Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2016.1165148

57 (2016) 29193–29200
December

Taylor & Francis
Taylor & Francis Group

Performance and optimization of lab-scale membrane bioreactors for synthetic municipal wastewater

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Received 13 December 2015; Accepted 29 February 2016

ABSTRACT

This study aimed to determine biokinetic coefficients and efficiency of three submerged membrane bioreactors (MBRs) comprising a conventional MBR, moving bioflim MBR (MB-MBR), and anoxic-oxic MBR (A/O-MBR) operated at laboratory scale for synthetic municipal wastewater (500 mg/L glucose chemical oxygen demand) at a hydraulic retention time of 8 h. The activated sludge was collected from sewage treatment plant I-9, Islamabad, and was acclimatized with synthetic wastewater for a time period of 60 d. The physico-chemical and biological parameters were determined as per standard methods. The Monod rate equation was applied for estimating specific growth rate (μ), decay rate constant (K_d), yield coefficient (Y), half-velocity constant (K_s), and maximum specific growth rate (μ_m). The A/O-MBR showed the highest removal efficiencies of total organic carbon and nitrogen (94 and 82% respectively) and also maximum kinetic coefficients were obtained and values of Y, K_d, K_s, and μ_{max} coefficients were 0.77 mg/mg, 0.066 d^{-1}, 271 mg/l, and 1.44 d^{-1}, respectively. Therefore, the study aimed at optimizing MBRs system by optimization of the kinetics.

Keywords: Wastewater treatment; Membrane bioreactor; Biokinetic coefficients; Monod equation

1. Introduction

With continuing depletion of fresh water resources, high urbanization and industrialization, treatment of wastewater is now becoming a serious issue for developing countries, especially Pakistan. This has resulted in a move toward water reuse and recycling involving various wastewater treatment technologies. In Pakistan, it has been estimated that around 2,000 million gallons of sewage is being discharged to local surface water bodies every day [1]. Municipal wastewater is not subjected to any treatment and none of the cities have any biological treatment process except Islamabad and Karachi (only 8% of the wastewater was treated before

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Presented at the 8th International Conference on Challenges in Environmental Science & Engineering (CESE-2015) 28 September—2 October 2015, Sydney, Australia

disposal) [2]. In rural areas, wastewater treatment is nonexistent, leading to pollution of surface and groundwater [3]. The wastewater treatment plants (WWTPs) that are operating mostly use conventional activated sludge treatment processes. However, the WWTPs are not regularly monitored, therefore biological kinetics are not being evaluated for optimization of process parameters and thus the treatment plant efficiency is not able to be enhanced. There is a dire need to develop WWTPs and upgrade existing systems, opting for more advanced and robust techniques to combat the ever increasing water demand.

Treatment technology for wastewater recycling encompasses a vast number of options. Membrane processes are regarded as key unit technology for advanced wastewater reclamation and reuse applications e.g. for artificial groundwater recharge, indirect potable reuse as well as for industrial process water production. Bioreactors differ from conventional reactors as living organisms present in the reactors and are operated under milder conditions of temperature and pressure. The ranges of operating conditions within bioreactors are usually determined by the biocatalyst (organisms) and often small. The membrane bioreactor (MBR) has become widely applicable for biological treatment of wastewater [4]. MBR treatment for municipal wastewater could effectively improve the quality of the effluent and the removal of chemical oxygen demand (COD), biochemical oxygen demand, and suspended solids (SS) were at least 95, 98, and 99%, respectively [5]. MBR technology is relatively new in sub-tropical region and much research is required to be carried out before its application at industrial level. Also, most of the integrated bioreactors reported lack of large scale implementation within industry and further work is required to evaluate the performance of these promising reactors on a larger scale. Hence, in this study a lab-scale MBR setup was established for parameters optimization and obtaining high effluent quality. The performance evaluation and membrane fouling behavior of three differently configured MBRs named as conventional MBR (C-MBR), moving biofilm (MB-MBR), and anoxic–oxic (A/O-MBR) are described in earlier work [6].

The efficiency of any wastewater treatment plant depends mainly upon technical design and the bacterial diversity in the treatment plant which contribute toward the biodegradation of the organic matter. Understanding microbial community is a key step toward the rational design and operation of functionally stable wastewater treatment systems [7]. The micro-organisms of mixed culture in wastewater treatment are very complex as their metabolic activities, growth rate, and substrate assimilation are interrelated and affect each other [7]. In the past, designs of biological wastewater treatment processes were based on the empirical parameters, which included hydraulic loading, organic loading, and retention time. The design utilizing empirical, as well as rational parameters based on biological kinetic equations [8] enhance efficiency of wastewater treatment process. Biokinetic coefficients of different wastewater treatment processes were evaluated by several investigators; applying the widely used Monod model [9–11]. The microbial population treating the wastewater in this study has already been characterized [12] however, the biological kinetics involved remain unknown. Hence, the MBRs in this study were operated in parallel with same operating conditions and were compared for their biomass growth rate, decay rate, and substrate utilization rate. This study will provide baseline data for the establishment of pilot-scale membrane treatment plant at NUST, for treating wastewater (15,000 gallons/d) generated by the campus.

2. Materials and methods

2.1. Experimental setup

Three lab-scale MBRs: C-MBR, MB-MBR, and anoxic–oxic MBR (A/O-MBR) were operated for a period of eight months. The acrylic reactors were rectangular in shape with working volumes of 16 L. Hollow fiber membranes made up of polyvinylidene fluoride with a pore size of 0.1 μm, an effective filtration area of 0.2 m^2, operation pressure of 1–30 kPa, and membrane permeate flux of 25 ml/min (Mitsubishi Rayon, Japan) were used in all three MBRs in submerged mode. A peristaltic pump (Master Flex, Cole-Parmer, USA) operated in a relaxation cycle of 10 min on and two min off was used to draw the permeate. The C-MBR was operated as a submerged MBR. In the MB-MBR, the Kaldness plastic media was added as a moving carrier for supporting the attached growth. The biofilm carriers were made of high-density polyethylene plastic material and their shape was cylindrical, having a cross on the inner side of the cylinder and rough tooth on the outside. The size of each cylindrical shaped media was 10 mm in diameter and 7 mm in height (1 cm dia.) with bulk density of 150 kg/m^3. A/O MBR was operated as a hybrid MBR including biofilm carrier and a mechanical mixer (Cole-Parmer) in one of the compartments for keeping sludge in suspension with less dissolved oxygen (DO). Reactors were aerated using diffusers and flow meters were used to measure and regulate the aeration rate. Wastewater was fed into the reactor using relay control unit for controlling the flow and auto level sensor.

The operating conditions of MBRs are hydraulic retention time 8 h, SRT 30 d, F/M 0.22 ± 0.03, and OLR 1,560 (mg/L/d).

2.2. Characters of the synthetic wastewater

Synthetic wastewater recipe was prepared by dissolving glucose (514 mg/L), NH_4Cl (190 mg/L), KH_2PO_4 (55.6 mg/L), and buffer $NaHCO_3$ (142.8 mg/L) along with trace elements ($CaCl_2$, Mg_2SO_4, $FeCl_3$, $MgCl_2$) in tap water. The stock solution was combined with tap water in a ratio 1:60 (i.e. 1 L of stock solution with 60 L of tap water) to make high strength domestic wastewater. The COD:N:P was 100:10:2.

2.3. Estimation of bacterial growth curves

The microbial growth curves were determined by drawing 300 ml activated sludge sample from reactors C-MBR, MB-MBR, and A/O-MBR and placing at shaking water bath. Spread Plate Count (SPC) was used as per microbiological methods [13] at 0, 2, 4, 6, 24, and 48 h. Serial dilution technique was used for determining SPC.

2.4. Analytical methods

MLSS and MLVSS were determined as per methods described in the Standard Methods [14]. Total organic carbon (TOC) and total nitrogen (TN) were measured using TOC analyzer (Analytikajena, Germany), pH monitored by Hach pH meter (sension 1) whereas, temperature and DO analyzed by Hach meter (sension 5).

2.5. Biokinetic coefficients

Monod model, common and widely used for determining the biokinetic coefficients, is given by equation:

$$\mu = \mu_m \frac{S}{K_s + S}$$

Biokinetic coefficients used for the design of activated sludge processes include specific growth rate (μ), maximum rate of substrate utilization per unit mass of micro-organisms (K), half-velocity constant or substrate concentration at one half the maximum specific growth rate (K_s), maximum cell yield (Y), and endogenous decay coefficient (K_d). For mixed culture of micro-organism found in wastewater, it has been observed that the rate of increase in biomass, dx/dt is directly proportional to the reactor biomass concentration, X, in the wastewater treatment system and the proportionality factor is known as specific growth rate constant [15]. The kinetic equation is given as follows:

$$R_g = \frac{dX}{dt} = \mu X$$

$$\mu = \frac{dX/dt}{X}$$

The mass of new cell produced per unit of substrate utilized or removed by the micro-organisms present in the system is called the cell yield. The kinetic equation is described below:

$$Y = \frac{R_g}{R_{su}} = \frac{dX/dt}{dS/dt}$$

where dX/dt = rate of change of biomass. dS/dt = rate of substrate removal.

During the exponential phase, nutrients are in excess and the organism is growing at its maximum specific growth rate, "μ_{max}" for the prevailing conditions:

$$K = \mu_m/Y \ (\text{day}^{-1})$$

where μ_m = maximum specific growth rate. Y = Yield coefficient.

The specific growth rate of micro-organism is closely related to the rate of substrate utilization and the net growth is observed even when micro-organisms are in starved conditions in the system. The value of limiting nutrients or substrate concentration at one half of the maximum growth rate of biomass (K_s) is termed as half-velocity constant given as:

$$K_s = \mu_m \ \frac{S}{\mu - S}$$

where μ_m = maximum specific growth rate. S = Growth limiting soluble substrate. K_s = Half-velocity constant.

When the substrate concentration S in the wastewater is at its minimum, the micro-organisms metabolize their own protoplasm (autodigestion) and the concentration of biomass in the reactor decreases due to death of some cells. The phenomenon is known as K_d. The rate of such biomass decay is proportional to the concentration of remaining biomass [15]. It is given by equation as:

$$K_d = -\frac{R_d}{X} \qquad \therefore R_d = -dX/dt$$

where R_d = rate of endogenous decay of biomass. X = Biomass concentration.

3. Results and discussion

3.1. Bacterial growth curves

An initial microbial count of C-MBR was 1.31×10^6 CFU/ml. The microbial growth decline after 24 h and entered into death phase, as the cells oxidize themselves to meet maintenance energy needs as evident from Fig. 1. The dissolved oxygen concentration also reduced from 6.79 to 1.48 mg/L after 48 h. The initial microbial growth rate of MB-MBR was around 1.6×10^6 CFU/ml and gradually increased to 5×10^6 CFU/ml after 4 h. The microbial growth reduced to 3×10^6 CFU/ml after 24 h with continued decline till 48 h. After placing the sludge in a shaking incubator the counts of the A/O MBR increased to 6.8×10^6–8.4×10^6 CFU/ml after 2–4 h, respectively. After 24 h, the counts started to decline and dropped to 1.2×10^6 CFU/ml after 48 h. The A/O MBR was evidently efficient and the hybrid growth conditions yielded maximum biomass. Metabolically active micro-organisms catalyze the pollutant removing reactions depending on the concentration of the catalyst i.e. the active biomass [16].

3.2. MLSS and MLVSS concentrations

MLSS of the MBRs was maintained above 5,000 mg/L. During start of the experiment MLSS and MLVSS concentrations of the sludge sample collected from C-MBR increased almost continuously reaching values of about 7.23 and 4.48 g/L, respectively up to 24 h. After 48 h of reaction time, MLSS value reduced to 4.01 g/L and MLVSS concentration almost reached to 3.18 g/L indicating death phase of microbial cultures. The MLSS and MLVSS concentration of sample sludge from MB-MBR increased to 8.85 and 6.126 g/L and reduced to 4.84 to 3.97 g/L, respectively. While increased concentration was obtained for A/O-MBR with 9.85 g/L (MLSS) and 7.68 g/L (MLVSS) for the initial 24 h and then gradually declined (Fig. 2).

3.3. Organic carbon and nitrogen removal

The average concentration of TOC in influent wastewater was 250 mg/L. With the increase in biomass growth substrate, organic carbon removal efficiency of almost 90% was achieved within 4–6 h in almost all of the samples. Comparatively, the performance of the samples obtained from A/O-MBR (94%) exhibited slightly better performance as compared to C-MBR and MB-MBR probably due to varied dissolved oxygen concentration in A/O MBR and presence of micro-organisms in various zones (Fig. 3). These results are in line with the study conducted by Fu et al. [17] with a maximum organic carbon removal of 94.6% along with 84.6% of TN using A/O-MBR with synthetic wastewater. Similarly, the MB-MBR showed greater TOC removal (92%) as compared to the C-MBR. The fouling propensity of the membranes was evaluated earlier [6] indicating that the addition of Kaldness media resulted in improved treatment performance and in the reduction of the cake layer over the membrane surface due to scouring of the membrane.

Coexistence of different nitrifiers which perform the same task implies functional redundancy, which may allow communities to maintain physiological capabilities when conditions change. Thus, a high

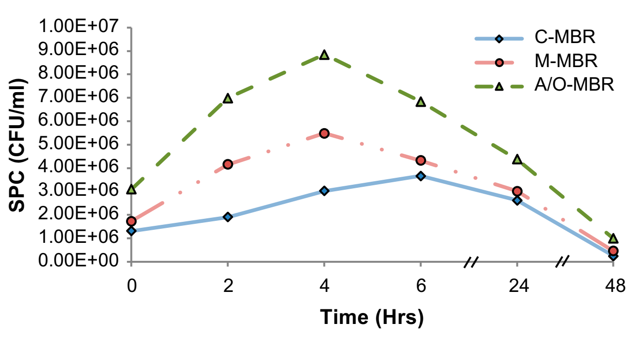

Fig. 1. Bacterial growth curves of the MBRs.

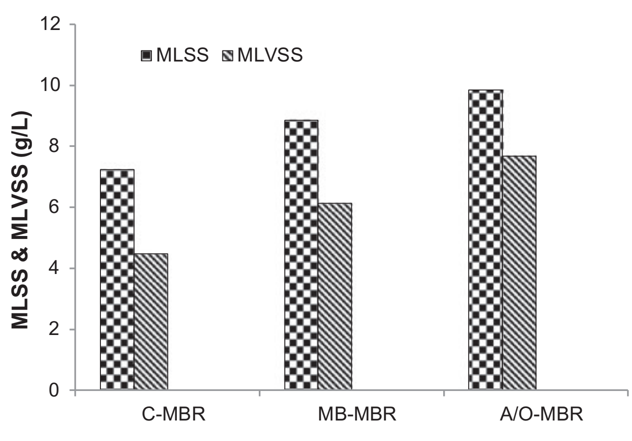

Fig. 2. Suspended solids concentrations in the MBRs.

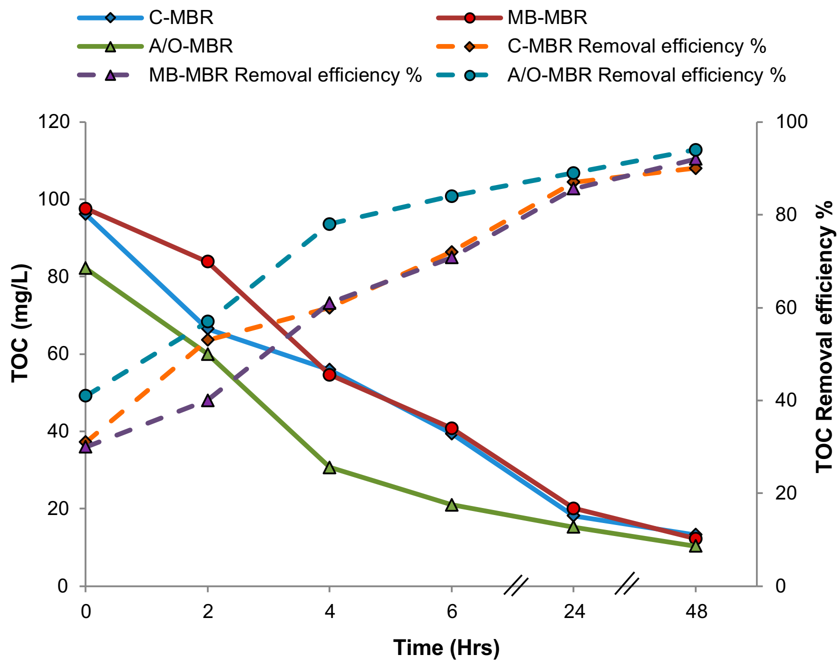

Fig. 3. The decrease in organic load with bacterial growth.

level of nitrifier diversity is thought to confer performance stability [18]. The TN of samples obtained from three MBRs is shown below (Fig. 4). It was found that the maximum TN removal of 82% was achieved from samples obtained from the A/O-MBR. The effective TN removal in A/O-MBR was achieved due to optimal conditions for denitrifying bacteria growth and anoxic conditions provided by addition of biofilm carrier and mechanical mixing. Microbial diversity enhanced simultaneous nitrification and denitrification process and improved the TN removal. These results are in line with the study conducted by Khan et al. [6] who observed substantial TN removal efficiency; that is, about 23% greater than the C-MBR and also detection of *P. aeruginosa* from A/O-MBR suggested that denitrification was dominated in A/O-MBR. The study also indicated that dominant families in the reactor contributing toward efficient treatment process included *Enterobacteriaceae* and *Pseudomonadaceae*. Sample sludge taken from the MB-MBR exhibited better

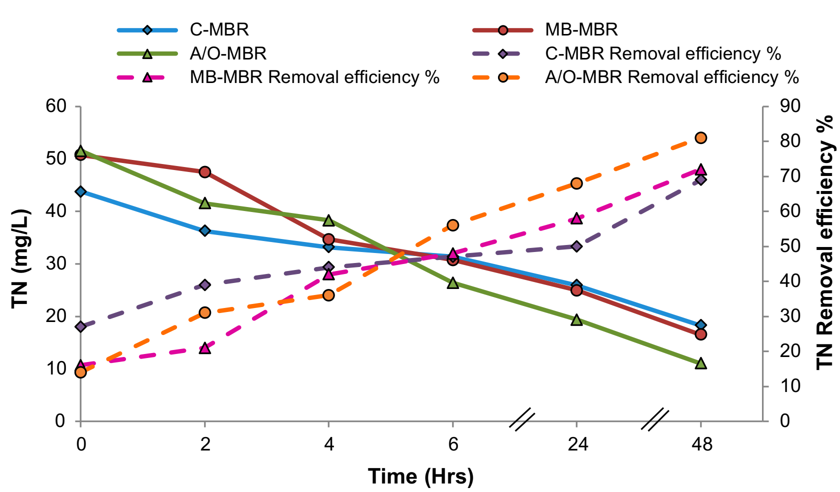

Fig. 4. % Removal efficiency of nitrogen content with time.

TN removal i.e. 72% than C-MBR. The addition of Kaldness media resulted in improved treatment performance. Nitrification in Kaldness MBRs has been thoroughly studied using both synthetic wastewater [19] and municipal wastewater [20]. Normally, the nitrite (NO_2^{-1}) and nitrate (NO_3^{-1}) produced by nitrifiers under aerobic condition would be cycled to an anoxic compartment to implement denitrification. Also discharge of nitrate to receiving water is preferable as compared to discharge of ammonia because nitrification in the receiving water may deplete the DO, simply as degradation of organic matter.

3.4. Biokinetic coefficients of MBRs treating synthetic domestic wastewater

Experimental data for substrate and biomass concentrations during the bacterial growth phase were used for the determination of kinetic parameters. Considering the saturation constant (K_s) and limiting substrate concentration quantities (S) during the exponential growth phase, the values for μ were calculated from Monod rate equation and the mean value was 0.26 d^{-1} for C-MBR [15]. For the evaluation of kinetic parameters of Y, K_d, K, μ_{max}, and K_s, a graphical method was adopted and the coefficient of determination (R^2) was determined to measure that to what extent the observed outcomes are replicated by the model. The obtained kinetic coefficients are summarized in Table 1 and similar results were found by Peng and Xue [21] and Al-Malack [22]. The value of R^2 of (Figs. 5a and 5b) was high (>0.95) confirming the applicability of Monod model.

In the batch experiments conducted on pure substrates and change in volatile suspended solid (VSS) over the experimental period were plotted against the TOC removal to obtain the observed yield coefficient graphically ($R^2 = 0.979$) for MB-MBR (Figs. 6a and 6b). The observed yield and decay coefficient in the system were estimated to be 0.465 mg/mg and 0.06 d^{-1} respectively. Similarly the half-saturation constant (K_s) and maximum substrate utilization rate (K) were obtained by curve fitting for glucose substrate (Fig. 6a) and value was 85.71 mg/L and 0.16 d^{-1}, respectively.

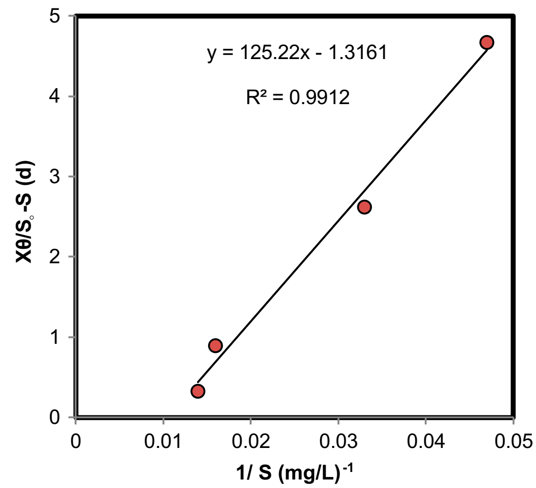

Fig. 5a. Monod model plot for estimation of K and K_s.

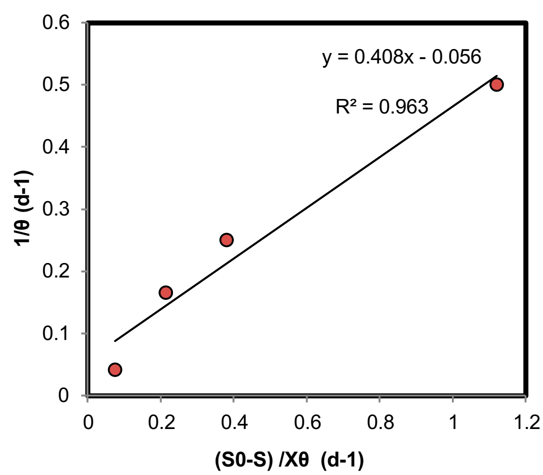

Fig. 5b. Monod model plot for estimation of Y and K_d.

Table 1
Monod kinetic coefficients for MBRs

Substrate	Y (mg/mg)	K_d (1/d)	μ_{max} (1/d)	K_s (mg/l)	K (1/d)	Refs.
Glucose	0.5–0.62	0.025–0.48	7.4–18.5	11–181	–	[22]
Synthetic	0.42–0.53	0.05–0.19	0.8–6.3	83–646	–	[22]
MWW	0.63–0.713	0.017–0.039	0.23–0.42	13.8–50.8	1–8	[25]
Synthetic	0.408	0.056	0.31	95	0.759	This study (C-MBR)
Synthetic	0.465	0.06	0.074	85.71	0.16	This study (MB-MBR)
Synthetic	0.770	0.066	1.44	271	1.87	This study (A/O-MBR)

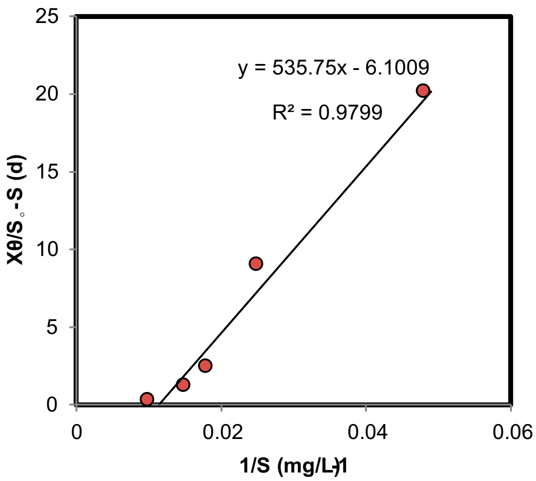

Fig. 6a. Monod model plot for estimation of K and K_s.

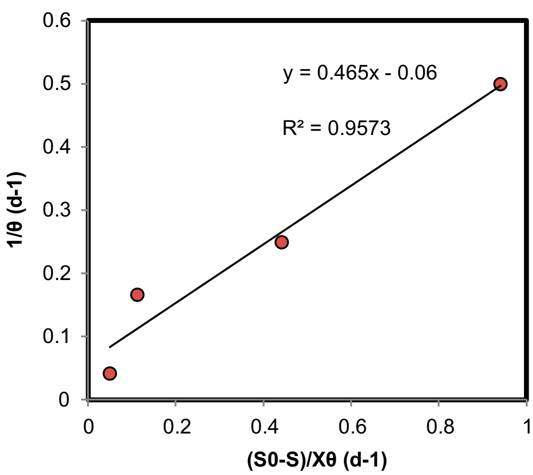

Fig. 6b. Monod model plots for estimation of Y and K_d.

The values for specific growth rate μ were calculated from Monod rate equation and the mean value was found out to be 0.063 d^{-1}.

Similar plots were obtained for A/O MBR for determination of biokinetic coefficients (Figs. 7a and 7b). The values of biokinetic coefficients obtained for A/O MBR were higher among all MBRs as shown below in Table 1. The MBR has also shown maximum efficiency in removal of TOC and TN. This is due to diversity of microbial flora prevailing in the system due to anoxic–oxic conditions. These results are in line with the earlier studies conducted by Cardinali-Rezende et al. [23] that wastewater treatment processes with hybrid anaerobic and aerobic conditions are most effective in mineralization of pollutants from wastewater. It is operationally and economically

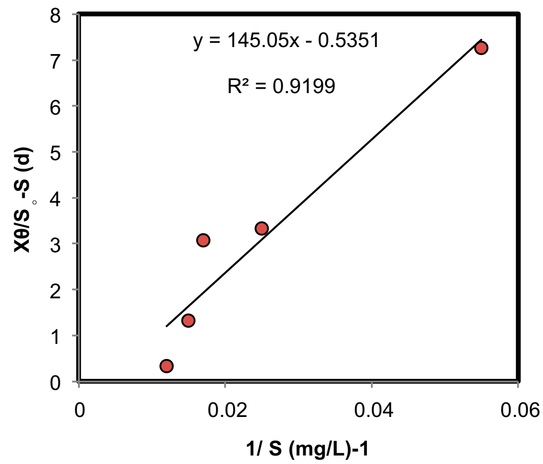

Fig. 7a. Monod model plot for estimation of K and K_s.

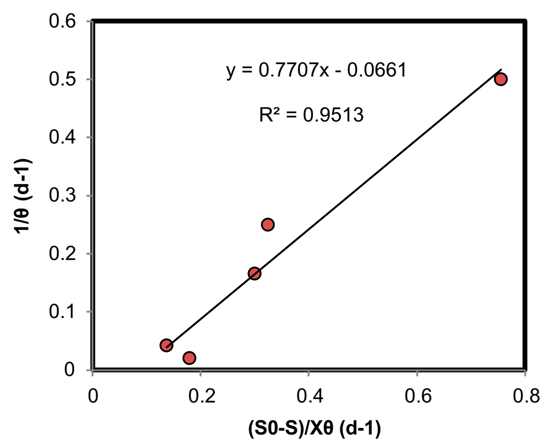

Fig. 7b. Monod model plot for estimation of Y and K_d.

advantageous to adopt anaerobic/aerobic processes in the treatment of high strength wastewaters, since it couples the benefit of anaerobic digestion (i.e. biogas production) with the benefits of aerobic digestion (i.e. better COD and VSS removal [24].

4. Conclusions

The MBR systems were investigated to evaluate the removal performance and the Monod model was used for estimation of kinetic coefficients. Hybrid growth conditions (anoxic/oxic) were found to be most efficient for treating synthetic domestic wastewater with 94% TOC removal and 82% TN removal. The biomass growth in A/O reactor was also high as compared to the other MBRs. MBR kinetic coefficients derived from this study were similar to those reported in the literatures. It is envisaged that the integrated anaerobic/aerobic MBRs will be able to treat high organic strength municipal wastewater and operate with minimum fouling tendency.

Acknowledgments

We gratefully acknowledge the financial support of Higher Education Commission (Project No. 20–1217/R&D/09), Pakistan, and also HEC, Pakistan and British Council, UK INSPIRE program (SP-192) to carry out this research.

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