten equation [11] is the suitable model that needs to be applied. The model describes the rate of enzymatic reactions by relating the reaction rate v with substrate S by the formula $v = V_{\max}[S]/(K_m + [S])$, where $V_{\max}$ is the maximum rate attained by the system that can be called as saturating substrate concentrations and K_m is the substrate concentration that takes half the value of $V_{\max}$.

A dynamic mathematical model has also been developed to predict the effluent quality of facultative wastewater stabilization ponds. A two-dimensional hydraulic model was employed considering dispersed flow and diffusion in horizontal and vertical directions, respectively. Resulting partial differential equation system was solved using finite difference methods and matrix manipulation techniques. The model has been calibrated and evaluated on the basis of collected data from a full-scale facultative stabilization pond [12].

Although many studies have been presented that are related to wastewater and its treatment by oxidation pond, most studies do not focus on demonstrating the control problem of mathematical models. This might happened because of the difficulty in having a reliable data to be used in the simulation procedure. This is the purpose of our study, which is to use the experimental data as the basis, and constructing the control experiment of mathematical model.

MATHEMATICAL MODEL

We modeled the wastewater treatment process using a system of partial differential equations (PDE), which is the first order PDE with coupled-equation:

The variables and parameters used in this mathematical model are as follows:

$M(x,t)$ is the concentration of PSB in the pond (mg/liter) where t varies from initial time up to 84 days.
$P(x,t)$ is the concentration of pollutant in the pond (mg/liter).
m_0 is the concentration of PSB in one liter of mPHO (mg/liter).
$U(t)$ is the amount of mPHO applied to the pond per liter in 84 days.
p_0 is the concentration of pollutant in one liter of sewage at CP1 (mg/liter).
v_s is the average amount of sewage coming in (liter/day).
v_p is the volume of the pond in liter.
υ is the velocity of wastewater in the pond (m/day).
c_1 to c_9 are constants determined by parameter estimations based on the experimental data at CP2.

The mathematical model is given as:

$$\frac{\partial P(x,t)}{\partial t} + \upsilon \frac{\partial P(x,t)}{\partial x} = (c_1 - c_2 P(t) - c_3 M(t))P(t) + c_4 \frac{v_s\ p_0}{v_p} \tag{1}$$

$$-c_5 \frac{(U(t) + v_s)\, P(x,t)}{v_p},$$

$$\frac{\partial M(x,t)}{\partial t} + \upsilon \frac{\partial M(x,t)}{\partial x} = (c_6 - c_7 M(t) - c_8 P(t))M(t) + c_9 \frac{m_0\, U(t)}{v_p} \tag{2}$$

$$-c_5 \frac{(U(t) + v_s)\, M(x,t)}{v_p},$$

where $0 \le t \le 84$ day, $0 \le x \le 54$ meter, and $\upsilon = 7.74144$ m/day.

At initial time and length namely t=0, and x=0, the value of pollutants is 0.32 mg/L, while the value of PSB is $1.5\text{x}10^{-6}$ mg/L. The initial conditions are presented by quadratic interpolation of the data at CP1 and CP2 when t=0,

$$P(x,0) = \frac{1}{54}\left(\frac{1.0\times 10^3}{10^8} - \frac{7.08\times 10^6}{10^8}\right)0.01851 x^2 + \frac{7.08\times 10^6}{10^8}, \tag{3}$$

$$M(x,0) = \frac{1}{54}\left(\frac{0.5\times 10^2}{10^8} - \frac{0.36\times 10^2}{10^8}\right)1.2751 x^2 + \frac{0.36\times 10^2}{10^8}. \tag{4}$$

The boundary conditions $P(0,t)$ and $M(0,t)$ can be calculated through linear interpolation of given data at CP1.

Parameter Estimation

The parameters of the proposed model can be estimated using a set of data collected through sampling from the pond in 84 days. Based on the given data, we want to determine the unknown parameters in equations (1-4) by the solution of parameter estimation problem. Then, a derivative-free optimization algorithm is employed to estimate the optimum value of the parameters $c_1, c_2, \ldots, c_9$. A random value for each parameter is initially generated, where the cost function of this problem can be formulated as follows,

$$f(c_1, ..., c_9) = \sum_{i=1}^{12} \left| P(t_i) - P^*(t_i) \right| + \sum_{i=1}^{12} \left| M(t_i) - M^*(t_i) \right|. \tag{5}$$

Here $P^*(t_i)$ and $M^*(t_i)$ is the amount of pollutant and PSB measured at CP2 at time t_i.

This cost function has to be minimized subject to the mathematical model, which has been described in (5). The current schedule of mPHO gave us the following parameters for the problem. These procedures were iteratively repeated until some acceptable values for the parameters are obtained. After performing the aforementioned optimization process, the values for the parameters are obtained as shown in Table 1.

TABLE 1. The parameters determined by parameter estimation.

Parameters	Value
c_1	0.32168
c_2	0.00237307
c_3	11.5246
c_4	0.0500592
c_5	0.0500258
c_6	0.0052575
c_7	0.677609
c_8	0.0831078
c_9	993.064

Using the above parameters, the mathematical model has been simulated and the numerical results are shown in Figure 1 and Figure 2. Figure 1 shows that although initially we do not have pollutant at that much, the dynamics of the system have caused the amount of pollutant to be slowly increases until it reaches some peak level because of the input of pollutant that enters the system from CP1. Eventually, the amount of pollutant can be reduced until it reaches a safe level by the end of treatment. While the variation of PSB along the pond has fluctuated with some pattern, it still cannot be reduced until the end of treatment as depicted in Figure 2. However, since PSB is not harmful to the environment, it is acceptable to release some unnecessary amount of PSB at discharged area.

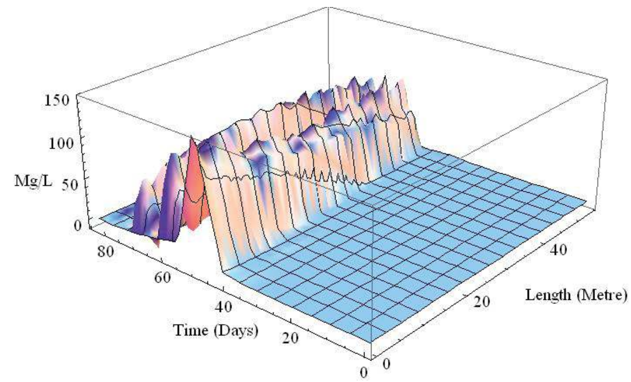

FIGURE 1. 3D graph of pollutant based on mathematical model.

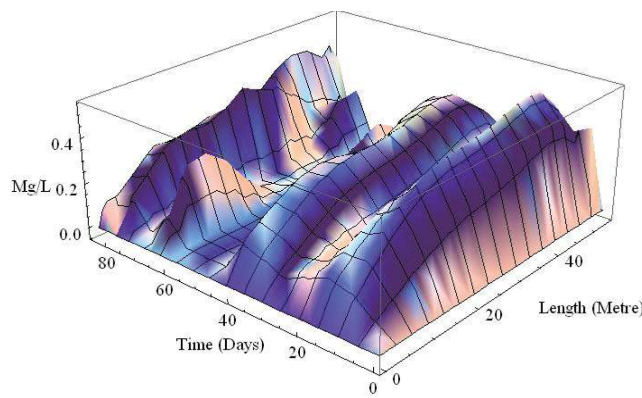

FIGURE 2. 3D graph of phototrophic bacteria based on mathematical model.

Optimal Control of mPHO

Now, using the parameters obtained in the previous section, an optimal control problem needs to be solved to obtain the optimum schedule for the application of mPHO in the pond that could reduce both the application cost of mPHO as well as the environmental cost.

The cost function of optimal control is given by,

$$J = \int_{0}^{84} [50\, U(t)^2 + \int_{0}^{54} \omega_p\, P(x,t)^2\, dx + \int_{0}^{54} \omega_m\, M(x,t)^2\, dx]\, dt, \tag{6}$$

where $U(t)$ is the schedule of mPHO application. In the equation of the cost function, the squares of variables are considered because we want *J* to be minimized in the sense of least squares. The function $U(t)$ is a step function on the interval $[0,84]$ and functions $P(x,t)$ and $M(x,t)$ are solutions of the proposed model (1) and (2). The weight parameters ω_P and ω_M are need to be selected according to the environmental requirements of the area under study. In this work, we set the values of both weight parameters at 1 to balance between environmental and application costs. The minimum of this cost function subject to the Equations (1-4) on the set of admissible schedules, which are satisfying in the mathematical model, results in approximating the optimal schedule $U(t)$. The solution of this control problem can be approximated through control parameterization method. In this method, the interval $[0,84]$ is partitioned into a few subintervals and the control function is approximated on each subinterval which gives us the optimal value for the application of mPHO in the pond as presented in Figure 3 and Figure 4.

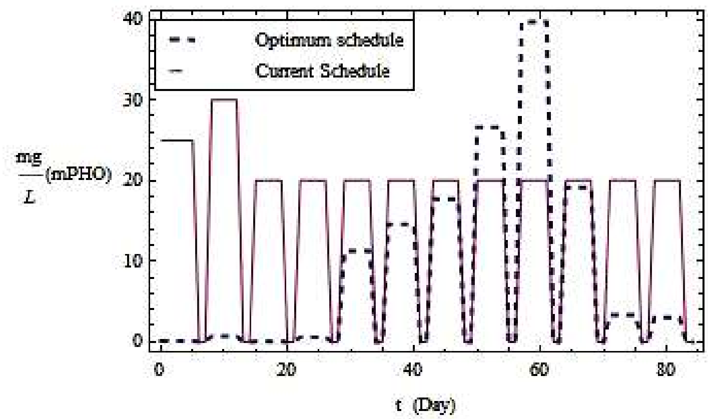

FIGURE 3. Optimum schedule of mPHO against the current schedule (solid line indicates optimum and dashed lines represent current).

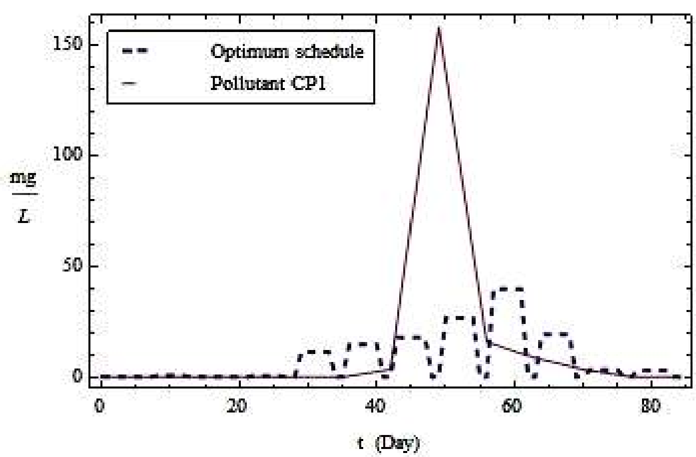

FIGURE 4. Optimum schedule of mPHO against the input of pollutant from CP1 (solid line indicates optimum and dashed lines represent pollutant at CP1).

Figure 3 suggests that, rather than applying constant amount of mPHO for 10 remaining weeks of treatment, we should vary its application according to the quality of wastewater entering the pond. By using the optimum schedule, we have already saved about 590 liters of mPHO that will cost RM 29, 500 since each liter of mPHO cost RM 50. Figure 4 shows how the input of pollutant and optimal schedule vary with time.

Based on the new schedule for mPHO application, we simulate the mathematical model again to see the effects of schedule on the value of pollutant and PSB. Figure 5 and Figure 6 show the application of a new schedule that significantly changes the amount of pollutant while it reduces the amount of mPHO.

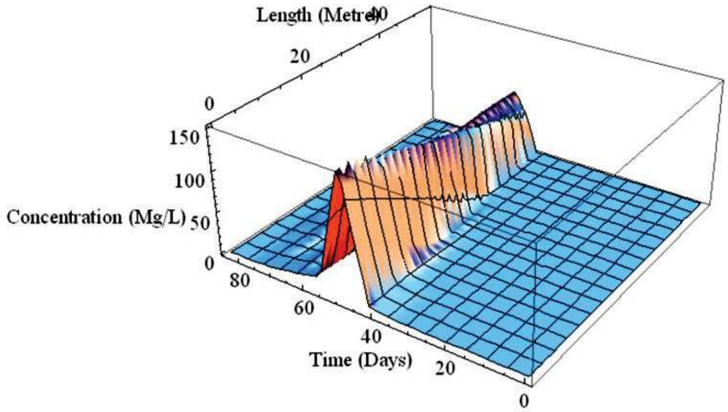

FIGURE 5. 3D graph of pollutant based on the optimum schedule.

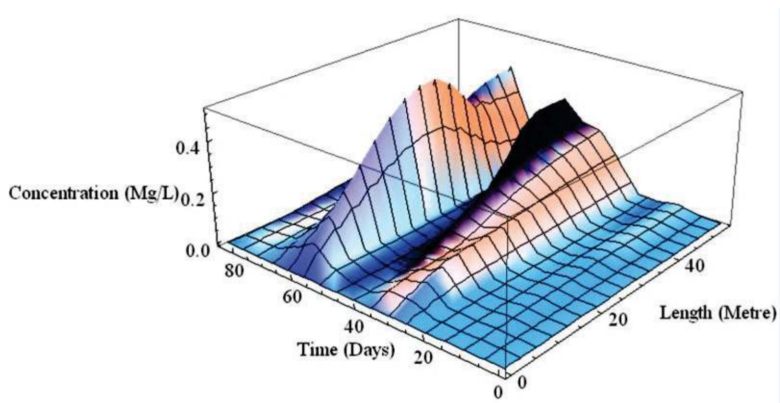

FIGURE 6. 3D graph of phototrophic bacteria based on the optimum schedule.

Figure 5 shows that the optimum schedule could control a huge amount of pollutant much quicker than current schedule. By using the control parameter, we could control the amount of pollutant while taking care of the uncontrollable amount of PSB as shown in Figure 6.

CONCLUSION

In this study, a mathematical model for wastewater treatment process of an oxidation pond was developed and using real data, a set of optimum parameters were obtained for the model. Then, a constructed optimal control problem was developed based on the proposed model to optimize the schedule of the application of mPHO. The control problem was solved through control parameterization approach and the model was simulated using the optimum schedule. The numerical results show that the models could produce a forecast with plausible results. The results have also proven the effectiveness of mPHO in improving water quality of oxidation pond.

ACKNOWLEDGMENTS

The authors would like to thank the Ministry of Higher Education Malaysia (MOHE) for the financial support through the research grant R.J130000.7809.4F637, UTM Centre for Industrial and Applied Mathematics (UTM-CIAM), and the laboratory teams from Johor Biotechnology & Biodiversity Corporation (J-Biotech) R&D for providing the real data.

REFERENCES

1. H. I. Abdel-Shafy and M. A. Salem, "Efficiency of oxidation ponds for wastewater treatment in Egypt" in *Wastewater Reuse–Risk Assessment, Decision-Making and Environmental Security* edited by M. K. Zaidi (Springer, Netherlands, 2007), pp. 175-184.
2. A. S. Hamzah, A. Banitalebi, A. H. Murid, Z. A. Aziz, H. Ramli, H. Rahman and N. Hamdon, Jurnal Teknologi **78** (3-2), 65-70 (2016).
3. A. S. Hamzah, A. H. Murid, Z. A. Aziz, Z. M. Zainuddin, H. Ramli, H. Rahman and N. Hamdon, Jurnal Teknologi **78** (4-4), 145-150 (2016).
4. M. B. Beck and P. C. Young, Water Research **9**, 769–776 (1975).
5. B. Pimpunchat, W. L. Sweatman, G. C. Wake, W. Triampo and A. Parshotam, Applied Mathematics Letters **22** (3), 304–308 (2009).
6. W. E. Dobbins, Journal of the Sanitary Engineering Division **90** (3), 53-78 (1964).
7. J. B. Shukla, A. K. Misra and P. Chandra, Nonlinear Analysis: Real World Applications **9** (5), 1851–1865 (2008).
8. W. E. Gates, J. T. Marler and J. D. Westfield, Water Research **3** (9), 663–686 (1969).
9. F. Nishimura, M. Watanabe, R. Takahashi and T. Akase, Water Science and Technology **45** (12), 37–44 (2002).
10. D. J. O'Connor, Water Research **3** (1), 65–79 (1967).
11. L. Edelstein-Keshet, *Mathematical models in biology* (Siam, Philadelphia, 1988).
12. B. Beran and F. Kargi, Ecological Modelling **181**, 39–57 (2005).