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Simultaneous removal of carbon, nitrogen and phosphorus in a multi-zone wastewater treatment system

Mahmood Alimahmoodi,* Laleh Yerushalmi and Catherine N. Mulligan

Abstract

BACKGROUND: The simultaneous removal of carbon, nitrogen and phosphorus under variable operating conditions during the start-up period of a new multi-environment hybrid wastewater treatment technology called BioCAST is reported in this paper. The presence of both suspended-growth and immobilized microorganisms, as well as the continuous circulation of mixed liquor between the three zones of aerobic, microaerophilic and anoxic, supported high removal efficiencies of organic and inorganic contaminants.

RESULTS: The removal efficiencies of carbon, nitrogen and phosphorus reached 99.3%, 98.0% and 92.3%, respectively, under varying organic loading rates in the range 0.4–3.0 kg m^{-3} d^{-1}, and nitrogen and phosphorus loading rates of 0.03–0.14 kg m^{-3} d^{-1} and 0.008–0.028 kg m^{-3} d^{-1}, respectively. Phosphorus removal increased steadily with the increase of nitrogen loading rate, producing a final effluent concentration of 2.9 mg L^{-1}. Low sludge generation was obtained along with a low biomass yield of 11.5%.

CONCLUSIONS: The start-up period of the BioCAST system demonstrated its potential for simultaneous removal of organic material, as well as nitrogen and phosphorus. Phosphorus removal demonstrated a strong dependence on nitrogen loading rate. Moreover, theoretical analysis of the liquid flow and energy balances in different zones of the treatment system showed that the pressure difference across the air diffuser is the governing force for the flow of liquid towards the aerobic zone and the controlling factor for the continuous circulation of mixed liquor among various zones.
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Keywords: wastewater treatment; multi-zone bioreactor design; nutrient removal; minimized waste sludge; air-lift reactor

INTRODUCTION

Simultaneous removal of organic carbonaceous compounds and nutrients, especially from high organic load and nutrient-rich wastewaters such as those produced in agricultural activities, has proven to be difficult. The performance of several biological treatment systems for the removal of carbon, nitrogen and phosphorus has been investigated.[1–4] The generation of a high volume of waste sludge and increased oxygen consumption have been among the major challenges facing conventional technologies that use aerobic biological treatment processes during the treatment of high organic load wastewaters.[5–9]

Sequencing batch reactors (SBR) have frequently been used for the treatment of high strength wastewaters.[10–15] Alternative biological treatment systems such as membrane bioreactors have also been used for the removal of carbonaceous contaminants and nutrients.[16,17] Among the various designs used in aerobic treatment systems, airlift reactors have attracted special interest due to their capacity for consolidation of several treatment units in a single reactor. Several design configurations of airlift reactors have been suggested to improve the reactor performance during nitrification/denitrification[18–21] and simultaneous COD, N and P removal.[21]

BioCAST is a new multi-environment wastewater treatment system, developed for high-rate and simultaneous removal of organic carbonaceous compounds and inorganic nutrients, notably nitrogen and phosphorus. The BioCAST system has the capacity to accumulate high concentrations of suspended-growth as well as attached-growth microorganisms at high solid retention time (SRT), making it particularly suitable for the treatment of high organic load and nitrogen-rich wastewaters. This technology has been designed to reduce sludge generation while having a smaller footprint compared with conventional technologies. Unlike the operation of SBRs, no elaborate timing or control system is required for the operation of the BioCAST system, and no special type of membrane, as used in membrane bioreactors, is required whose operation is limited due to occasional clogging often during full-scale applications.

We previously reported on the long-term operation of the BioCAST system during the treatment of a synthetic wastewater that lasted for 225 days.[22] That study showed that despite the capacity of this technology for the simultaneous removal of

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* Correspondence to: Dr. Mahmood Alimahmoodi, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, H3G 2 W1, Quebec, Canada. E-mail: mahmood.alimahmoodi@concordia.ca

Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, H3G 2 W1, Quebec, Canada

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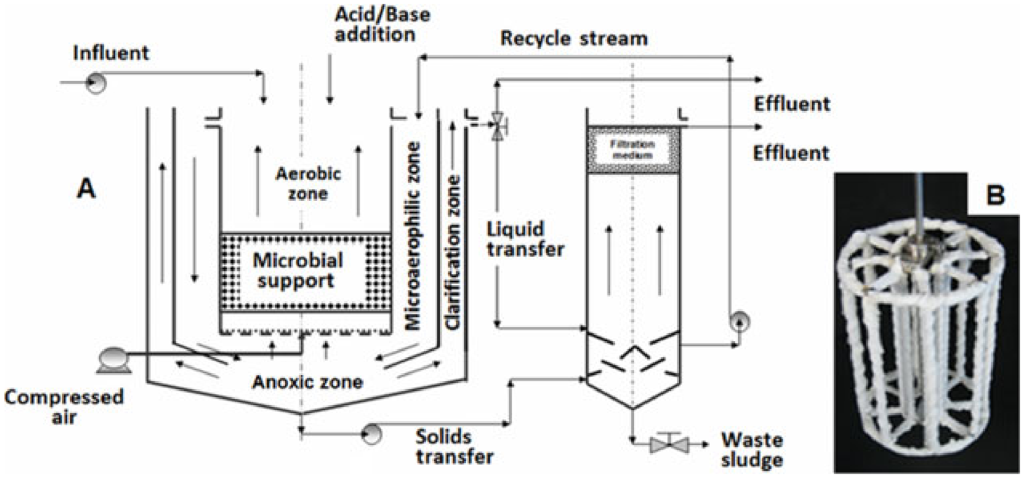

Figure 1. (A) Schematic representation of the multi-zone BioCAST wastewater treatment system; (B) structure of the microbial support.

carbon, nitrogen and phosphorus, the removal of phosphorus was very sensitive to the operating conditions, and in particular to the nitrogen loading rate. During the reported operation, the phosphorus removal efficiency remained below 50% as long as the nitrogen loading rate was below 0.05 kg m^{-3} d^{-1}, along with a nitrogen-to-phosphorus (N/P) ratio of less than 3. In that study, high phosphorus removal rates were established after 160 days of operation. The present study discusses the early development of phosphorus removal in the BioCAST system along with the removal of carbon and nitrogen during the start-up period that lasted for 48 days. This paper also addresses the controlling mechanism for the circulation of mixed liquor between the three zones in the first bioreactor of the BioCAST technology which is an important feature of this treatment system and exposes the contaminants to three different environmental conditions every few minutes. The study of hydrodynamic properties of this treatment system,[23,24] showed that the aerobic zone exhibits properties of airlift reactors, and at high air flow rates the reactor mixing performance is close to that observed in continuous stirred tank reactors (CSTR). Moreover, the mass transfer coefficient increases with increasing superficial gas velocity while the gas hold-up is a stronger function of superficial gas velocity for openings of smaller size (1/2″) between the aerobic and microaerophilic zones. Those studies also showed that the liquid circulation velocity is independent of the influent flow rate and can be controlled by the air flow rate and the number and size of openings between the aerobic and microaerophilic zones. The superficial liquid velocity is independent of the influent liquid flow rate, while being dependent on the hydraulic retention time (HRT) in the aerobic zone.

MATERIALS AND METHODS

Wastewater composition

The performance of the treatment system was examined using a synthetic wastewater with glucose as the carbon and energy source. The base synthetic wastewater had the following composition (in mg L^{-1}): glucose (1200–4800), urea (250), $(NH_4)_2SO_4$ (360–1100), KH_2PO_4 (47.5–135), K_2HPO_4 (47.5–135), $NaHCO_3$ (1000–1500), $MgSO_4.7H_2O$ (30), $CaCl_2.H_2O$ (30). The trace mineral solution was added at 1 mL L^{-1} with the composition of (in mg L^{-1}): $MnSO_4H_2O$ (100), $FeCl_3.6H_2O$ (1500), $CuSO_4$ (60), $ZnSO_4.7H_2O$ (300), KCl (30), EDTA (12000), $CoCl_2$ (100), $NiCl_2$ (100), H_3BO_3 (15). The concentrations of glucose, ammonium sulfate and phosphates were adjusted during operation of the treatment system in order to provide the required COD, TN and TP concentrations in the influent.

Experimental set up

The multi-environment BioCAST system uses two separate but interlinked bioreactors. The first bioreactor has an aerobic zone in the middle, a microaerophilic zone at the sides of the aerobic zone, an anoxic zone under the aerobic zone and inside the cone at the bottom of the bioreactor, and a clarification zone outside and around the microaerophilic zone. The various zones are physically separated but they are in fluid communication with each other. The presence of four biological zones with different environmental conditions defined based on their respective concentrations of dissolved oxygen (DO) and oxidation-reduction potential (ORP), and the underlying interactions between these zones support the growth and proliferation of a diversified group of microorganisms required for the removal of different contaminants. Figure 1(A) shows a schematic diagram of the multi-environment BioCAST technology.

The laboratory-scale bioreactors were fabricated by the company AC Plastics in Quebec, Canada. The volumes of aerobic, microaerophilic and anoxic zones, located in the first bioreactor were 17, 61 and 22 L, respectively, while the volume of clarification zone was 85 L. The diameters of aerobic, microaerophilic and clarification zones were 16.7, 35.7 and 49.5 cm, respectively. The heights of aerobic and microaerophilic zones were 91 cm and 100 cm, respectively. The second bioreactor contained an anaerobic zone at the bottom, a solid–liquid separation zone in the middle and a filtration unit at the top. This bioreactor had a diameter of 12 cm and a total volume of 12 L. The height of the bioreactors was 1.13 m.

The aerobic zone has been designed based on the concept of air-lift reactors. Mixed liquor flows upward in this zone (riser) and downward in the microaerophilic zone (downcomer) on a continuous basis. Air is introduced through three custom-built air diffusers located at the bottom of the aerobic zone. Aeration supplies oxygen for aerobic biological processes while ensuring proper mixing of liquid. Aeration also produces liquid circulation between the three adjacent zones; aerobic, microaerophilic and anoxic. This implies that the treatment system does not use any pumps for liquid mixing and circulation between the zones.

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Eight openings, at two sizes of 1/2″ and 1″, are installed 15 cm below the reactor's top which allow control of the circulating liquid flow rate and dissolved oxygen concentrations in the three zones, thus creating different treatment zones. They also control the instantaneous hydraulic retention time of mixed liquor in the aerobic zone (HRT_{inst}), defined as the residence time of liquid in this zone during a single cycle. The continuous circulation of mixed liquor between the three zones promotes denitrification of nitrates and nitrites in the microaerophilic and anoxic zone shortly after their formation in the aerobic zone through ammonia nitrification, preventing the accumulation of these inorganic contaminants that may exert inhibitory effects on microbial metabolism. Liquid circulation also aims to support the accumulation of microbial biomass in the mixed liquor, producing a high biomass concentration and a high mean cell residence time (MCRT) or solids retention time (SRT) that contribute to increased biodegradation rate of contaminating substances as well as a low biomass yield.

The aerobic zone contains suspended and attached-growth microorganisms, immobilized on a custom-built support medium placed in the center of the aerobic zone and above the diffusers. The support medium consists of two concentric cylindrical structures wrapped in geotextile which had a filamentous structure for biomass attachment and formation of biofilm (Fig. 1(B)). A polyethylene continuous non-woven geotextile (Texel Inc., Quebec) with density 950 kg m^{-3} and specific surface area 1500 m^2 m^{-3} was used. The porosity of this geotextile was estimated to be 0.88. This arrangement permits the BioCAST system to benefit from the established attributes of suspended-growth and fixed-film treatment systems. The second bioreactor is designed for sludge digestion, solid–liquid separation and filtration. The filtration unit was filled with granulated peat moss with an average diameter of 0.5 to 0.7 cm and a particle density of 0.7 g mL^{-1}. COD removal takes place in all the different zones, while the nitrification process is carried out in the aerobic zone. Nitrogen removal proceeds by the denitrification of the generated nitrite and nitrate in the microaerophilic and anoxic zones. Phosphorus removal benefits from the presence of aerobic and anaerobic conditions that are needed to promote the growth and accumulation of phosphorus removing organisms (PAOs), commonly contributing to biological phosphorus removal. The effluent from the first bioreactor is directed to the second bioreactor for additional clarification, while the sludge generated is transferred from the anoxic zone to the anaerobic zone of the second bioreactor for digestion. There is a recycle stream between the anaerobic zone in the second bioreactor and the aerobic/microaerophilic zone in the first bioreactor. The digestion of waste sludge in the anaerobic zone provides volatile fatty acids (VFAs) that are needed for the phosphorus removal and denitrification processes. Table 1 presents the design conditions of dissolved oxygen (DO), pH and oxidation/reduction potential (ORP) in various zones of the treatment system.

Table 1. Design characteristics of treatment zones in the multi-environment treatment system

Parameter Zone	DO (mg L^{-1})	pH	ORP (mV)
Aerobic	4.0–6.0	7.0–8.5	> +200
Microaerophilic	0–2.0	7.0–8.5	0 to 100
Anoxic	0	6.0–7.0	−100 to +100
Anaerobic	0	6.5–7.5	< −200

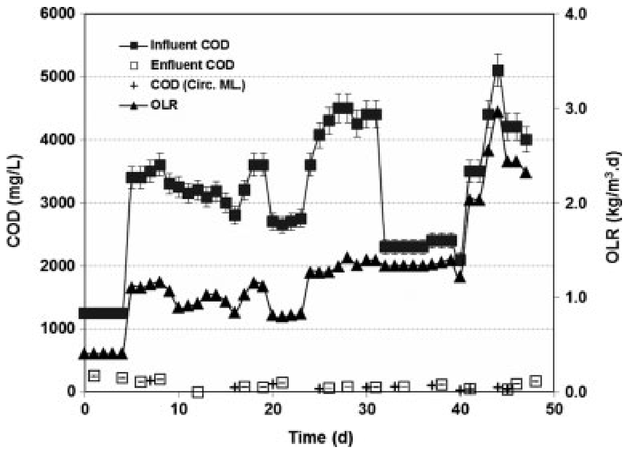

Figure 2. Time-dependent changes in the organic loading rate (OLR), and the influent, effluent, and circulating mixed liquor (circ. ML) COD concentrations.

Reactor start-up and operation

Operation of the treatment system started following inoculation with equal volumes of a sample of aerobic biomass from a food processing plant in Candiac, Quebec, and a sample of anaerobic biomass from ADI System Inc., in New Brunswick, Canada, producing an overall biomass concentration of 420 mg L^{-1} in the mixed liquor. Operation of the treatment system was examined at selected ranges of operating conditions in terms of the organic loading rate (OLR), hydraulic retention time (HRT), and the concentrations of COD, TN and TP in the influent.

Operation of the first bioreactor started in batch mode with flow recirculation between the clarification and aerobic zones. Continuous feeding started after 1 week of batch operation when the removal efficiency of COD had reached 80%. During continuous operation, the OLR increased gradually from 0.4 kg m^{-3} d^{-1} to 3.0 kg m^{-3} d^{-1}, while the hydraulic retention time (HRT) decreased from 3.7 to 1.7 days. The air flow rate through the aerobic zone was 10–15 L min^{-1} and the operating temperature was 20 ± 1°C. The COD concentration in the influent ranged from 1250 to 5100 mg L^{-1} while nitrogen and phosphorus concentrations varied in the range 76–232 mg L^{-1} and 22.5–49 mg L^{-1}, respectively. These concentrations correspond to nitrogen and phosphorus loading rates of 0.03–0.14 kg m^{-3} d^{-1} and 0.008–0.028 kg m^{-3} d^{-1}, respectively. The variations of organic loading rate (OLR) and the influent, effluent, and mixed liquor COD concentrations are shown in Fig. 2.

Operation monitoring and control

The pertinent operating parameters in various zones including liquid pH and dissolved oxygen (DO) concentrations in the aerobic and microaerophilic zones, oxidation-reduction potential (ORP) in the microaerophilic and anoxic zones, and air flow rate in the aerobic zone were continuously monitored and/or controlled using electrodes and probes. The DO concentration was controlled by the inlet air flow rate and by the number and size of openings between the aerobic and microaerophilic zones. A DO probe (Submersible DO probe, 0–20 pp, 10′, Cole Parmer, Canada), a DO controller/transmitter (Eutech instrument-Model alpha, DO2000 W) and a gas flow meter (AALBORG- Model GFM 47, 0–100 Std

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L min^{-1}) were used in the control and monitoring of dissolved oxygen concentration. A data logger and acquisition system (Dickson-Model ES120) connected to a computer was used for continuous data acquisition and storage.

Analytical methods

Liquid samples were initially filtered through 0.45 µm syringe filters and the required dilutions were made for concentrated samples. The COD concentration was measured using a closed reflux colorimetric method (EPA standard method 410.4). Filtered samples were digested at 150°C for 2 h followed by measuring their optical density at 600 nm. TN and TP in the liquid samples were determined using a colorimetric method after digestion of the samples at 100°C for 1 h. TN was determined according to the persulfate digestion method (HACH method 10071) and TP according to the ascorbic acid method (EPA method 365.2). NH_3-N was determined according to the salicylate method (EPA method 350.1), NO_2-N according to the diazotization method (EPA method 354.1), and NO_3-N according to the reaction of nitrate ions with 2,6-dimethylphenol (EPA methods 353.2). Total Kjeldahl nitrogen (TKN) was calculated from the difference between TN and the sum of nitrate and nitrite.

Total phosphorus content of the waste sludge was measured spectrophotometrically using the vanadomolybdophosphate method.[25,26] The concentration of solids in the sludge was determined using gravimetric methods (Standard Methods 2540 B and D). The samples were oven-dried at 105°C ± 2°C for the measurement of TSS and were further dried in a furnace at 550°C ± 2°C to determine the VSS concentration of sludge. Microbial observations were performed using a digital camera and a Micromaster desktop microscope (model S11035).

Theoretical considerations

The underlying mechanism and the forces that control the flow of mixed liquor and ensure its continuous circulation between the aerobic, microaerophilic and anoxic zones are discussed and analyzed. Liquid circulation is caused by the difference in the fractional gas holdup (i.e. different mean densities) that exists between the aerobic and microaerophilic zones, creating a hydrostatic pressure difference between the bottoms of the two zones, and acting as a driving force for liquid circulation. Liquid circulation is responsible for solid fluidization. The liquid continuously circulates between the three zones while a fraction of liquid freely flows towards the clarifier and leaves the system on a continuous basis. The small fraction of liquid that exits the system with the accumulated solids (sludge) through the bottom of the anoxic zone has not been considered in this analysis since its flow is controlled by valves and not by energy balances inside the liquid. Therefore, this analysis considers the division of liquid between two streams: one that flows through the aerobic zone and a second one that flows through the clarifier and eventually exits the system.

Liquid flow in aerobic Zone

For the circulating liquid in the first reactor, the major fraction of liquid at the bottom of the microaerophilic zone flows towards the aerobic zone due to the balance between pressure, velocity and elevation in the aerobic zone and the clarifier. The following relationship must hold in order to ensure the flow of liquid towards the aerobic zone:

$$\Delta P_{\mathrm{diff.}} + \Delta P_{\mathrm{clarif.}} > \Delta P_{\mathrm{aerob.}} \tag{1}$$

where $\Delta P_{\mathrm{diff.}}$, $\Delta P_{\mathrm{clarif.}}$ and $\Delta P_{\mathrm{aerob.}}$ represent the pressure drop across the air diffuser, head loss in the clarifier and head loss in the aerobic zone due to water height and friction, respectively. The Bernoulli's equation was used to evaluate pressure drop in the aerobic zone, which is assumed to resemble a cylindrical pipe. The presence of the stationary support material for the development of fixed biofilm in this zone does not cause any pressure drop due to its specific design and the non-clogging nature of the biofilm. The energy balance between the two points (1 and 2) located at the top and bottom of the aerobic zone is expressed as follows:

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + Z_2 + \frac{W_s}{g} + h_f \tag{2}$$

where w_s is the net external work, i.e. air blower power output, h_f is the head loss due to friction in the aerobic zone, v is liquid velocity ($Q/A = 4Q/\pi D^2$), and A and D are the cross-sectional area and diameter, respectively. Since in this zone, $Q_1 = Q_2$ and $v_1 = v_2$, Equation (2) can be rewritten as follows:

$$P_1 - P_2 = \rho g\,(Z_2 - Z_1) + \rho w_s + \rho g h_f \tag{3}$$

$$h_f = f\frac{L}{D}\frac{v^2}{2g} \tag{4}$$

where f is the friction factor, L is the height of the aerobic zone ($Z_2 - Z_1$), D is the diameter of the aerobic zone, v is liquid velocity, and ρ is the density of liquid entering the aerobic zone. The friction factor (f) can be found from the Moody chart[27] by knowing the Reynolds number, $Re = \rho vD/\mu$, where, μ is the fluid viscosity. Equations (3) and (4) can be combined into the following equation:

$$\Delta P = \frac{8fL\rho Q^2}{\pi^2 D^5} + \rho g\,(Z_2 - Z_1) + \rho w_s \tag{5}$$

The first, second and third terms on the right-hand-side of Equation (5) represent the head loss due to friction, the head loss due to elevation, and the head loss across the air diffuser due to the action of air blower, respectively. In the case of clogging of the support material due to excessive biofilm growth, an additional term of $\Delta P_{\mathrm{biofilm}}$ should be added to the right-hand-side of Equation (5). The head loss along the clarification zone is estimated by using the governing equation for the fluid flow in concentric cylinders:

$$\frac{d}{dr}\left(r\mu\frac{dv}{dr}\right) = \frac{d}{dx}\,(P + \rho gL) \tag{6}$$

Integration of Equation (6) between the two points (r = a, r = b) in this zone, and solving the resulting equation for the liquid flow rate, will result in the following expression:

$$Q_c = \int_a^b v.2\pi r dr = \frac{\pi\,(-\Delta P + \rho gL)}{8\mu L}\left[a^4 - b^4 - \frac{(a^2 - b^2)^2}{\ln\frac{a}{b}}\right] \tag{7}$$

From which, ΔP can be derived as:

$$\Delta P = \rho gL - \frac{8\mu\, Q_c L}{\pi\left[a^4 - b^4 - \frac{(a^2 - b^2)^2}{\ln\frac{a}{b}}\right]} \tag{8}$$

The first and second terms in this equation denote the elevation head loss and the head loss due to liquid motion in the clarification zone, respectively.

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RESULTS AND DISCUSSION

Estimation of governing forces that control liquid circulation

The liquid flow in the aerobic zone had a Reynolds number of 4000, indicating a transitional flow regime in this zone. The three terms in Equation (5) were estimated to be 0.04, 7468 and 2800 kg m^{-1} s^{-2} for the head loss due to friction, elevation and air diffusers, respectively, implying that the height of water and the action of air blower control the head loss in this zone.

In the clarifier zone, the two terms in Equation (8) were estimated to be 8000 and 7.1×10^{-7} kg m^{-1} s^{-2} for the liquid elevation and motion, respectively, making the height of water control the head loss in the clarification zone. The results show that the condition of Equation (1) has been met and also, the head loss due to elevation in the clarifier is only slightly higher than that in the aerobic zone. This implies that the pressure difference across the air diffuser due to the action of the air blower is the main governing force for the flow of liquid towards the aerobic zone and the controlling factor for the continuous circulation of liquid between the aerobic, microaerophilic and anoxic zones.

Treatment studies

The time-dependent changes in the influent, effluent, and mixed liquor concentrations of TN and TP, as well as effluent concentrations of nitrite-, nitrate-, and ammonia nitrogen are presented in Fig. 3(A) and (B). Continuous liquid circulation between the three zones of aerobic, microaerophilic and anoxic, having various concentrations of dissolved oxygen and ORP, resulted in rapid denitrification of nitrite and nitrate shortly after their generation, thus preventing their possible inhibitory effects on the microbial biomass. As a result, nitrate and nitrite remained at low concentrations in the mixed liquor and effluent and below 2.5 mg L^{-1} throughout the study. Nitrogen removal rate was controlled by nitrification as exhibited by the accumulation of ammonia during the first 25 days of operation (Fig. 3(A)), most likely resulting from the slow growth and proliferation of nitrifying bacteria that are needed for ammonia nitrification. The gradual build-up and accumulation of microbial biofilm, including the slow-growing nitrifiers, on the support medium increased their concentration and retention time, which enhanced the removal efficiency of nitrogen to 98%. During this period, the removal rate of TN exhibited a close relationship with its loading rate and increased steadily with increase of loading rate (Fig. 4). The total nitrogen concentration in the effluent gradually decreased from 85 mg L^{-1} to 4.3 mg L^{-1} (Fig. 3(A)).

The TP removal efficiency increased above 50% only when the TN loading rate reached above 0.05 kg m^{-3} d^{-1} (Fig. 5) which occurred after 30 days of operation. During the long-term operation of this treatment system, it was shown that even after almost 150 days of operation, the TP removal efficiency remained below 50%, corresponding to TN loading rates below 0.05 kg m^{-3} d^{-1}.[22] On the other hand, the phosphorus removal rate was enhanced with increase of N/P ratio, and exhibited a positive correlation with this ratio. This suggests that the low efficiency of TP removal was probably because of the applied loading rates and operating conditions rather than duration of operation. The results of the present study and our former investigation[22] showed that it is indeed the operating conditions, especially the loading rate of nitrogen that controls TP removal. The increase of TP removal efficiency with increase of TN loading rate is presented in Fig. 5, which also depicts the increase of TN removal efficiency with TN loading rate. With the increase of phosphorus removal efficiency, its concentration in the effluent decreased gradually and reached a minimum value of 2.9 mg L^{-1} towards the end of the examined operation period (Fig. 3(B)).

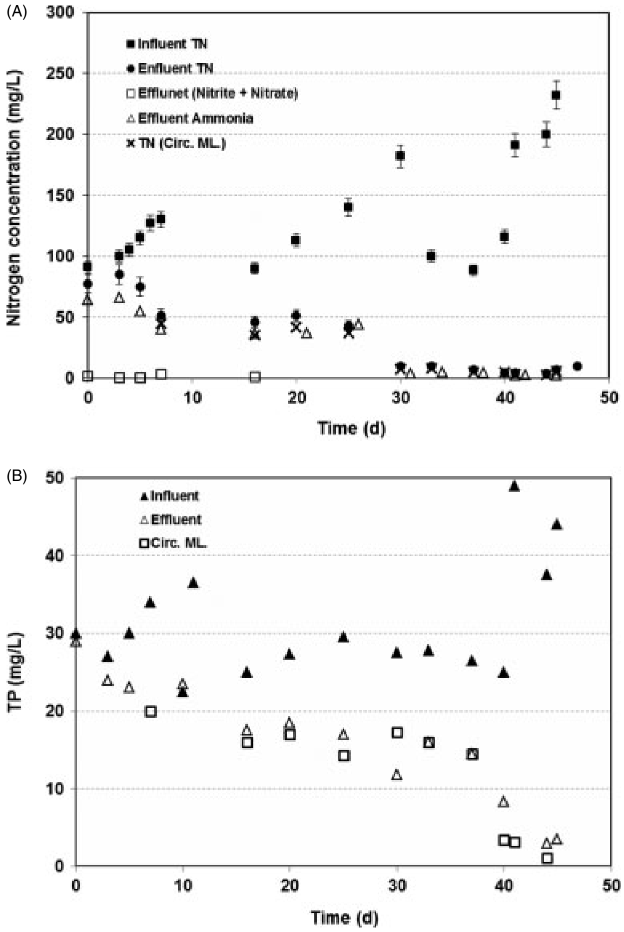

Figure 3. Time-dependent changes in the influent and effluent concentrations of (A) nitrogen species (circ. ML = circulating mixed liquor), and (B) phosphorus.

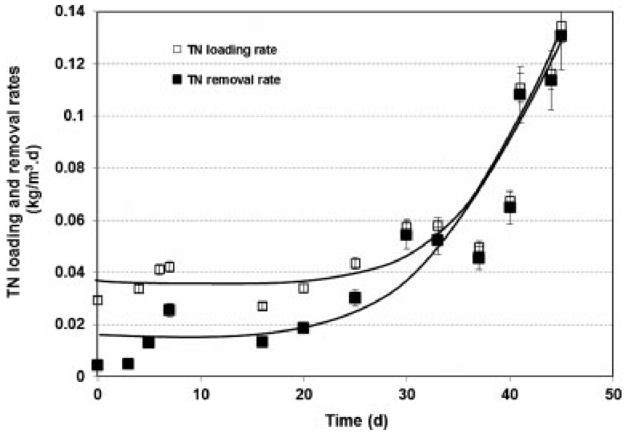

Figure 4. Variations of the loading rate and removal rate of nitrogen (TN) during the operating period.

Figure 6(a) and (b) shows that the removal rate of phosphorus closely followed the nitrogen loading rate (Fig. 6(a)) while exhibiting a low dependence on the COD loading rate (Fig. 6(b)). The removal rate of phosphorus ranged from 0.003 kg m^{-3} d^{-1} to

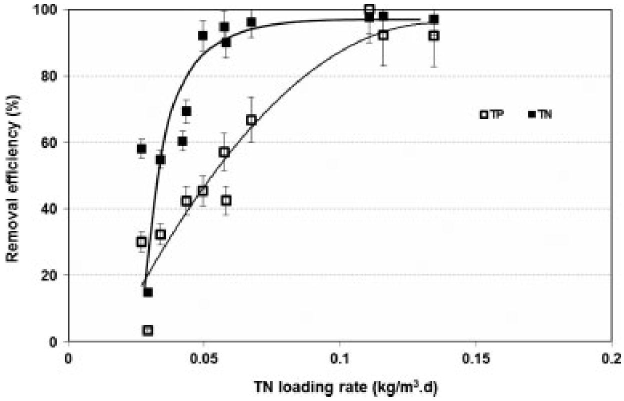

Figure 5. Variations of removal efficiencies of nitrogen and phosphorus, and nitrogen loading rate during the operating period.

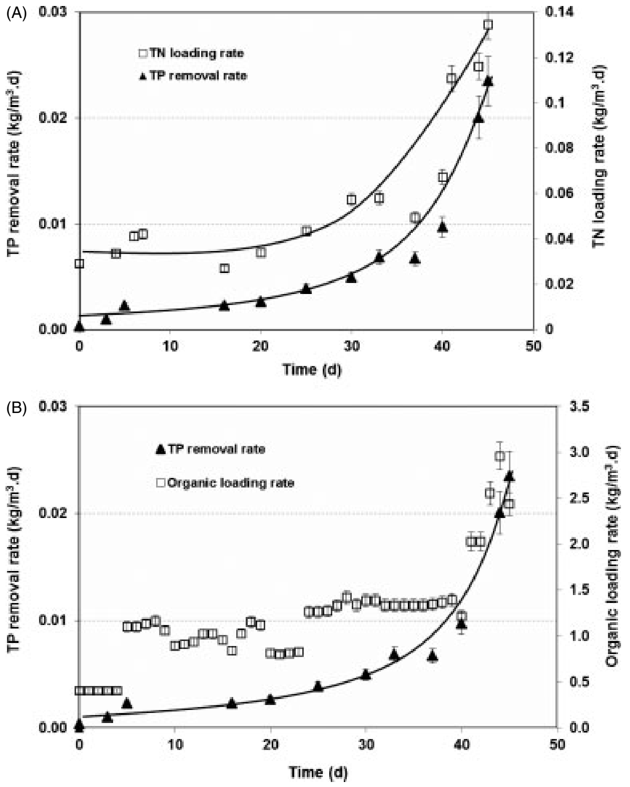

Figure 6. (A) Variations of the total phosphorus removal rate and nitrogen loading rate and (B) variations of the total phosphorus removal rate and organic loading rate during the operating period.

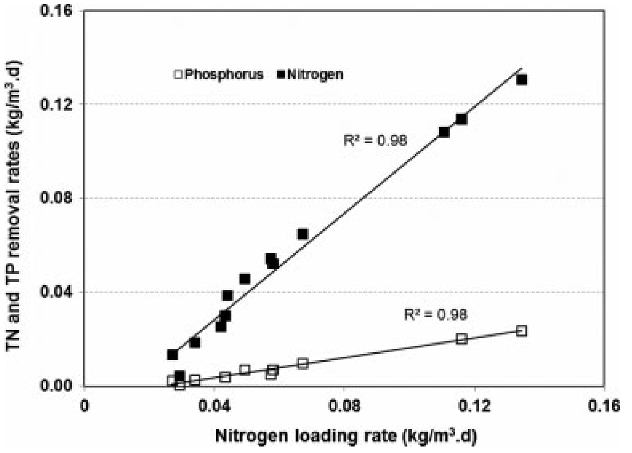

Figure 7. Relationship between the removal rates of total nitrogen and total phosphorus and nitrogen loading rate.

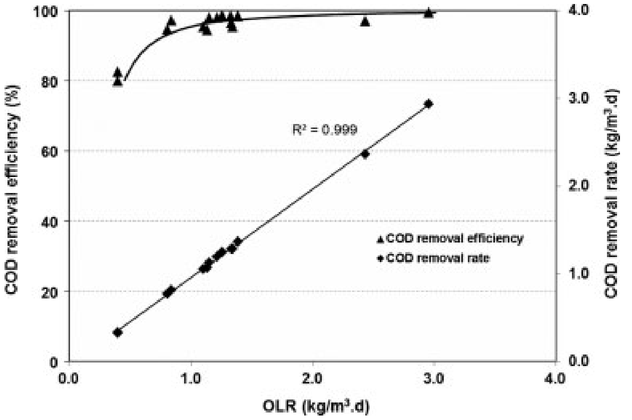

Figure 8. Relationship between the removal rate and removal efficiency of COD and the organic loading rate (OLR).

0.024 kg m^{-3} d^{-1}, while the removal rate of total nitrogen ranged from 0.01 to 0.13 kg m^{-3} d^{-1}.

Figure 7 presents the linear correlation between the removal rates of nitrogen and phosphorus and nitrogen loading rate. The dependence of TP removal on the nitrogen loading rate and the operating conditions has been observed before.[28] Moreover, the results obtained demonstrate close relationships between the removal rates of nitrogen and phosphorus and the N and P loading rates, as reported before.[2,4,29–32] This is due to the possible presence of microorganisms that are involved in both denitrification and phosphorus removal processes, and utilization of the generated VFA in the anaerobic zone by these organisms. The operating conditions of pH and ORP in the anaerobic zone were maintained to favor VFA generation and to minimize CH_4 production, shown by its negligible concentrations in the liquid and gas samples from this zone. Along with TN and TP removal, the COD removal efficiency increased steadily with increase of its loading rate, reaching 99.3% (Fig. 8). Correspondingly, the effluent COD concentration decreased from 250 mg L^{-1} at the start of continuous operation to 35 mg L^{-1} after 48 days (Fig. 2). The increase of COD removal efficiency with loading rate was reported before,[30] where 99% COD removal rate was obtained during the operation of reactors with increase of organic loading rates (OLR) from 1 to 8 kg COD m^{-3} d^{-1}. Figure 8 also presents the linear relationship between the COD removal rate and its loading rate.

During the start-up period, the generated sludge concentration increased from 10 000 to 26 400 mg L^{-1}, while its phosphorus content increased from 1.1% to 4.8% (dry basis). The high phosphorus concentration in the sludge suggests the presence of phosphorus accumulating organisms (PAOs) that are known to accumulate phosphorus in their intercellular spaces, and the establishment of a luxury phosphorus removal process in the treatment system.[33,34] The presence of this group of organisms is supported by the constant circulation of mixed liquor between the anaerobic and microaerophilic/aerobic zones that exposed the microorganisms to aerobic and anaerobic environments on a continuous basis. During continuous operation of the treatment system, the concentration of suspended

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microorganisms increased to 3000 mg L^{-1} in the mixed liquor while the concentration and thickness of biofilm formed on the support medium increased to 17000 mg L^{-1} and 3.8 mm, respectively. Moreover, the phosphorus content of the biofilm showed an increase, reaching 3% during the period examined. The formation and evolution of biofilm in the system examined has been reported before.[35] The overall biomass yield during the reported operating period was 11.5% while a maximum sludge retention time of 50 days was reached.

CONCLUSIONS

The operation of a multi-environment BioCAST treatment system during the start-up period lasting 48 days was investigated. It was shown that the removal efficiencies of COD, total nitrogen and total phosphorus increased to 99.3%, 98.0% and 92.3%, respectively. These removal efficiencies were obtained despite varying influent concentrations of contaminants that increased to 5100 mg COD L^{-1}, 232 mg TN L^{-1} and 49 mg TP L^{-1}. The removal rate and removal efficiency of phosphorus were mainly dependent on the TN loading rate, and increased substantially when this parameter increased above 0.05 kg $m^{-3}.d^{-1}$. The low effluent concentrations of nitrate, nitrite and phosphorus reaching 0.2, 0.02 and 2.9 mg L^{-1}, respectively, with increasing influent nitrogen and phosphorus loading rates suggest the development of nitrification/denitrification processes as well as phosphorus accumulating organisms in the system. A sludge yield of 11.5% and sludge retention time of 50 days were obtained in the treatment system during the period examined.

The high biomass concentration and increased solid retention time (SRT), contributing to increased removal rates of contaminants and low sludge generation are among the important aspects of this treatment system. Moreover, the rapid growth of concentrated biofilm on geotextile material can reduce the start-up period, increase the bioreactor content of biomass, and enhance the capacity of the treatment system to treat wastewaters having high organic loading rates.

The results of this study demonstrate the capacity of the treatment system examined to treat high-strength and nutrient-rich wastewaters at varying influent loading rates. The performance of the system for the treatment of wastewaters resulting from animal husbandry and agricultural activities are under investigation.

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