



Evaluation of Effective Operational Cycle Time and Bioprocess Parameters in a Sequential Batch Reactor for Efficient Organic and Nutrient Removal from Domestic Sewage

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PAPER INFO

Paper history:

Received 17 June 2015

Accepted in revised form 31 August 2015

Keywords:

Cycle time
Organic Loading rate
Nitrogen removal
Phosphate removal
Wastewater treatment
sequential batch reactor

A B S T R A C T

Anaerobic, anoxic and aerobic environment can be simulated in the single stage sequential batch reactor (SBR). Various design conditions viz., combinations of different phase time and different cycle time, hydraulic residence time (HRT), substrate loading rate, sludge age (SRT) and aeration time were analyzed for optimum biological treatment. The pilot runs were evaluated with the design conditions of food/microbe ratio (F/M) 0.2 per day and MLSS of 4950 mg/L. For the given design conditions 4, 5 and 6 hours cycle lengths were analyzed for their efficient performance with 30-33% of decant volume for sewage containing C:N:P of 100:8:2. Studies on 4 hours cycle resulted in the maximum overall organic and nutrient removal efficiency at SRT of 26 days and HRT of 12 hours. Efficient sequencing of reactions with respect to the simulated biological conditions in the pilot plant studies resulted in better oxygen recovery and low power consumption. Also, the enforced biological selector phase condition resulted in high microbial reaction rates for organic and nutrient removal. The removal efficiencies with 4 hours cycle time of COD, nitrogen ($\text{NH}_4\text{-N}$) and phosphate ($\text{PO}_4\text{-P}$) were 90, 92 and 78%, respectively. This study offers a potential option of low HRT nutrient removal SBR process.

doi: 10.5829/idosi.ijee.2015.06.04.08

INTRODUCTION

Various biological processes are widely applied to treat the wastewaters with diverse characteristics from both urban and rural sectors. A wide variety of contaminants, such as organic matter and nutrients (mainly nitrogen and phosphorous) can be biologically degraded to reduce the discharge levels in water bodies (rivers, lakes and seas) [1]. The biological system is ideal for wastewater treatment due to its high rate of organic degradation [2]. Biological nutrient removal benefits can be achieved using a SBR, by simulating the appropriate optimal biological processes. In the SBR system, external clarifiers and flow equalization tanks may not be essential and thus, offer low cost of facilities and operation management than those of conventional

systems like activated sludge process [3]. SBR systems, applied to nitrification and denitrification, offer various advantages including: minimal space requirements, ease of management and possibility of modifications during trial phases through on-line control of the treatment strategy [4]. The improved regulations over nutrient discharge limits to natural water systems drive for the need in design improvements in SBR system to achieve thorough nitrification, denitrification along with COD removal and phosphate removal [5]. Instead of trains of reactors for nutrient removal, if denitrification can be attained without any carbon substrate under anoxic condition, the circulation of liquid from aerobic to anoxic phases is unnecessary and thus nitrogen and phosphorus can be removed in a single SBR [3]. Various studies have been carried out for analysis of simultaneous nitri-denitrification (SND) process in SBR reactor operated with high HRT.

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Tsuneda et al. proposed an anaerobic/aerobic/anoxic (AOA) process using a SBR for simultaneous phosphorus and nitrogen removal from wastewater with high efficiencies [3]. The objective of study conducted by Akin and Ugurlu was to establish control strategies for biological phosphorus and nitrogen removal using oxidation reduction potential (ORP), dissolved oxygen (DO) and pH profiles [4]. Kargi and Uygur studied nutrient removal from synthetic wastewater by sequencing batch operation at different SRTs varied from 5 and 30 days at six different levels with a overall cycle time of 10.5 hours obtained high CNP (carbon, nitrogen and phosphate) removal [6]. Obaja et al. studied biological removal of nutrients in piggery wastewater with high organic matter, nitrogen and phosphorus content in a SBR with anaerobic, aerobic and anoxic stages with HRT of 1 day and SRT of 11 days [7]. Another study on SBR showed the treatment of simulated dairy wastewater (SDW) in terms of COD and total Kjeldahl nitrogen (TKN) removal by aerobic SBR [8]. Optimum HRT of 1 d with volume exchange ratio of 0.5 was found sufficient to treat SDW. The research was undertaken to examine the time courses of COD, NH₃-N and DO during the SND process, with particular reference to the question of whether SND is a physical or microbiological phenomenon [9]. The conducted study showed how the carbon and nitrogen (C/N) ratio controls the SND in a sequencing SBR [10-12]. All experimental studies supported by SND phenomenon reports low rate of the biological reactions. As DO is lowered in aerobic phase causes low aerobic degradation and nitrification rates; also presence of oxygen leads to low denitrification in the same reaction cycle by SND phenomenon.

The present study explains the potential application of low HRT and cycle time with an objective of obtaining high organic and nutrient removal efficiency. Present SBR works on high reaction rates because of providing optimum biological process conditions in different phases.

MATERIALS AND METHODS

Wastewater Composition

The wastewater used in this study was from a sewage treatment plant located at Thermax Ltd, Pune, India. The fluctuations in wastewater strength was seen with COD, ammonical N and total PO₄-P (CNP) load coming to the plant on Saturday and Sunday of each week due to low usage during weekends. The characteristics of the STP plant wastewater are detailed

in Table 1.

Table 1. Factory effluent characteristics of the pilot scale SBR plant

Parameter	STP Influent
COD (mg/L)	426.77±106.8
BOD (mg/L)	205±54.3
TKN (mg/L)	45.3±11.2
Ammonical N (mg/L)	33.58±8.72
Total PO ₄ (mg/L)	8.6±2.26
Alkalinity (mg/L)	280±64
O&G (mg/L)	120±41
TS (mg/L)	624±118
TDS (mg/L)	520±84
TSS (mg/L)	104±21
VSS (mg/L)	72±13
pH	7.2±0.5

Reactor Set-Up and Operation

The SBR pilot plant was designed to treat wastewater of sewage treatment plant (STP) situated at Thermax Ltd, Pune. The pilot scale SBR was composed of following elements: the equalization tank, the reactor, feed pump, air compressor, control panel with timers and pneumatic actuated valves to control the sequencing operation (Figure 1). The SBR pilot plant volume comprised of 1200 liters capacity with mild steel as material of construction. A cylindrical reactor with a maximum working volume of 1115 liters was seeded with activated sludge from a tube settler from nearby plant.

The reactor was operated at ambient temperature and operated periodically with a pre-defined cycle comprising of different phases. During filling phase influent is fed from the bottom of the tank and intermittent air purging for 1min with a periodicity of 15 minutes is envisaged to keep the reactor contents under homogenous conditions. Aerobic conditions were achieved by compressed air injections connected to a rotameter to measure the air flow rate. Filling was done with the water pump, while wastage and draw events were conducted by two different pneumatic actuated valves. At the end of the reaction time of each cycle, an estimated amount of sludge was removed from the reactor under aerobic conditions while mixing, to maintain the desired SRT. During the decant phase treated wastewater was discharged from the reactor until a predefined minimum reactor water level (747 liters) was reached which was 33% decanting of reactor volume.

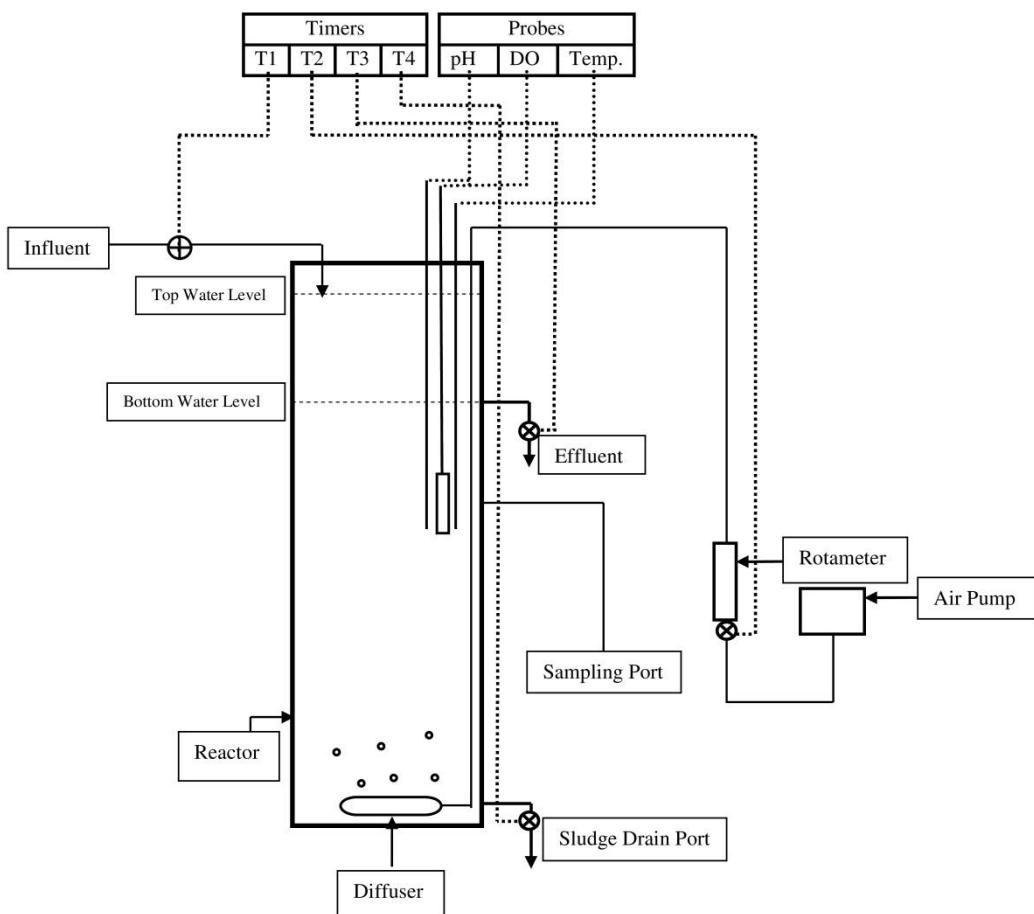


Figure 1. Schematic diagram of SBR used in experiments

Pilot plant experimentation

Three different cycles were analyzed for their treatment efficiency. Every cycle has filling phase (without simultaneous aeration), to create anoxic and anaerobic conditions suitable for denitrification and phosphate release, respectively. The duration of anoxic – anaerobic cycles was 1, 1.5 and 3 hours in 4, 5 and 6 hours cycles, respectively. The pilot plant was operated for three different cycle times (Figure 2) for one month each at similar operating conditions. During overall experimentation, the mixed liquor suspended solids (MLSS) was maintained to 3000 - 4000 mg/L with mixed liquor volatile suspended solids (MLVSS) of 2400 - 3200 mg/L. The sludge volume index (SVI) was maintained at 100 -120 mL/g to assure effective sludge settling. The operational details of different phase cycles of HRT, F/M, design air flow rate, oxygen required per day, aeration time per day per tank, cycles per day, volume treated per cycle and SRT were mentioned in Table 2.

Sampling, Analytical and Calculation Procedures

Influent samples were collected during the filling

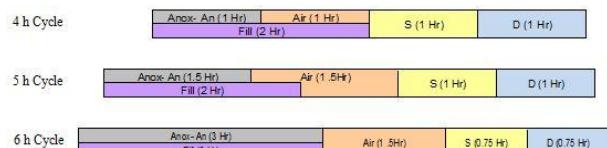


Figure 2. Experimental cycle designs with different phases in SBR

Table 2. Process operating conditions of SBR during experimentation

Cycle Time	Hours	6	5	4
Treatment Volume	Liters per Day	1471.8	1766.16	2207.7
HRT	Hours	18	15	12
MLSS	mg/L	3300	3960	4950
F/M	per day	0.2	0.2	0.2
Decant fraction	%	33	33	33
Design air flow rate	m ³ /h	5.3	5.3	3.97
Oxygen Required	kg/day	0.929	1.114	1.393
per day				
Aeration time per	Hours	6	7.2	12
day per tank				
Cycles per day	Numbers	4	4.8	6
Volume Treated	Liters	368	368	368
/Cycle	Days	16.1	20	26
SRT				

phase. Treated effluent samples were collected during the decanting period, at the end of the operation cycle. For the analysis of MLSS and SVI sampling was done from a single sampling port. These samples were collected during the aeration cycle. The SBR samples were analyzed according to standard methods (APHA, 2005) protocols[13]. The COD was analyzed by APHA method 5220B (potassium dichromate method), whereas analysis of biological oxygen demand (BOD) was done by APHA method 5210B. The analysis of sludge volume index (SVI) was carried by APHA method 2710D. SVI is the volume in milliliters occupied per one g of a suspension after 30 minutes settling.

$$\text{SVI} = \text{settled sludge volume (mL/L)} * 1000/\text{suspended solids (mg/L)}$$

Further the analysis of total organic nitrogen and the ammonical nitrogen was done by titrimetric method described in APHA method number 4500-NHorgB and 4500-NH₃ E. The nitrate nitrogen was analyzed by ultraviolet spectrophotometric screening method (APHA method: 4500-NO₃⁻ B), where the measurement of UV absorption at 220 nm enables rapid determination of NO₃⁻. Because some dissolved organic matter may absorb at 220 nm and NO₃⁻ does not absorb at 275 nm, the second measurement made at 275 nm may be used to correct the NO₃⁻ value. The extent of this empirical correction is related to the nature and concentration of organic matter and may vary from one sample to another. The analysis of total phosphorous was done by colorimetric method. APHA method 4500-P C, whereas the total suspended solids and volatile solids were analyzed by APHA method: 2540 D & E. Reactor DO was analyzed by Hanna make DO meter (Model no. HI9146-04). In the present study, the SRT, HRT and air requirements were calculated by using calculation given in Met-Calf Eddy[14].

RESULT AND DISCUSSION

Effect of different cycle time and HRT on CNP removal

As these experiments were carried out on actual sewage, hence the inlet load of COD, ammonical nitrogen and total PO₄-P (CNP) were varying. The evaluations of different cycle time and HRT were done on actual effluent received. After the acclimatization time, the sampling and analysis were done and readings were plotted, shown in Figure 3. Each set of cycle time were analyzed for 18 days readings separately. In the pilot plant experimentation of 6 hours cycle (Figure 3a) with 3 hours of feed phase received high variation in inlet CNP. The effluent analysis shown the average reduction of COD from 371.02 to 49.37 mg/L, average concentration of ammonical nitrogen reduced from

30.59 to 2.17 mg/L, but total phosphates were less significantly reduced from 7.37 to 4.10 mg/L. The average outlet nitrate was 4.31 mg/L, which was lower than 5 mg/L; that was due to long anoxic phase. The 5 hour cycle also shown the similar results (Figure 3b), but on varying load and cycle phases duration. In which the average COD, ammonical nitrogen and total phosphates were reduced from 452.6, 37.27 and 8.90 mg/L to 65.86, 4.32 and 4.15 mg/L, respectively, whereas the average nitrate was 8.86 mg/L, which was higher than 6 hour cycle. The 4 hours cycle had given most significant results (Figure 3c), with average influent COD, ammonical nitrogen and total phosphates concentrations 456.72, 32.90 and 9.55 mg/L reduced to 42.51, 2.81 and 2.07 mg/L, respectively.

The average nitrate concentration of 4 hour cycle was 6.99 mg/L. Three cycles were effectively performed for COD and ammonical nitrogen removal; however, they represent a distinct effect on phosphate removal (Figure 4). The 4 hours cycle has higher percentage phosphate removal than 5 and 6 hours cycles. All aerobic phase reactions reached DO of 4-5 mg/L, where at high COD and nitrification was observed at low HRT. The previous study compared the high DO (above 3 mg/L on average) SND and SND via nitrite at low DO (0.4–0.8 mg/L) resulted in average efficiencies of SND in high DO and low DO reactor were 7.7 and 44.9%, respectively[11]. Holman and Wareham achieved over 75% of nitrogen removal through the SND process[9]. Current requirements of above 90% nitrogen removal cannot meet with SND phenomenon at low HRT.

Effect of Fill time to Anoxic-Anaerobic time

Three cycles were analyzed for Fill time to Anoxic-Anaerobic time ratio (F/AA) and its effect on treatment efficiency. DO of anoxic-anaerobic fill phase was zero. This assures anoxicity in presence of nitrate and anaerobicity in absence of nitrate in anoxic-anaerobic fill.

The F/AA was 2, 1.33 and 1 for 4, 5 and 6 hours SBR cycle time respectively. The percentage reduction chart of CNP of these three different cycle showed that, varying the F/AA not affected the aerobic organic oxidation and nitrification reactions. The results show that decrease in percentage phosphate reduction with decrease in F/AA ratio and increase in cycle time. Table 3 showing that, the F/AA ratio decreases and only aeration time increase might have the effect on phosphate reduction profiles.

Effect of aeration time on phosphate reduction

Total aeration time of 4, 5 and 6 hours cycles was 1, 1.5 and 1.5 hours, respectively (Table 3) which include the only aeration plus the simultaneous aeration and feeding time. Merely aeration times were 0, 1 and 1.5 hours with respective 4, 5 and 6 hours cycle (Table 3).

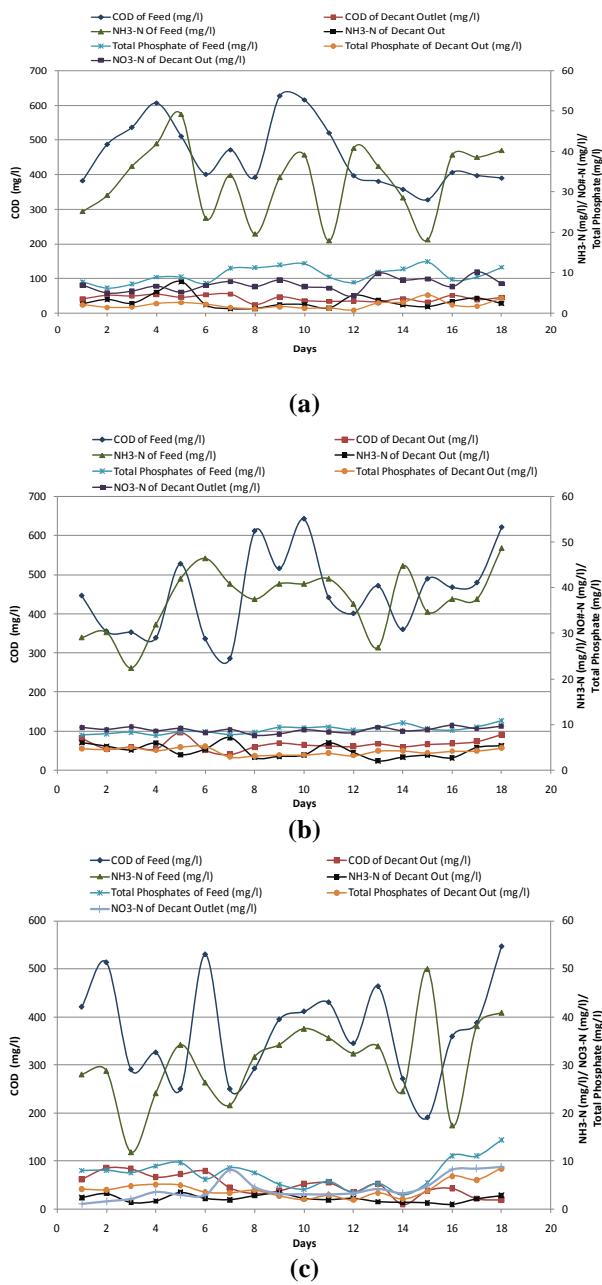


Figure 3. Performance of 6 hours cycle (a), 5 hours cycle (b) and 4 hours cycle (c) for organic and nutrient removal by SBR system

TABLE 3. Different phase time compositions of 4, 5 and 6 hour cycles

Total Cycle Time	Fill to Anoxic-Anaerobic time Ratio	Total Aeration Time	Only Aeration Time	Avg. Phosphate reduction
Hours	Hours	Hours	Hours	%
4	2	1	0	78.1
5	1.33	1.5	1	53
6	1	1.5	1.5	43.9

The reduced percentage phosphate reduction correlated with increasing only aeration time suggest the possibility of secondary phosphate release at the end of aerobic reaction phase. The low substrate level at the end of 5 and 6 hour cycle, its suggested that the aerobic endogenous respiration may cause to secondary phosphate release for energy maintenance of the microbial metabolism[15]. A sensitivity analysis study of Biowin model was conducted, which indicated that heterotrophic anoxic yield, anaerobic hydrolysis factors of heterotrophs, heterotrophic hydrolysis; oxic endogenous decay rate for heterotrophs and oxic endogenous decay rate of polyphosphate-accumulating organisms (PAOs) had the most impact on predicted effluent total PO₄-P concentration[16]. In present experiments, variations in fill, anoxic and aeration phase durations were reflected as phosphate reduction. The 6 hour cycle had the only aeration phase of 1.5 hours which may reduce the organic substrate much before ending the aeration phase, causing endogenous decay, polyhydroxy butyrate (PHB) hydrolysis or polyphosphate cleavage in presence of excess external electron acceptors. But in case of 4 hour cycle simultaneous feed and aeration, because of continuous supply of substrate, cycle might not follow secondary release of phosphate or endogenous decay.

Effect of reactor load on overall percentage reduction

The 4, 5 and 6 hours cycles feed composition with C:N:P ratio was 100:8:2 with different phosphate reduction profiles. The similar study claims that the optimum C:N:P ratio for simultaneous nitrogen and phosphate removal was found to be 100:5:1, in which the efficiencies of 88.31 and 97.56% were achieved, respectively [17]. The data demonstrated that a low C/N ratio resulted in a rapid carbon deficit, causing an unbalanced SND process in SBR [10]. But present study does not claim SND having separate phases of anoxic, anaerobic and aerobic environments proposes the high rates of denitrification, phosphate release-uptake and organic oxidation reactions with low cycle time, hence HRT. Table 4 shows the average varying carbon, nitrogen and phosphate loading rates to during different SBR cycle time. The graphs of percentage reduction verses loading rates showed that high COD (Figure 5a) and nitrogen (Figure 5b) loading rates were not much affected on respective percentage reduction. But, the low COD loading rate of 6 hours cycle and nitrogen loading for 5 hour cycle showed the inconsistency in their percentage reduction. The decreased phosphate loading rate in 6 hours cycle showed decrease in percentage phosphate removal at range of 25 to 60 % and it was increased to 70 to 90 % in 4 hours cycle with high phosphate as well as carbon load (Figure 5c).

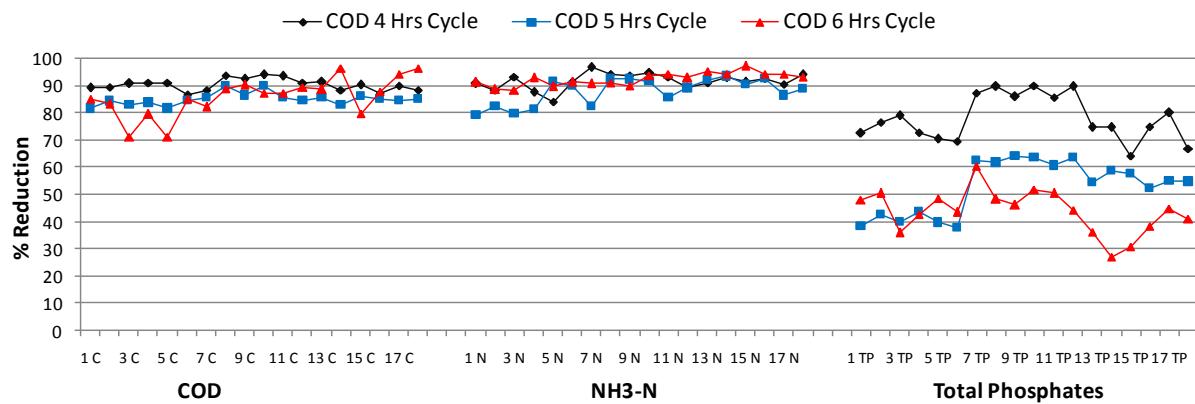


Figure 4. Cumulative percentage reduction chart of organic and nutrient by different cycle time of SBR system

TABLE 4. Different SBR cycle time with COD, nitrogen and phosphate per day reactor loadings

SBR Cycle Time	Hours	4	5	6
Avg. COD loading rate	kg/m ³ .d	0.822	0.652	0.445
Avg. Nitrogen loading rate	kg/m ³ .d	0.059	0.054	0.037
Avg. Phosphate loading rate	kg/m ³ .d	0.017	0.013	0.009

Another study showed the removal efficiency of soluble COD, soluble nitrogen and soluble phosphorus were 85, 93 and 89%, respectively. In addition, the applied loading rates were 2.7 kg COD/m³.d, 0.43 kg NH₄-N/loading m³.d and 0.06 kg PO₄-P/m³.d, respectively [12]. The high organic loading rate, at given 4 hours cycle with 0.2 F/M showed the higher phosphate reduction compared to 5 and 6 hours cycle.

Effect of SRT on SBR performance

The high SRT showed the high CNP removal capacity. SBR cycle time of 4, 5 and 6 hours had the operating SRT of 26, 20, 16.1 days, respectively. The results showed that the varying SRT does not have an effect on carbon and nitrogen removal performance, but significantly affected on percentage phosphorus removal. The SRT study of MBR system verified with the Biowin modeling and the kinetic parameters predicted by the polynomial correlations were found to predict well the effluent water quality at 35 days SRT with above 80% phosphate reduction[16]. Work done on synthetic waste showed that, SBR with SRT of 10 days and cycle time of 10.5 hours obtained highest COD (94%), NH₄-N (84%) and PO₄-P (70%) removal efficiencies[6]. In the present SBR study, 26 days of SRT with 4 hours cycle time showed the expected high removal efficiency of COD (90%), nitrogen (92%) and phosphate (78%) than 16.1 days SRT of 6 hours cycle removal efficiency of COD (86%), nitrogen (93%) and phosphate (44%) (Figure 4).

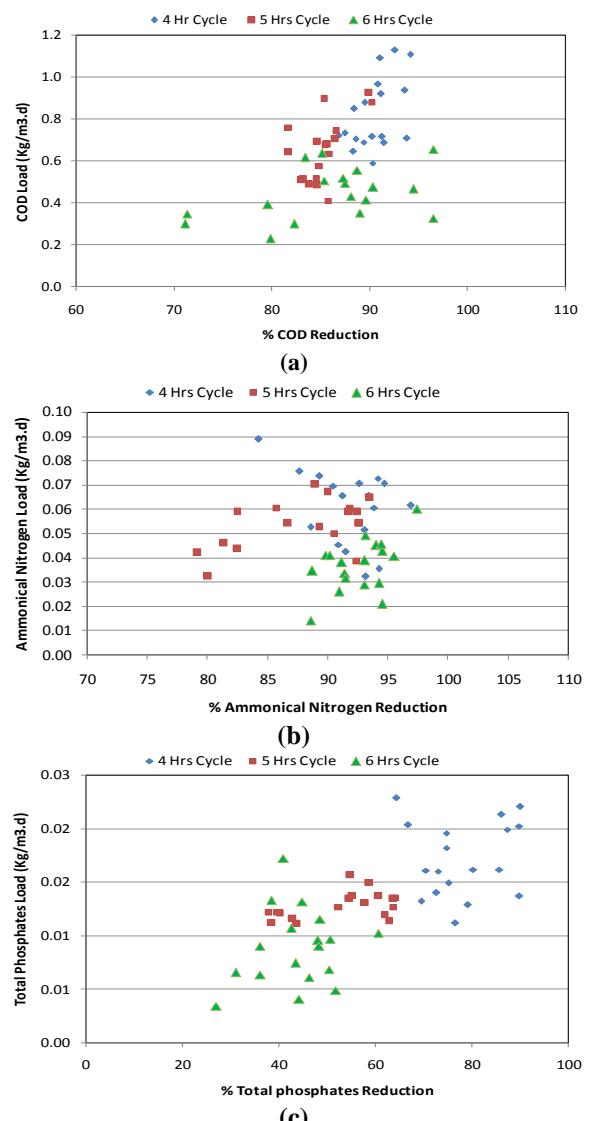


Figure 5. Total CNP loading rate compared with respective percentage reduction in SBR

CONCLUSION

SBR treatment technology has been evaluated for 4, 5 and 6 hours cycle with varying CNP loading rate, HRT and SRT. The CNP loading rates, aeration cycle phase, feed to anoxic-anaerobic ratio and SRT are the important parameters which can influence the SBR wastewater treatment performance. CNP loading rates are important to maintain the C:N:P ratios and require reaction times to achieve maximum treatment efficiency. Aeration cycle phase can be controlled for avoiding secondary phosphorus release and further sludge demineralization with increase in SVI. Providing proper feed to anoxic-anaerobic ratio will increase the denitrification and phosphate release efficiency and helps in sludge granulation. Present SBR study resulted with the optimum operating conditions on feed composition C:N:P of 100:8:2 were 4 hours of cycle time, SRT of 26 days and HRT of 12 hours with highest removal efficiency of COD (90%), nitrogen (92%) and phosphate (78%).

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Persian Abstract

DOI: 10.5829/idosi.ijee.2015.06.04.08

چکیده

محیط هواشنی و بیهوایی را می‌توان در راکتور تک مرحله‌ای ناپیوسته متوالی (SBR) شبیه سازی کرد. شرایط مختلف طراحی، یعنی ترکیبی از زمان مختلف فارها و زمان مختلف چرخه‌ها، زمان اقامت هیدرولیک (HRT)، سرعت بستر در حال بارگذاری، عمر لجن (SRT) و زمان هوادهی برای درمان بیولوژیکی مطلوب مورد بررسی قرار گرفت. دستگاه آزمایشگاهی با شرایط طراحی نسبت غذا به میکروب ۰,۲ در هر روز و ۴۹۵۰ mg/L MLSS ۳۰-۳۳٪ از حجم ریخته شده فاضلاب حاوی C:N:P برابر ۱۰۰:۸:۲ مورد بررسی قرار شده با توجه به طول چرخه ۴، ۵ و ۶ ساعت برای بررسی عملکرد بازده با ۱۲ HRT روز و ۲۵ روز ساعت شده است. تعیین توالی مطالعات انجام شده در چرخه ۴ ساعت منجر به حداقل راندمان حذف کلی مواد آلی و مغذی در SRT ۱۲ ساعت شده است. تعیین توالی گرفت. مطالعات انجام شده در چرخه ۴ ساعت منجر به حداقل راندمان حذف مواد آلی و مغذی در HRT ۷۸ و ۹۰ درصد بود. این مطالعه یک گزینه بالقوه از روند حذف SBR مواد مغذی با پایین ارائه می‌دهد.