PERFORMANCE PREDICTION OF ROTATING BIOLOGICAL CONTACTOR IN WASTEWATER TREATMENT APPLICATIONS

Dr. Amer D. Zmat
College of Engineering
AL-Qadisiya University

Dr. Ali H. GHAWI
College of Engineering
AL-Qadisiya University

Abstract:

Biofilm models were used to model and predict the performance of Rotating Biological Contactors (RBC) in wastewater treatment plants. Assessment techniques have been adopted to evaluate this method in terms of hydraulic loading and Biochemical Oxygen Demand (BOD) removal. The results revealed that RBC not only is efficient, but also proven to be odor controlling reactor. RBC provides efficient mixing and reduces time of retention to minimum, so that a great reduction of area of treatment plants will be achieved.

Key word: BOD, COD, organic material, wastewater, biofilm.

تخمين الأداء للملامسات البايولوجية الدوارة في محطات معالجة المياه الثقيلة

الدكتور عامر دحام زماط
كلية الهندسة
جامعة القادسية

الدكتور علي هادي غاوي
كلية الهندسة
جامعة القادسية

الخلاصة:

تم استخدام موديلات الأغشية البيولوجية لتمثيل وحدة معالجة مياه الصرف الصحي التي تعتمد الملامسات البيولوجية الدوارة. جرى تقيم ذلك النوع من الوحدات من خلال دراسة تأثير معامل التحميل الهيدروليكي على كفاءة الإزالة لـل BOD . ثم جرى تقيم زيادة عدد الأقراص البيولوجية (bio-disks) على كفاءة العملية، واظهرت نتائج الدراسة و التحليل إن عملية الخلط الجيد التي تحققها الملامسات البيولوجية الدوارة نتيجة الدوران ترفع كفاءة عملية المعالجة بشكل ملموس وتقلل زمن البقاء المطلوب للمعالجة و بالتالي يؤدي إلى اختزال المساحات والكلف لبناء مثل تلك الوحدات.

Nomenclature

A	a lumped parameter which is equal to $\frac{kX_f}{D_f}$, mg·L−1
Aw	surface area of the disk, m^2
A	the slope for $\frac{dS_f}{dz}\|_{z=0}$ as expressed to be a linear correlation with S_B, m^{-1}
B	the intercept for $\frac{dS_f}{dz}\|_{z=0}$ as expressed to be a linear correlation with S_B, $kg{\cdot}m^{-4}$
D_f	diffusion coefficient of substrate within the biofilm, $cm^2{\cdot}h^{-1}$
K_i	constant for inhibition, $mg{\cdot}L^{-1}$
Ks	saturation constant, $mg{\cdot}L^{-1}$
K	maximum specific substrate consumption rate, s^{-1}
L_f	biofilm thickness, mm
Lt	length of the reactor, m
Q	flow rate, m3·d−1
Ra	substrate consumption rate by the microbes attached on the disc, $kg{\cdot}m^{-2}{\cdot}s^{-1}$
S	substrate concentration, $mg{\cdot}L^{-1}$
S_0	substrate influent concentration, $mg{\cdot}L^{-1}$
S_B	liquid phase substrate concentration, $mg{\cdot}L^{-1}$
Se	substrate effluent concentration, $mg{\cdot}L^{-1}$

Introduction

Rotating biological contactor (RBC) has been widely used for the secondary treatment of domestic and industrial wastewaters. The RBC consists of a series discs attached to a common shaft. The wastewater is fed into the contactor with a certain flow rate. All the discs are partially submerged into the wastewater. When the discs are continuously rotated by the shaft, a subsequent submergence and exposure to atmosphere will take place. Thus, the microbial film on the disc that is initially in contact with the nutrients of the wastewater phase and then with the oxygen in the atmosphere. Hence, the organic compounds in the wastewater would serve as the nutrients for the microbes to digest and grow. By such periodical operation, the microbes would grow and a certain sludge film thickness would be obtained.
The RBC is used because of its advantages such as high specific surface area, high activated sludge concentration, better sludge settling, process stability, and low maintenance and power consumption. Benefield and Randall [1] described the design of the biological treatment processes for wastewaters [1]. Two pilot-scale RBCs with PE discs arranged in four stages were used [2] for the treatment of 2-nitrophenol or 2-chlorophenol contained synthetic wastewater. Opatken and Bond [3] treated a leachate with high concentration of ammonia-nitrogen (20-1000 mg/L) by the nitrification process with a pilot-scale RBC. Different experiments were conducted to determine the operating parameters of the RBC treatment system. Buisman *et al.* [4] compared three different bioreactor systems for the removal of sulphide containing wastewater.

Stirred reactor, biorotor reactor and upflow reactor were used for comparison. The biomass support materials of Rasching rings and polyurethane were also compared.
It is obvious that the biofilm disc is very important for the RBC performance. Brower and Barford [5] introduced different biological fixedfilm systems in their report [5]. In 1978, a theoretical model for RBC systems was provided so that process design criteria for a pilot-plant RBC process can be established and be compared with the activated sludge process [6]. Since RBC is composed of a series of discs with microbial growth in a film. The film model is certainly important for it. Mass transfer problems across the film should also be taken into consideration. The steady-state biofilm kinetic models were proposed for both conditions of deep and shallow biofilms [7]. In the adopted model, mainly Monod growth model with substrate diffusion along single dimension was assumed.
The film was assumed to be of a planar form. The substrate flux was also discussed. The deep biofilm model with Monod assumption for completely mixed and plug flow biofilm reactors was analyzed [8]. Such biofilm reactors were found to be extremely sensitive to the surface parameters. Models are based on Monod growth kinetics.
Activated sludge reactors and rotating biological contactors demonstrated that both suspended and attached growths can be effective methods for treating the wastewater as described above. Sagy and Kott [9] examined fecal coliform bacteria and *Salmonella typhimurium* die-off in an experimental RBC which received settled domestic sewage from the city main sewer. The behavior of the microbes on the biofilm is fairy important. Most biofilms are formed by mixed species. Gupta and Gupta used a mixed culture aerobic biofilm to remove carbon and nitrogen from a synthetic domestic sewage [10].
RBC is an essential treatment process for treating industrial wastewater. Meanwhile, it is also a very interesting system for theoretical analysis. Hence, in this work, we established the model for the biofilm system based on both Mond and substrate inhibition mechanisms. With the models, the operation conditions as well as the number of the biofilm discs can be analyzed

Developed Of Mathematical Model

The biofilm reactor being considered has a length of L_t and a flow direction parallel to the horizontal axis as shown in Fig. 1. The schematic representation of a biofilm is shown in Fig. 2. It was assumed that the fluid was well-mixed in the radial direction and the substrate consumption from the suspended microbial can be negligible when compared to that of the attached biofilm.

Consider an infinitesimal volume in a biofilm reactor, by the mass balance for a shell,

$$\frac{\partial}{\partial t}\left(\frac{V_t}{L_t}\cdot\Delta y\cdot S_B\right)=(QS_B)_y-(QS_B)_{y+\Delta y}-R_a\cdot\frac{A_w}{L_t}\cdot\Delta y \qquad (1)$$

where V_t is the volume of wastewater in the biofilm reactor, L_t is the length of the reactor, R_a is the substrate consumption rate by the microbial attached on the disc, S_B is liquid phase substrate concentration, and Q is the flow rate. If we divide both sides of equation 1 by Δy, we obtain

$$\frac{V_t}{A_w}\frac{\partial S_B}{\partial t} = -\frac{Q \cdot L_t}{A_w}\frac{\partial S_B}{\partial y} - R_a \tag{2}$$

If the substrate consumption rate by the attached microbial on the disc is equal to the substrate diffusion rate at the surface of the film, then,

$$\frac{V_t}{A_w}\frac{\partial S_B}{\partial t} = -\frac{Q \cdot L_t}{A_w}\frac{\partial S_B}{\partial y} + D_f \left.\frac{\mathrm{d}S_f}{\mathrm{d}z}\right|_{z=0} \tag{3}$$

where D_f is the diffusion coefficient of substrate within the biofilm, S_f is the substrate concentration in the biofilm, and z is the axis along the biofilm thickness. Under steady state assumption

$$\frac{\mathrm{d}S_B}{\mathrm{d}y} = \frac{D_f \cdot A_w}{Q \cdot L_t}\left.\frac{\mathrm{d}S_f}{\mathrm{d}z}\right|_{z=0} \tag{4}$$

The following boundary conditions were implemented to solve equation 4.

1. The boundary conditions in case of thick biofilm:

$$\text{B.C. 1} \qquad S_B = S_0 \qquad \text{at} \quad y = 0;$$

$$\text{B.C. 2} \qquad S_B = S_e \qquad \text{at} \quad y = L_t$$

For the case of thick biofilm with Monod kinetics $\mu = \mu_m\, S/Ks + S$.

$$R_a = -D_f \left.\frac{\mathrm{d}S_f}{\mathrm{d}z}\right|_{z=0} = D_f\sqrt{2A\left[S_B + K_s \ln\left(\frac{K_s}{K_s + S_B}\right)\right]} \tag{5}$$

Where $A = \frac{kX_f}{D_f}$ and k is the maximum specific substrate consumption rate [t^{-1}].

For the case of the thick film with substrate inhibition kinetic

$$\mu = \frac{\mu_m\, S}{K_s + S + S^2 / K_i}$$

(1) If $K_i/K_s < 4$, then

$$R_a = D_f\sqrt{A\left\{K_i \ln\left(1 + \frac{S_B}{K_s} + \frac{S_B^{\,2}}{K_i\, K_s}\right) - \frac{2K_i^{1.5}}{\sqrt{4K_s - K_i}}\left\{\tan^{-1}\left[\frac{2S_B + K_i}{\sqrt{K_i(4K_s - K_i)}}\right] - \tan^{-1}\left[\frac{K_i}{\sqrt{K_i(4K_S - K_i)}}\right]\right\}\right\}} \tag{6}$$

(2) If $K_i/K_s > 4$, then

$$R_a = D_f \sqrt{A\left\{K_i \ln\left(1+\frac{S_B}{K_s}+\frac{S_B^{\,2}}{K_i\,K_s}\right)-\frac{K_i^{1.5}}{\sqrt{K_i-4K_s}}\ln\frac{[2S_B+K_i-\sqrt{K_i(K_i-4K_s)}][K_i+\sqrt{K_i(K_i-4K_s)}]}{[2S_B+K_i+\sqrt{K_i(K_i-4K_s)}][K_i-\sqrt{K_i(K_i-4K_s)}]}\right\}} \quad (7)$$

(3) If $Ki/Ks = 4$, then

$$R_a = -D_f \cdot \left.\frac{\mathrm{d}S_f}{\mathrm{d}z}\right|_{z=0} = 2D_f\sqrt{2AK_s\left[\ln\left(\frac{S_B}{2K_s}+1\right)-\frac{S_B}{S_B+2K_s}\right]} \quad (8)$$

Substituting the above equations (Eqs. (5)-(8)) into Eq. (4), we obtain the following results,

- **Without substrate inhibition:**

$$\frac{\mathrm{d}S_B}{\mathrm{d}y} = -\frac{D_f \cdot A_w}{Q \cdot L_t}\cdot\sqrt{2A\left[S_B + K_s \cdot \ln\left(\frac{K_s}{K_s+S_B}\right)\right]} \quad (9)$$

- **With substrate inhibition:**

(1) If $K_i/K_s < 4$,

$$\frac{\mathrm{d}S_B}{\mathrm{d}y} = -\frac{D_f A_w}{QL_t}\sqrt{A\left\{K_i \ln\left(1+\frac{S_B}{K_s}+\frac{S_B^{\,2}}{K_i K_s}\right)-\frac{2K_i^{1.5}}{\sqrt{4K_s-K_i}}\left\{\tan^{-1}\left[\frac{2S_B+K_i}{\sqrt{K_i(4K_s-K_i)}}\right]-\tan^{-1}\left[\frac{K_i}{\sqrt{K_i(4K_s-K_i)}}\right]\right\}\right\}} \quad (10)$$

(2) If $K_i/K_s > 4$,

$$\frac{\mathrm{d}S_B}{\mathrm{d}y} = -\frac{D_f A_w}{QL_t}\sqrt{A\left\{K_i \ln\left(1+\frac{S_B}{K_s}+\frac{S_B^{\,2}}{K_i K_s}\right)-\frac{K_i^{1.5}}{\sqrt{K_i-4K_s}}\ln\frac{[2S_B+K_i-\sqrt{K_i(K_i-4K_s)}][K_i+\sqrt{K_i(K_i-4K_s)}]}{[2S_B+K_i+\sqrt{K_i(K_i-4K_s)}][K_i-\sqrt{K_i(K_i-4K_s)}]}\right\}} \quad (11)$$

(3) If $K_i/K_s = 4$,

$$\frac{\mathrm{d}S_B}{\mathrm{d}y} = -\frac{2 \cdot D_f \cdot A_w}{Q \cdot L_t}\cdot\sqrt{2AK_s\left[\ln\left(\frac{S_B}{2K_s}+1\right)-\frac{S_B}{S_B+2K_s}\right]} \quad (12)$$

The above equations are all first-order ordinary differential equations. They can be solved for the numerical solution of $S_B|_{z=L}$, which is the exit substrate concentration, S_e, by the fourth-order Runge- Kutta method.

2. The boundary conditions in case of thin biofilm:

$$\text{B.C. 1} \qquad S_f = S_B \qquad \text{at} \quad z = 0 \, ;$$

$$\text{B.C. 2} \qquad \frac{dS_f}{dz} = 0 \qquad \text{at} \quad z = L_f$$

S_f and $\frac{dS_f}{dz}\Big|_{z=0}$ can be solved by finite difference and the exit substrate concentration $S_B\, |_{z=L}$ can be further obtained. Based on the above theorem and assumptions, the effluent substrate concentration can be computed. During the computation process, several operation conditions, which draw influence on the performance of the biofilm reactor, such as influent substrate concentration, length of reactor, total surface area of the biofilm, flow rate, numbers of reactors in series, film thickness should be provided. The growth and diffusion parameters related to the biofilm such as K_s, K_i, k, X_f , and D_f should be given as well.

For the thin biofilm, under Monod kinetics assumption, when the substrate concentration in liquid phase is higher, the substrate consumption rate R_a would be higher as well. For substrate inhibition kinetics assumption the result is similar, which is higher substrate consumption rate for higher liquid phase substrate concentration. However, when the substrate concentration is too high, substrate inhibition would cause the decreasing of substrate consumption rate. It can be inspected from Fig. 3 that under certain range of S_B, $\frac{dS_f}{dz}\Big|_{z=0}$ (R_a) is a linear function of S_B for the case of thin film. Therefore, $\frac{dS_f}{dz}\Big|_{z=0}$ can be expressed as

$$\frac{dS_f}{dz}\Big|_{z=0} = a.S_B + b \tag{13}$$

where a is the slope and b is the intercept. a and b are dependent on the range of S_B. Provided that the liquid phase substrate concentrations were $S_{B,1}$ and $S_{B,2}$, then,

$$\left(\frac{dS_f}{dz}\Big|_{z=0} \right)_{S_B = S_{B,1}} = a \cdot S_{B,1} + b \, , \tag{14}$$

$$\left(\frac{dS_f}{dz}\Big|_{z=0} \right)_{S_B = S_{B,2}} = a \cdot S_{B,2} + b \, . \tag{15}$$

Combining Eqs. (14) and (15), *a* and *b* can then be obtained. Substituting Eq. (13) into Eq. (4), then,

$$\int_{S_{B1}}^{S_{B2}} \frac{\mathrm{d}S_B}{a \cdot S_B + b} = \int_{y_1}^{y_2} \frac{D_f \cdot A_w}{Q \cdot L_t} \mathrm{d}y \,, \tag{16}$$

$$S_{B2} = -\frac{b}{a} + \left(S_{B1} + \frac{b}{a} \right) \exp \cdot \left(\frac{a \cdot D_f \cdot A_w \cdot \Delta y}{Q \cdot L_t} \right). \tag{17}$$

Results And Discussion

Six stages biofilm reactors for wastewater treatment was considered in the following analysis. Both Monod kinetic and substrate inhibition kinetic were applied in this study. The length of the biofilm reactor was set to be 5.0 m. The total surface area for treatment was 5,000 m2. Kinetic parameters for cell growth were K_s = 100 mg/L and X_f = 20,000 mg/L. The diffusivity of the biofilm was D_f = 0.02 cm^2/h. Flow directions of the influent feed were set to be parallel to the horizontal axis of the reactor. For flow direction parallel to the axis, the biofilm reactor maybe regarded to be a plug flow reactor (PFR).

The BOD removal efficiency was evaluated in terms of inlet substrate concentration at different hydraulic loadings, as shown in Fig. 4. The results show that higher hydraulic loadings exhibit higher BOD removal efficiency at low inlet substrate concentration whereas, lower hydraulic loadings can result in very low BOD removal efficiency at higher inlet substrate concentration.

Fig. 5 shows that increasing the number of bio-disks can steeply reduce the effluent substrate concentration for different inlet substrate concentration. These results may be used by designers to determine the required number of disks for specific inlet and outlet constraints.

Fig. 6 shows that law inlet substrate concentration slightly affect the substrate removal efficiency when hydraulic loading increased, while high inlet concentration can cause significant drop in the removal efficiency as a threshold value in exceeded.

It can be seen from Fig. 7 that low inlet substrate concentration is very sensitive to the number of bio-disks, whereas, higher inlet concentration show gradual response to the number of bio-disks.

The COD removal in terms of hydraulics loadings was compared to BOD removal. **Figure 8** below was adopted from [11] for comparison.

The effect of hydraulic loading on COD removal efficiency was also adopted from [11] to be compared with the BOD removal efficiency.

Figure 10 shows that dissolved oxygen is steeply declined as the thickness of the biofilm increases. This interprets that the process is diffusion-controlled.

The submergence ratio of bio-disks was investigated in terms of the dissolved oxygen and number of stages of the process (Fig. 11). Submergence ratios between 0.4 and 0.6 were found to appropriate and effective than higher and lower ratios.

Conclusion

Based on Monod kinetics and substrate inhibition kinetics for the biofilm, the model for the substrate removal efficiency of a 6 stage biofilm reactor was established. The influence of feeding rate, hydraulic loading and organic loading rate (hydraulic retention time) was investigated and discussed. RBC technology was found to be cost effective in wastewater treatment as it considerably reduces both the size of equipments and the number of unit operations.

References

[1] Benefield, L. D. and C. W. Randall, *Biological Process Design for Wastewater Treatment*, Prentice Hall, New York, U.S.A. (1980).

[2] Tokuz, R. Y., "Biodegradation and Removal of Phenols in Rotating Biological Contactors," *Water Sci. Technol.*, **21**(12), 1751 (1989).

[3]Opatken, E. J. and J. J. Bond, "RBC Nitrification of High Ammonia Leachates," *Environ. Prog.*, **10**(1), 60 (1991).

[4] Buisman, C. J., B. Wit, and G. Lettinga, "Biotechnological Sulphide Removal in Three Polyurethane Carrier Reactors: Stirred Reactor, Biorotor Reactor, and Upflow Reactor," *Water Res.*, **24**(2), 245 (1990).

[5] Brower, J. B. and C. C. Barford, "Biological Fixed-Film Systems," *Water Environ. Res.*, **69**, 487 (1997).

[6] Clark, J. H., E. M. Moseng, and T. Asano, "Performance of a Rotating Biological Contractor under Varying Wastewater Flow," *J. Water Poll. Control Fed.*, **50**, 896 (1978).

[7] Rittmann, B. E. and P. L. McCarty, "Model of Steady-State-Biofilm Kinetics," *Biotechnol. Bioeng.*, **22**(11), 2343 (1980).

[8] Suidan, M. T. and Y. T. Wang, "Unified Analysis of Biofilm Kinetics," *J. Environ. Eng.*, **111**(5), 634 (1985).

[9] Sagy, M. and Y. Kott, "Efficiency of Rotating Biological Contractor in Removing Pathogenic Bacteria from Domestic Sewage," *Water Res.*, **24**(9), 1125 (1990).

[10] Gupta, A. B. and S. K. Gupta, "Simultaneous Carbon and Nitrogen Removal in a Mixed Culture Aerobic RBC Biofilm," *Water Res.*, **33**(2), 555 (1999).

[11] Kossay K. Al-Ahmady" Effect of Organic Loading on Rotating Biological Contactor Efficiency"*Int. J. Environ. Res. Public Health*, *2(3)*, 469-477 (2005).

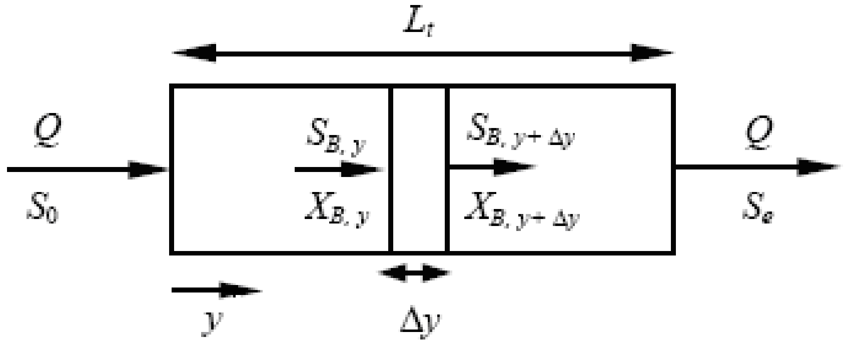

Figure 1. Schematic represent of a biofilm reactors.

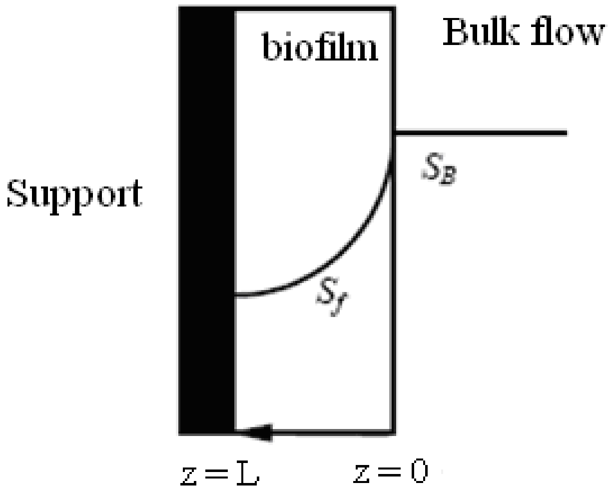

Figure 2. Schematic representation of a biofilm.

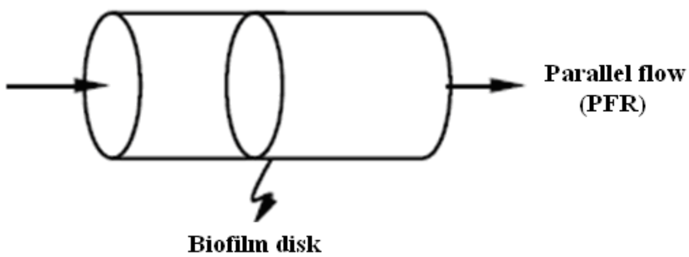

Figure 3. Representation of biofilm reactors (Plug Flow Reactor PFR)

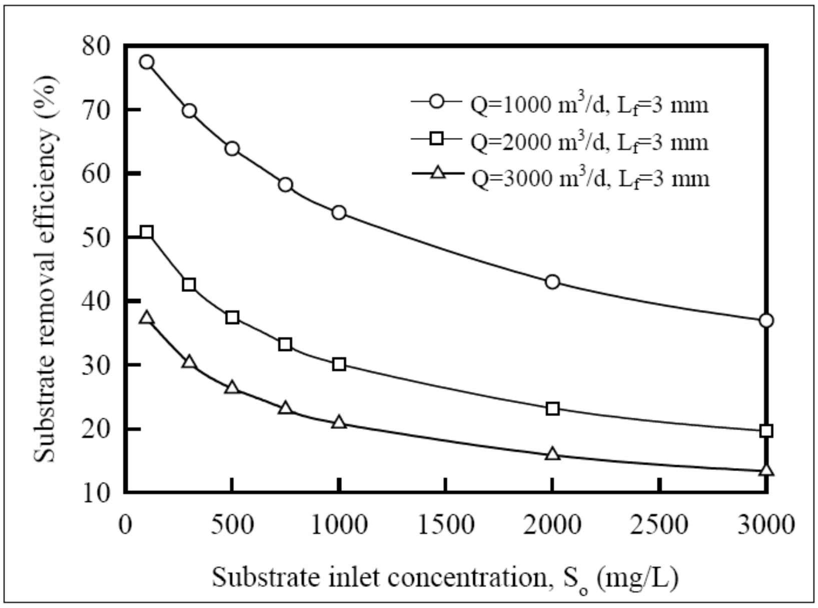

Figure 4: Substrate (BOD) removal efficiency with respect to inlet concentration under different flow rates and 3 mm biofilm active thicknesses.

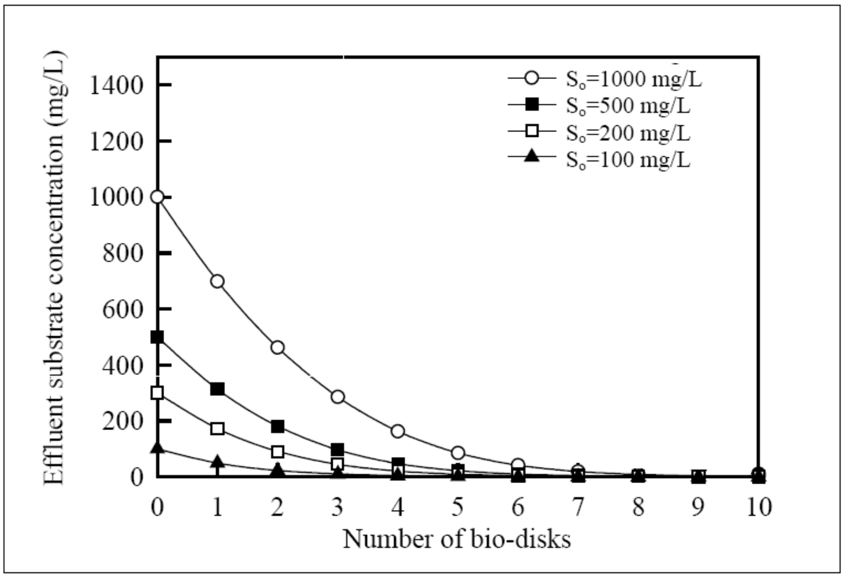

Figure 5: Effluent substrate concentration with respect to number of biofilm disks under different substrate inlet concentration

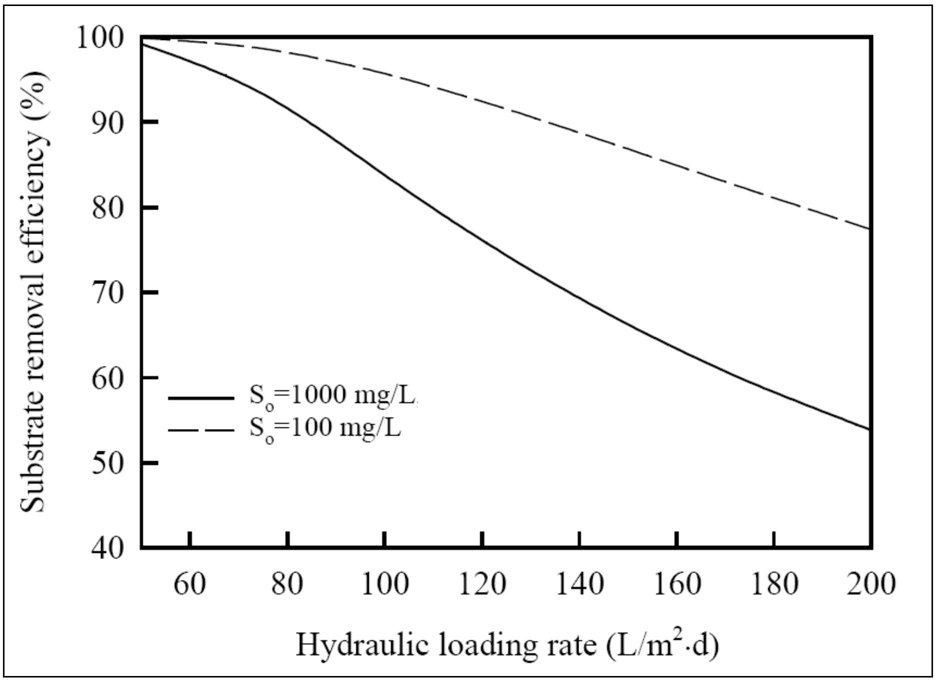

Figure 6: Effect of hydraulic loadings on the substrate removal efficiency at law and high inlet substrate concentrations.

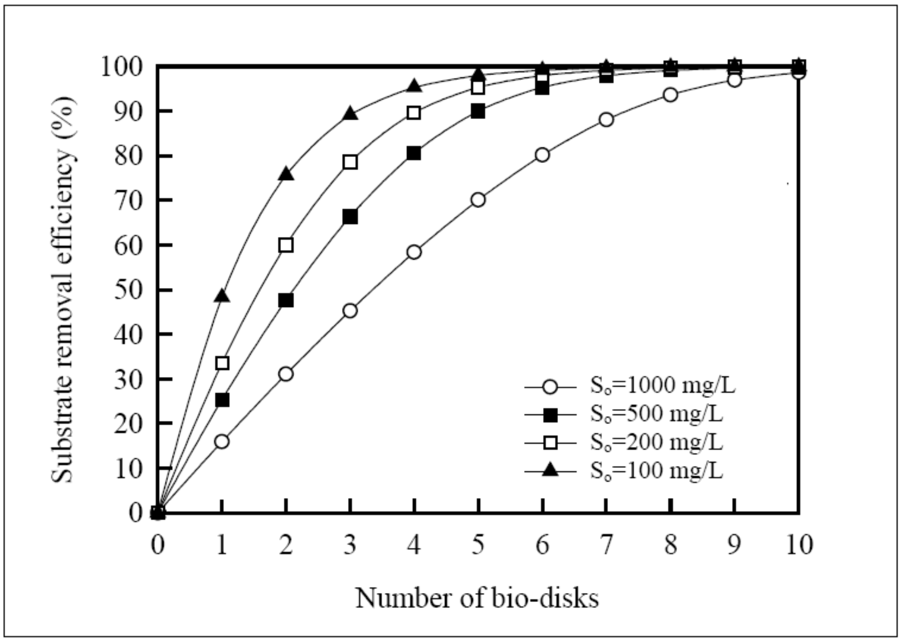

Figure 7: Effect of the number of bio-disks on substrate removal efficiency at different inlet

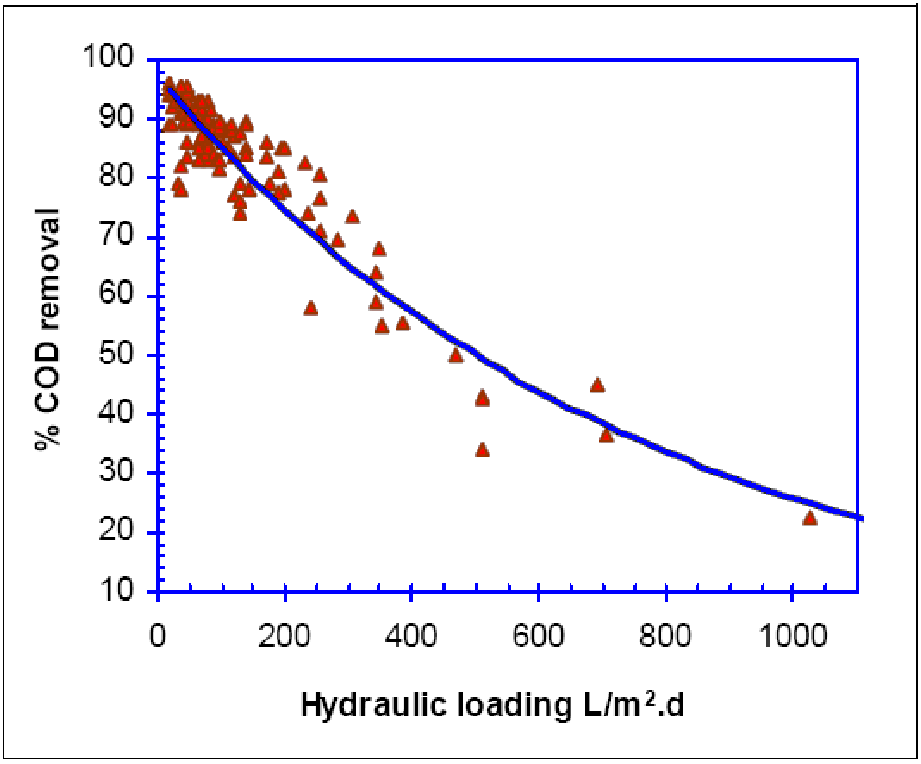

Figure 8: Effect of hydraulic loading on % COD removal.

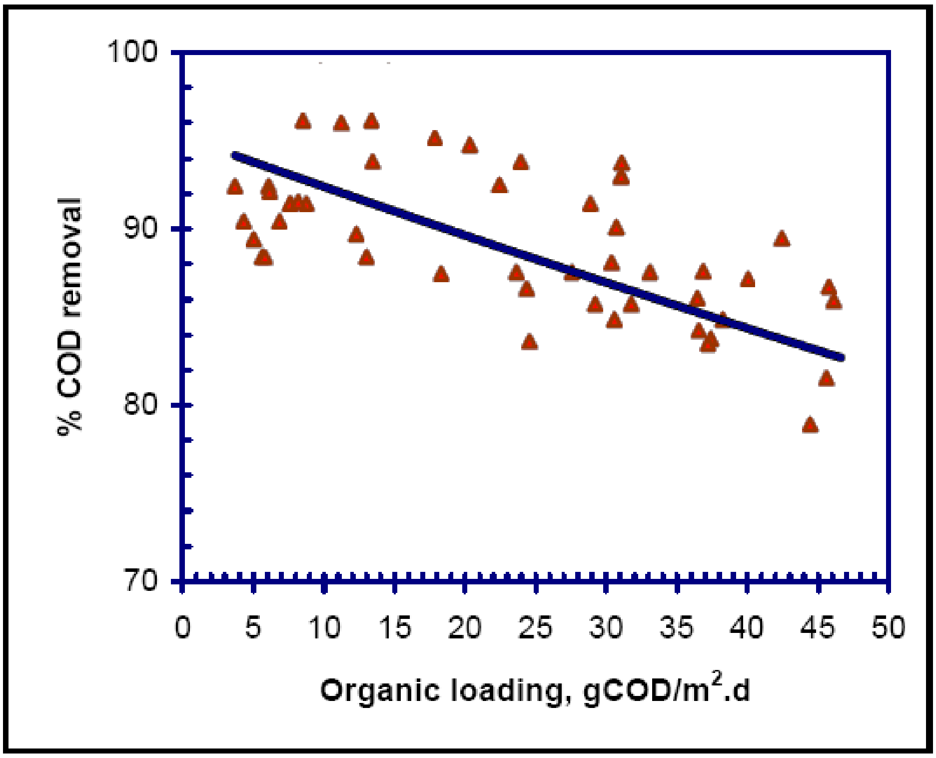

Figure 9: Effect of organic loading on the COD removal efficiency

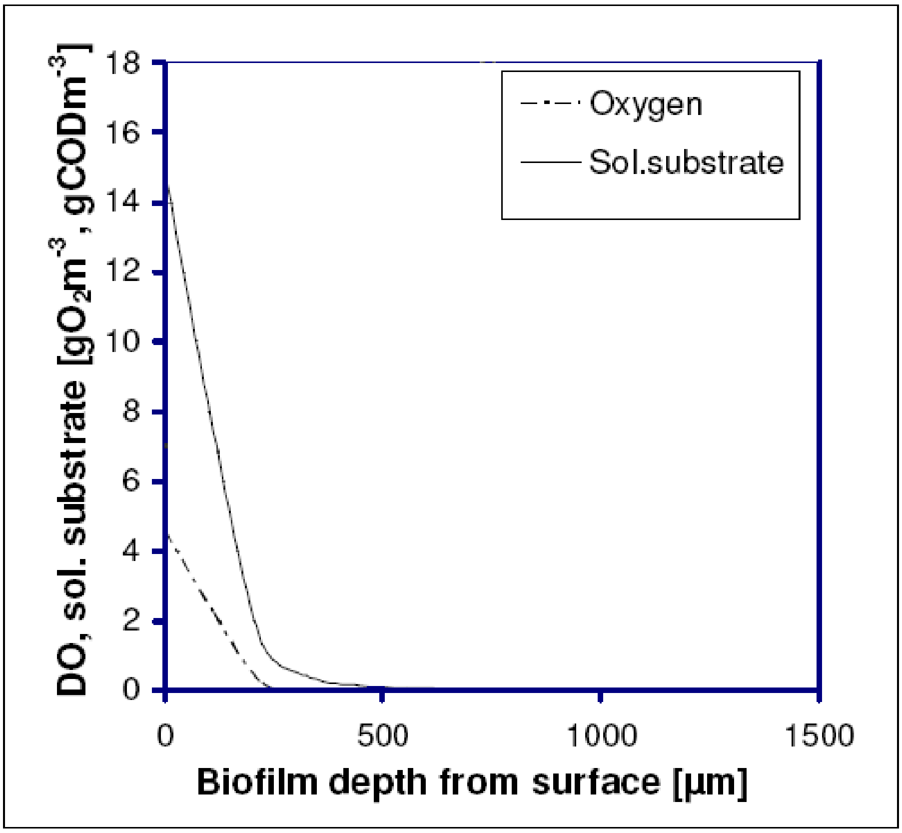

Figure 10: Concentration profiles of organic substrate, and dissolved oxygen inside the biofilm in RBC stages

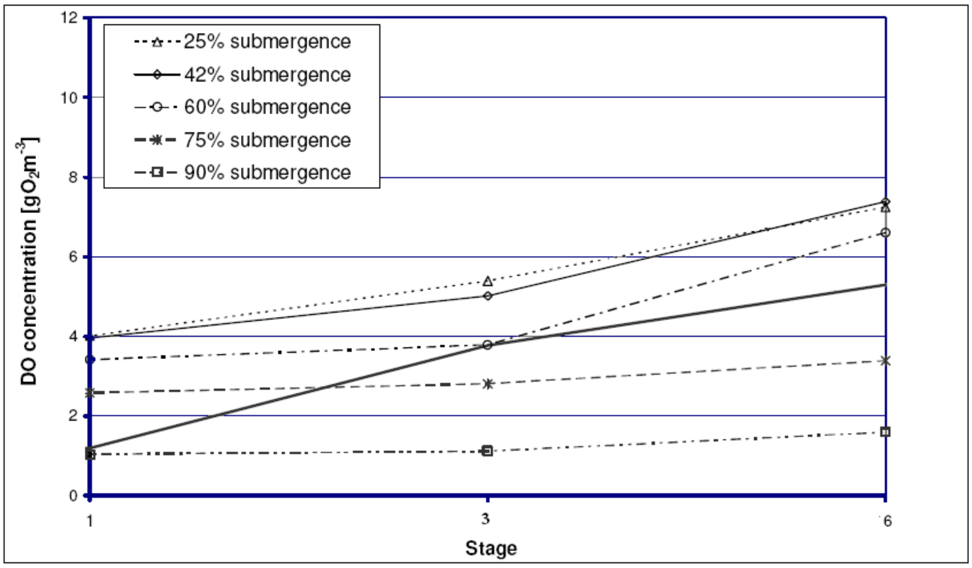

Figure11: The DO concentration in bulk liquid under varying submergence ratio in RBC stages